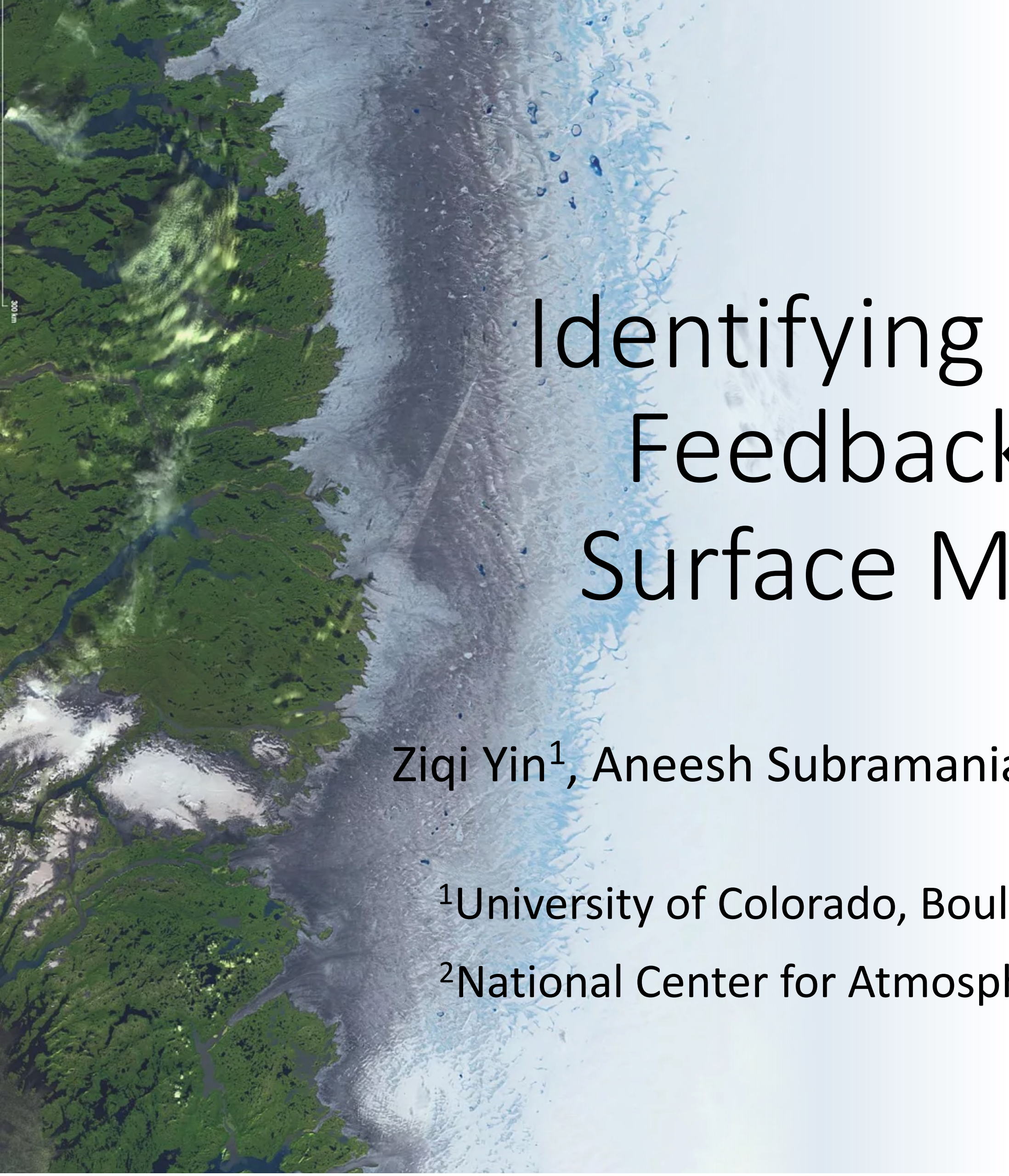
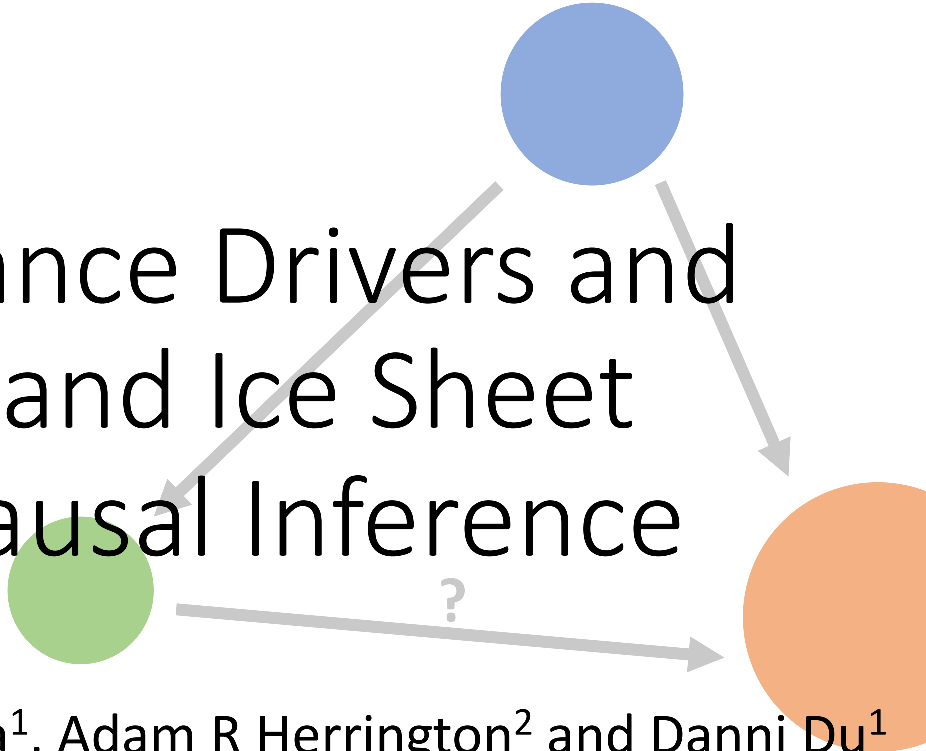


Identifying Energy Balance Drivers and Feedbacks of Greenland Ice Sheet Surface Melt Using Causal Inference



