Supporting Information for

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

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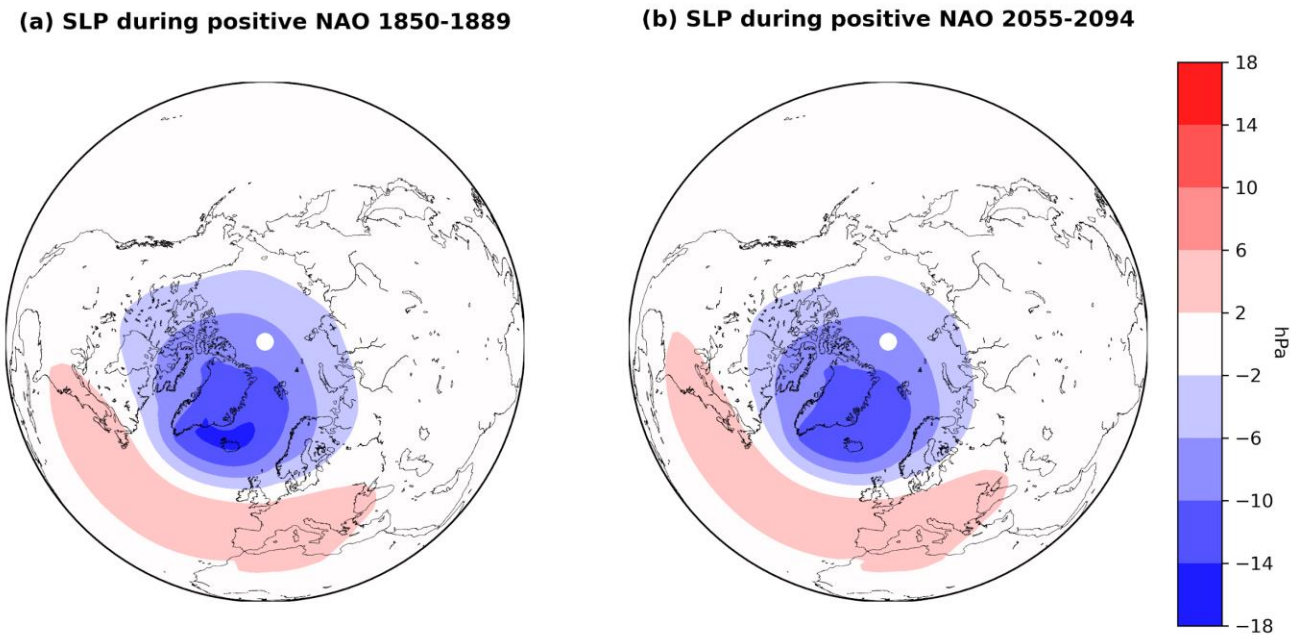
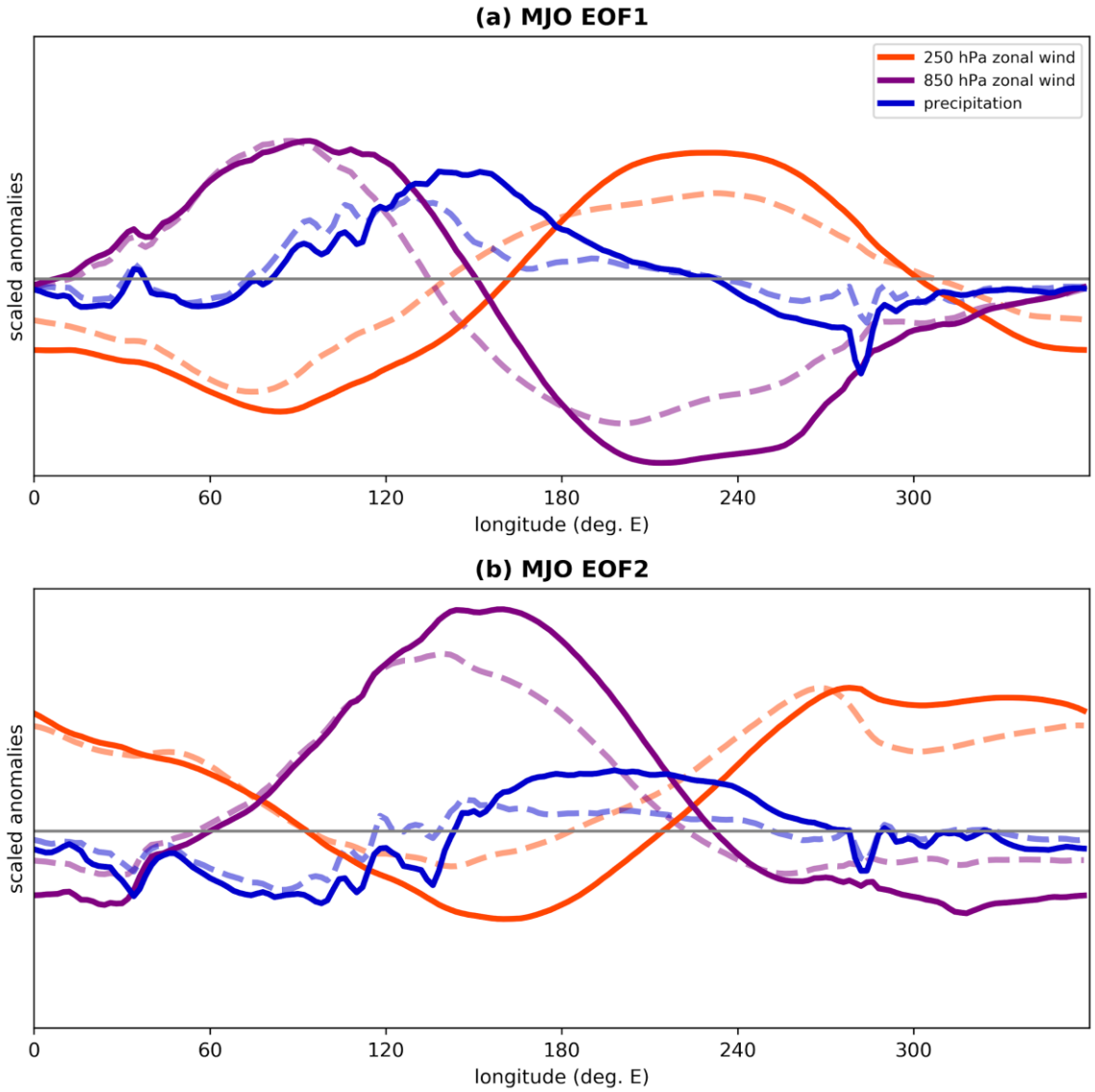
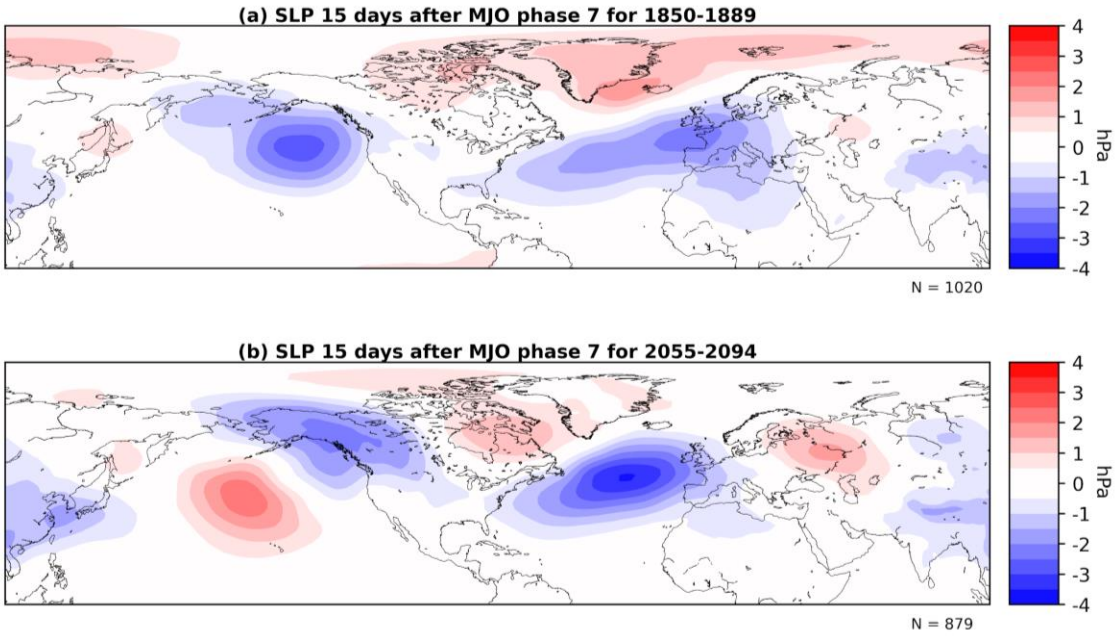


