Causal relationships between oceanic and atmospheric drivers of heat content in the Nordic Seas in CMIP6 models

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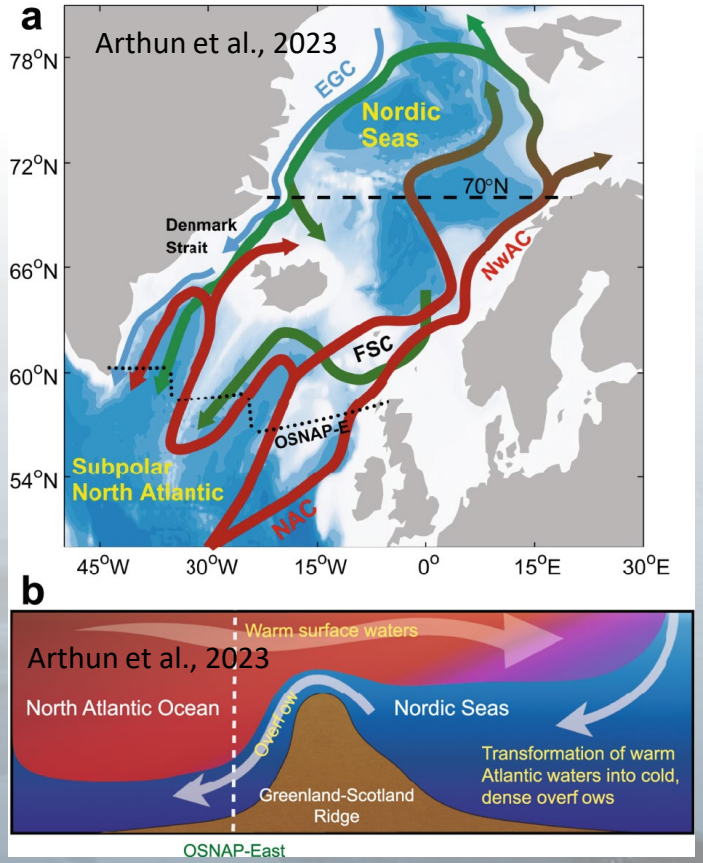
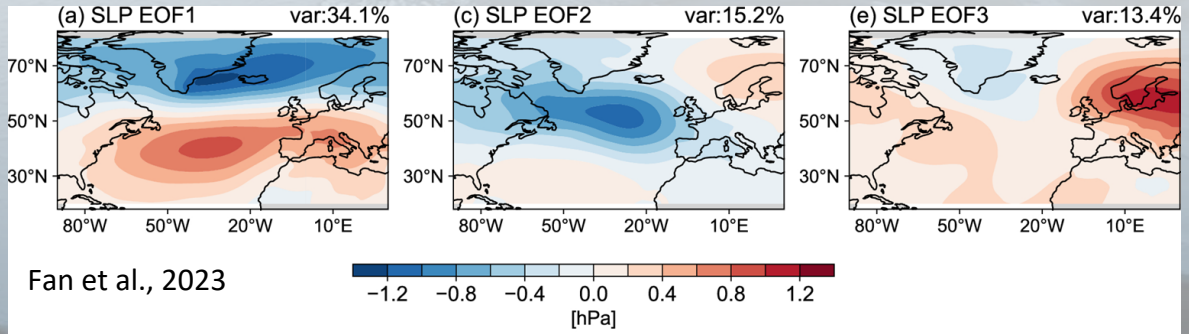
Complex Internal Variability of Nordic Seas (Greenland, Iceland, Norway Seas)



Nordic Seas (NS) link Arctic and North Atlantic circulation: the eastern NS acts as a major conduit for Atlantic waters into the Arctic, while the western NS serves as a pathway for Arctic waters into the Atlantic.

NS are a region of deep water formation, where Atlantic waters sink and contribute to the deep branch of the AMOC.

The region is also influenced by major modes of atmospheric variability, such as the North Atlantic Oscillation (NAO) , East Atlantic (EAP), and Scandinavian patterns (SCA).