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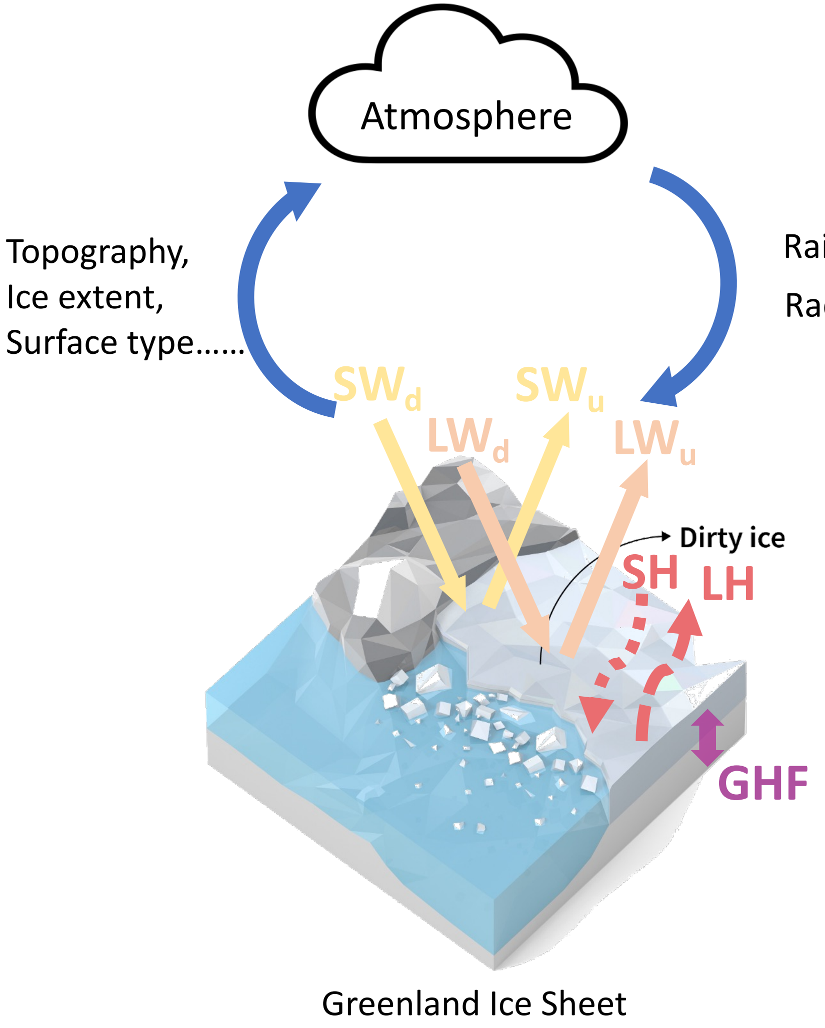
LIWG meeting 2024 Feb

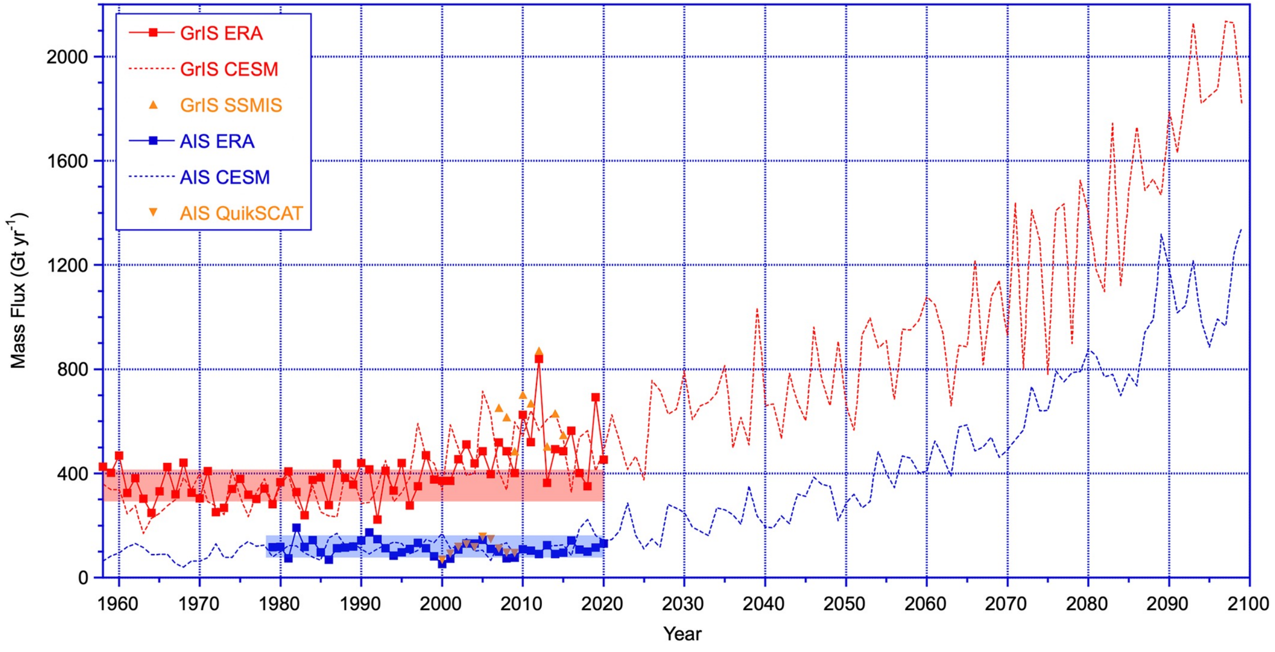
Interactions & feedbacks between the GrIS & atmosphere



