



*Supplement of*

## **Changing effects of external forcing on Atlantic–Pacific interactions**

**Soufiane Karmouche et al.**

*Correspondence to:* Soufiane Karmouche (sou\_kar@uni-bremen.de)

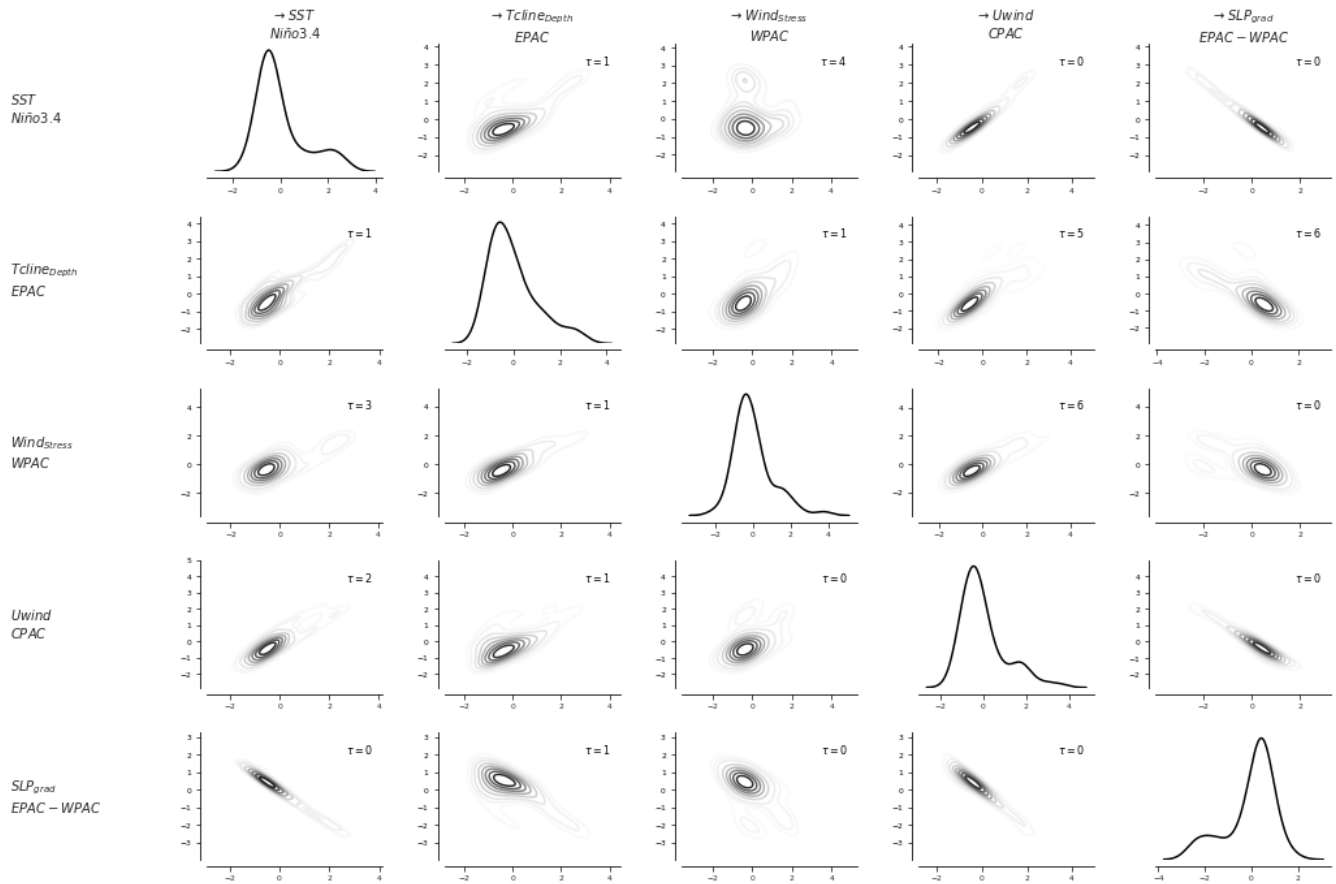
The copyright of individual parts of the supplement might differ from the article licence.

## List of Figures

	S1	Density plots derived from kernel density estimation (analogous to histograms) are shown off-diagonal. Along the diagonal, the marginal distributions are non-Gaussian for most variables. As mentioned in Sect 3.2, the skewed distributions are handled with the <i>RobustParcorr</i> conditional independence test in the proof of concept (Sect. 3.2.1).	2
5	S2	Lag function plot showing the lagged dependencies between the variables in Sect. 3.2.1 for six months. Most dependencies decay by $\tau = 3$ time steps, hence the choice for $\tau_{max} = 3$ [months] in the proof of concept (Sect. 3.2.1).	3
10	S3	Lagged p-value matrix for the cross-MCI coefficients in the causal graph shown Fig. 2b. The x-axis of each scatter subplot shows the time lag from $\tau_{min} = 0$ to $\tau_{max} = 3$ [months]. The p-values are shown on the y-axis for each pair (see variable names left and top of each subplot) and denote the uncertainty of each estimated dependency. The p-values below the significance threshold $\alpha_{pc}$ (here $\alpha_{pc}=0.1$ ) are shown in red.	4
15	S4	Ensemble-averaged indices from the Pacific pacemaker ensemble (10 members) for a) TNA, b) PNA, c) Niño3.4, d) PWCu, e) NAO, and f) ATL3 for the 1950-2014 period. The time series in orange (blue) represent the indices calculated before (after) subtracting MEM. Shadings denote the 25th-75th percentile range.	5
	S5	Same as Fig. S4 but for the Atlantic pacemaker ensemble (10 members) for the 1950-2013 period.	6
20	S6	Lagged p-value matrices for the coefficients on the causal graphs shown in Fig. 3b and c. The Figure is rotated $90^\circ$ to the left to fit the page format. a) There are five subplots for the five windows analyzed in each panel (see corresponding Fig 3b) each resembling the p-values matrix shown in Fig. S3 but for the indices and parameters used in Sect. 4.1. Here, $\tau_{min} = 0$ and $\tau_{max} = 4$ [seasons i.e. 3-monthly averages]. The p-values below the significance threshold $\alpha_{pc}$ (here $\alpha_{pc}=0.2$ ) are shown in red. Panel (a) corresponds to causal graphs in Fig. 3b (OBS, see the title and corresponding subtitles in Fig. 3b for each window period). The pairs of adjacencies that were not estimated following assumptions (listed in Sect. 3.2.2) have p-values approaching 1. b) Same as (a) but correspond to graphs shown in Fig. 3c (OBS minus MEM).	7
25	S7	Causal graphs with no background knowledge. a) PCMCi+ causal networks corresponding to the ones shown in Fig. 3b obtained when no assumptions are introduced i.e. all dependencies between all variables at all lags (up to $\tau_{max}$ ) are considered. These might contain conflicting ( $X_i^t \times - \times X_j^t$ ). b) Same as (a) but for the causal graphs of Fig. 3c.	8
30	S8	Similar to Figs S3 and S6 but for causal graphs shown Fig 4 (panels a-d here correspond to panels a-d in Fig. 4). Significance threshold $\alpha_{pc}$ is set to 0.2 here.	9
	S9	Similar to Fig. S7 but for the causal graphs in Fig. 4 (panels a-d here correspond to panels a-d in Fig. 4).	10
35	S10	Similar to Figs S6 but for causal graphs shown Fig. 5b and c. The significance threshold $\alpha_{pc}$ is set to 0.01 here.	11
	S11	Similar to Fig. S7 but for the causal graphs in Fig. 5b and c.	12
	S12	Similar to Figs S6 but for causal graphs shown Fig. 6b and c. The significance threshold $\alpha_{pc}$ is set to 0.01 here.	13
40	S13	Similar to Fig. S7 but for the causal graphs in Fig. 6b and c.	14
	S14	Similar to Fig. S6 but for the causal graphs shown in Fig. 7a-d. The significance threshold $\alpha_{pc}$ is set to 0.05 here.	15
	S15	Similar to Fig. S7 but for corresponding to the causal graphs in Fig. 8 (panels a-d here correspond to panels a-d in Fig. 8)	16

