The Rate of Information Transfer as a Measure of Rapid Changes in Arctic Sea Ice

David Docquier[1], Stéphane Vannitsem[1], Francesco Ragone[1], Klaus Wyser[2], and X. San Liang[3]

[1]Royal Meteorological Institute of Belgium
[2]Rossby Centre, Swedish Meteorological and Hydrological Institute
[3]Fudan University

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Abstract

Arctic sea ice has substantially changed over the past four decades, with a large decrease in sea-ice area and volume. The exact causes of these changes are not entirely known. In our study, we make use of the Swedish Meteorological and Hydrological Institute Large Ensemble (SMHI-LENS). This ensemble consists of 50 members realized with the EC-Earth3 global climate model and covers the period 1970-2100. We apply the Liang-Kleeman information flow method to analyze the cause-effect relationships between Arctic sea ice and its potential drivers. We show that recent and future changes in Arctic sea ice are mainly driven by air and sea-surface temperatures and ocean heat transport. Conversely, changes in Arctic sea ice also considerably impact temperature and ocean heat transport. Finally, we find a progressive decrease in the influence of sea-ice area and volume on air temperature and ocean heat transport through the twenty-first century.

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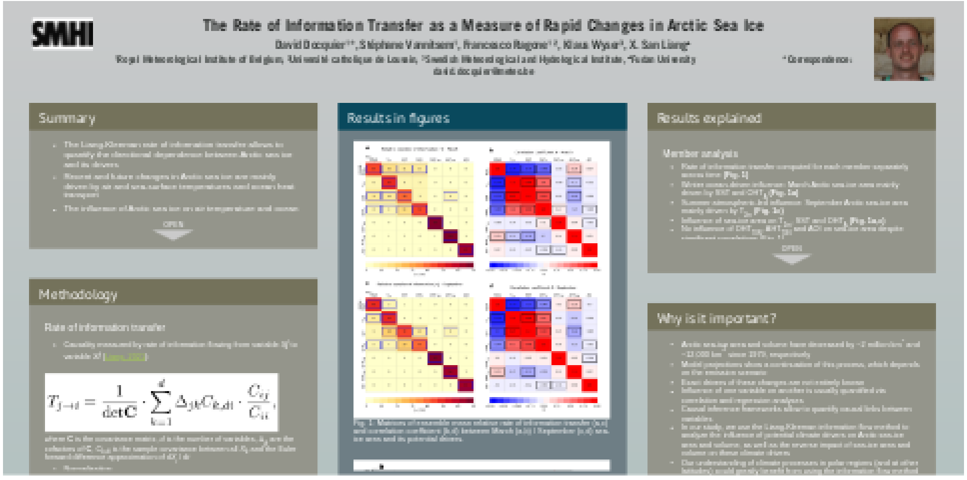

David Docquier[1*], Stéphane Vannitsem[1], Francesco Ragone[1 2], Klaus Wyser[3], X. San Liang[4]

[1]Royal Meteorological Institute of Belgium, [2]Université catholique de Louvain, [3]Swedish Meteorological and Hydrological Institute, [4]Fudan University *Correspondence: david.docquier@meteo.be

PRESENTED AT:

SUMMARY

- The Liang-Kleeman rate of information transfer (see Methodology) allows to quantify the directional dependence between Arctic sea ice and its drivers

- Recent and future changes in Arctic sea ice are mainly driven by air and sea-surface temperatures and ocean heat transport (see Results)

- The influence of Arctic sea ice on air temperature and ocean heat transport progressively decreases through the twenty-first century (see Results)

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METHODOLOGY

1. Rate of information transfer

- Causality measured by rate of information flowing from variable *Xj* to variable *Xi* (Liang, 2021 (https://www.mdpi.com/1099-4300/23/6/679)):

$$T_{j\to i} = \frac{1}{\det\mathbf{C}} \cdot \sum_{k=1}^{d} \Delta_{jk} C_{k,di} \cdot \frac{C_{ij}}{C_{ii}},$$

where **C** is the covariance matrix, *d* is the number of variables, Δ_{jk} are the cofactors of **C**, $C_{k,di}$ is the sample covariance between all X_k and dX_i / dt (Euler forward difference approximation), C_{ij} is the sample covariance between X_i and X_j, C_{ii} is the sample variance of X_i.

