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

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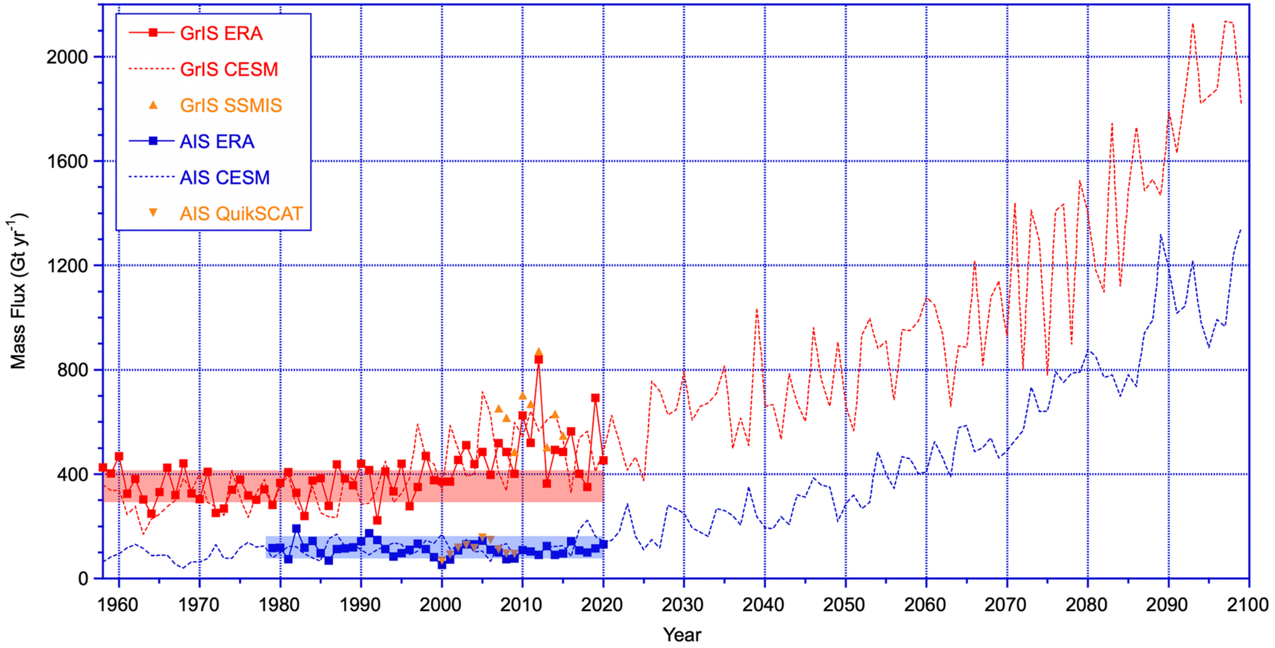
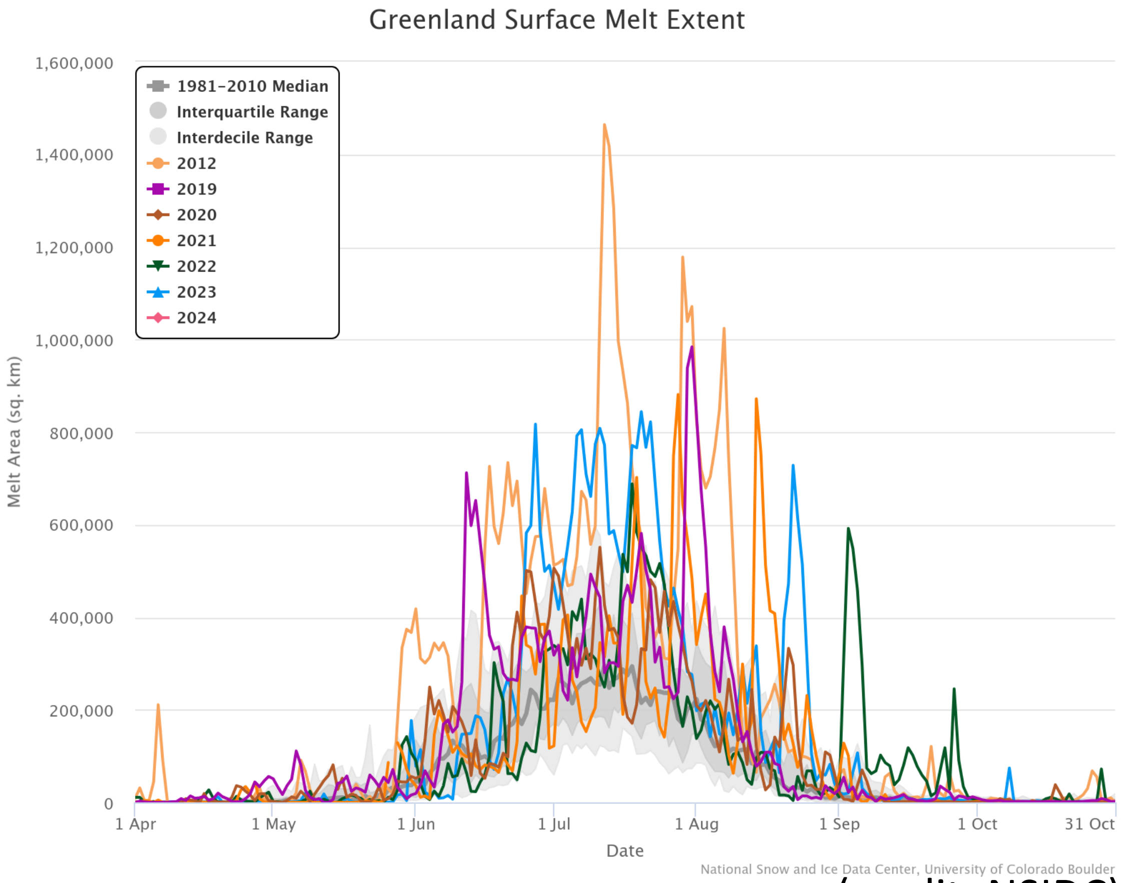
GrIS Surface Melt change & variability