## 45 1 Supplementary Material for Section 3.2.1 (Proof of Concept)

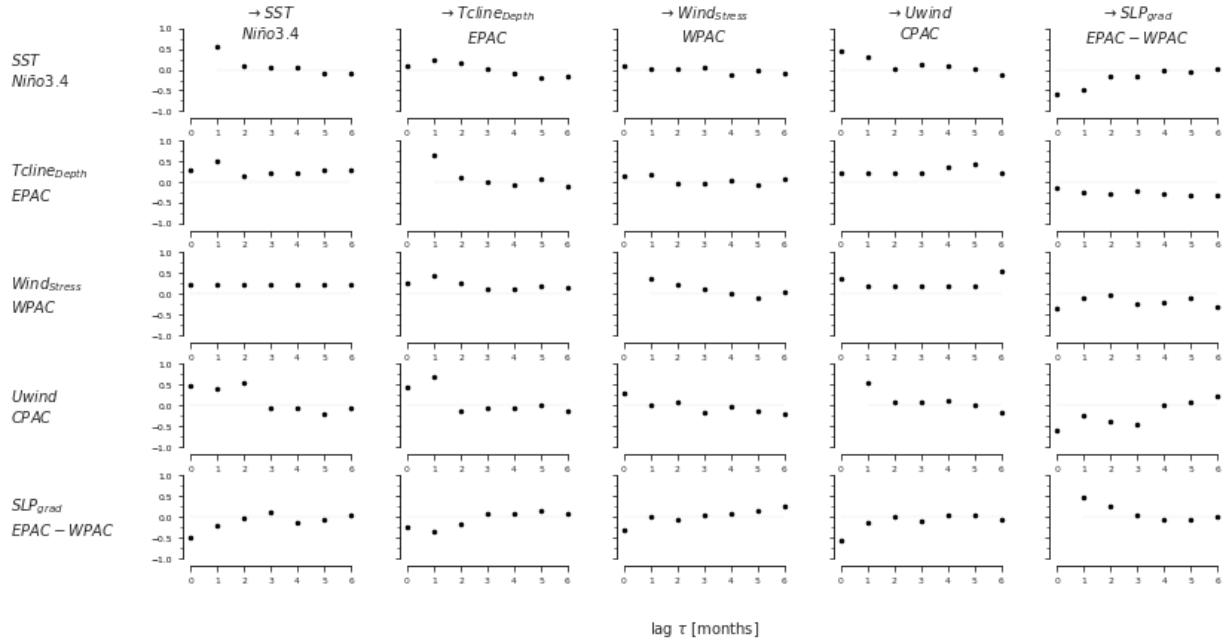
Figures S1 and S2 show two of the pre-processing steps taken to decide the conditional independence test (Fig. S1) and the maximum time lag  $\tau_{max}$  (Fig. S2) during the PCMCI+ analysis. The non-Gaussian marginal distribution and hence the use of *RobustParcorr* is only applicable for Sect. 3.2.1. The density plots for the data used in Sect. 4 (not shown) did not reveal such distributions, hence, *Parcorr* was used as conditional independence test there. Similar to Fig. S2, the lag function plots for the variables in Sect. 4 (not shown) are analyzed to decide  $\tau_{max}$ . Except for a PNA-NAO connection at 8-season lag (having no physical basis), all dependencies decay after a maximum lag of 4 time lag steps, hence the use of  $\tau_{max} = 4$  seasons. Figure S3 shows the p-values (uncertainty) associated with the PCMCI+ estimated coefficients during the proof-of-concept analysis shown in Fig. 2.



**Figure S1.** Density plots derived from kernel density estimation (analogous to histograms) are shown off-diagonal. Along the diagonal, the marginal distributions are non-Gaussian for most variables. As mentioned in Sect 3.2, the skewed distributions are handled with the *RobustParcorr* conditional independence test in the proof of concept (Sect. 3.2.1).

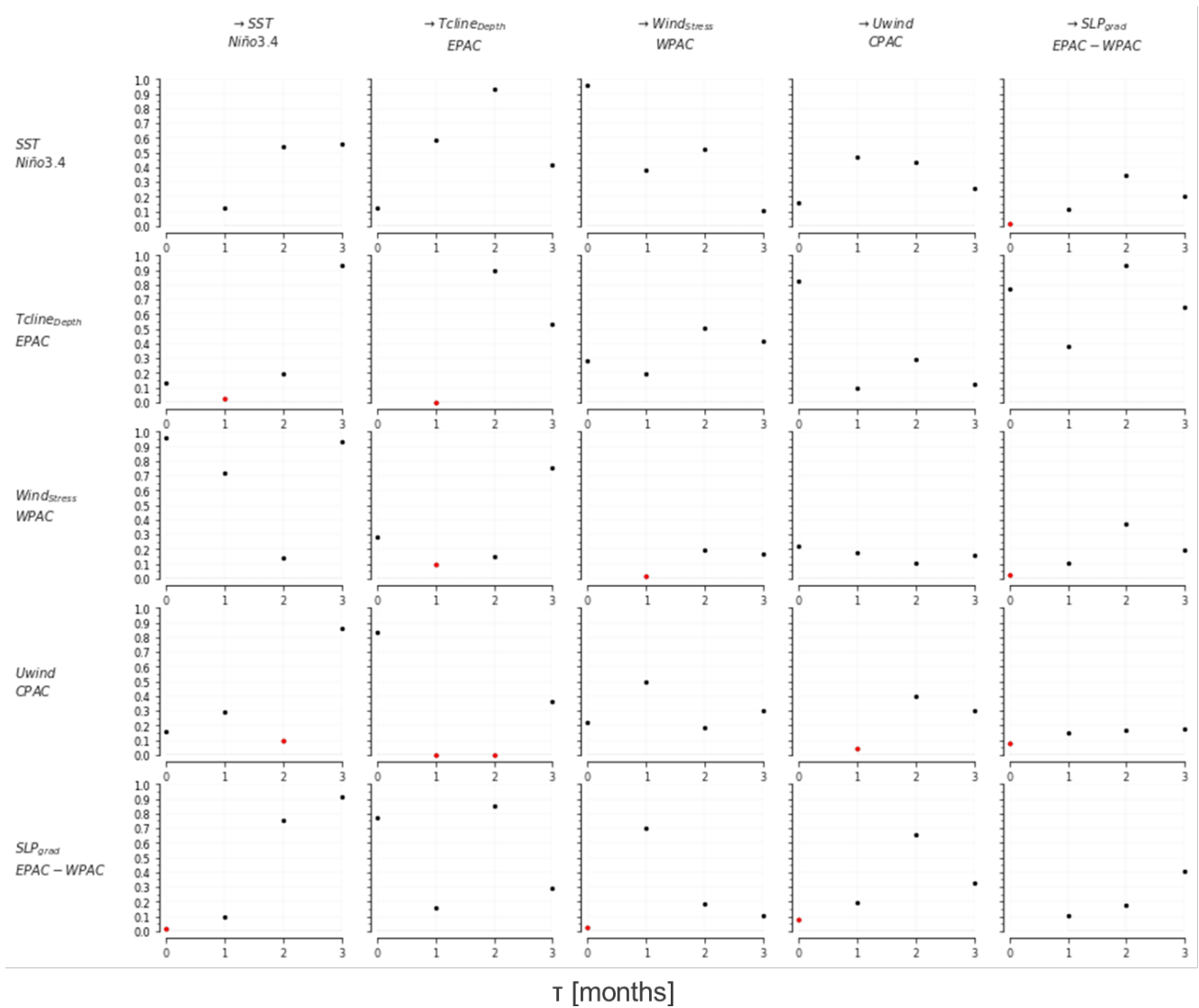
## 2 Supplementary Material for Section 4

55 In this supplementary section, we show the averaged time series of the six variables used in the analysis of Atlantic-Pacific interactions (Sect. 4.2) for the Pacific pacemaker ensemble (Fig. S4) and the Atlantic pacemaker ensemble (Fig. S5). The p-value