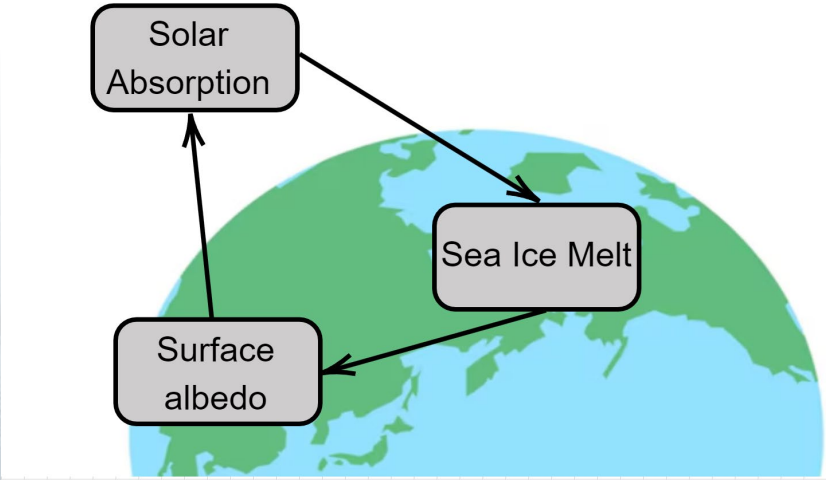


Fan et al., 2023

Background - Causality

- HiLAT-RASM aims to study and quantify feedbacks within Arctic system

- Feedbacks are bi-directional **causal relationships**
- **Causal inference** is the process of determining the *directional influence* of one variable on another
  - Distinguish cause from effect, rather than correlation



Data and Methods

Methods:

We apply the Liang-Kleeman information flow method to study Nordic Seas Dynamics related to complex internal variability of the region (Liang 2021; Dorr et al., 2024).

$$T_{2\to1} = \frac{C_{11}C_{12}C_{2,d1} - C_{12}^2 C_{1,d1}}{C_{11}^2 C_{22} - C_{11}C_{12}^2}$$

GCM	PiCtrl years
CanESM5	1000
GISS-E2-1-G	851
HadGEM3-GC31-LL	2000
IPSL-CM6A-LR	2000
MPI-ESM1-2-LR	1000
MRI-ESM2-0	701
ACCESS-ESM1-5	1000
ACCESS-CM2	500
CMCC-CM2-SR5	500
CMCC-ESM2	500
EC-Earth3	500
EC-Earth3-AerChem	500

Oceanic Transports

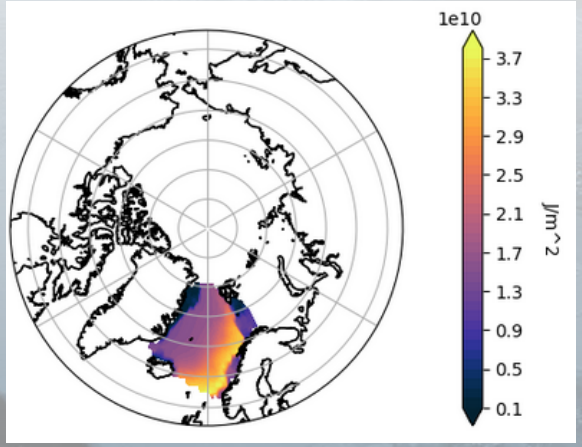
1) DS: Denmark Strait

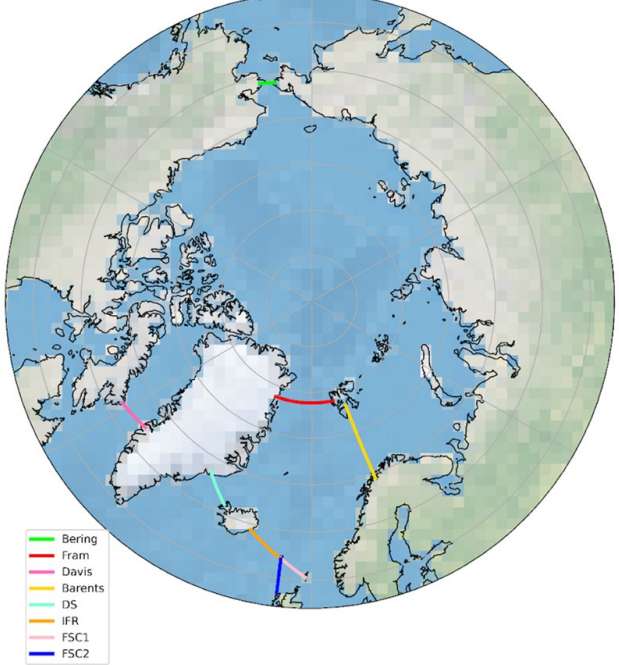
2) IFR: Iceland–Faroe Ridge

3) FSC: Faroe–Shetland/Scotland Channel

4) Barents Strait

5) Fram Strait





Heat content **6)** upper upper 100m, **7)** 100-600 m, **8)** below 600m, **9)** Surface heat flux