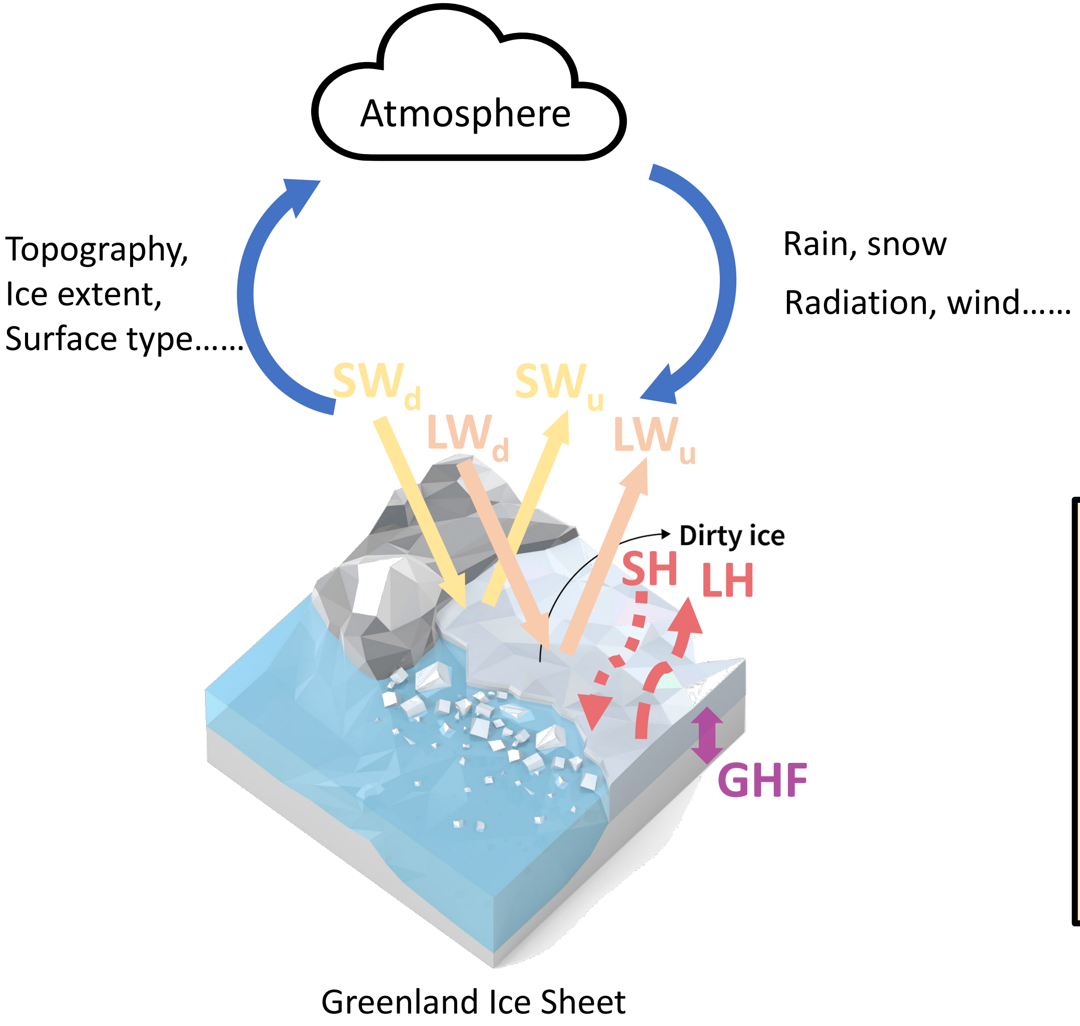


(van den Broeke et al. 2023)



(credit: NSIDC)

Interactions & feedbacks between the GrIS & atmosphere



- Albedo/melt feedback
- Geometry/SMB feedbacks

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Melt energy = $LW_{net} + SW_{net}$ + LH + SH+ GHF

1. What is the relative importance of the SEB components and processes for driving GrIS surface melt?
2. Under global warming, will there be a regime shift?

Causal inference

The causal inference method

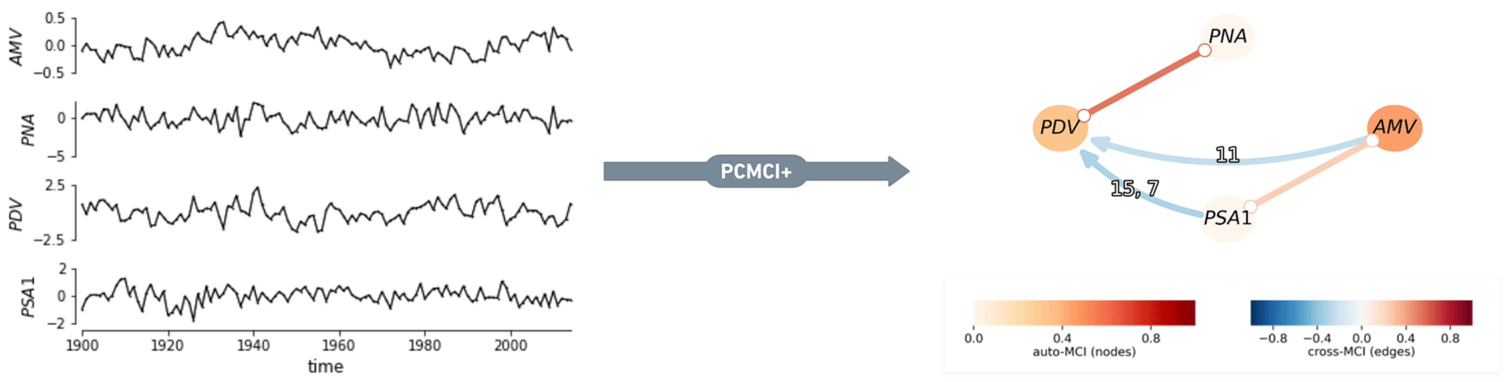
① **PCMCI+** (Peter Clark Momentary Conditional Independence) is a causal discovery framework developed by Runge et al. (2019, 2020).

Suitable for time series with

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

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).