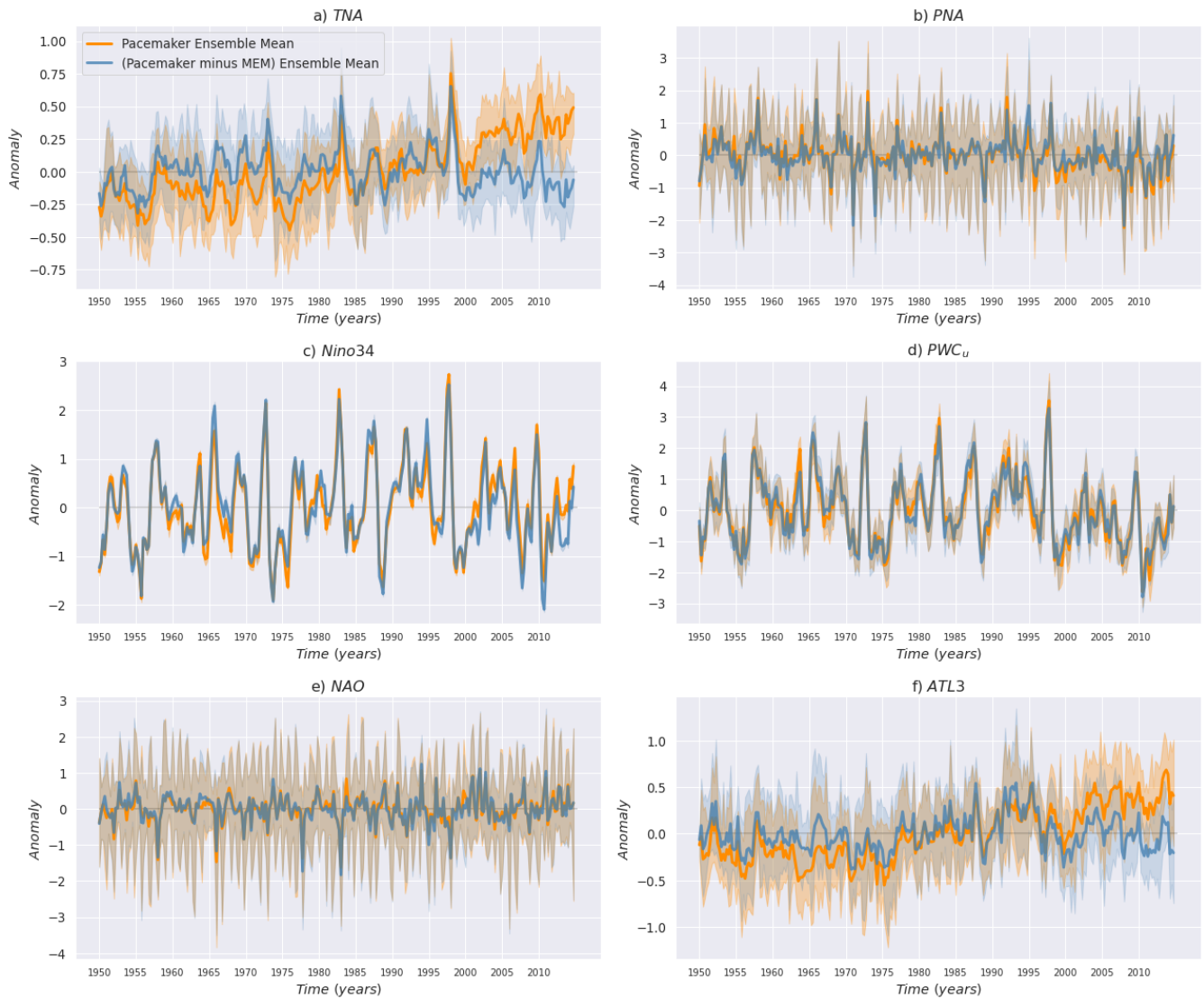


**Figure S2. Lag function plot showing the lagged dependencies between the variables in Sect. 3.2.1 for six months. Most dependencies decay by  $\tau = 3$  time steps, hence the choice for  $\tau_{max} = 3$  [months] in the proof of concept (Sect. 3.2.1).**

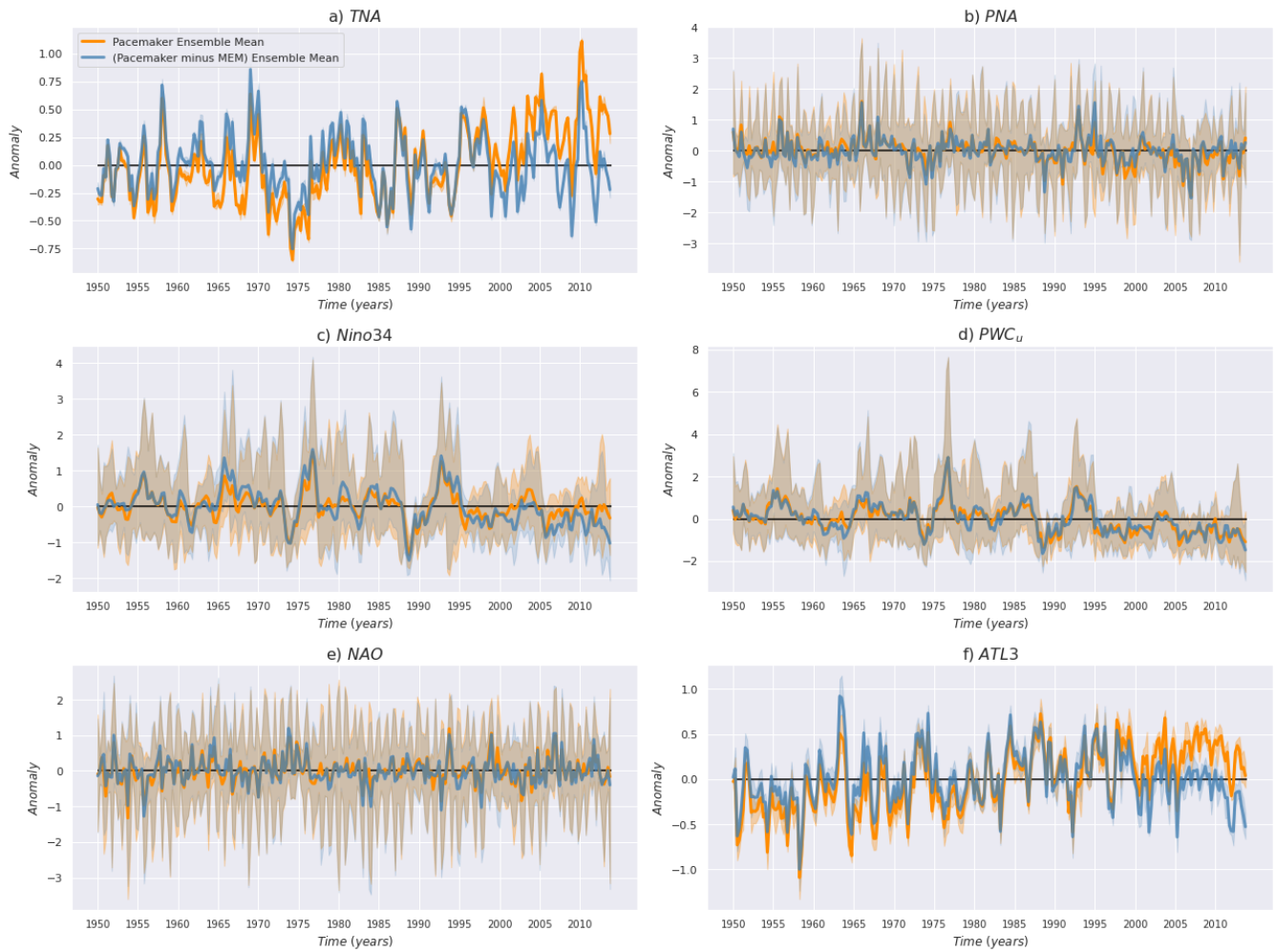
60 matrices for the PCMCI+ estimated dependencies (the coefficients in all causal graphs) in Sect. 4. These present an uncertainty measure of the respective cross(auto)-MCI coefficients. The links shown on the causal graph have p-values lower than  $\alpha_{pc}$  and are shown in red in the odd-numbered Figs S7-15. The significant threshold  $\alpha_{pc}$  is set to 0.2 in Sect. 4.1, 0.01 in Sect. 4.2, and 0.05 in Sect. 4.3. We also show in the even-numbered Figs S6-14, the causal graphs obtained through PCMCI+ when no background knowledge is introduced. As discussed in methods (Sect. 3), the PCMCI+ networks might contain conflicting links ( $X_i^t \times - \times X_j^t$ ) at lag zero. The potential differences between the links shown here (Supplementary material) and the ones on the main manuscript lie in the adjacencies that were not considered by PCMCI+ due to the assumptions introduced and listed in Sect. 3.2.2 (based on background knowledge, sensitive analyses, and inspection of the conflicting edges).



