Causes of recent and future Arctic sea-ice changes

David Docquier[1], S. Vannitsem[1], F. Ragone[1,2], K. Wyser[3], X. S. Liang[4]

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1. Introduction

- Arctic sea-ice area has decreased by ~ 2 million km^2 since 1979
- Arctic sea-ice volume has decreased by ~ 12,000 km^3 since 1979
- Model projections show a continuation of this process, which depends on the emission scenario
- 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
- In our study, we use the Liang-Kleeman (2005) 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

2. Methodology

Rate of information transfer

- Causality measured by rate of information flowing from variable X_2 to variable X_1 (Liang, 2014):

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

C_{ij} covariance between X_i and X_j
$C_{i,dj}$ covariance between X_i and dX_j / dt

- Normalization (Liang, 2015): $\tau_{2\to1} = T_{2\to1}/Z_{2\to1}$ $\quad Z_{2\to1} = |T_{2\to1}| + \left|\frac{dH_1^*}{dt}\right| + \left|\frac{dH_1^{noise}}{dt}\right|$
  - If $|\tau_{2\to1}|$ = 0%: X_2 does not influence X_1; if $|\tau_{2\to1}|$ > 0%: X_2 influences X_1
- Time series should be long enough and stationary
- Application to climate studies, e.g. Vannitsem et al. (2019)
- Application to N variables: Liang (2021)

Climate model data

- SMHI-LENS: 50 members run with the global climate model EC-Earth3 (Wyser et al., 2021)
- 1970-2014: CMIP6 forcing
- 2015-2100: SSP1-1.9 and **SSP5-8.5 (shown here)**
- Variables: March/September Arctic sea-ice area (SIA), March/ September Arctic sea-ice volume (SIV), Arctic near-surface air temperature (T_{2m}), total Arctic Ocean heat transport (OHT_A), ocean and atmospheric heat transports at 70°N (OHT_{70N}, AHT_{70N}), winter Arctic Oscillation Index (AOI) **[Fig. 1]**

3. Results

Member analysis

- Rate of information transfer computed for each member separately across time **[Fig. 2]**
- Ensemble mean rate of information transfer and statistical significance via bootstrap resampling with replacement and Fisher's method
- Winter-ocean driven influence: March Arctic-sea ice area mainly driven by SST and OHT_A **[Fig. 2a]**
- Summer atmospheric-led influence: September Arctic sea-ice area mainly driven by T_{2m} **[Fig. 2c]**
- Influence of sea-ice area on T_{2m}, SST and OHT_A **[Fig. 2a,c]**
- No influence of OHT_{70N}, AHT_{70N} and AOI on sea-ice area despite significant correlations **[Fig. 2]**

Time analysis

- Rate of information transfer computed for each period of 5 years separately across the member space **[Figs. 3-4]**
- Statistical significance via bootstrap resampling
- 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 **[Figs. 3-4]**
- 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. 4]**

4. Conclusions and Outlook

- The Liang-Kleeman rate of information transfer 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
- The influence of Arctic sea ice on air temperature and ocean heat transport progressively decreases through the 21st century
- Our understanding of climate processes in polar regions (and at other latitudes) could greatly benefit from using the information flow method
- More information: Docquier et al. (in review; preprint: https://doi.org/10.1002/essoar.10507846.1)