- Normalization:

$$\tau_{j\to i} = \frac{T_{j\to i}}{Z},$$

where *Z* is the normalizer, which takes into account influences from all variables on variable X_i as well as the effect of noise.

- If | $\tau_{j\text{-->}i}$ | = 100 %, X_j has the maximum influence on X_i
- If | $\tau_{j\text{-->}i}$ | = 0 %, X_j has no influence on X_i
- Statistical significance computed via bootstrap resampling (95% confidence interval)

2. Climate model data

- SMHI-LENS (Swedish Meteorological and Hydrological Institute Large Ensemble): 50 members run with the global climate model EC-Earth3 (Wyser et al., 2021 (https://gmd.copernicus.org/articles/14/4781/2021/))
- Model components: IFS cy36r4 (atmosphere; ~ 80 km), NEMO3.6/LIM3 (ocean/sea ice; ~ 1°)
- 1970-2014: CMIP6 forcing
- 2015-2100: SSP1-1.9 and SSP5-8.5 (**results shown here are for SSP5-8.5**)
- Variables: March / September Arctic sea-ice area (SIA), March / September Arctic sea-ice volume (SIV), Arctic near-surface air temperature (T_{2m}; annual mean), Arctic sea-surface temperature (SST; annual mean), total Arctic Ocean heat transport (OHT_A; annual mean), ocean and atmospheric heat transports at 70°N (OHT_{70N}, AHT_{70N}; annual mean), winter Arctic Oscillation Index (AOI)

More details: Docquier et al. (in review), preprint available on ESSOAr (https://doi.org/10.1002/essoar.10507846.1)