**Figure S3.** Lagged p-value matrix for the cross-MCI coefficients in the causal graph shown Fig. 2b. The x-axis of each scatter subplot shows the time lag from  $\tau_{min} = 0$  to  $\tau_{max} = 3$  [months]. The p-values are shown on the y-axis for each pair (see variable names left and top of each subplot) and denote the uncertainty of each estimated dependency. The p-values below the significance threshold  $\alpha_{pc}$  (here  $\alpha_{pc}=0.1$ ) are shown in red.



**Figure S4.** Ensemble-averaged indices from the Pacific pacemaker ensemble (10 members) for a) TNA, b) PNA, c) Niño3.4, d) PWC<sub>u</sub>, e) NAO, and f) ATL3 for the 1950-2014 period. The time series in orange (blue) represent the indices calculated before (after) subtracting MEM. Shadings denote the 25th-75th percentile range.

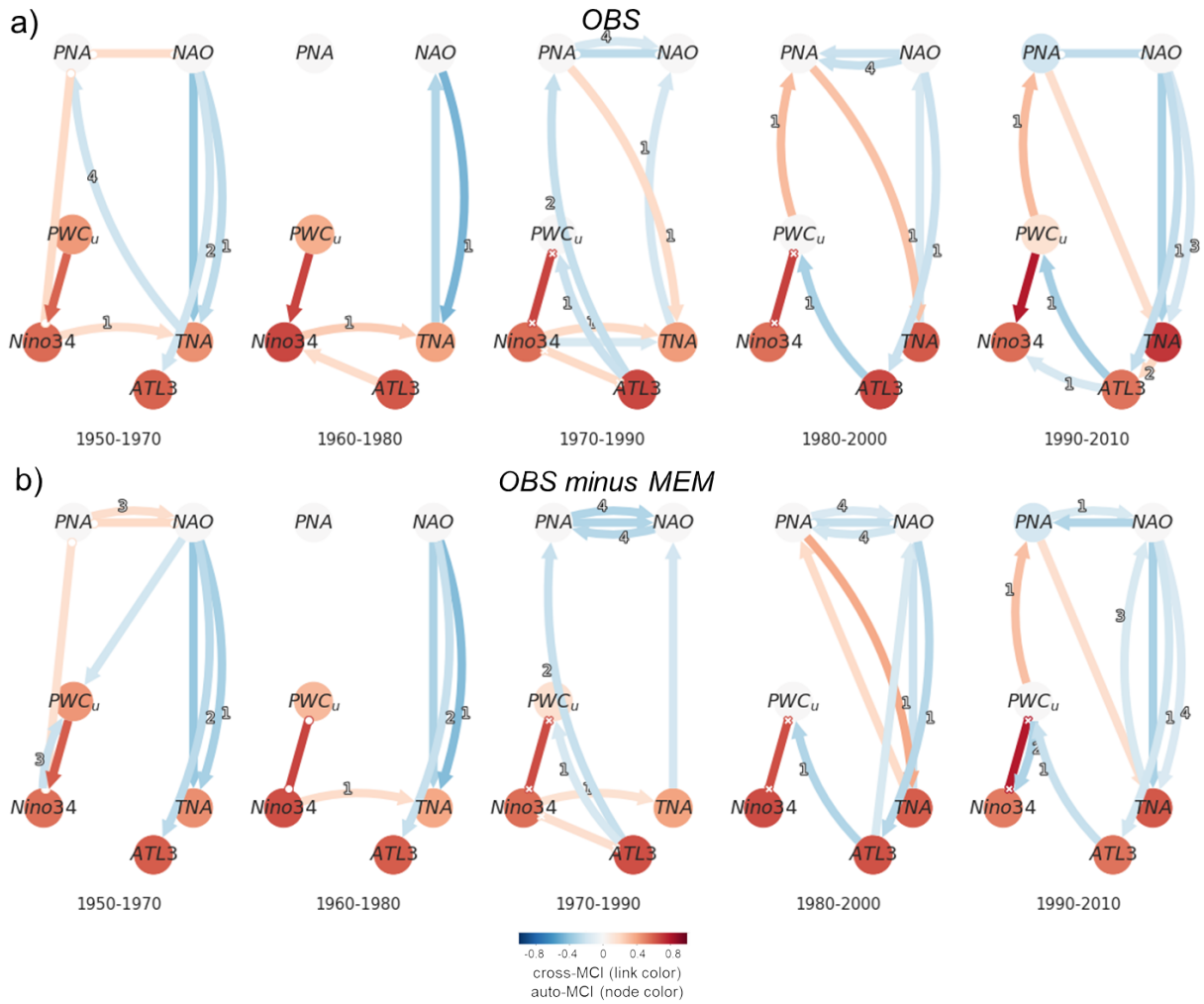


**Figure S5.** Same as Fig. S4 but for the Atlantic pacemaker ensemble (10 members) for the 1950-2013 period.



Figure S6. Lagged p-value matrices for the coefficients on the causal graphs shown in Fig. 3b and c. The Figure is rotated  $90^\circ$  to the left to fit the page format. a) The are five subplots for the five windows analyzed in each panel (see corresponding Fig 3b) each resembling the p-values matrix shown in Fig. S3 but for the indices and parameters used in Sect. 4.1. Here,  $\tau_{min} = 0$  and  $\tau_{max} = 4$  [seasons i.e. 3-monthly averages]. The p-values below the significance threshold  $\alpha_{pc}$  (here  $\alpha_{pc}=0.2$ ) are shown in red. Panel (a) corresponds to causal graphs in Fig. 3b (OBS, see the title and corresponding subtitles in Fig. 3b for each window period). The pairs of adjacencies that were not estimated following assumptions (listed in Sect. 3.2.2) have p-values approaching 1. b) Same as (a) but correspond to graphs shown in Fig. 3c (OBS minus MEM).