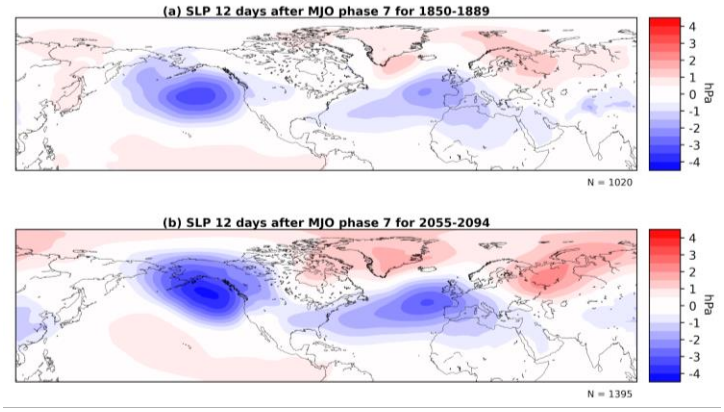
Supp. Figure 1: Ensemble-mean composites of winter-time sea-level pressure anomalies during the positive phase of the North Atlantic Oscillation over (a) 1850-1889 (historical; 3 members) and (b) 2055-2094 (SSP585; 5 members), under historical and SSP585 forcing, respectively.

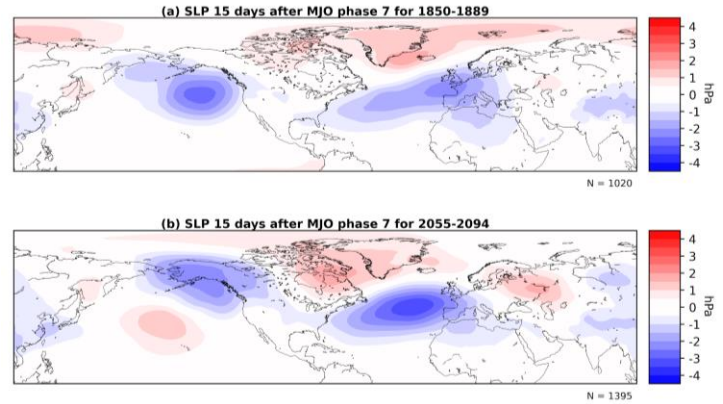


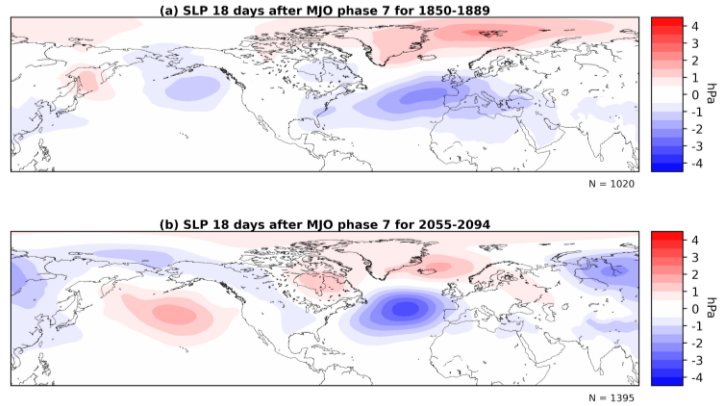
Supp. Figure 2: Ensemble-mean MJO (a) EOF 1, (b) EOF 2 as a function of longitude and separated by variable. Dashed lines denote the historical period (1850-1889) and solid lines denote the future period (2055-2094).