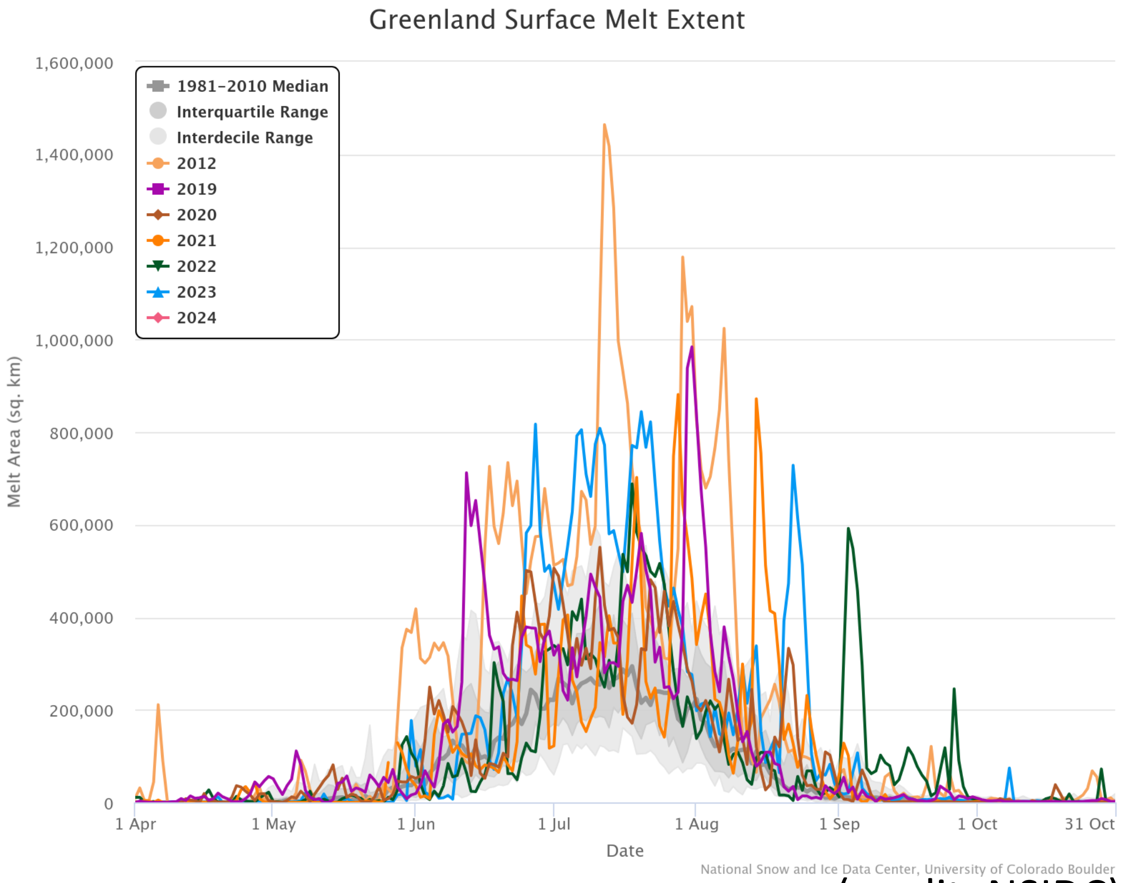
- Albedo/melt feedback
- Geometry/SMB feedbacks
- Melt & accumulation/discharge feedbacks

Melt energy = LW_{net} + SW_{net}
+ Latent heat + Sensible heat + Ground heat

GrIS Surface Melt change & variability

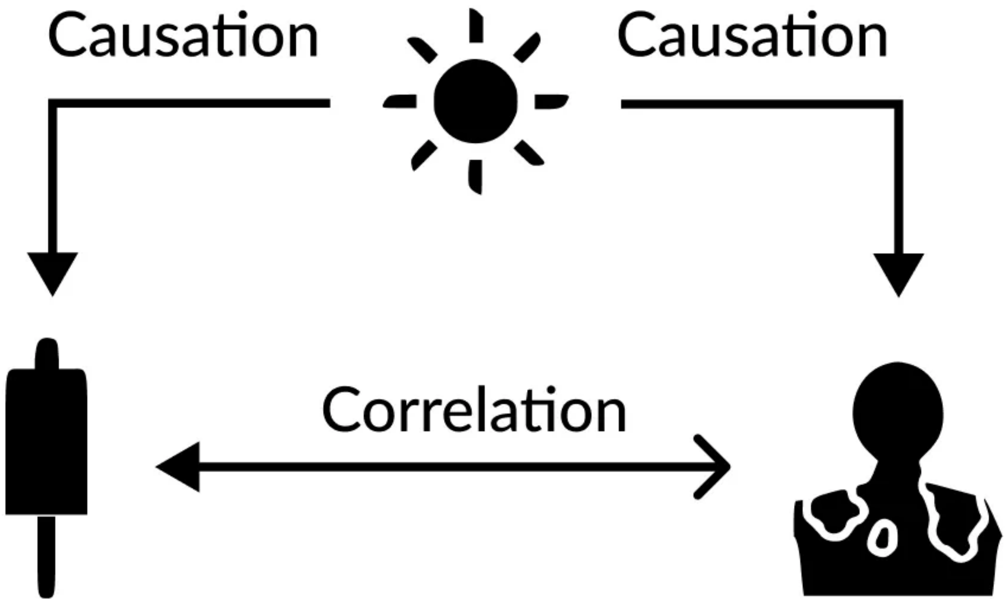


(van den Broeke et al. 2023)

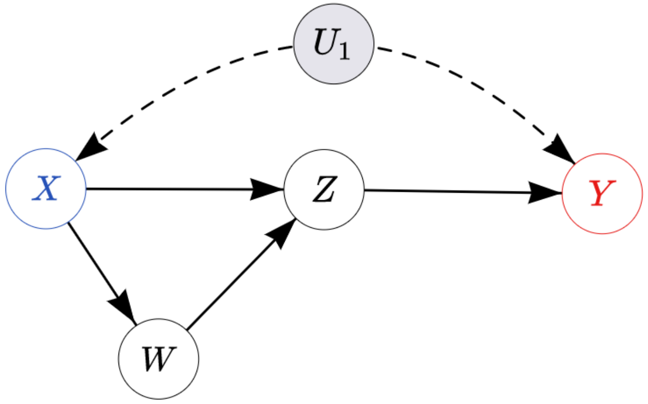


(credit: NSIDC)