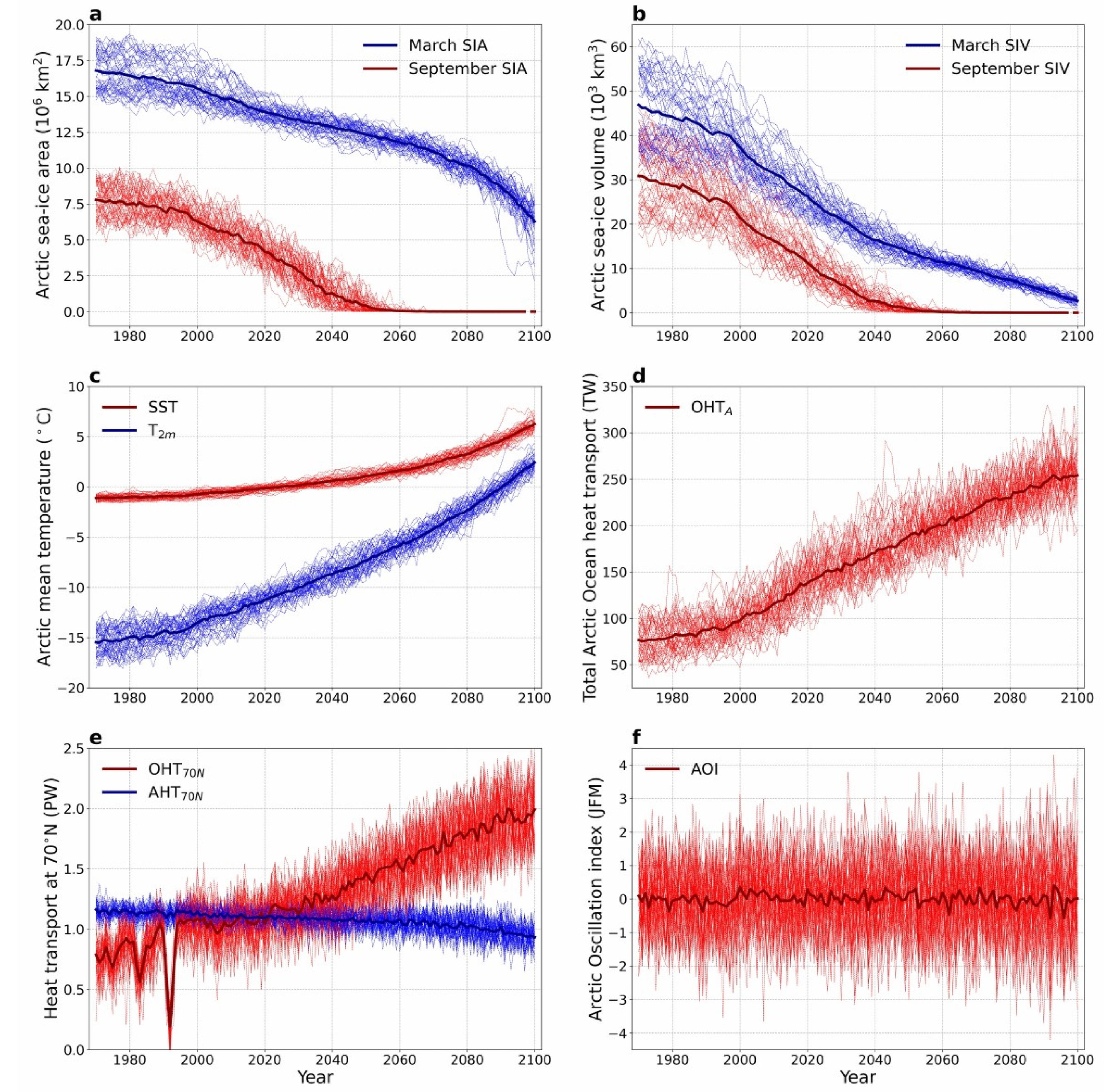


Fig. 1: Time series of all considered variables

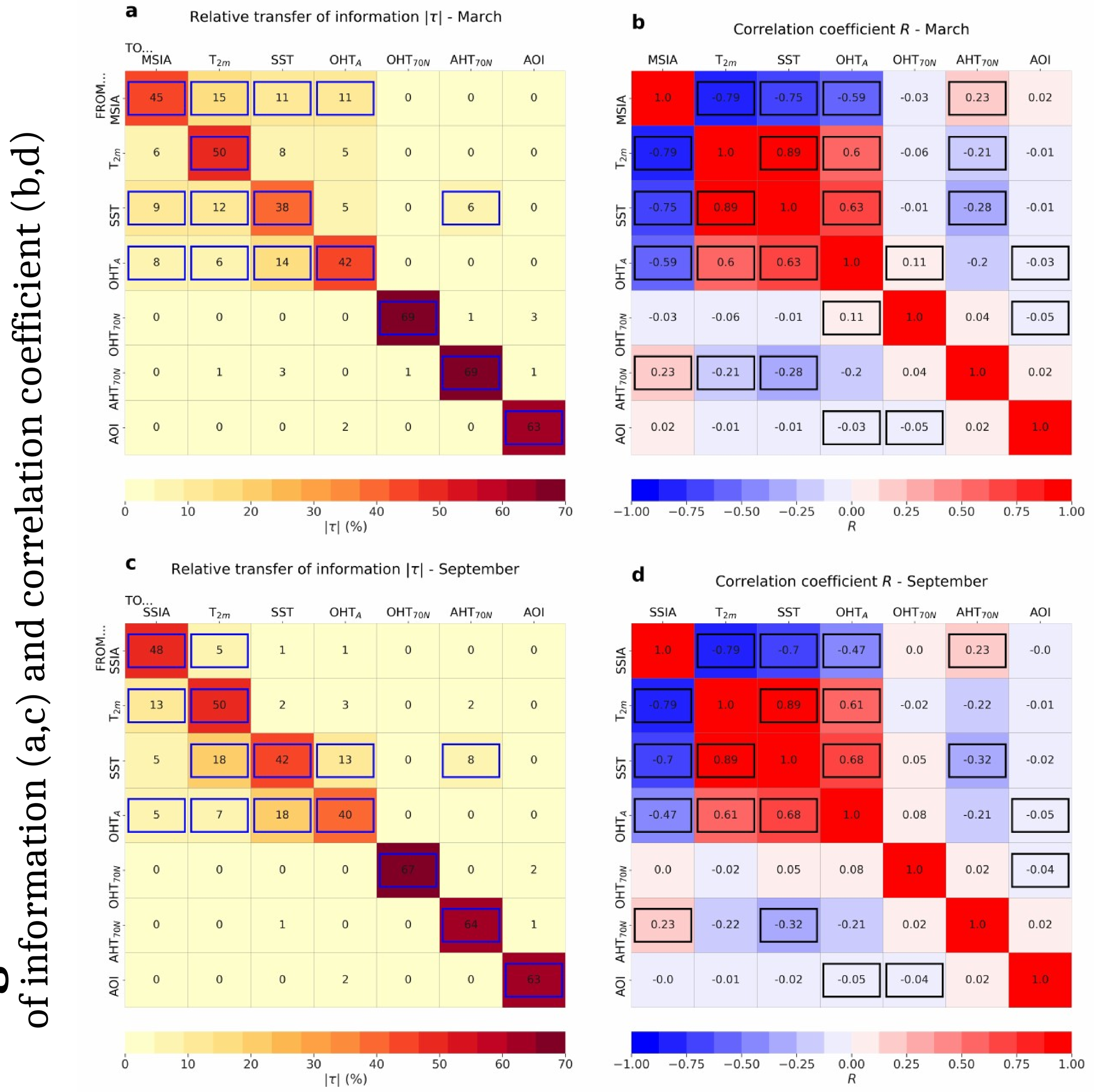


Fig. 2: Matrices of ensemble mean relative transfer of information (a,c) and correlation coefficient (b,d)

Fig. 3: Time evolution of relative rate of information transfer and correlation coef. for each period of 5 years; T_{2m} – March sea-ice area (MSIA) (a) and OHT_A – MSIA (b)