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



Detrended timeseries

Causal network

(Karmouche et al. 2023)

Assumptions:

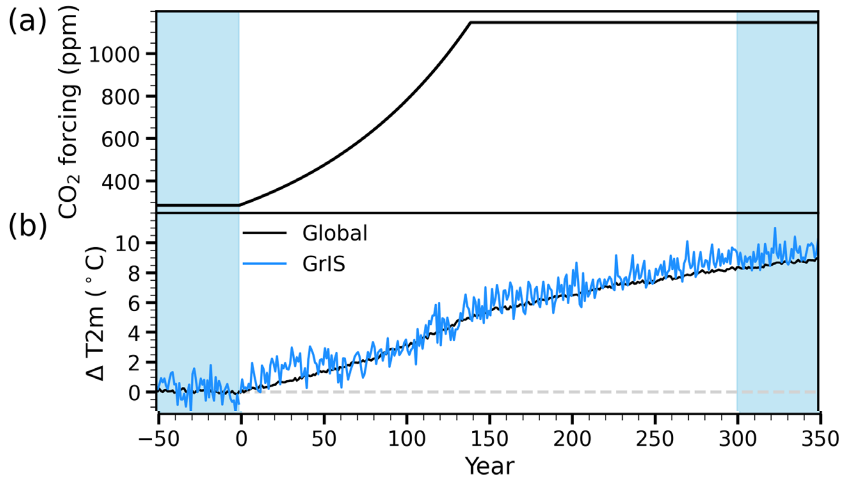
- Causal Markov condition
- Causal faithfulness
- Causal sufficiency
- Stationarity (through preprocessing)
- Linear dependencies (relatively short sample size)
- Acyclicity
- Gaussian noise distribution

Data

Coupled CESM2-CISM2:

- Historical simulation (1° grid; Muntjewerf et al. 2020a)
- Idealized warming simulation

1) 1° grid (Muntjewerf et al. 2020b)
2) VR-grid: 1/4° refinement over the Arctic (Yin et al. in review)



Regional Climate Models:

- RACMO2.3p2 (5.5km; Noël et al. 2018)
- MAR v3.14 (10km; Fettweis et al.)

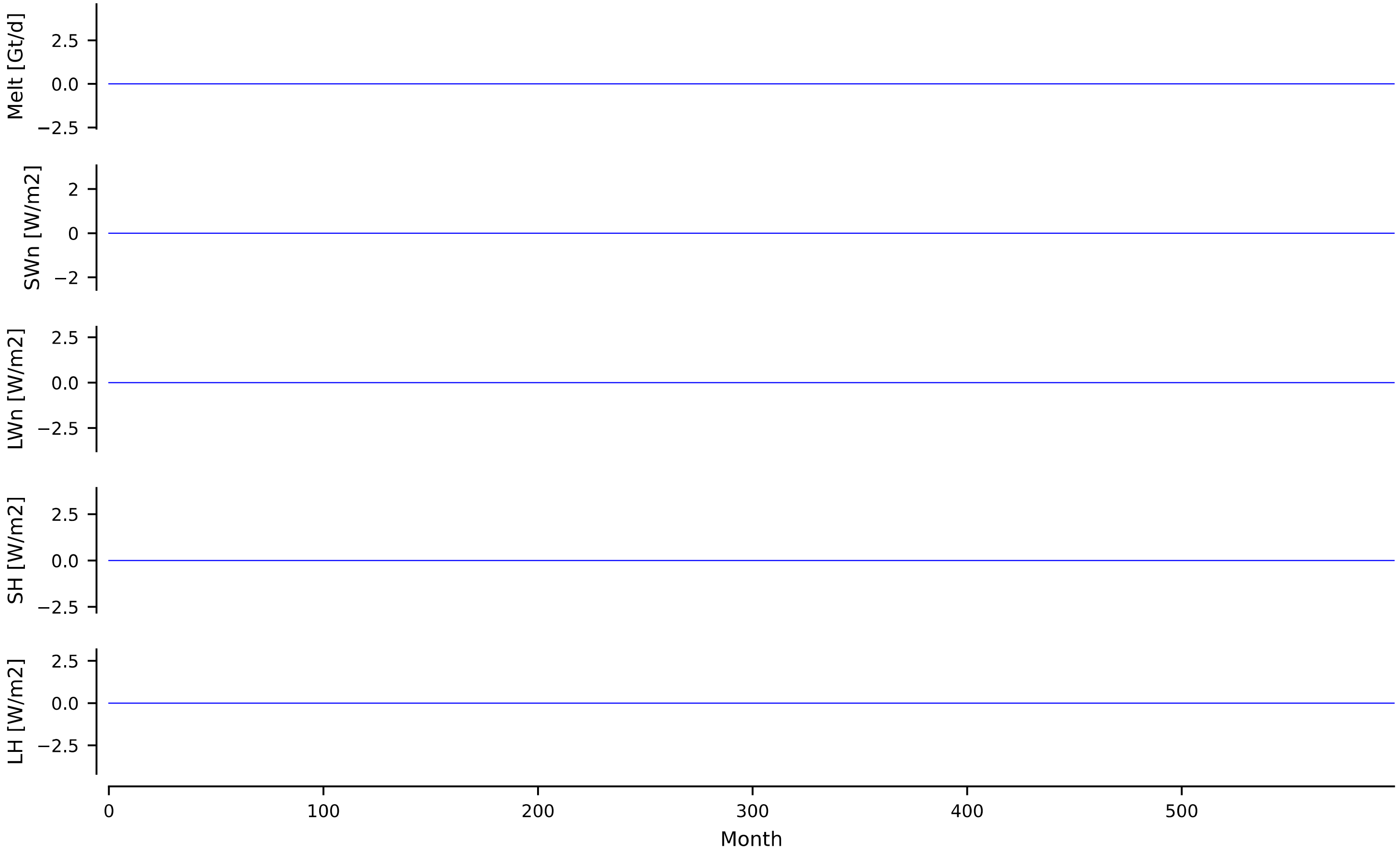
Firn model:

- GEMB v1 (regridded to 10km; Gardner et al. 2023)

- Variable selection:
  Melt flux, SW_n, LW_n, SH, LH
- Monthly time resolution
- Averaged over the ablation zone