Causation vs Correlation

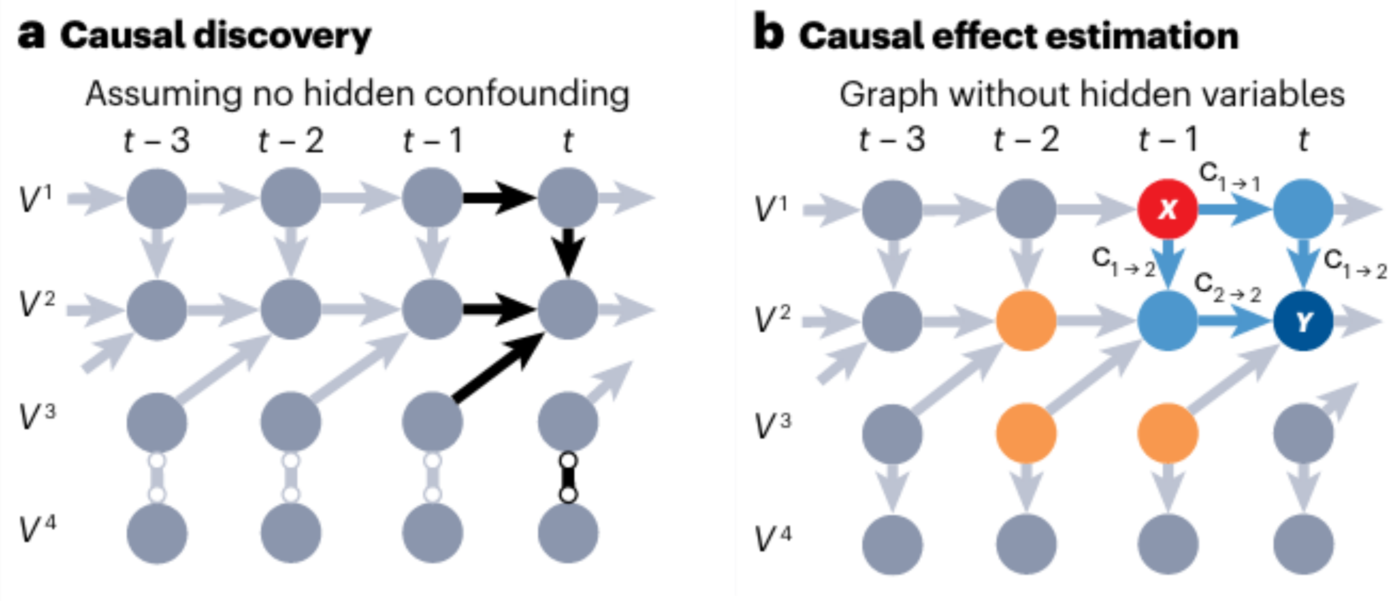


Causal inference



Causal inference is a discipline to formalize the pursuit of identifying, modeling, and quantifying causal relationships.

Two pillars of current causal learning:



- Learning qualitative causal relationships
- Quantifying causal effects given qualitative relationships

Research questions

1. What is the relative importance of the SEB components and processes for GrIS summer surface melt?

2. Under global warming, will there be a regime shift?

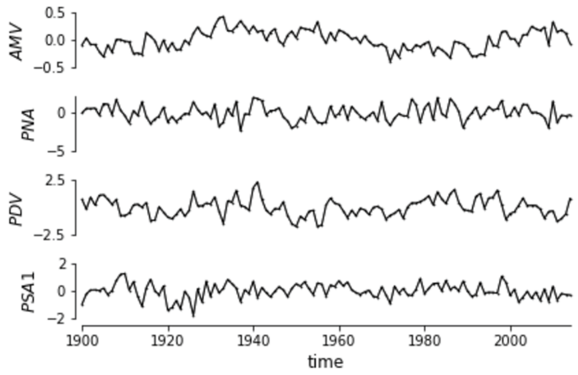
The causal inference method

① **PCMCI** (Peter Clark Momentary Conditional Independence) is a causal discovery framework developed by Runge et al. (2019).

Suitable for time series with

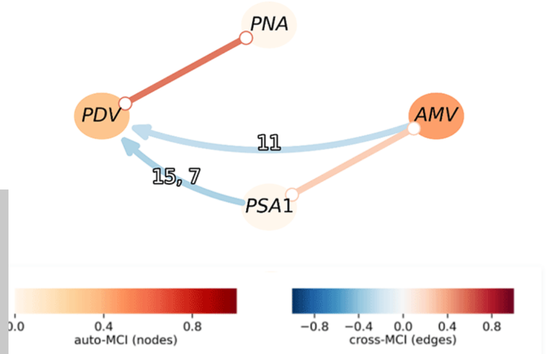
- high dimensionality (number of variables, time lags, autocorrelation)
- nonlinear dependencies

Example: application of the **PCMCI+** algorithm to modes of climate variability



Detrended timeseries

An extended version that can also detect contemporaneous causal links (Runge, 2020)



Causal network

(Karmouche et al. 2023)

② **Wright's path method** is a method to assess the effects of a set of variables acting on a specified outcome via multiple causal pathways developed by Sewall Wright (1918).

Assumptions:

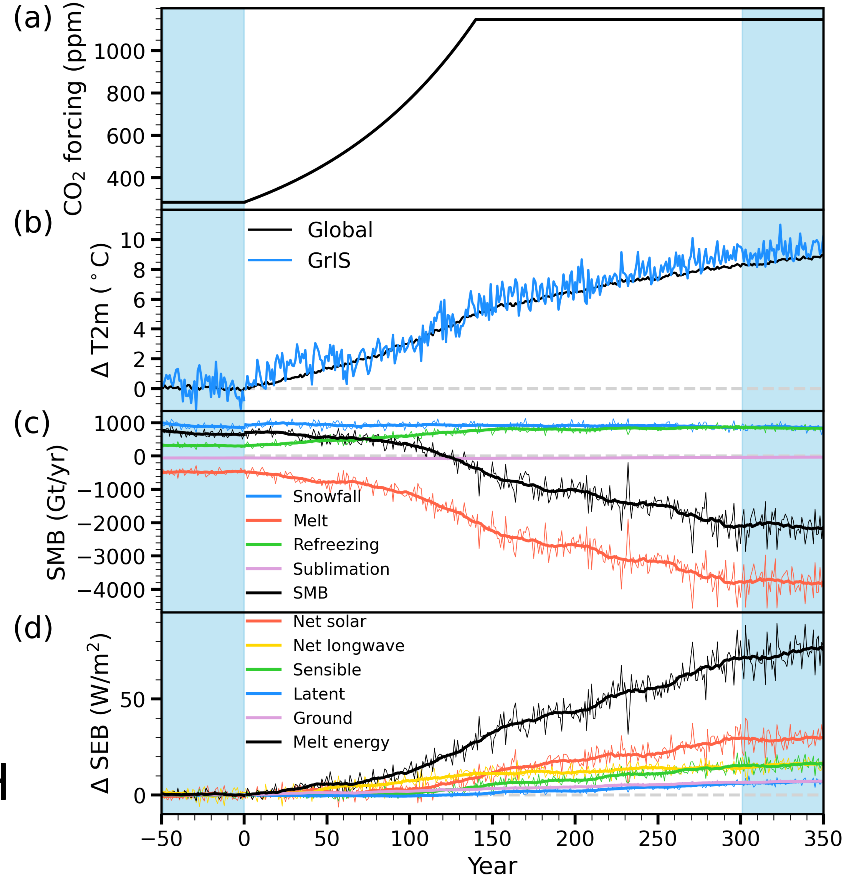
- Causal Markov condition
- Causal faithfulness
- Causal sufficiency
- Stationarity (through preprocessing)
- Linear dependencies (relatively short sample size)
- Acyclicity
- Gaussian noise distribution