**Figure S7. Causal graphs with no background knowledge. a) PCMCI+ causal networks corresponding to the ones shown in Fig. 3b obtained when no assumptions are introduced i.e. all dependencies between all variables at all lags (up to  $\tau_{max}$ ) are considered. These might contain conflicting ( $X_i^t \times - \times X_j^t$ ). b) Same as (a) but for the causal graphs of Fig. 3c.**

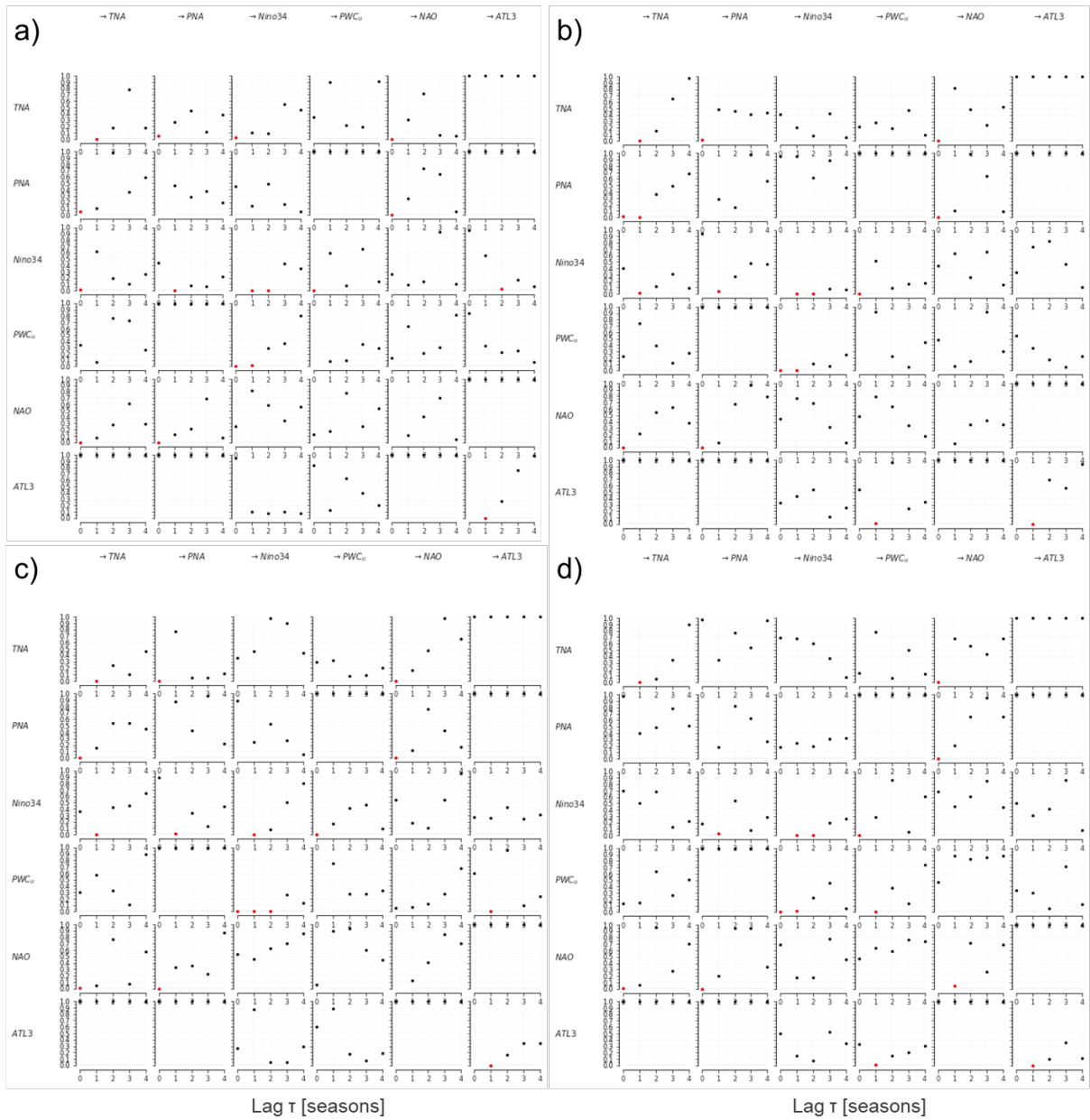


Figure S8. Similar to Figs S3 and S6 but for causal graphs shown Fig 4 (panels a-d here correspond to panels a-d in Fig. 4). Significance threshold  $\alpha_{pc}$  is set to 0.2 here.

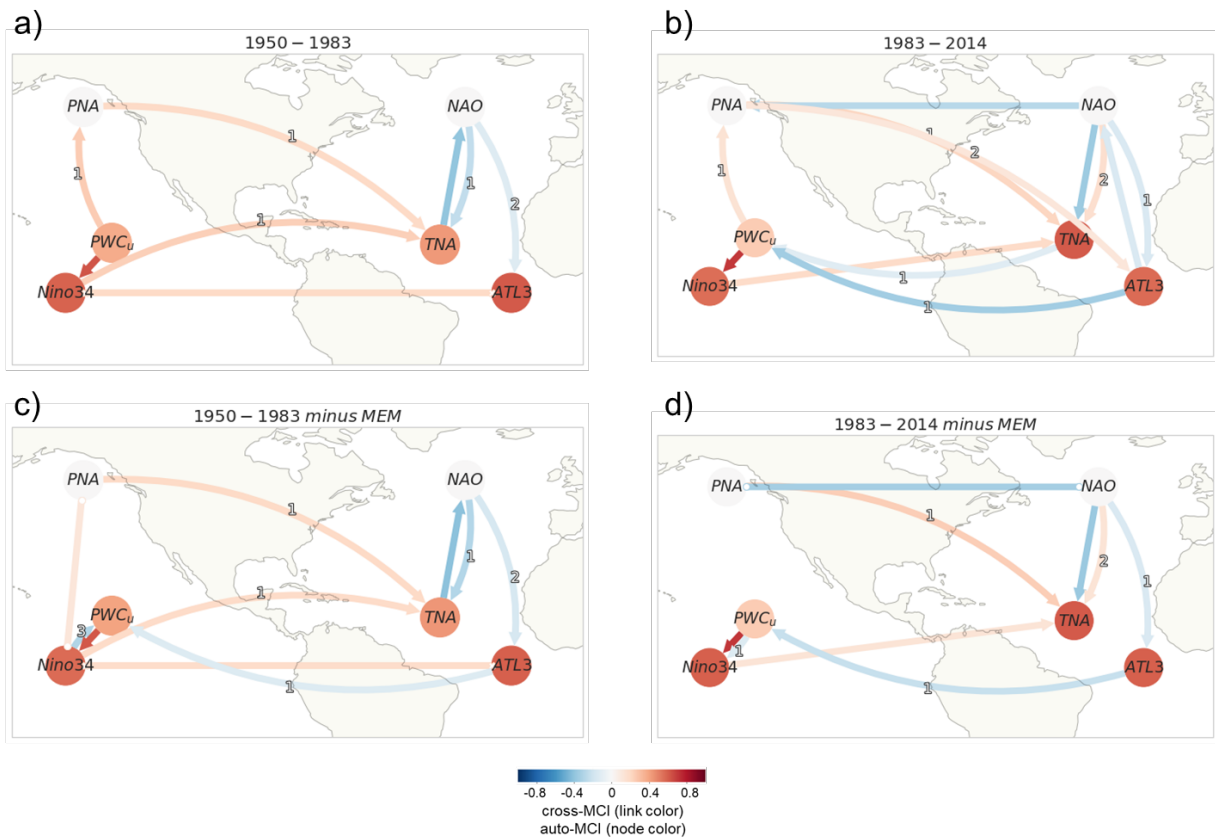
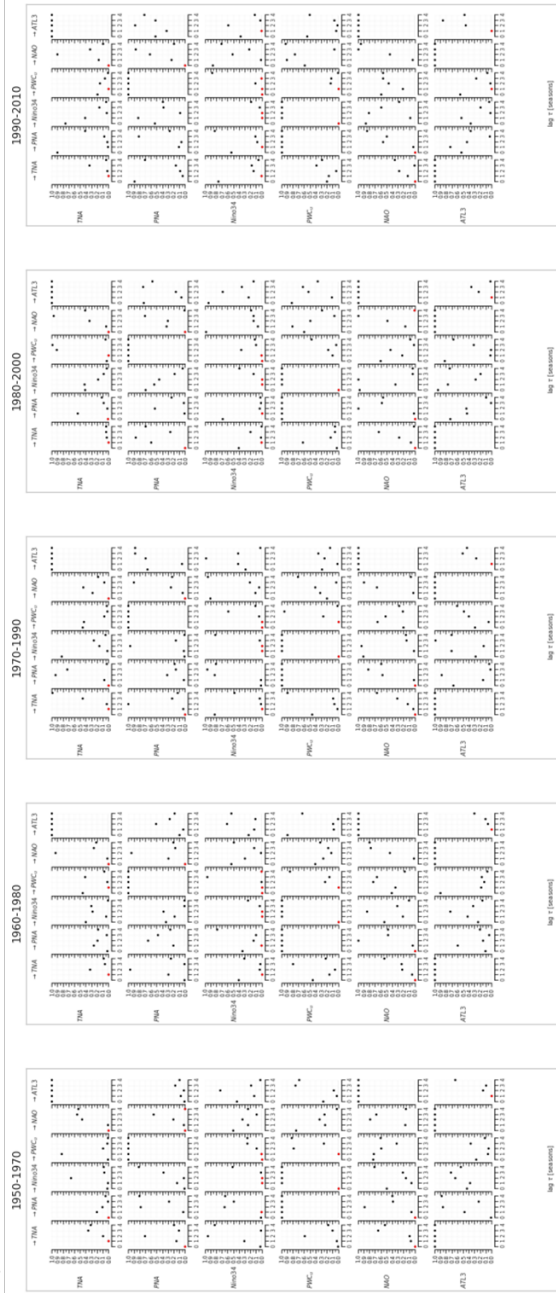


Figure S9. Similar to Fig. S7 but for the causal graphs in Fig. 4 (panels a-d here correspond to panels a-d in Fig. 4).

