# Influence of snow on surface air temperature in the Northern Hemisphere and its impact on subseasonal prediction

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## Significance statement

- Snow cover significantly impacts weather and climate in the Northern Hemisphere and influences sub-seasonal to seasonal (S2S) atmospheric predictability. Accurately representing snow–atmosphere interactions in S2S models remains a challenge.
- This study employs Liang–Kleeman information flow analysis, a method based on information theory, to quantify causal relationships in snow–atmosphere dynamics.
- This method provides an unprecedentedly detailed picture of snow cover impacts and enables us to compare the morels' representation with observations, helping to identify deficiencies in the models.

## Methods and Data

### Liang-Kleeman information flow analysis

The Liang-Kleeman information flow (LKIF) analysis can detect causality based on the time evolution of information entropy for a given dynamical equation. Its maximum likelihood estimate for a linearized form is derived as

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

where $C_{ij}$ is the sample covariance between $X_i$ and $X_j$, and $C_{i,dj}$ is the sample covariance between $X_i$ and the time derivative of $X_j$ using the Euler forward scheme (Liang 2014). Following Liang (2015), we present normalized information flow in this study (hereafter simply referred to as causality). For further details, see Takaya et al. (2023).

### Data

We used the fifth generation ECMWF reanalysis (ERA5) and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis for snow cover, snow water equivalent, 2-m temperature. We also used reforecast data from the Japan Meteorological Agency (JMA), the European Center for Medium-Range Weather Forecasts (ECMWF), and the China Meteorological Administration (CMA) provided by the WWRP/WCRP Sub-seasonal to seasonal prediction (S2S) Project. We used weekly average data for all analyses.

## References

**Takaya, Y., Komatsu, K.K., Ganeshi, N.G. *et al.* (2024)** A sub-monthly timescale causality between snow cover and surface air temperature in the Northern Hemisphere inferred by Liang–Kleeman information flow analysis. ***Climate Dynamics***, 62, 2735–2753. https://doi.org/10.1007/s00382-024-07112-6

## Results ① Hot spots of snow cover influence

The LKIF analysis identified hotspots where snow cover has a significant impacts on 2-m temperature (Fig .1). The hot spots depend on months and regions, which are closely tied to the seasonal evolution of snow cover. The identified hotspots were also supported by the analysis of snow water equivalent.

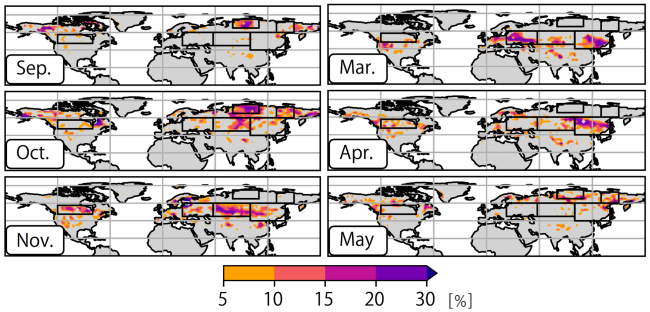



**Figure 1** Normalized information flow from weekly averages of SC to SAT by month for MERRA-2. The MERRA-2 reanalysis data of four consecutive weeks (7 days averages) starting from 1st of the month (denoted in each panel) were used for the calculation for each month. Boxes indicate cold spots identified in this study: East Siberia (60° N–72.5° N, 130° E–150° E), East Asia (40° N–60° N, 100° E–140° E), Canada (47.5° N–57.5° N,120° W–80° W), Eastern Europe (45° N–60° N, 22.5° E–57.5° E), Central Asia (45° N–60° N, 57.5° E–100° E), North Eurasia (65° N–75° N, 80° E–110° E). Only statistically significant regions based on the bootstrap method (5,000 times resampling) are colored.

## Results ② Seasonality and model evaluation

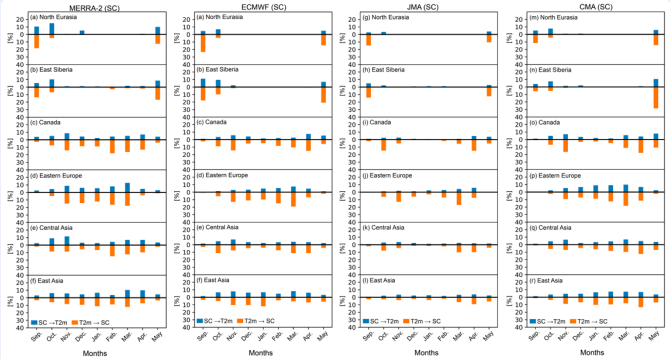



**Figure 2** The seasonality of the SC–SAT causality averaged over the cold spot regions (land only). Blue bars indicate the normalised causality from weekly mean SC to weekly mean SAT. Orange bars indicate the normalised causality from weekly mean SAT to weekly mean SC. Results for MERRA-2 reanalysis, ECMWF, JMA, CMA models.

## Results ③ Impacts on the predictability

We compared the potential predictability of 2-m temperature in terms of correlation skill between models with weak (JMA) and strong (ECMWF) snow cover influence on 2-m temperature (Fig. 3). The ECMWF model presents larger predictability of 2-m temperature than the JMA model, presumably due to the stronger influence of snow on 2-m temperature.

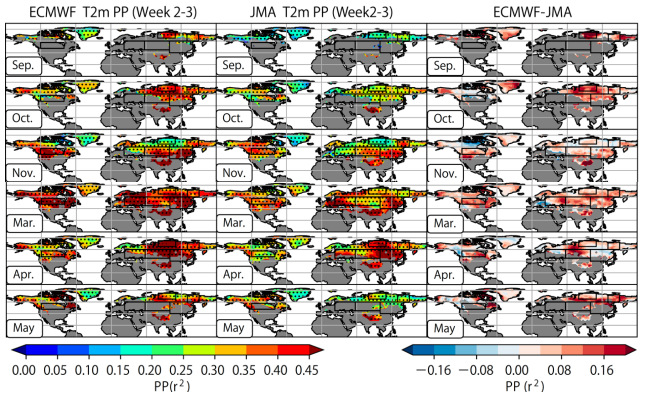



**Figure 3** The potential predictability of SAT assessed by squared Pearson correlation coefficients for Week 2–3 averages for the (left) ECMWF and (middle) JMA models. (right) Differences in the potential predictability between the ECMWF and JMA reforecasts from close initial dates. The stippling in the left and middle panels indicates statistically significant regions based on the bootstrap method (5,000 times resampling).

## Summary

- This study used Liang–Kleeman information flow to analyze the causal link between snow cover (SC) and surface air temperature (SAT) variability, identifying seasonal "hotspots" where snow significantly influences SAT.
- The results refine previous findings, highlighting limitations in the S2S model representation of SC–SAT interactions.
- This method offers a practical way to diagnose model shortcomings without extensive experiments, providing insights for improving S2S predictability. These findings enhance the understanding of snow-atmosphere interactions and their role in future climate predictability.

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