Supporting Information for

Strengthened causal connections between the MJO and the North Atlantic with climate warming

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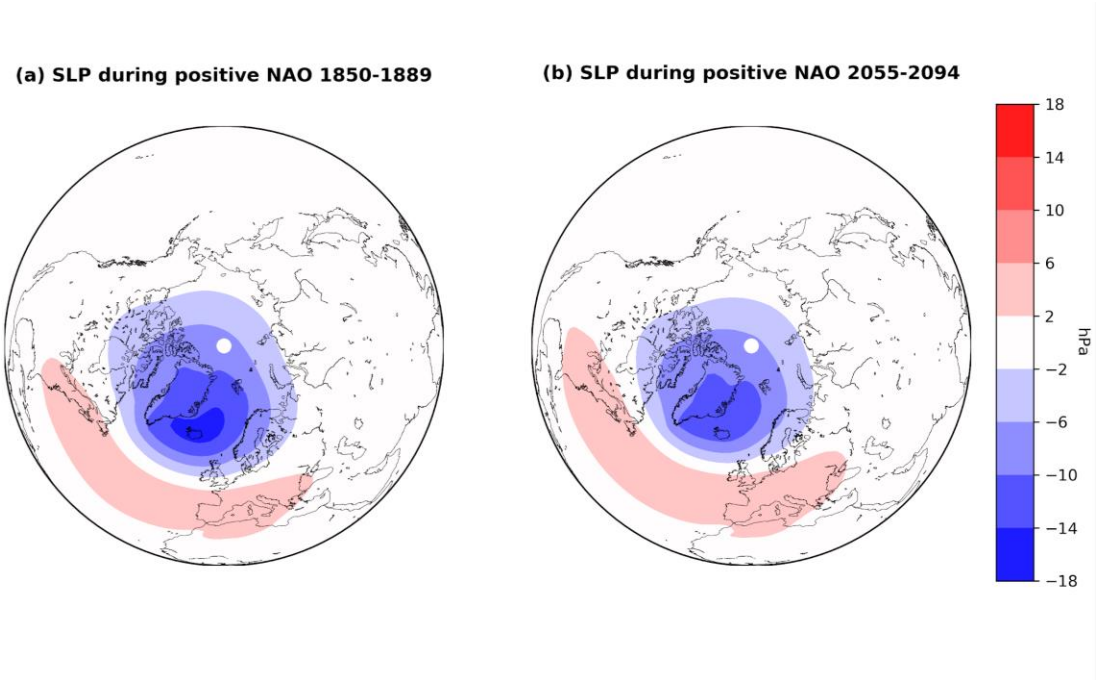
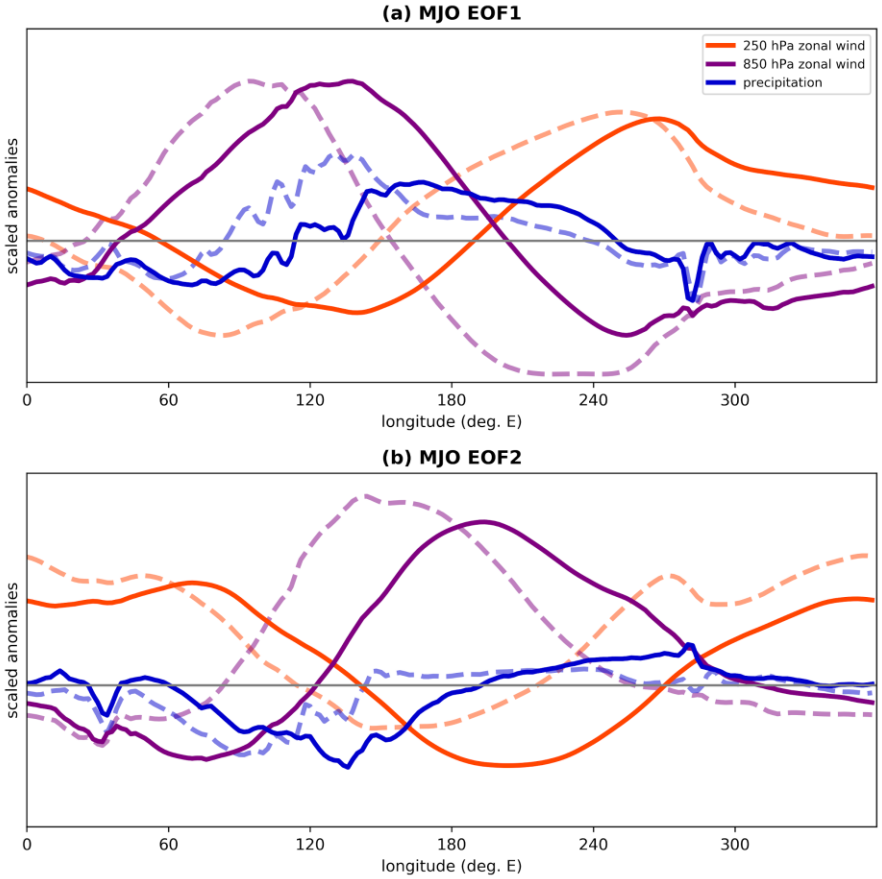
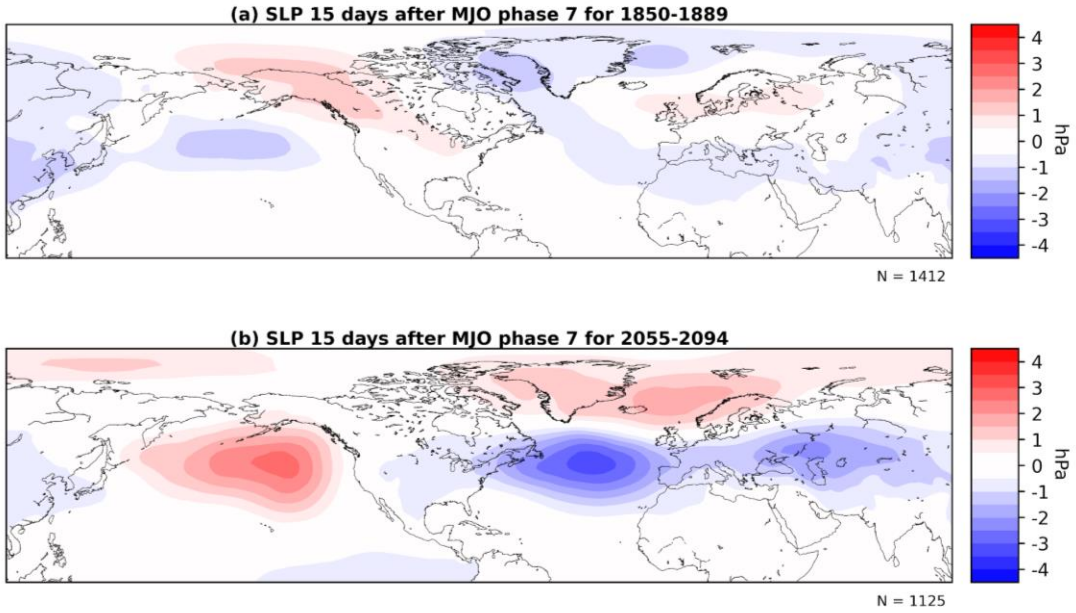