*Pacific pacemaker*

a)



b)

*Pacific pacemaker minus MEM*

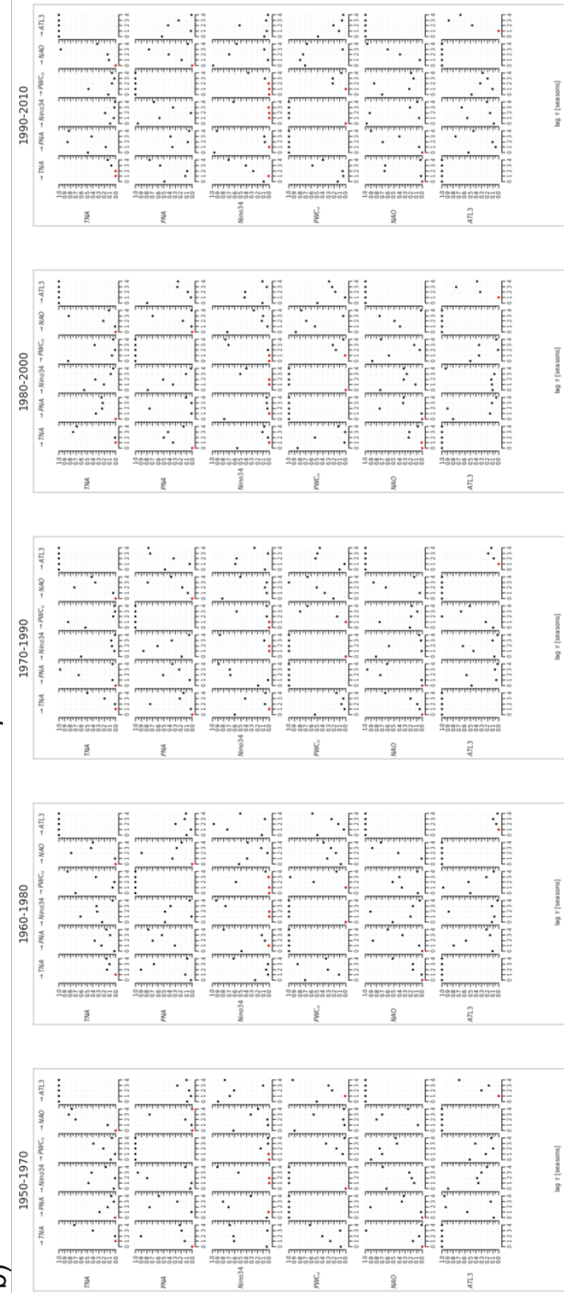


Figure S10. Similar to Figs S6 but for causal graphs shown Fig. 5b and c. The significance threshold  $\alpha_{pc}$  is set to 0.01 here.

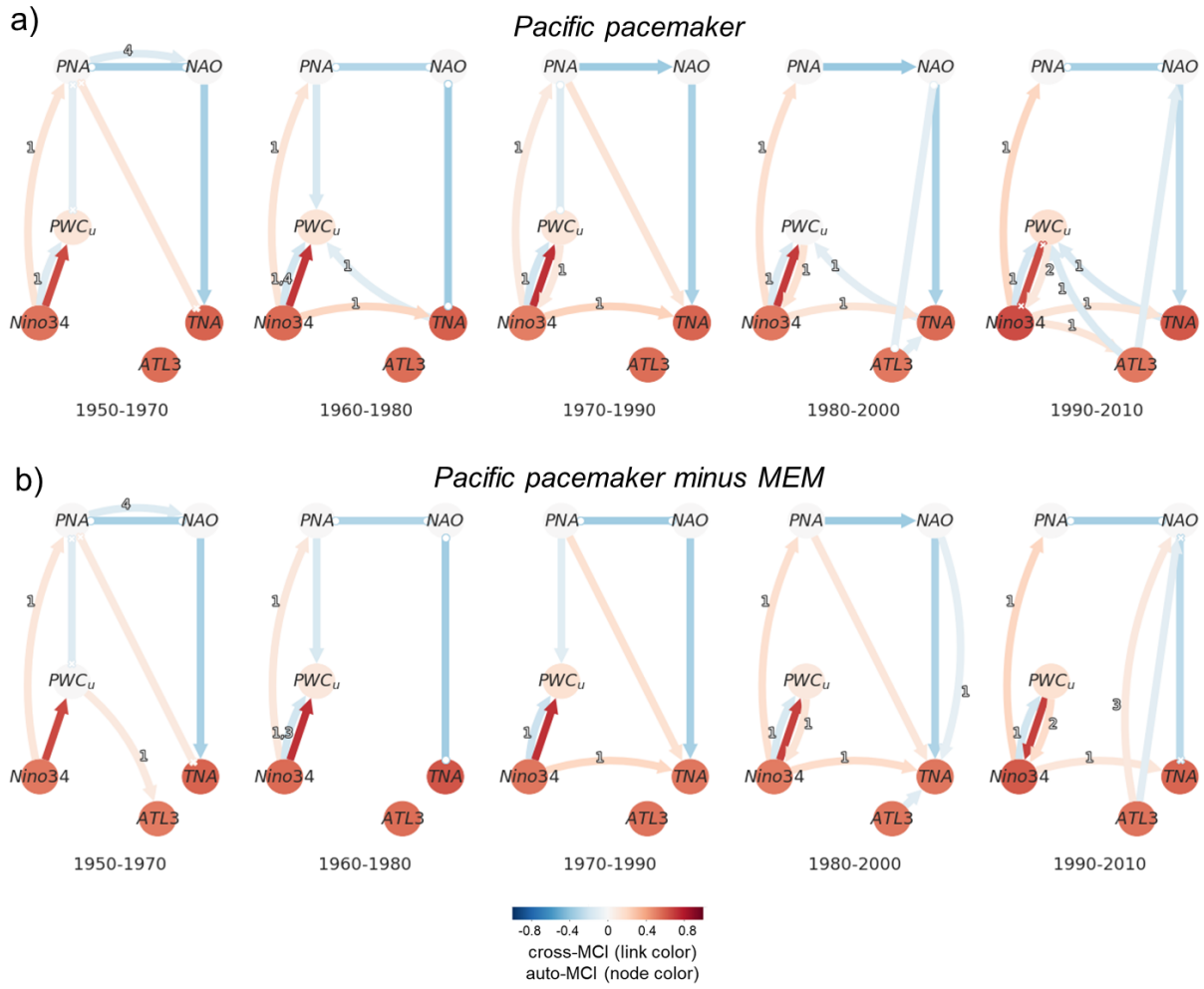
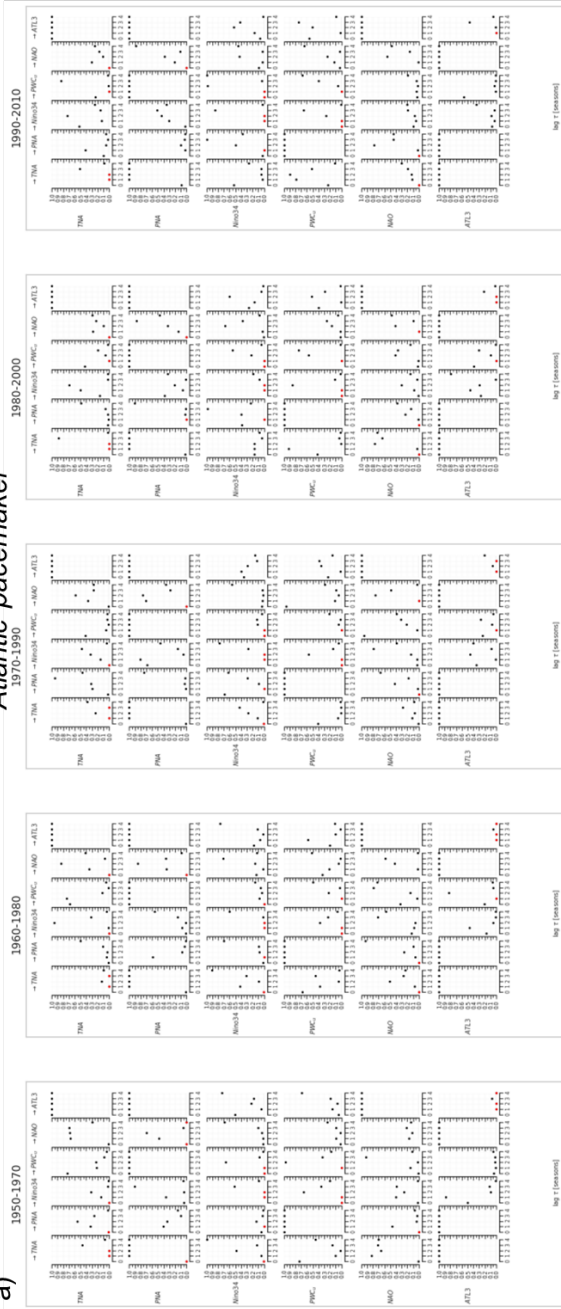