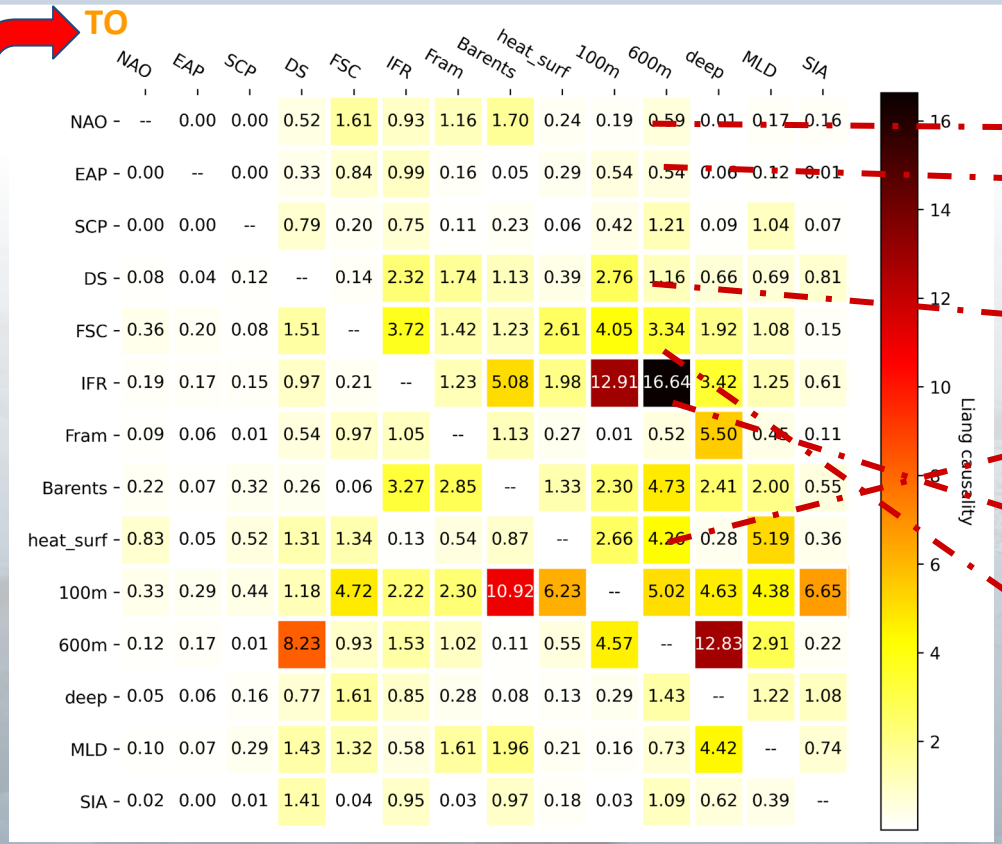
Atmospheric modes:

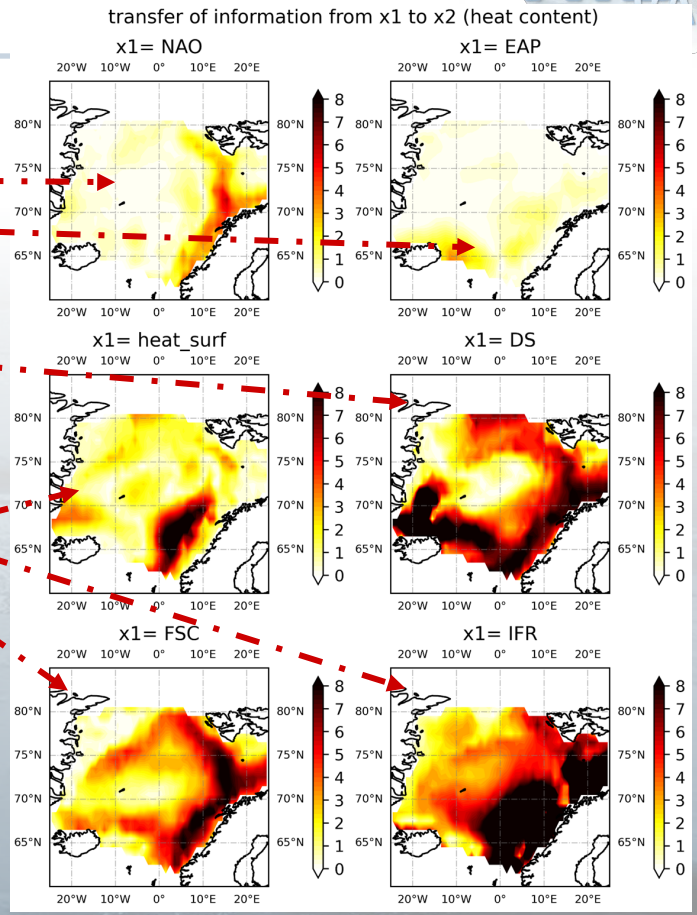
10) NAO, **11)** SCP, **12)** EAP

13) Area of Deep Mixed Layer in March

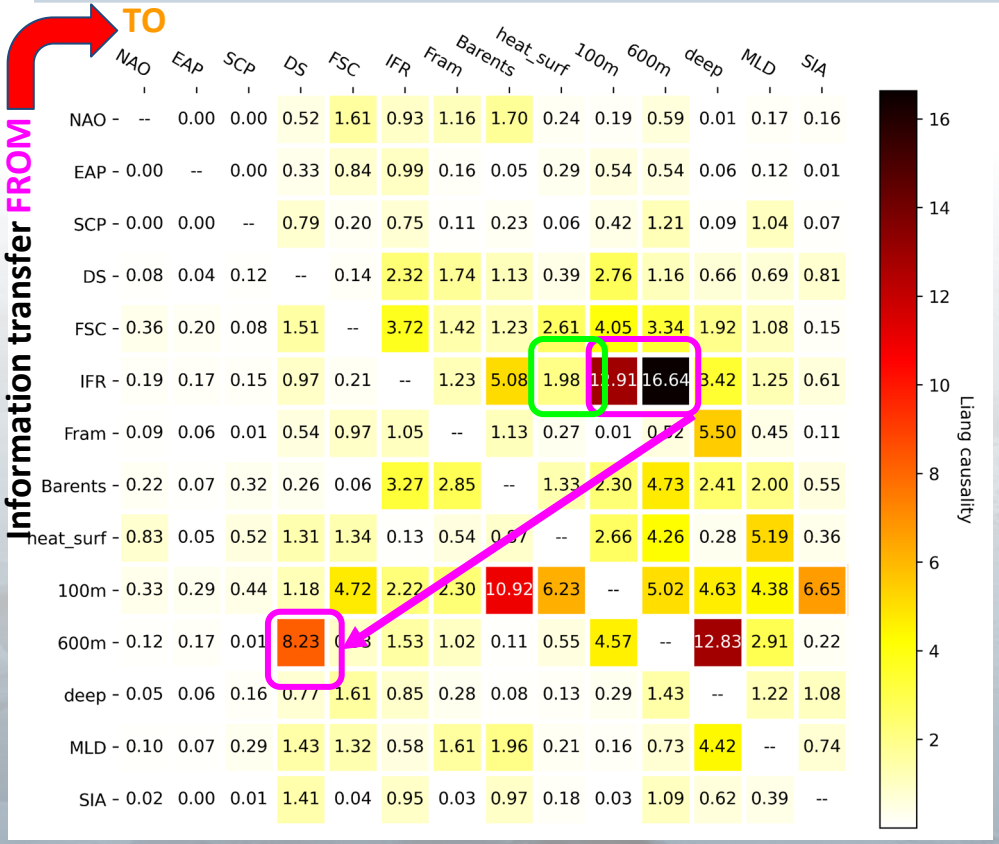
14) Ice Area in September

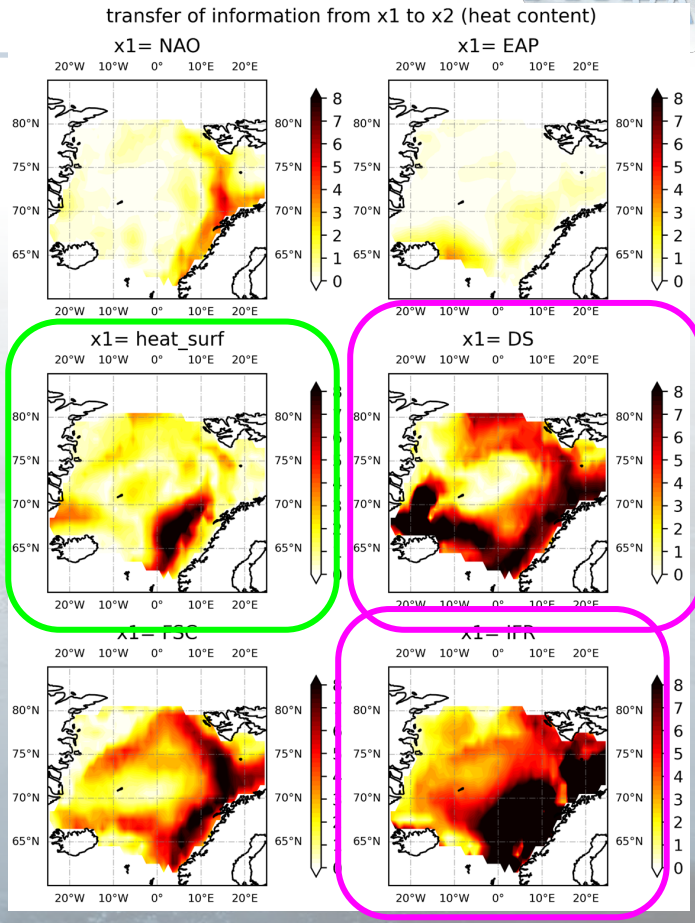
Liang-Kleeman causality results



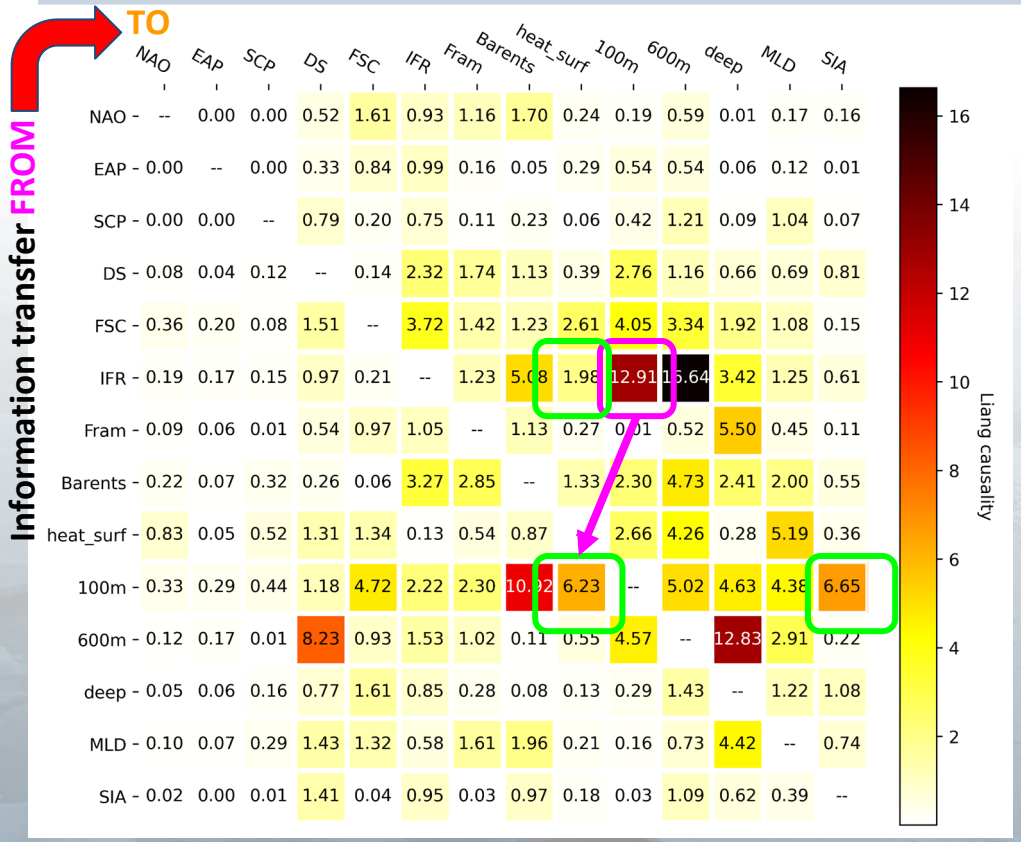


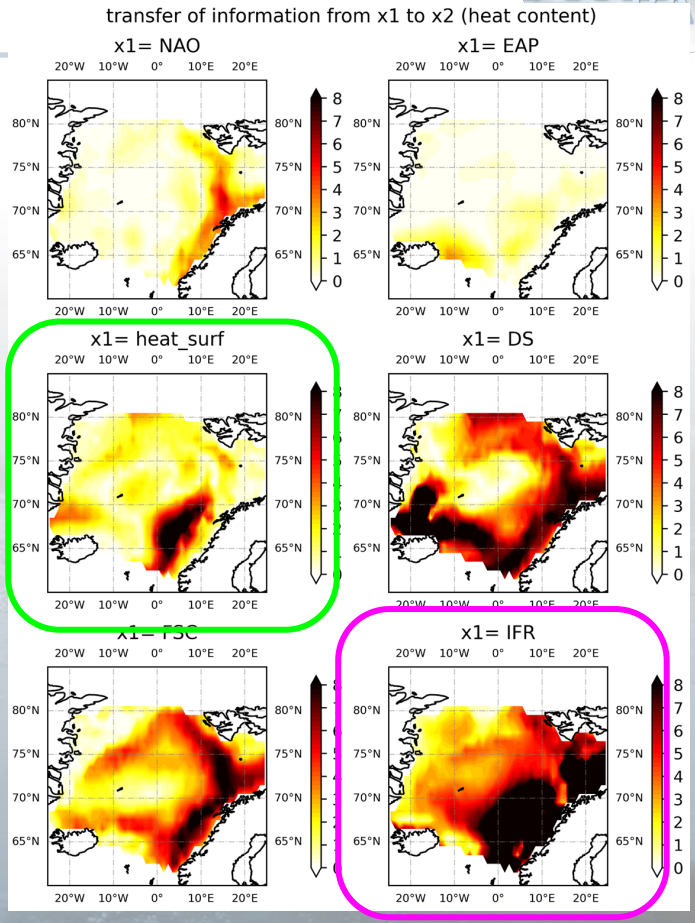
Liang-Kleeman causality results