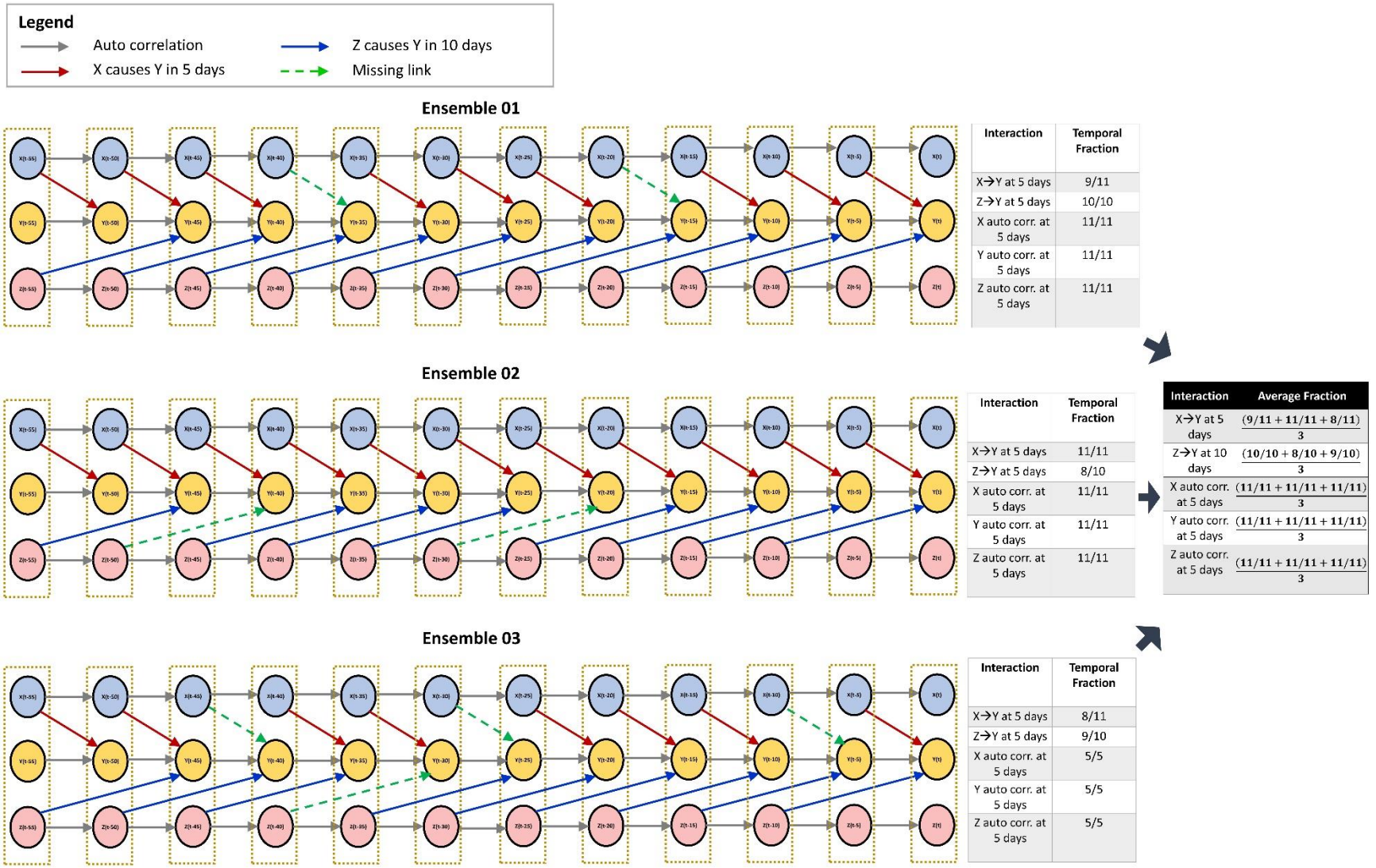
Supp. Figure 1: Ensemble-mean composites of winter-time sea-level pressure anomalies during the positive phase of the North Atlantic Oscillation over (a) 1850-1889 and (b) 2055-2094, under historical and SSP585 forcing, respectively.