Figure S11. Similar to Fig. S7 but for the causal graphs in Fig. 5b and c.

*Atlantic pacemaker*

a)



*Atlantic pacemaker minus MEM*

b)

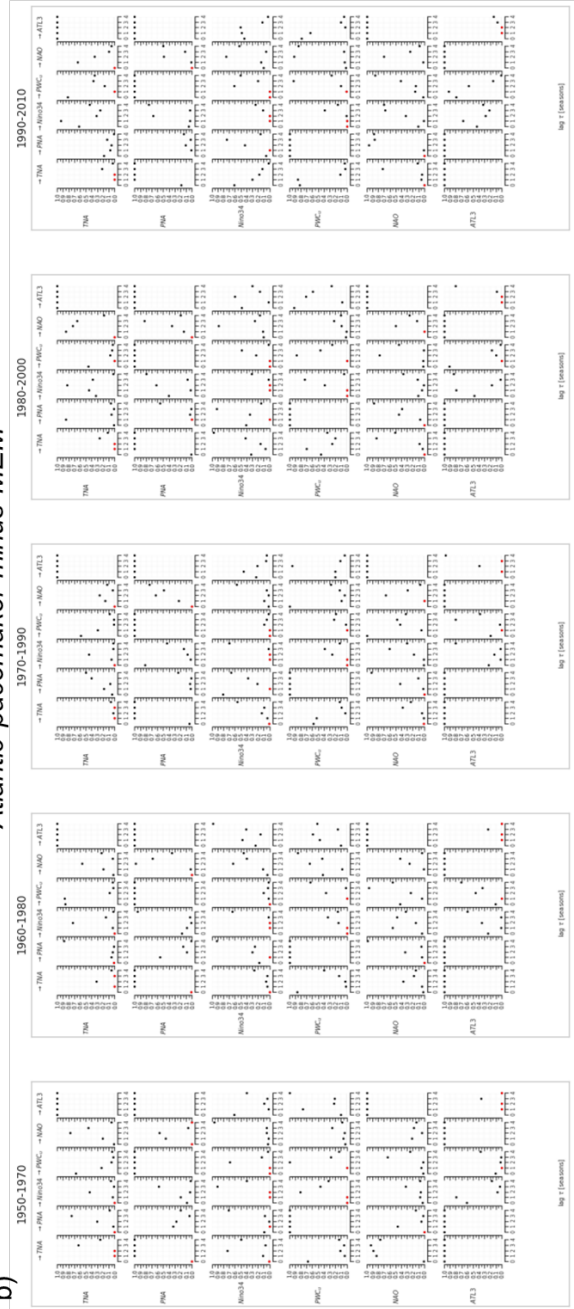


Figure S12. Similar to Figs S6 but for causal graphs shown Fig. 6b and c. The significance threshold  $\alpha_{pc}$  is set to 0.01 here.

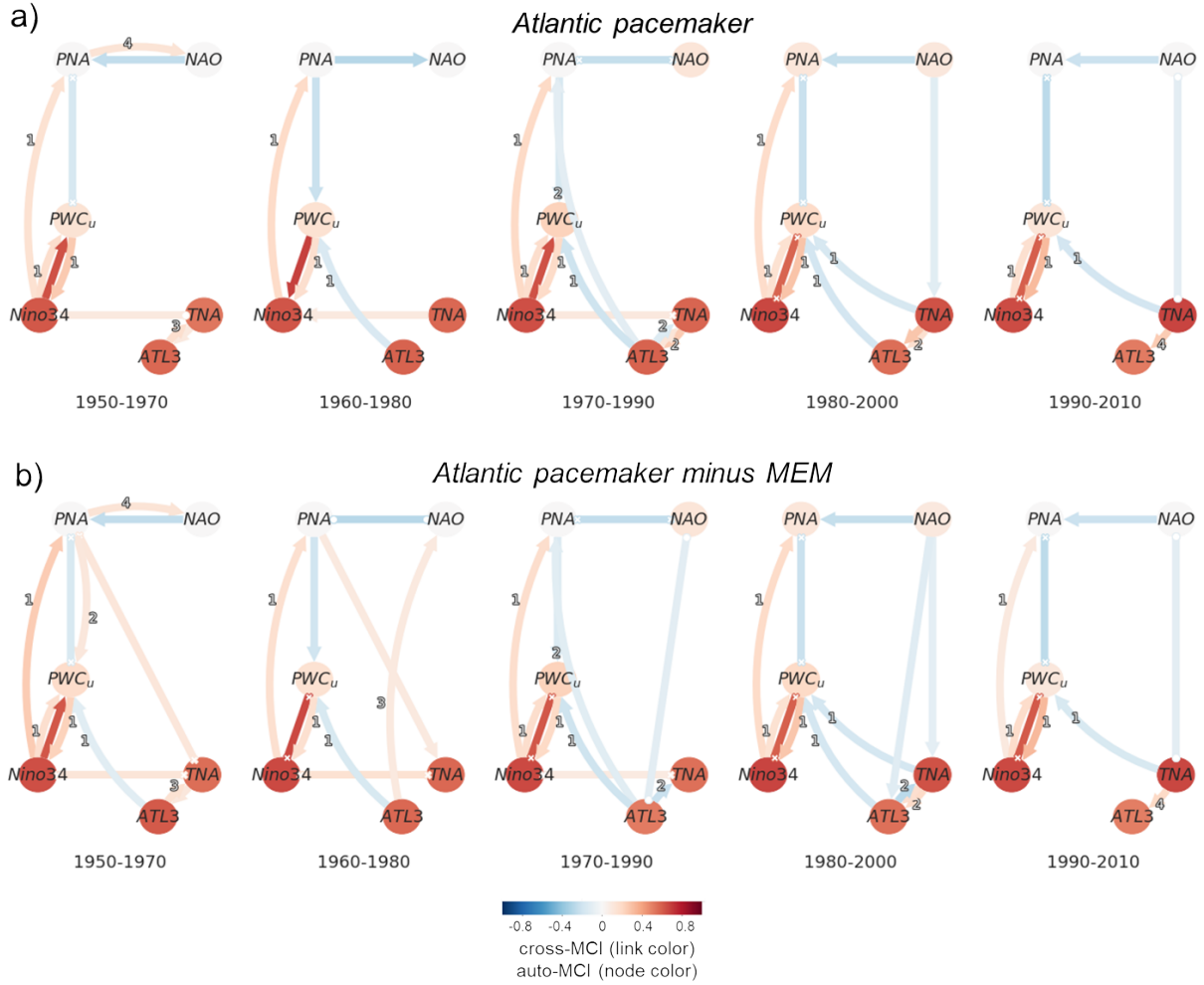


Figure S13. Similar to Fig. S7 but for the causal graphs in Fig. 6b and c.