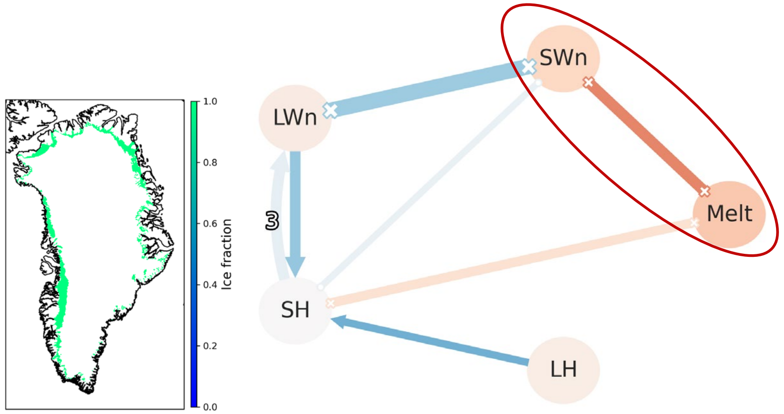
Data preprocessing

- **Detrending**: remove long term trends (decadal Gaussian kernel (15 years))
- **Normalization**: remove seasonal mean, divide by seasonal standard deviation

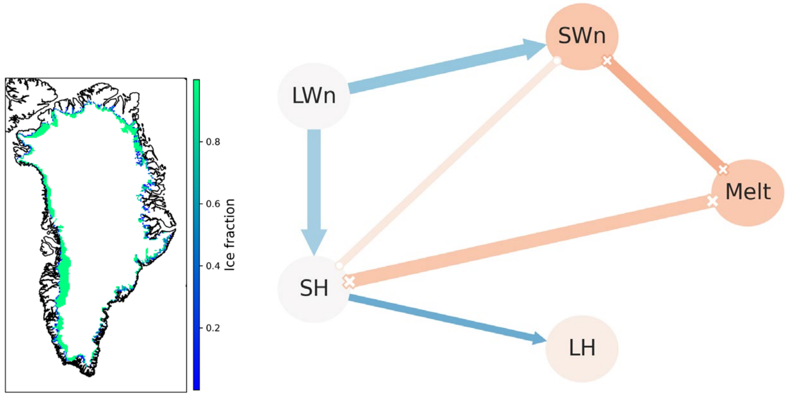


Model evaluation with causal graphs

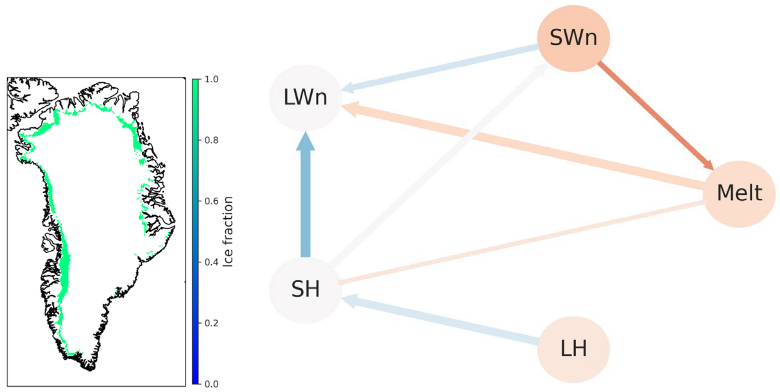
RACMO (5.5km), 1940-2014



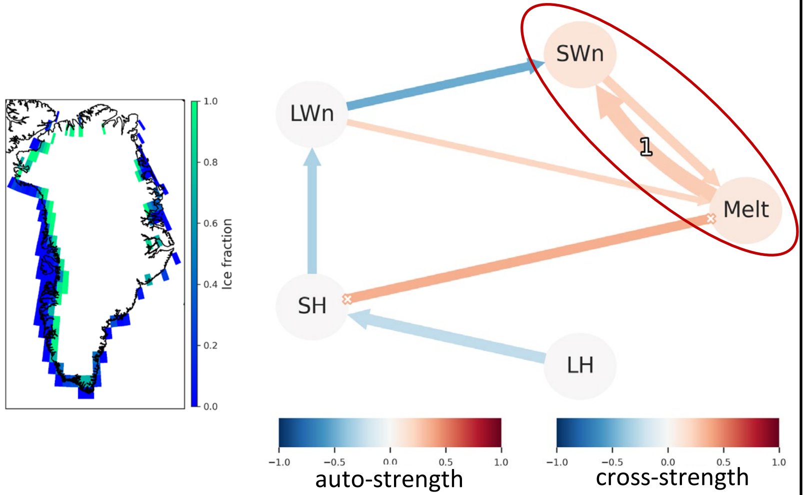
MAR (10km), 1940-2014



GEMB (10km), 1979-2023

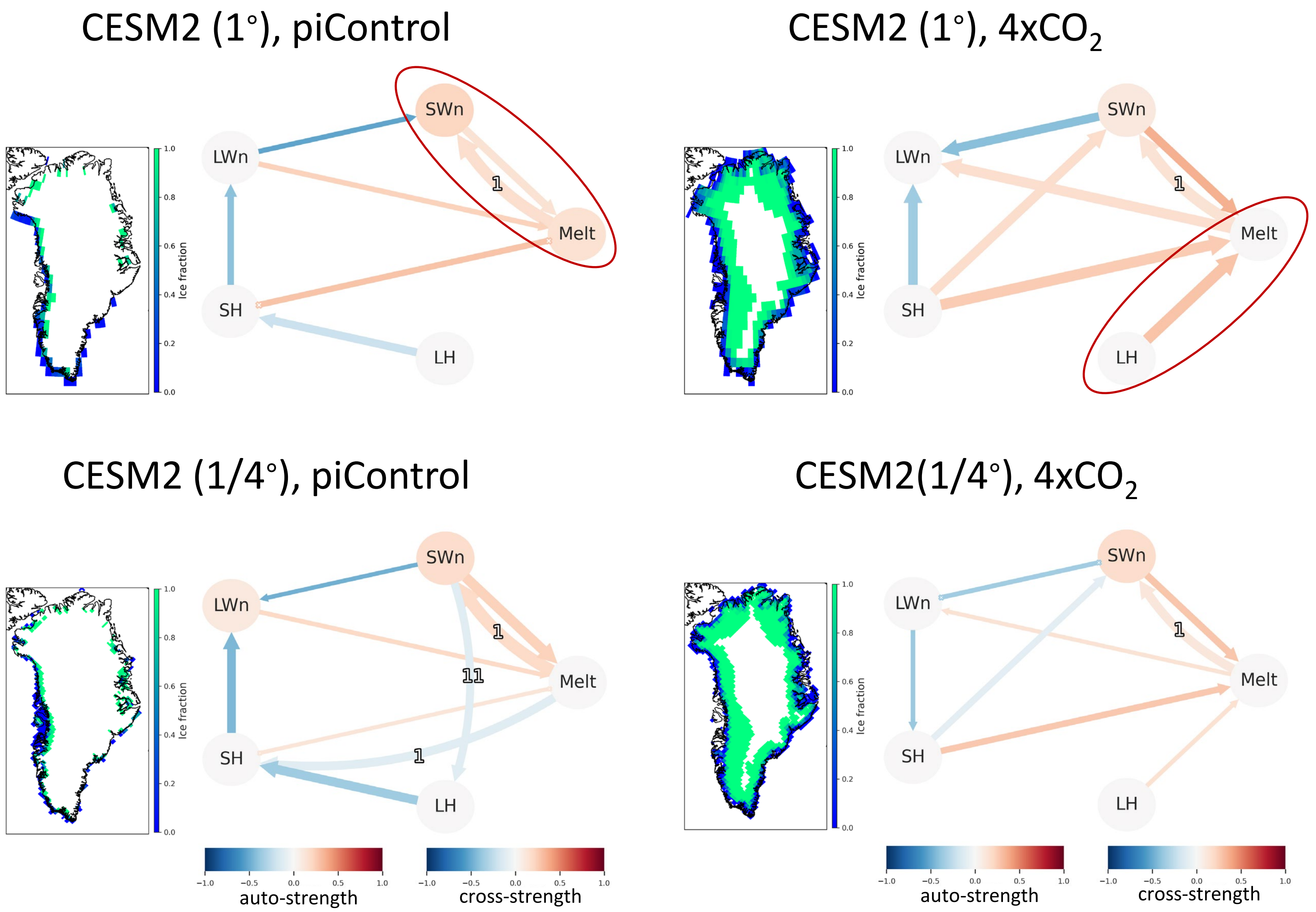


CESM2 (1°), 1940-2014



- All the models agree on the positive contemporaneous links between SW_n, SH and Melt