RESULTS IN FIGURES

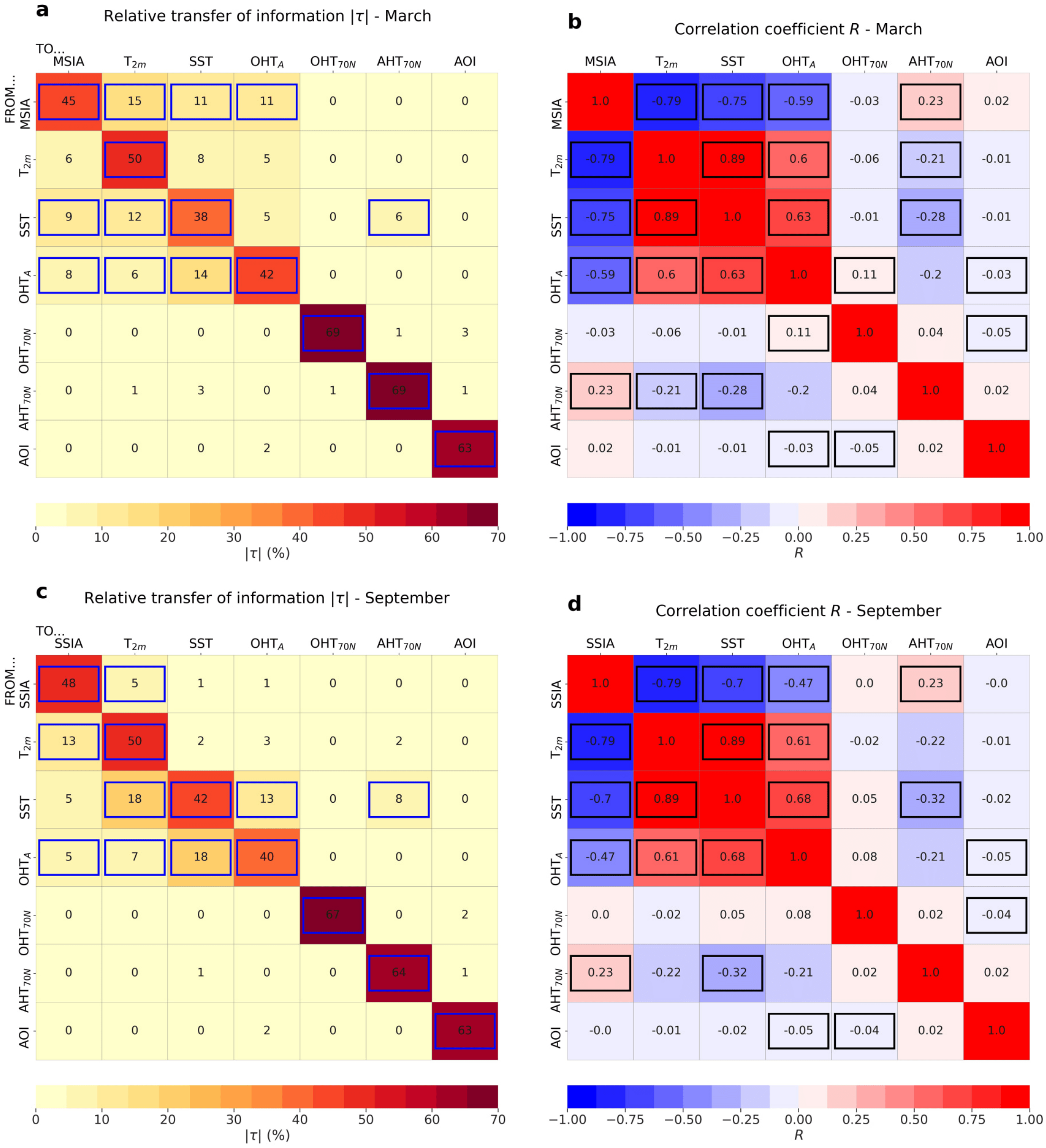

Fig. 1: Matrices of ensemble mean relative rate of information transfer (a,c) and correlation coefficient (b,d) between March (a,b) / September (c,d) sea-ice area (SIA) and its potential drivers (T_{2m}: Arctic near-surface temperature; SST: Arctic sea-surface temperature; OHT_A: total Arctic Ocean heat transport; OHT_{70N}: ocean heat transport at 70°N; AHT_{70N}: atmospheric heat transport at 70°N; AOI: Arctic Oscillation Index).