Data– Fully coupled CESM2.2-CISW2.1 simulation (Yin et al. in prep)

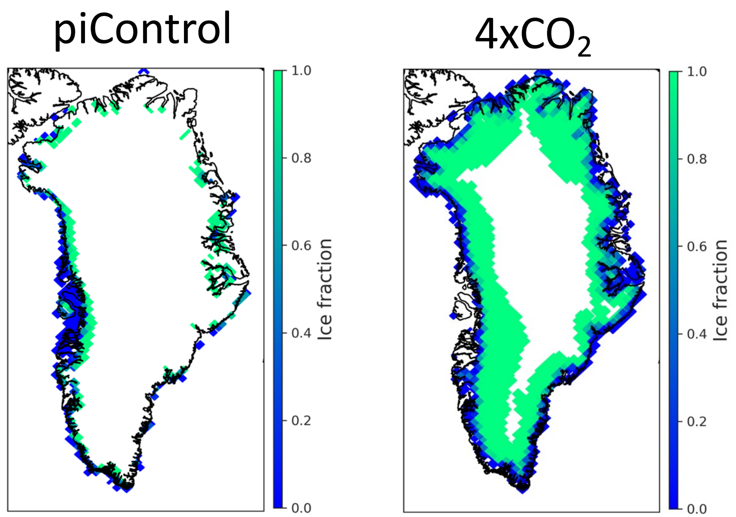
- Variable-resolution grid for atmosphere & land (1/4° over the Arctic and 1° elsewhere)
- 180yrs preindustrial control + 350yrs idealized warming scenario
- Monthly time resolution

Variables selection:

Melt energy = $SW_n + LW_n + SH + LH$

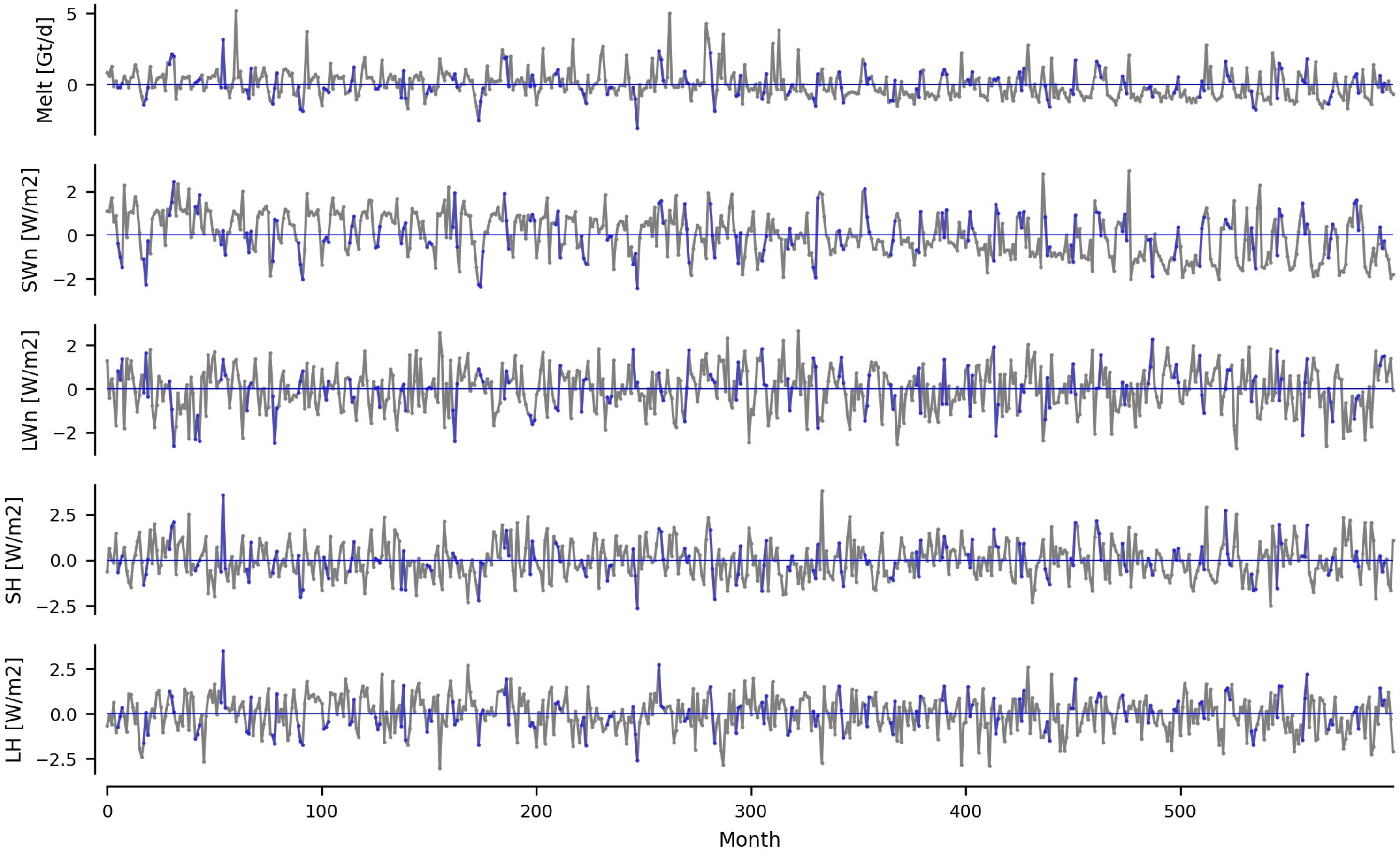


Averaged over the ablation zone

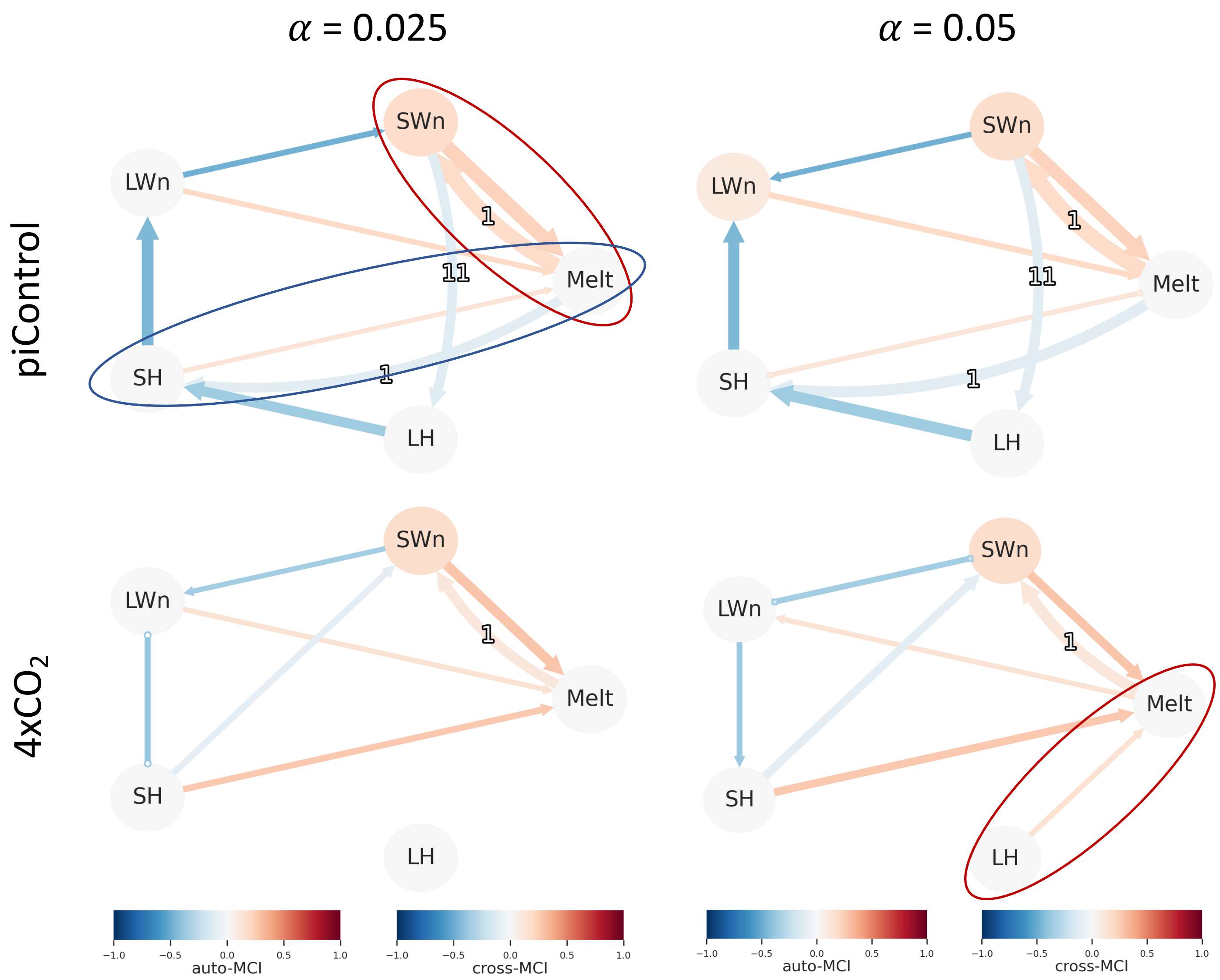


Data preprocessing

- **Detrending**: remove long term trends (decadal Gaussian kernel (15 years))
- **Normalization**: remove seasonal mean, divide by seasonal standard deviation
- **Masking**: samples at time t can only come from Jun-Aug



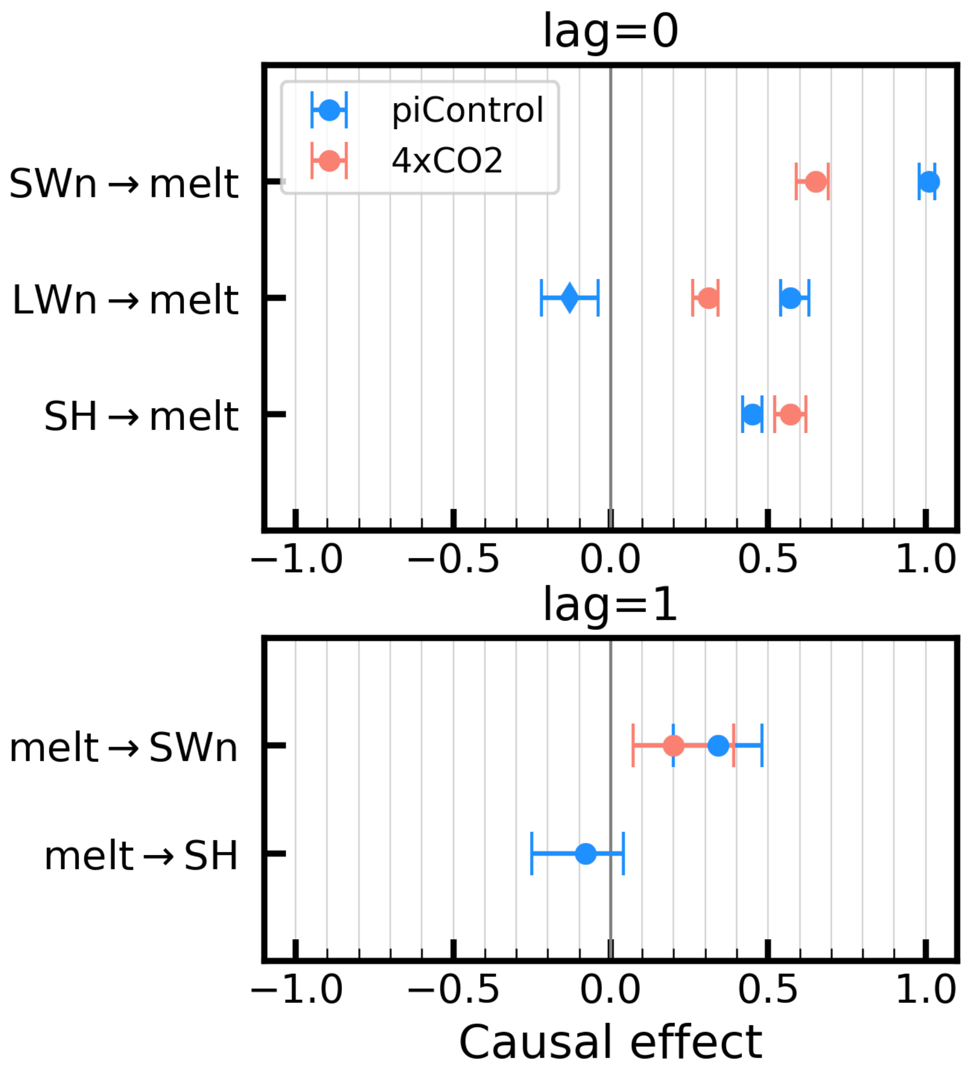
Causal discovery



- SW$_n$, LW$_n$ and SH have contemporaneous positive direct effect on melt; with significance level of 5%, LH→Melt is also detected for the 4xCO_2 period.