- CESM2 has a lagged melt/albedo feedback loop, while the RCMs have a conflicting adjacency

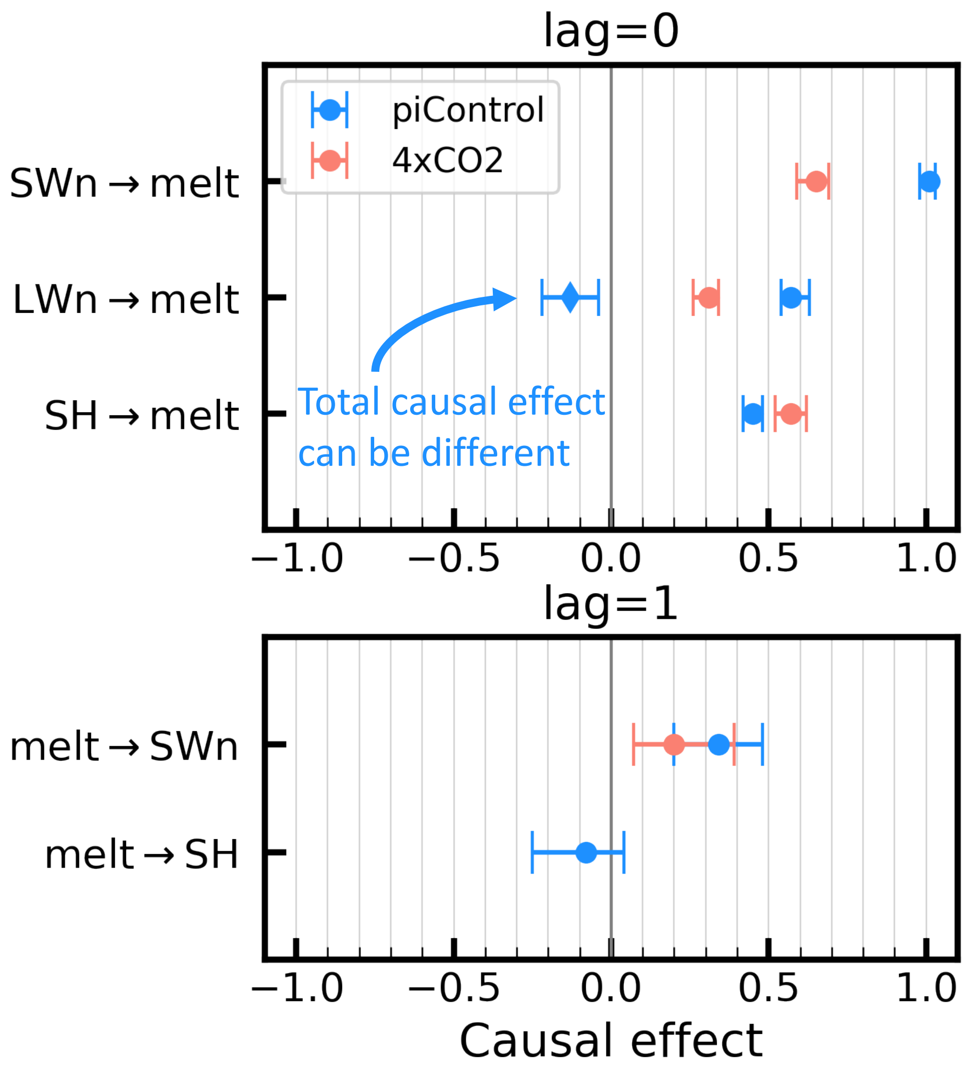
Changes under global warming



- The lagged melt/albedo feedback is robust
- Positive LH→Melt is detected in the $4xCO_2$ period

Background | Methods | **Results** | Summary

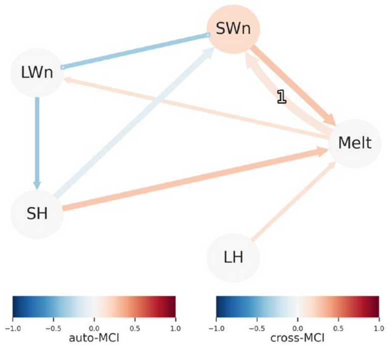
Causal effect estimation

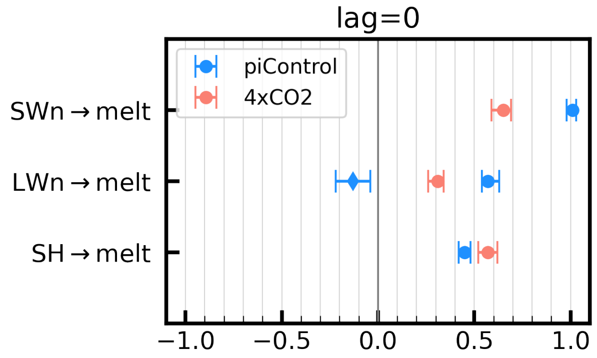


- For direct causal effect, the relative importance of SH increases compared to the radiative fluxes in a warmer climate, but SW_n remains dominant.