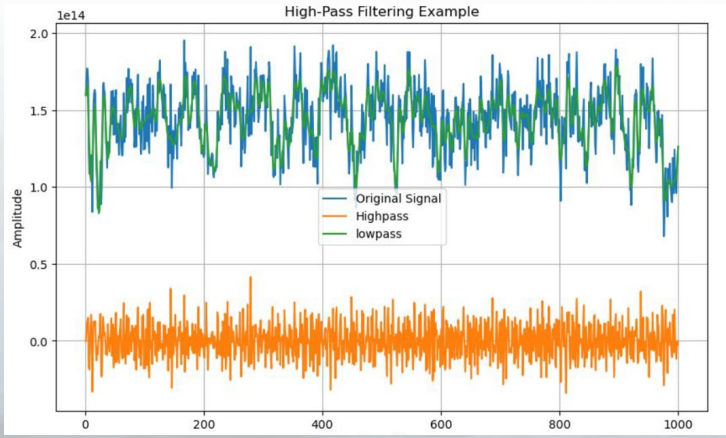
Liang-Kleeman causality results





Separating longer and shorter variability

10 year filter

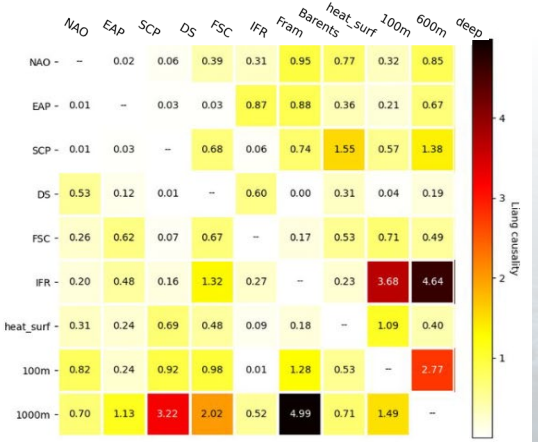


Longer frequencies

Shorter frequencies

To

From



Methodology - ML Framework for Nonlinear Causality Based on the Koopman Operator

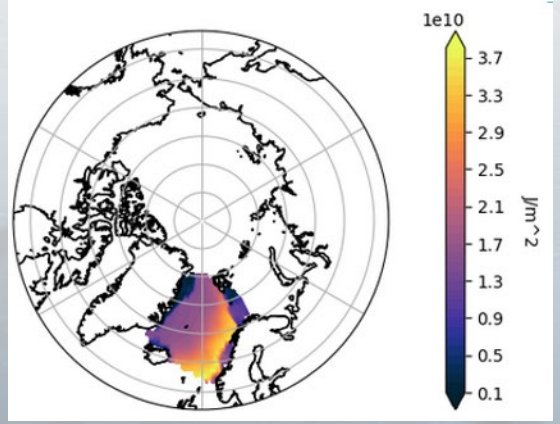
- High level - What did we do:
  - The **Koopman operator** is a mathematical tool which models system evolution
  - The Koopman operator is approximated with ML
  - Theory: If there is (dynamical) influence, it can be detected with the Koopman operator

Paper (Under revision): *Causal Discovery in Nonlinear Dynamical Systems using Koopman Operators, Rupe et. al.*