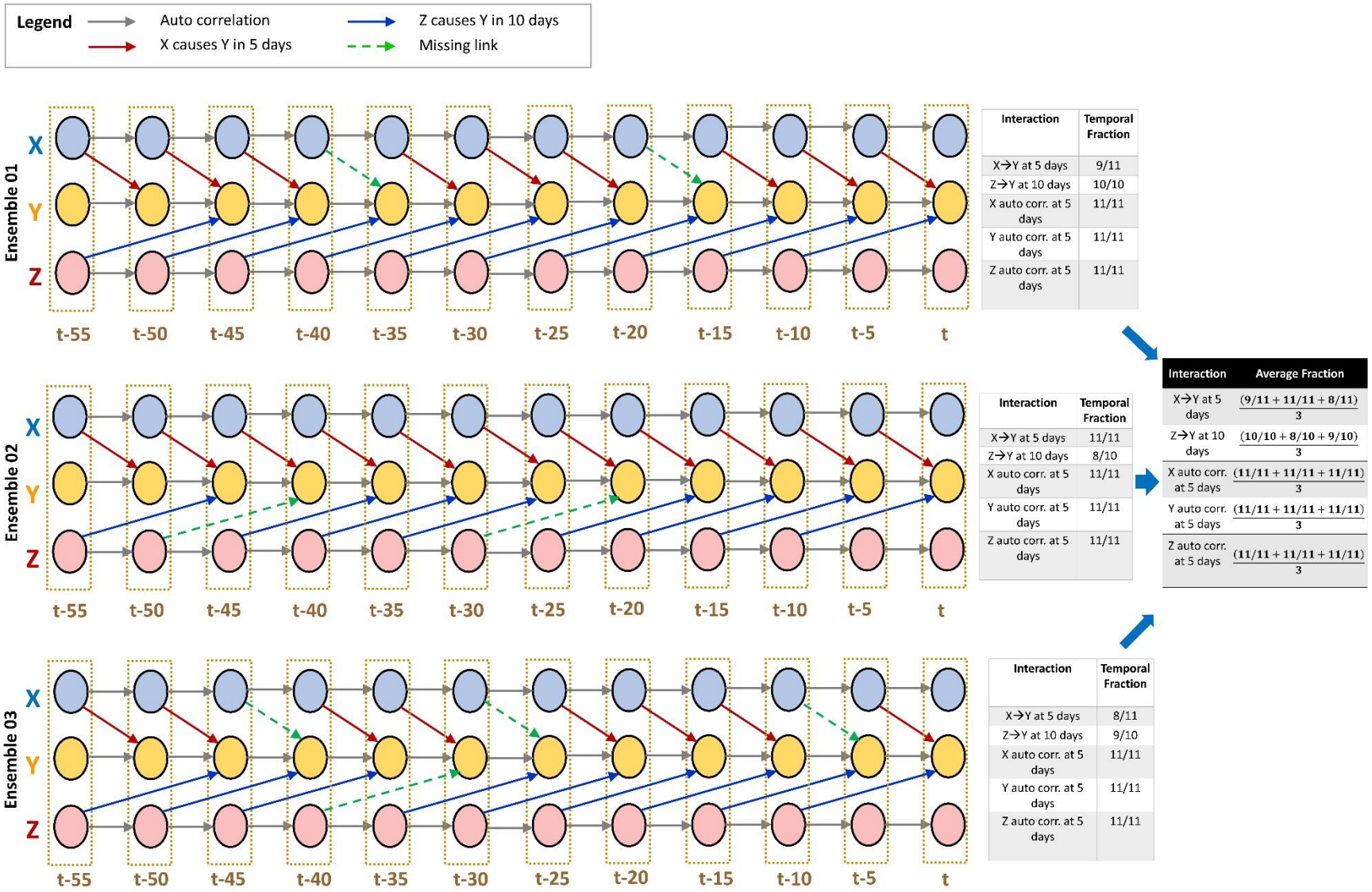
Supp. Figure 3: Average over 3 ensemble members from the historical and SSP585 simulations of sea-level pressure anomalies 15 days following MJO phase 7 events for periods under (a) historical (1850-1889; members 1, 2, 3) and (b) SSP585 forcings (2055-2094; members 1, 2, 3).