Summary & next steps

- Causal inference let us focus on few important drivers and can detect lagged feedback loops for Greenland surface melt, but problems exist
- Causal graph from CESM2 is comparable to those from higher-resolution RCMs but with differences
- 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 surface melt, with increasing roles of turbulent heat fluxes





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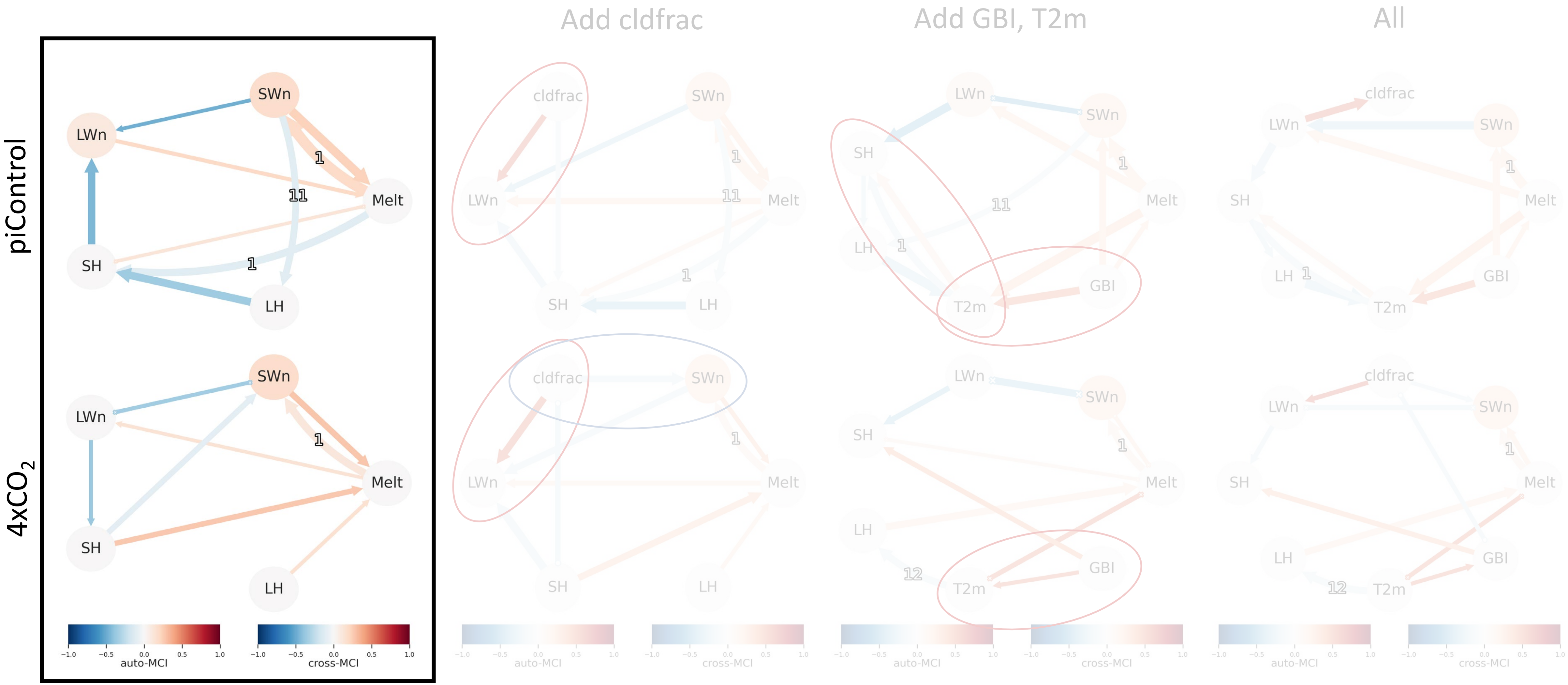
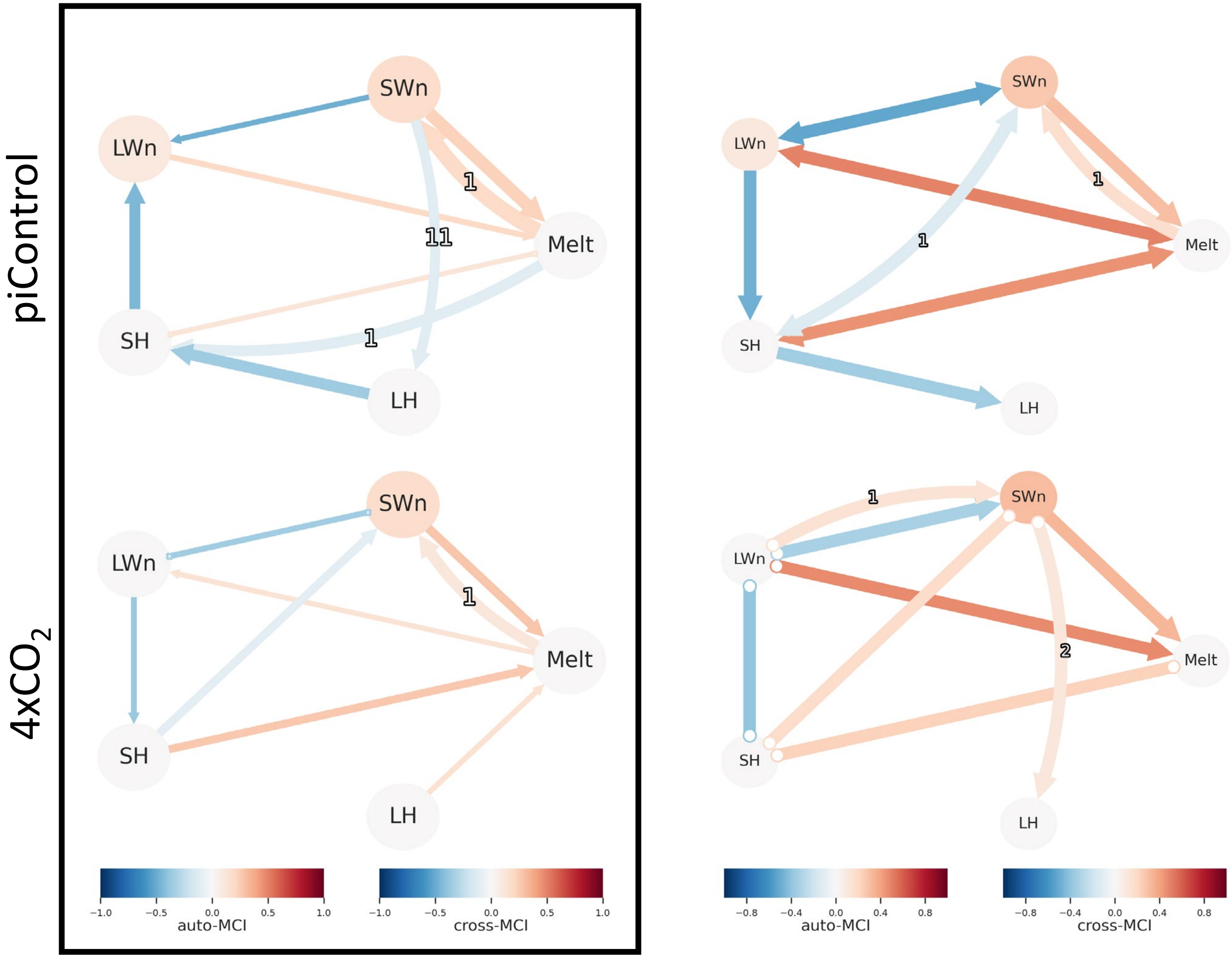
Towards a complete graph…