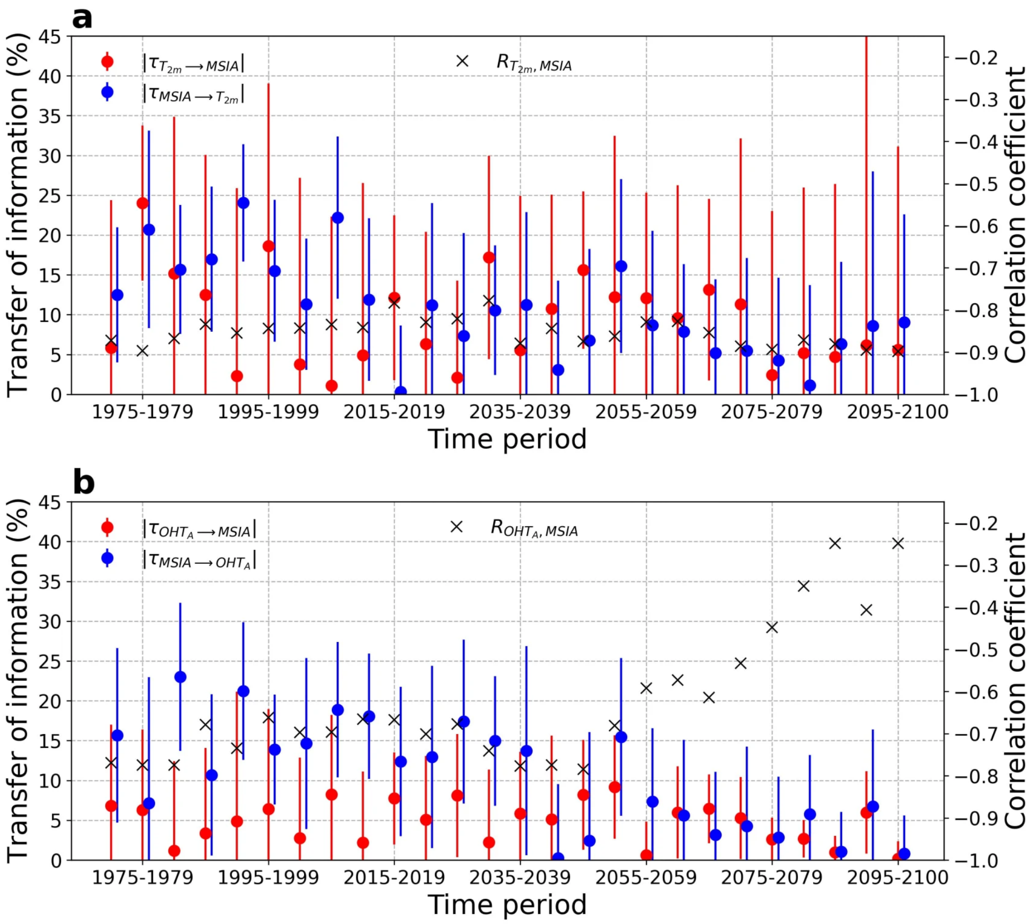

Fig. 2: Time evolution of relative rate of information transfer (dots and error bars) and correlation coefficient (crosses), for each period of 5 years, between March sea-ice area (MSIA) and near-surface air temperature (T_{2m}) (a), and between MSIA and total Arctic Ocean heat transport (OHT_A) (b).