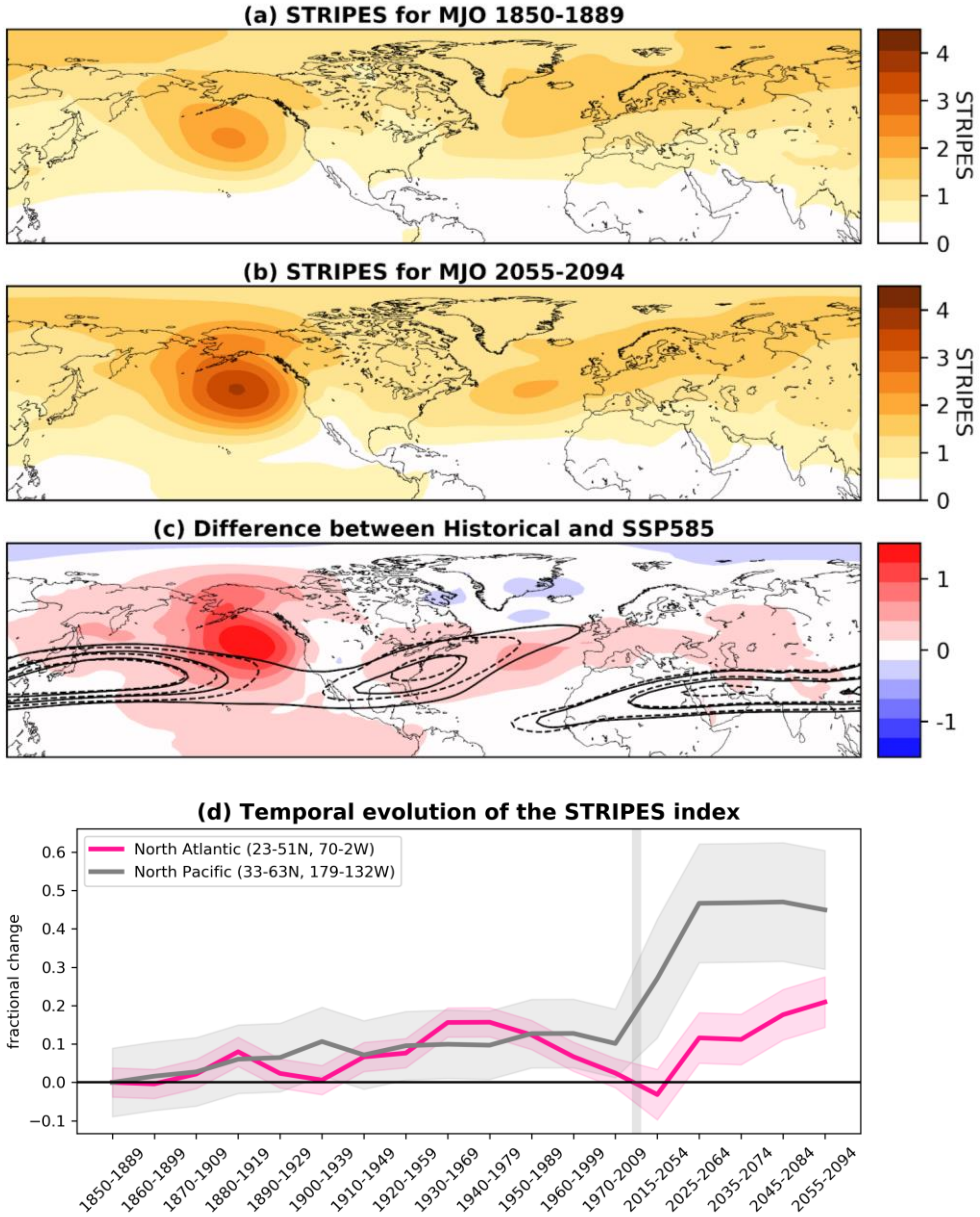


Supp. Figure 4: As in Figure 1, but showing 12, 15 and 18 days after MJO phase 7.

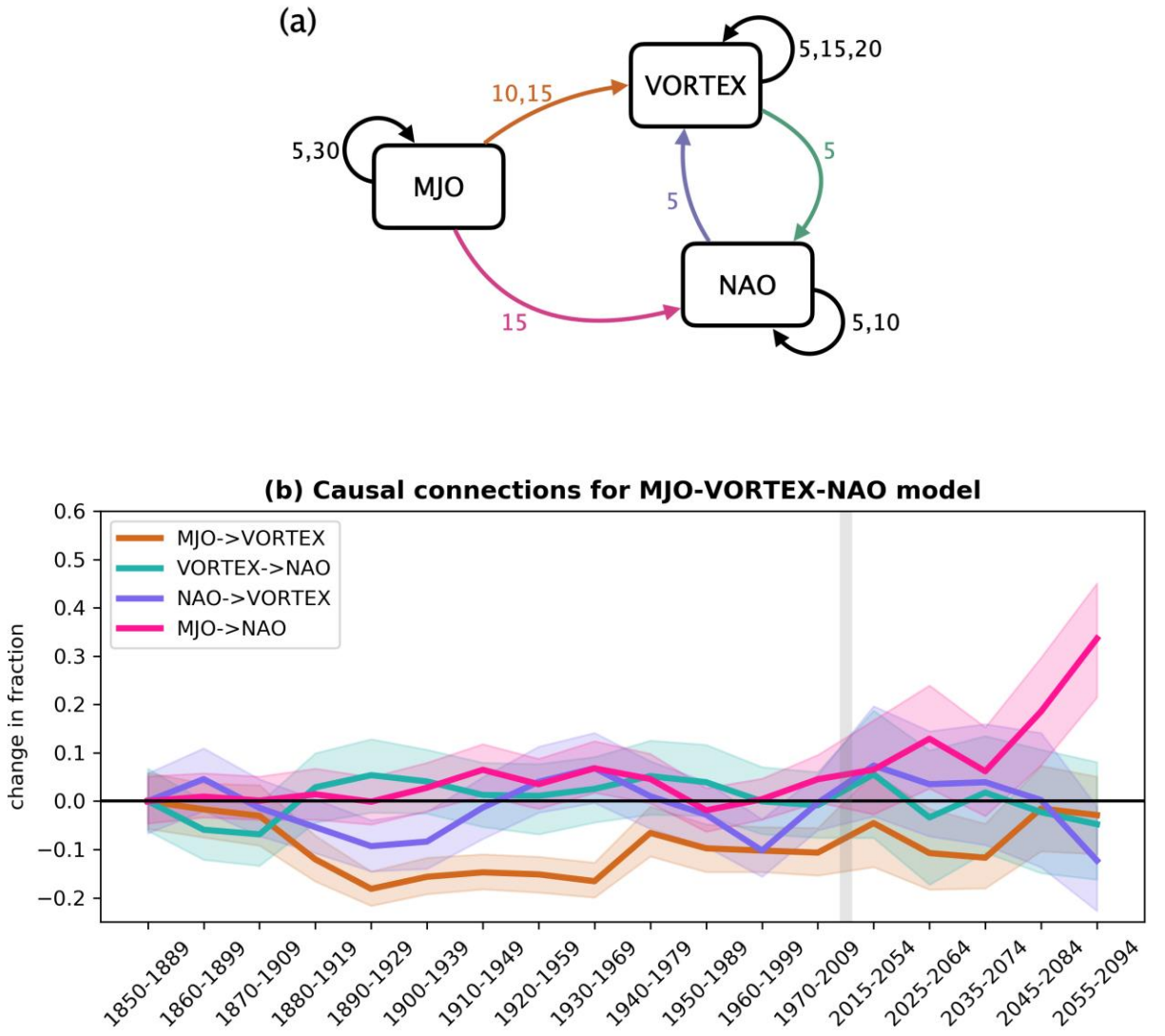


Supp. Figure 5: A toy example of three Directed Acyclic Graphs (DAGs) learned by PC-stable for three different ensemble members of a climate model.

In Supp. Figure 5, each DAG is a temporal model consisting of the variables X, Y, Z and their lagged copies at time delays 5,10, …, 50,55. 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). Here X(t) represents the original time series of variable X, while for example, X(t-10) represents the time series that is lagged by 10 days. 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.



Supp. Figure 6: As in Figure 2, but for the "low top" CESM2 simulations. STRIPES values averaged over ensemble members for the (a) historical (1850-1889; 9 simulations) and (b) future (2055-2094; 3 simulations) periods, as well as their (c) difference.



Supp. Figure 7: As in Figure 3, but for the "low top" CESM2 simulations. (a) Example graphical causal model for MJO phases 6/7, the VORTEX, and the NAO based on results from historical ensemble member 9 over 1970-2009 using a tcf cutoff of 0.5. (b) Fraction of causal connections relative to the ensemble-mean value in 1850-1889 for causal models of the MJO-VORTEX-NAO using alpha=0.1. Results are averaged over delays of 5, 10 and 15 days and averaged over all MJO phases and ensemble members. Shading denotes 90% confidence bounds based on Monte Carlo resampling. The gray vertical bar denotes a break in the x-axis due to the transition from historical to SSP585 simulations.