(α = 0.05)

Latent-PCMCI: extension allows unobserved variables

(Gerhardus and Runge, 2020)



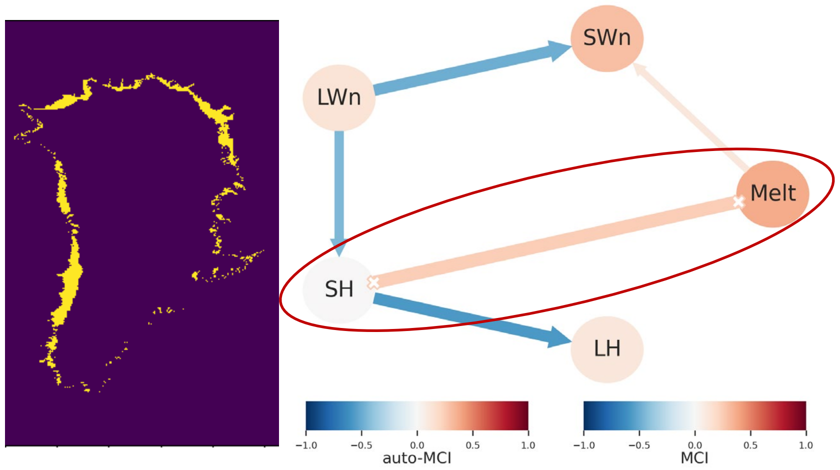
(α = 0.05)

(α = 0.01)

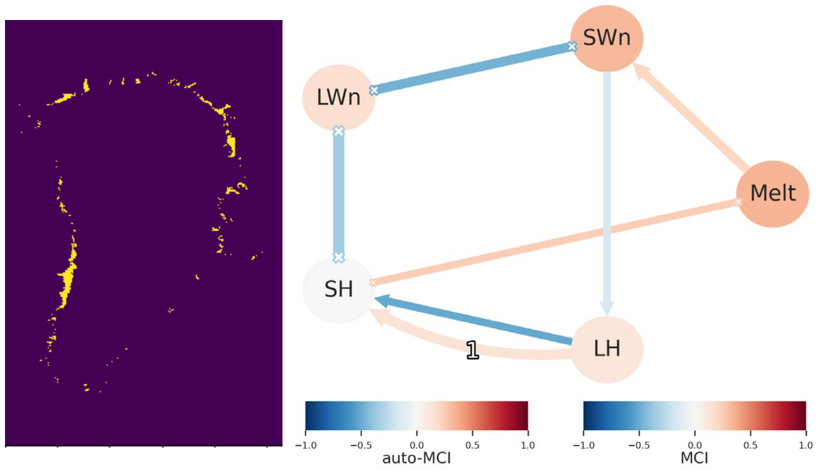
Similar problem as PCMCI+, but there is a way to implement physical knowledge.

Model evaluation – RACMO melt with ERA5 SEB fluxes (1958-2022)