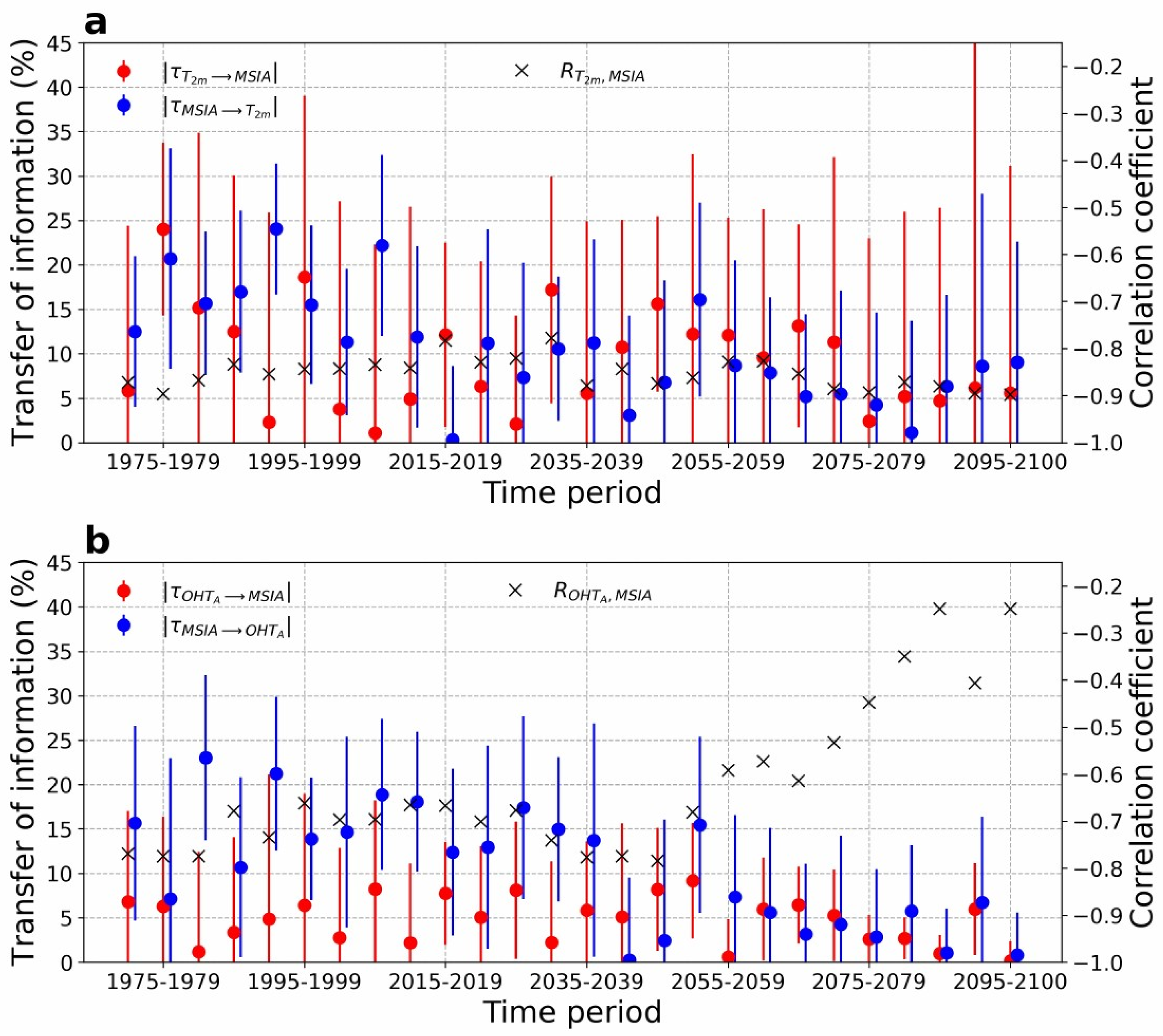
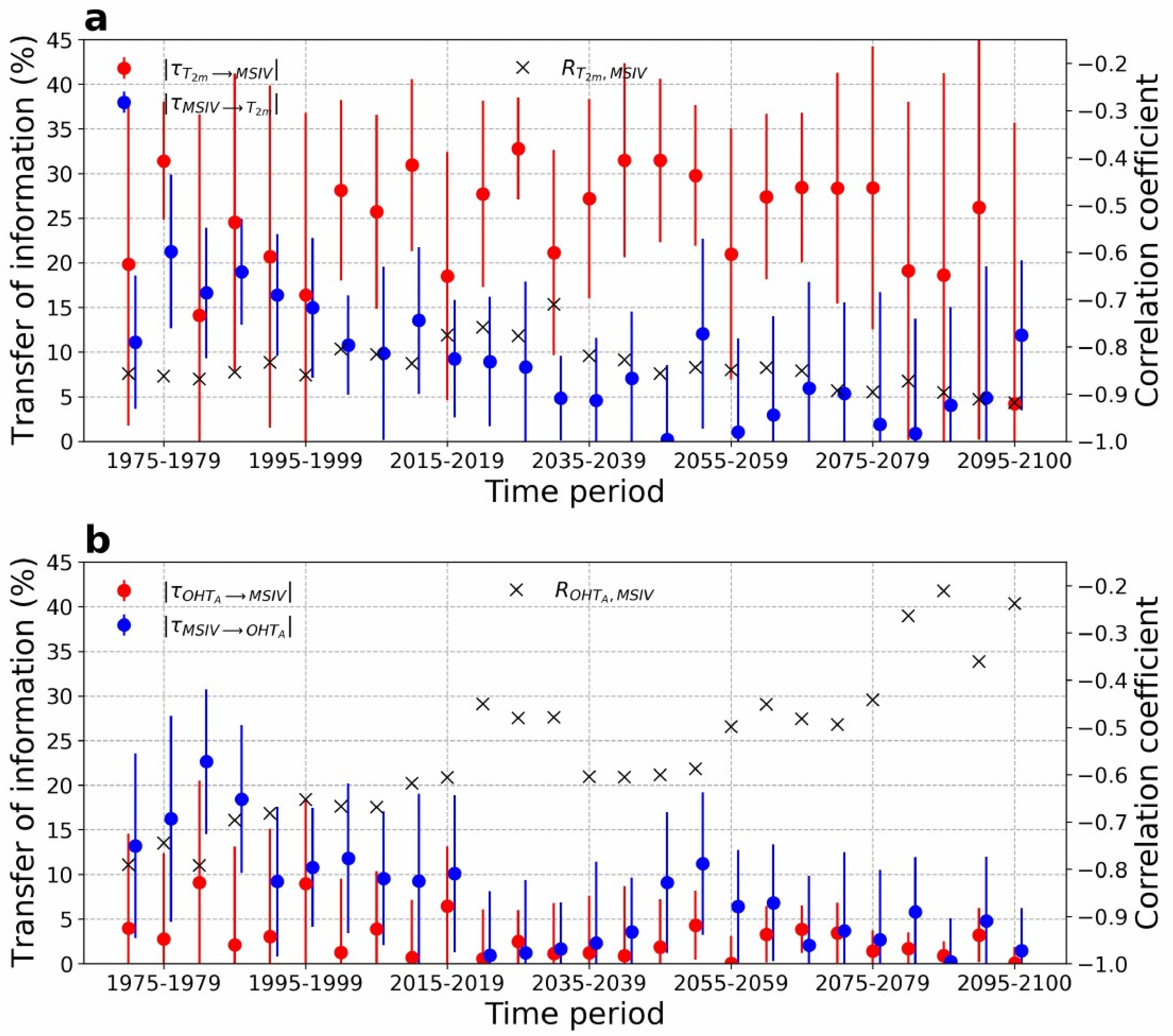


Fig. 4: Same as Fig. 3 for T_{2m} – March sea-ice volume (MSIV) (a) and OHT_A – MSIV (b)



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