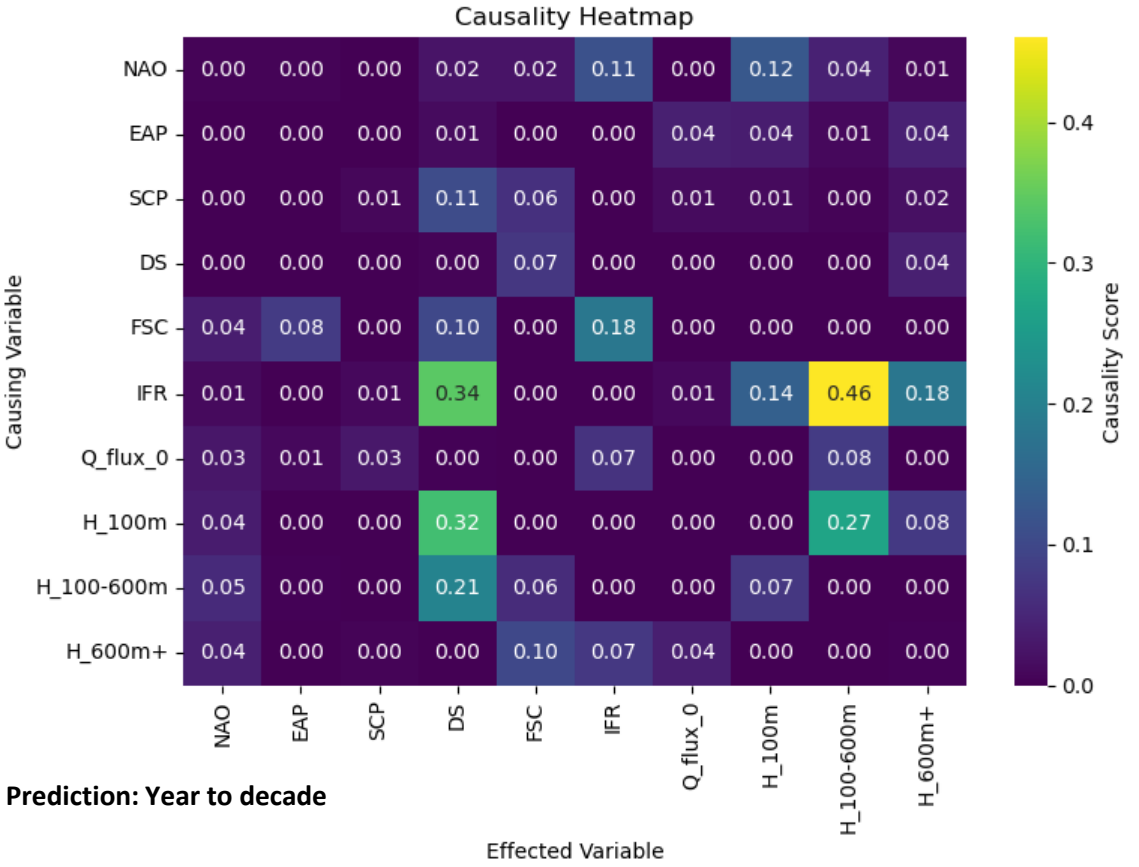
Derek DeSantis
https://www.hilat.org/team.html

Results - Some Causal Analysis for Ocean Heat Transport

1. NAO
2. EAP (east atlantic pattern)
3. SCP (scandinavian pattern)
4. DS (heat transport through Denmark strait)
5. FSC (heat transport through Faroe-Scotland strait)
6. IFR (heat transport through Iceland-Faroe ridge)
7. surface heat flux (ocean-atmosphere, negative out from ocean)
8. top 100 m heat content
9. 100-600 m heat content
10. 600-bottom m heat content



Region for variables 7-10



Prediction: Year to decade

Results - Some Causal Analysis for Ocean Heat Transport

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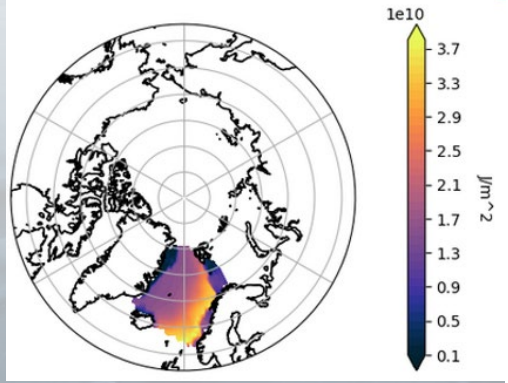