- Melt/albedo feedback is detected for both periods, with one-month lagged Melt→SW$_n$; for piControl, there is a negative feedback loop between SH & Melt, which is not detected during 4xCO_2.

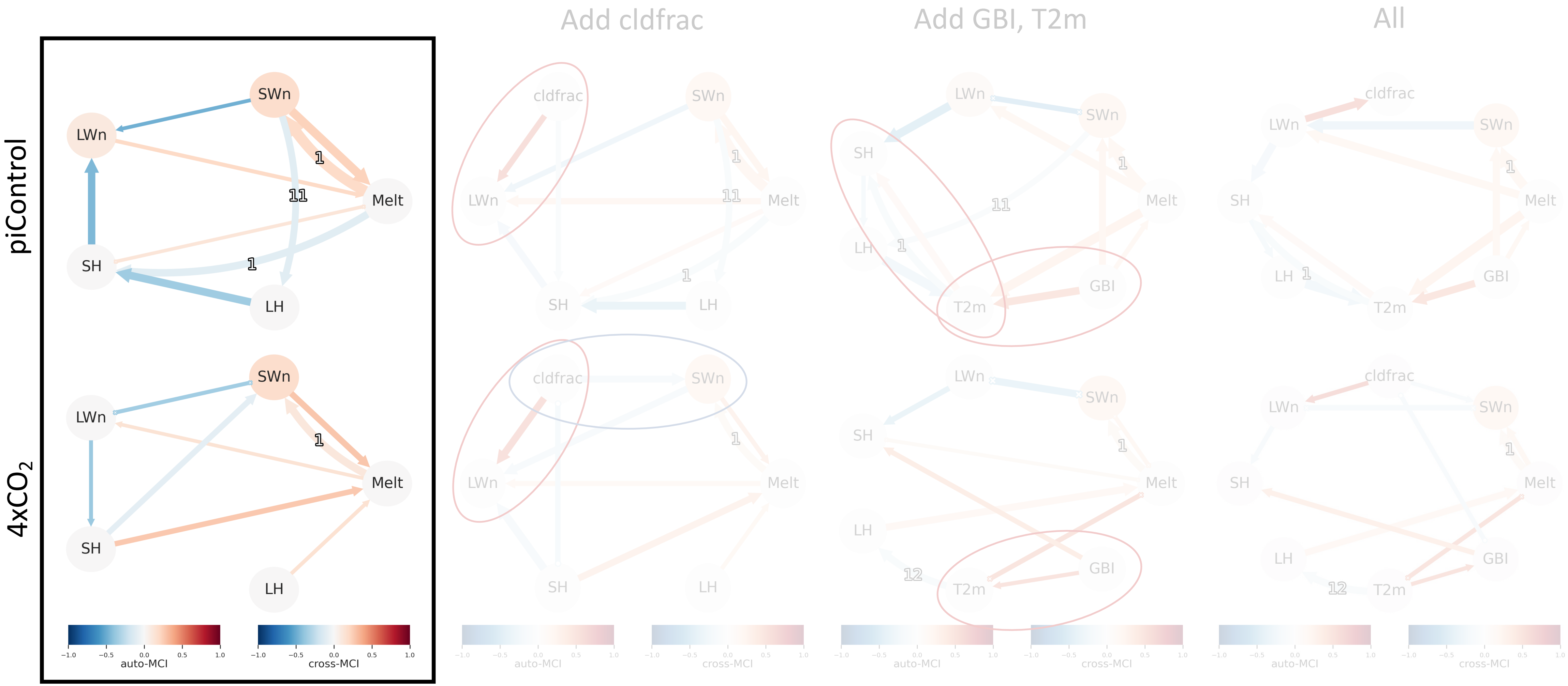
Causal effect estimation



- For direct causal effect, the relative importance of SH increases compared to the radiative fluxes in a warmer climate, but SW_n remains dominant.

- Estimating total causal effect (direct + indirect) requires a complete and more robust causal graphs.