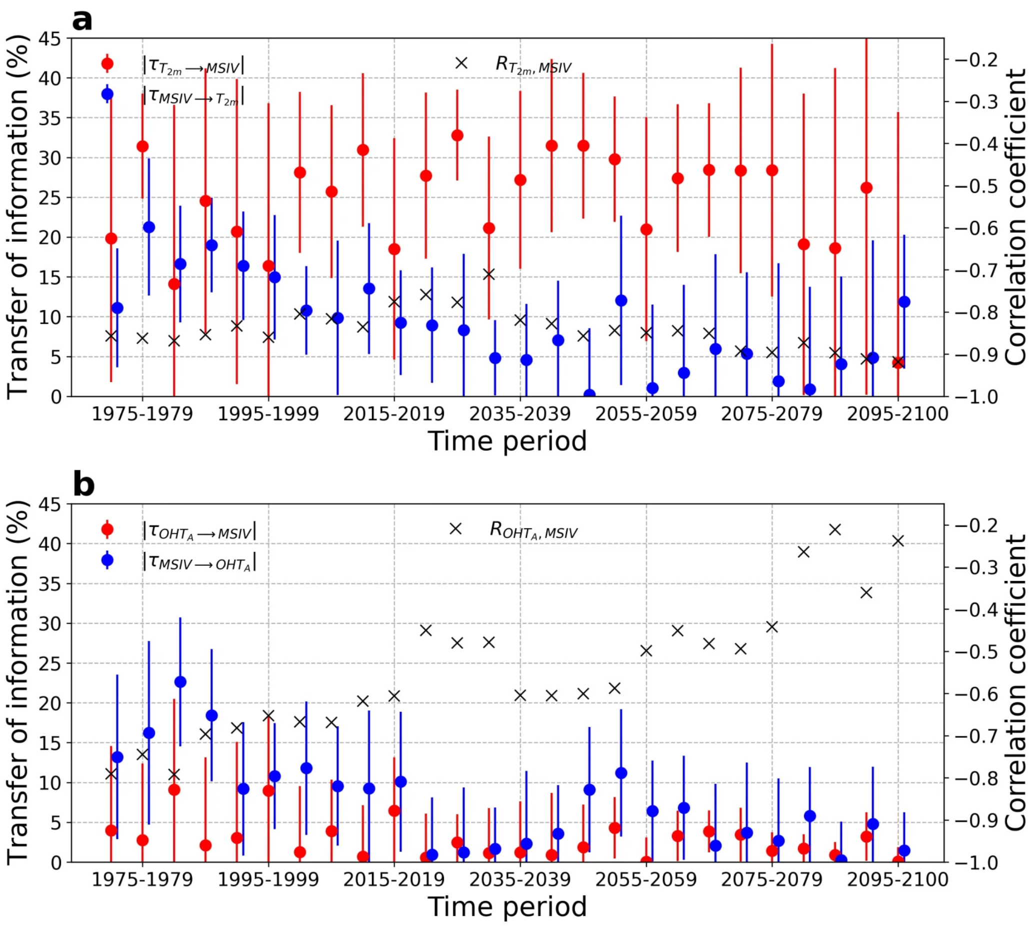

Fig. 3: Time evolution of relative rate of information transfer (dots and error bars) and correlation coefficient (crosses), for each period of 5 years, between March sea-ice volume (MSIV) and near-surface air temperature (T_{2m}) (a), and between MSIV and total Arctic Ocean heat transport (OHT_A) (b).

RESULTS EXPLAINED

1. Member analysis

- Rate of information transfer computed for each member separately across time and then merged together (ensemble mean) **(Fig. 1)**
- Winter ocean-driven influence: March Arctic sea-ice area mainly driven by Arctic sea-surface temperature (SST) and Arctic Ocean heat transport (OHT_A) **(Fig. 1a)**
- Summer atmospheric-led influence: September Arctic sea-ice area mainly driven by Arctic near-surface air temperature (T_{2m}) **(Fig. 1c)**
- Influence of sea-ice area on T_{2m}, SST and OHT_A **(Fig. 1a,c)**
- No influence of ocean and atmospheric heat transports at 70°N (OHT_{70N} and AHT_{70N}) and winter Arctic Oscillation Index (AOI) on sea-ice area despite significant correlations (Fig. 1) --> external driver at play

2. Time analysis

- Rate of information transfer computed for each period of 5 years separately across the member space **(Figs. 2-3)**
- Progressive loss of influence of sea-ice area and volume on T_{2m} and OHT_A --> weaker interactions as sea-ice area and volume decrease **(Fig. 2)**
- Rate of information transfer from T_{2m} to sea-ice volume remains more constant across time than from OHT to sea-ice volume --> long-lasting effect of T_{2m} **(Fig. 3)**

More information: Docquier et al. (in review), preprint available on ESSOAr (https://doi.org/10.1002/essoar.10507846.1)

WHY IS IT IMPORTANT?

- Arctic sea-ice area and volume have decreased by ~2 million km^2 and ~12,000 km^3 since 1979, respectively (Onarheim et al., 2018 (https://doi.org/10.1175/JCLI-D-17-0427.1); Schweiger et al., 2019 (https://doi.org/10.1175/JCLI-D-19-0008.1))
- Model projections show a continuation of this process, which depends on the emission scenario (SIMIP, 2020 (https://doi.org/10.1029/2019GL086749); Docquier & Koenigk, 2021 (https://doi.org/10.1038/s43247-021-00214-7))
- Exact drivers of these changes are not entirely known
- Influence of one variable on another is usually quantified via correlation and regression analyses
- Causal inference frameworks allow to quantify causal links between variables, and thus go beyond classical correlation analyses
- In our study, we use the Liang-Kleeman information flow method to analyze the influence of potential climate drivers on Arctic sea-ice area and volume, as well as the reverse impact of sea-ice area and volume on these climate drivers (Liang, 2021 (https://doi.org/10.3390/e23060679))
- Our understanding of climate processes in polar regions (and at other latitudes) could greatly benefit from using the information flow method

AUTHOR INFORMATION

David Docquier[1]*, Stéphane Vannitsem[1], Francesco Ragone[1,2], Klaus Wyser[3], X. San Liang[4]

[1]Royal Meteorological Institute of Belgium (RMIB), Brussels, Belgium

[2]Université catholique de Louvain (UCLouvain), Louvain-la-Neuve, Belgium

[3]Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden

[4]Fudan University, Shanghai, China

*Correspondence: david.docquier@meteo.be

ABSTRACT

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