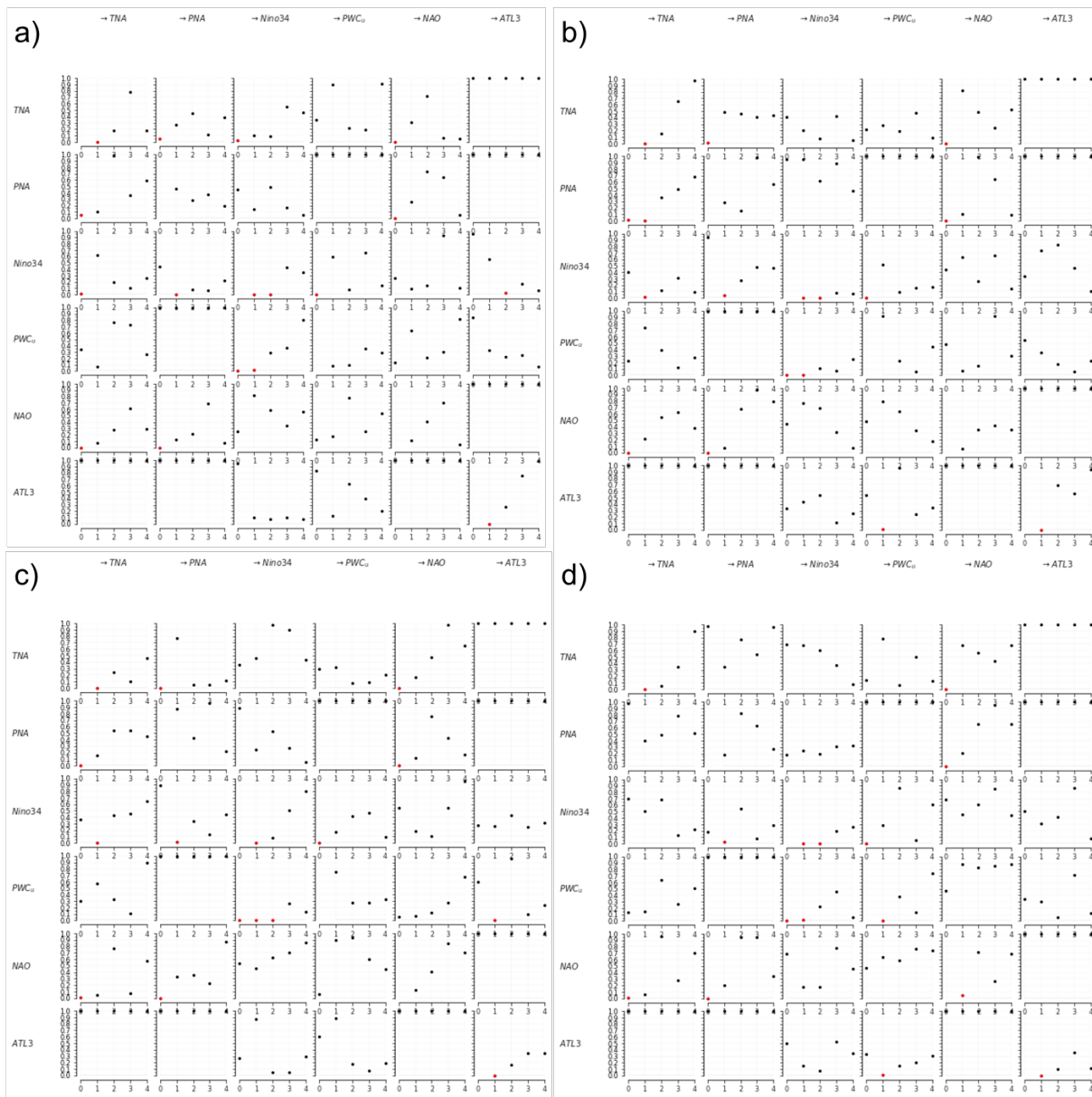


Figure S14. Similar to Fig. S6 but for the causal graphs shown in Fig. 7a-d. The significance threshold  $\alpha_{pc}$  is set to 0.05 here.



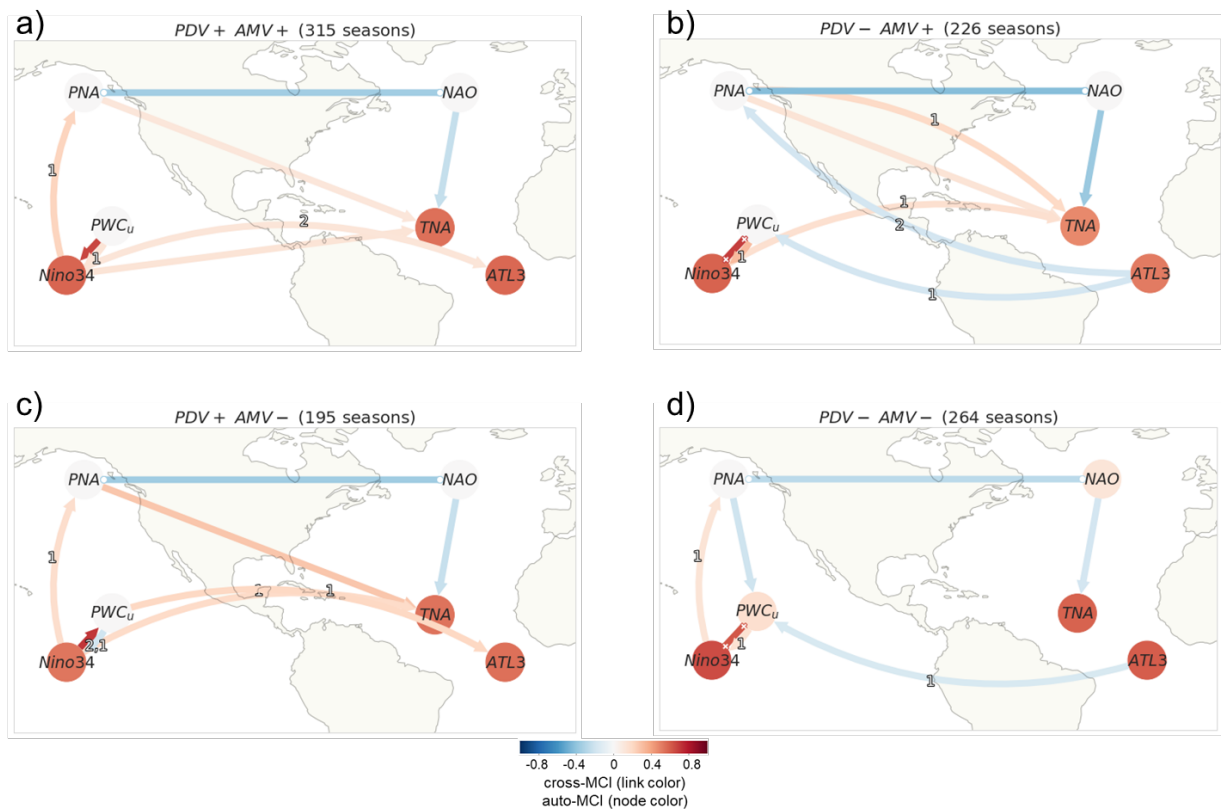


Figure S15. Similar to Fig. S7 but for corresponding to the causal graphs in Fig. 8 (panels a-d here correspond to panels a-d in Fig. 8)