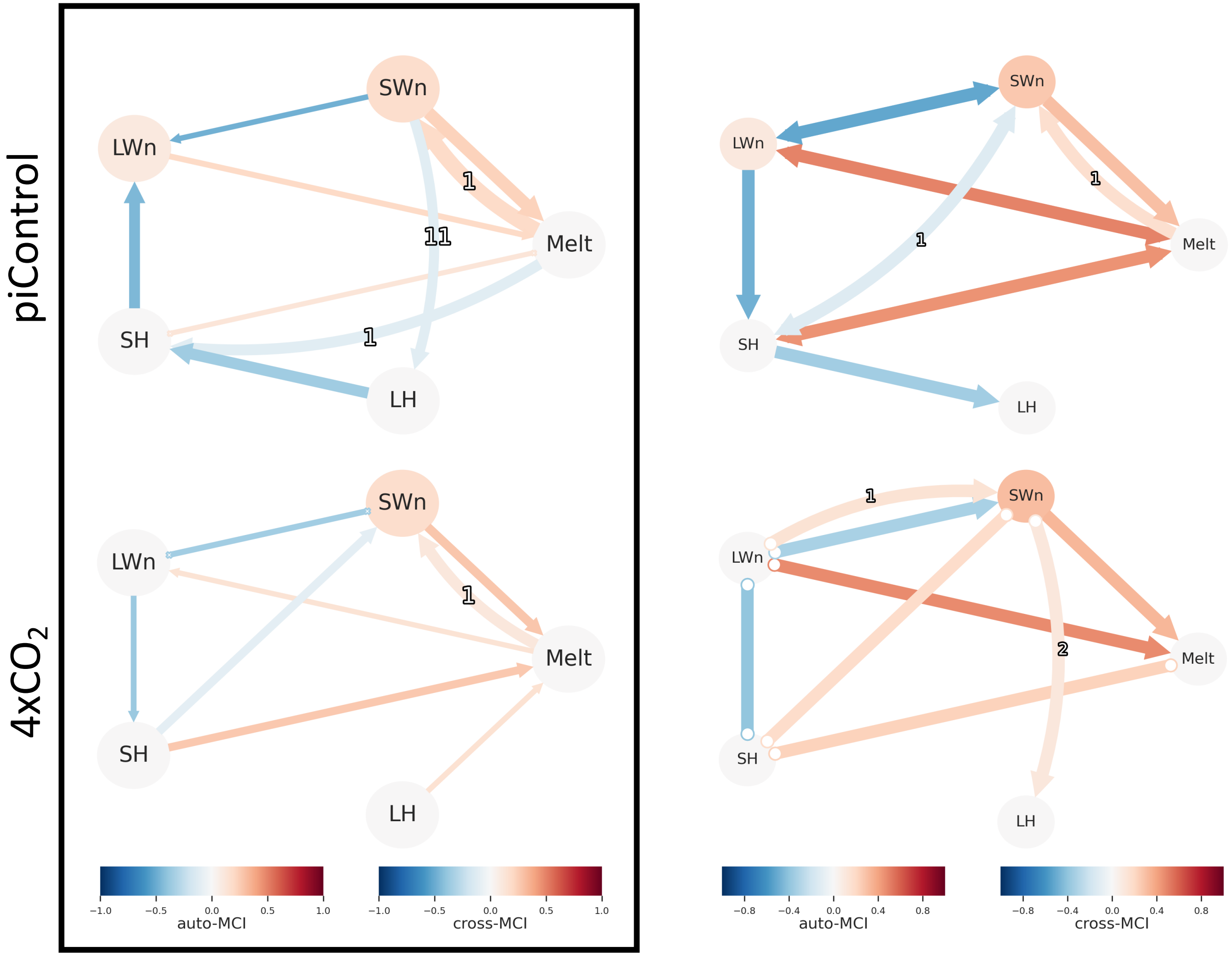
Towards a complete graph…



(α = 0.05)

Latent-PCMCI: version allowing unobserved variables

(Gerhardus and Runge, 2020)



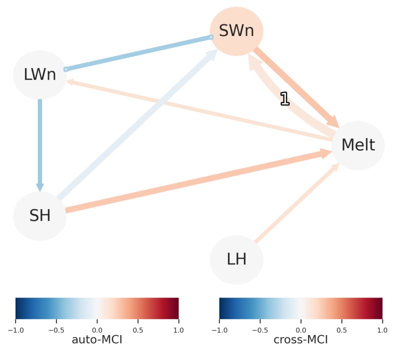
(α = 0.05)

(α = 0.01)

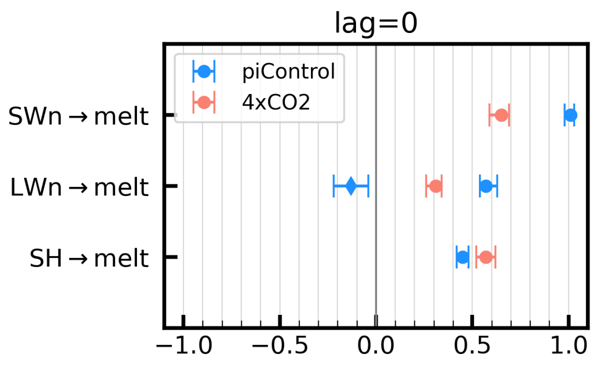
Similar problem as PCMCI+, but there is a way to implement physical knowledge.

Summary & next steps

- Causal inference let us focus on few important drivers and can detect lagged feedback loop for Greenland summer melt
- Net shortwave radiation acts as the dominant direct melt driver
- In a warmer climate, there is a regime shift of the direct effects of SEB terms on Greenland summer melt, with increasing role of turbulent heat fluxes



- Experiment with more variables and model parameters, then summarize a robust graph, based on which the total causal effect can be estimated
- Implement physical knowledge
- Compare with results detected from observation/reanalysis



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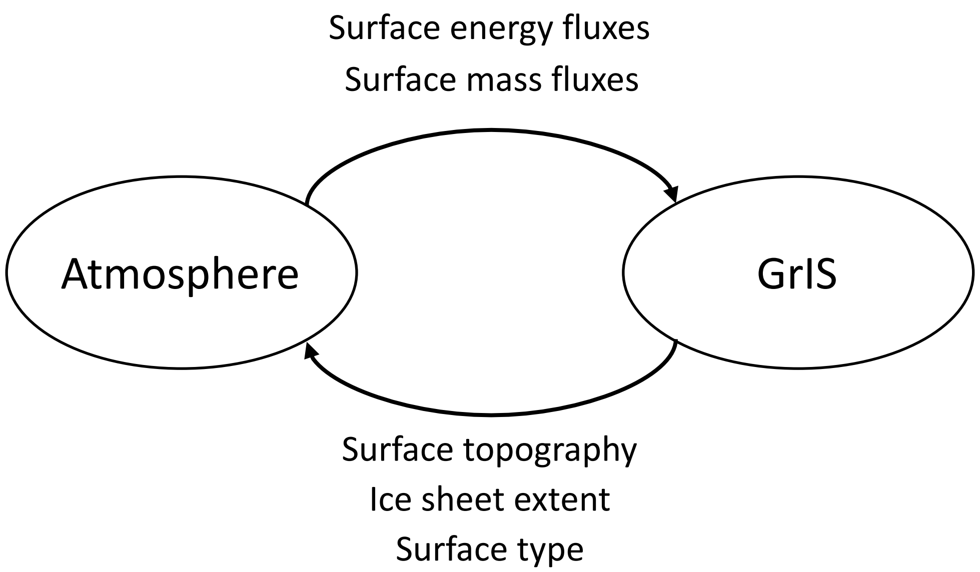
Interactions & feedbacks between the GrIS & atmosphere



Albedo/melt feedback

(+) melt $\uparrow \Rightarrow$ albedo $\downarrow \Rightarrow SW_{net} \uparrow$

Geometry/SMB feedbacks

(-) mass $\uparrow \Rightarrow$ ablation area $\uparrow$

(+) melt $\uparrow \Rightarrow$ elevation $\downarrow \Rightarrow$ temperature $\uparrow$

(+/-) regional topography / accumulation or melt
e.g., orographic precipitation

Melt & accumulation/discharge feedbacks

(-) melt $\uparrow \Rightarrow$ marginal thickness $\downarrow \Rightarrow$ discharge $\downarrow$
snow $\uparrow \Rightarrow$ marginal thickness $\uparrow \Rightarrow$ discharge $\uparrow$
snow $\uparrow \Rightarrow$ slope $\uparrow \Rightarrow$ discharge $\uparrow$

(+) melt $\uparrow \Rightarrow$ basal traction $\downarrow \Rightarrow$ discharge $\uparrow$