Supp. Figure 2: Ensemble-mean MJO (a) EOF 1, (b) EOF 2 as a function of longitude and separated by variable. Dashed lines denote the historical period (1850-1889) and solid lines denote the future period (2055-2094).



Supp. Figure 3: Average over 3 ensemble members from the historical and SSP585 simulations of sea-level pressure anomalies 15 days following MJO phase 3 events for periods under (a) historical (1850-1889; members 1, 2, 3) and (b) SSP585 forcings (2055-2094; members 4, 10, 11).



Interaction	Temporal Fraction
X→Y at 5 days	9/11
Z→Y at 5 days	10/10
X auto corr. at 5 days	11/11
Y auto corr. at 5 days	11/11
Z auto corr. at 5 days	11/11

Interaction	Temporal Fraction
X→Y at 5 days	11/11
Z→Y at 5 days	8/10
X auto corr. at 5 days	11/11
Y auto corr. at 5 days	11/11
Z auto corr. at 5 days	11/11

Interaction	Temporal Fraction
X→Y at 5 days	8/11
Z→Y at 5 days	9/10
X auto corr. at 5 days	5/5
Y auto corr. at 5 days	5/5
Z auto corr. at 5 days	5/5

Interaction	Average Fraction
X→Y at 5 days	$\frac{(9/11 + 11/11 + 8/11)}{3}$
Z→Y at 10 days	$\frac{(10/10 + 8/10 + 9/10)}{3}$
X auto corr. at 5 days	$\frac{(11/11 + 11/11 + 11/11)}{3}$
Y auto corr. at 5 days	$\frac{(11/11 + 11/11 + 11/11)}{3}$
Z auto corr. at 5 days	$\frac{(11/11 + 11/11 + 11/11)}{3}$

Supp. Figure 4: A toy example of three Directed Acyclic Graphs (DAGs) learned by PC stable for three different ensemble members of a climate model.

In Supp. Figure 4, each DAG is a temporal model consisting of lagged copies of the variables. X(t) represents the original time series of variable X, while for example, X(t-25) represents the time series that is lagged by 25 days. We expect any robust causal interactions between variables to repeat consistently in the temporal models. An interaction that pops up arbitrarily may indicate a false discovery. We calculate a temporal consistency fraction as a means to distinguish the robust connections from false discoveries. In this model, an interaction between X and Y at a time delay of 5 can occur a maximum of 11 times as X(t-55)→Y(t-50), X(t-50)→Y(t-45), ..., X(t-10)→Y(t-5), and X(t-5)→Y(t). In the DAG for ensemble 01, this interaction occurs 9 out of the 11 possible times, with missing interactions (represented by green dashed arrows) between X(t-40)→Y(t-35), and X(t-20)→Y(t-15) resulting in a temporal consistency fraction of 9/11. Similarly, an interaction between Z and Y at a time delay of 10 days can occur a maximum of 10 times. This interaction occurs 10 times in this DAG resulting in a fraction of 10/10. We average the temporal fraction of each interaction over the different DAGs to understand how robust these signals are in the climate model. For example, the average fraction for the X→Y interaction at a 5-day delay is calculated as (9/11+11/11+8/11)/3.