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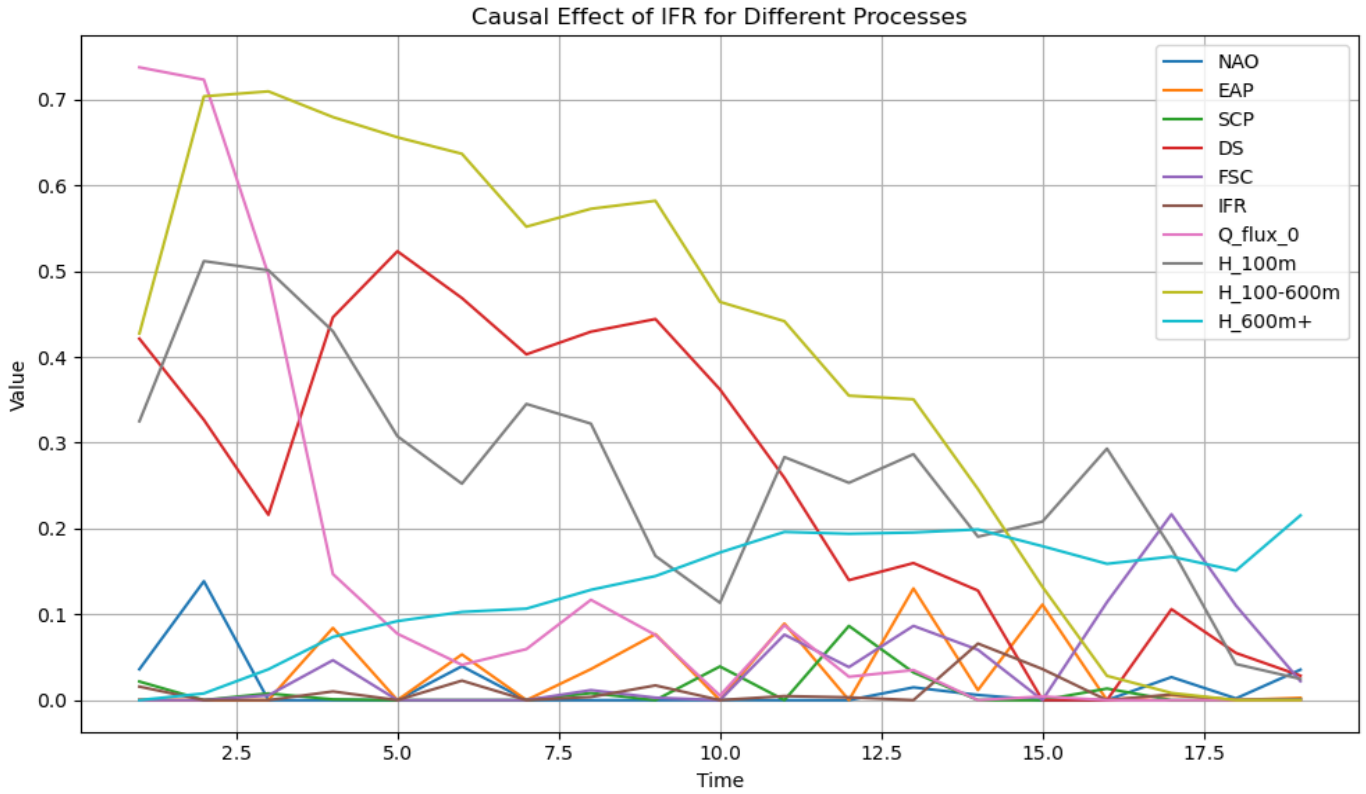


Current and Future work

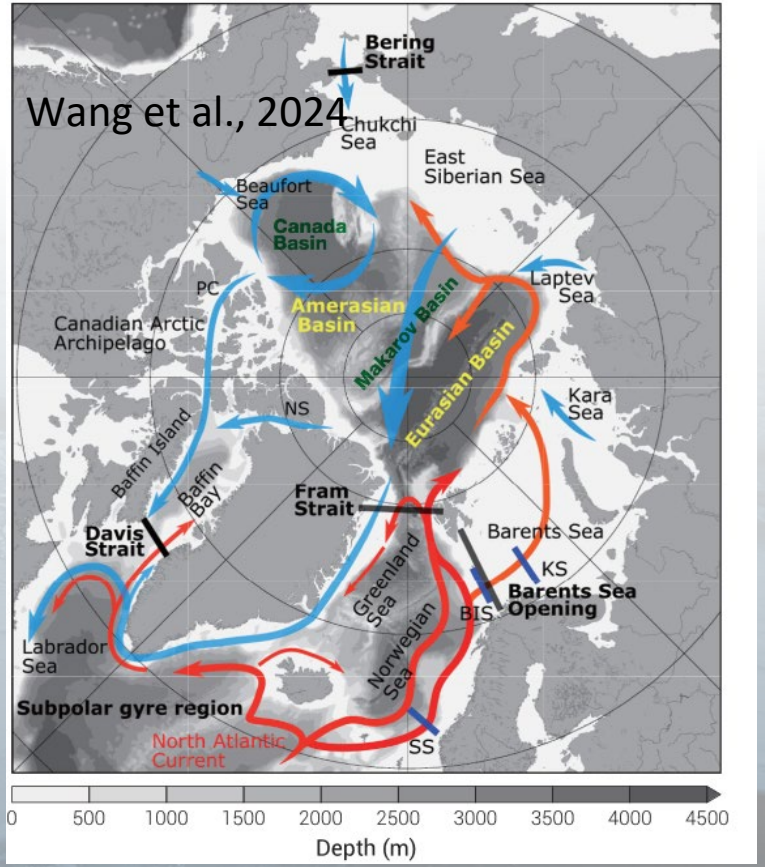
Work in progress:

Expand analysis to ~40 CMIP6 GCMs and add SSP5-8.5 scenario to the study

Future directions of research (following the Atlantic waters in the Arctic):

Kara-Barents Sea analysis

Rest of Eurasian and Amerasian basins (Impact of Bering Strait and Pacific Climate modes like ENSO/IPO?)



Thank you!

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