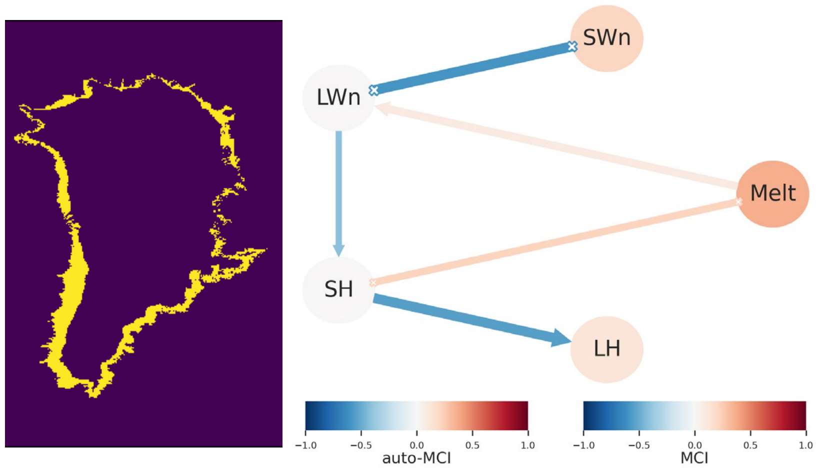
Average ablation area



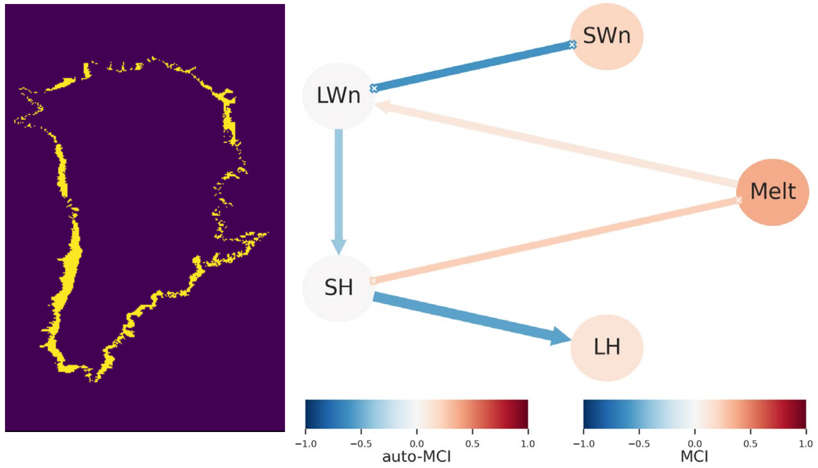
Constant ablation area



Large melt (>1mm/day) area

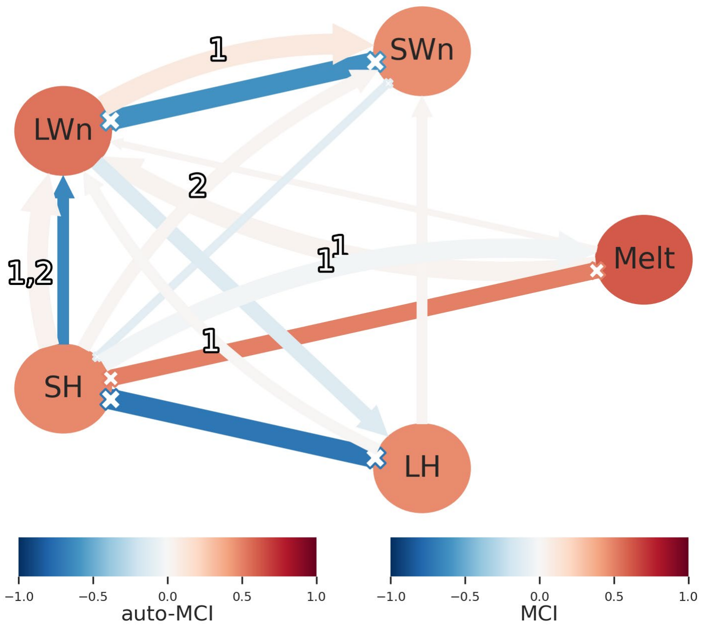


Large melt (>2mm/day) area

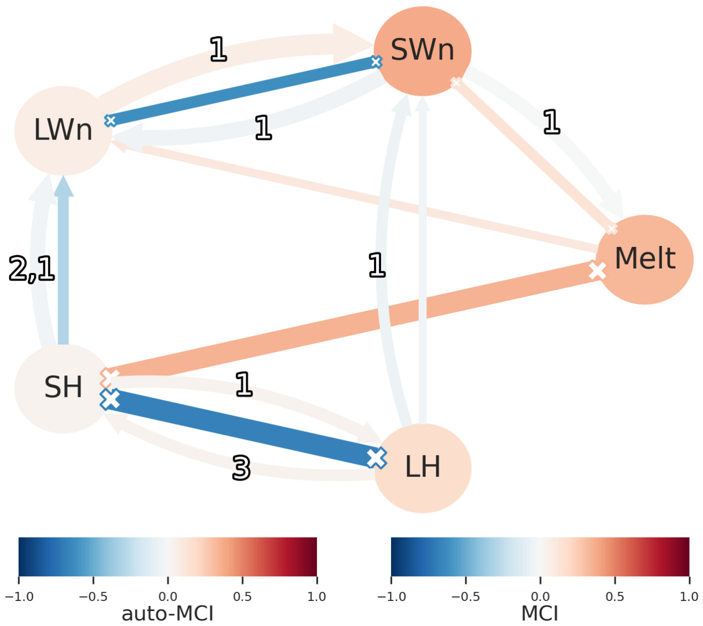


Daily mean, 5-day mean...

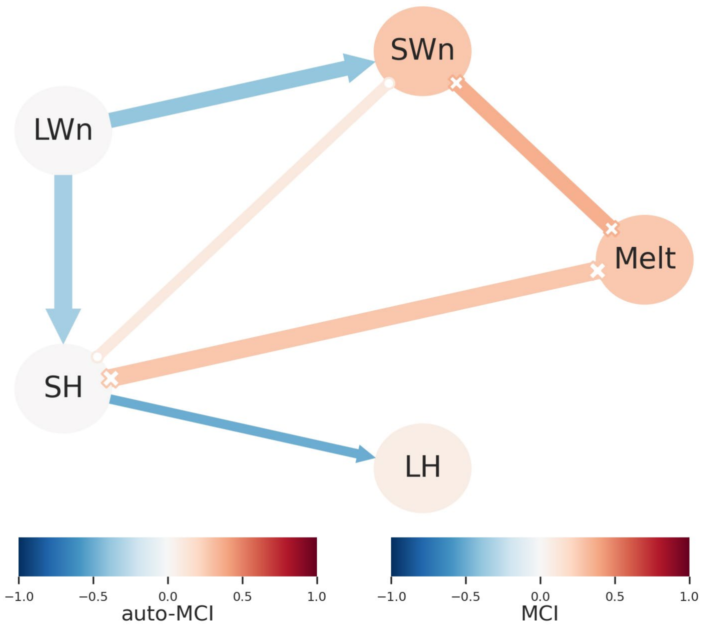
MAR(v3.14, 10km), 1940-2014, daily mean



MAR(v3.14, 10km), 1940-2014, 5-day mean



MAR(v3.14, 10km), 1940-2014, monthly mean



Notes: