Arctic seasonal variability and extremes, and the role of weather systems in a changing climate

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BACKGROUND

The Arctic climate is changing dramatically. Long-term trends in surface temperature and sea ice extent caused by anthropogenic warming strongly affect the Arctic atmosphere [1,2]. Air-sea-ice feedback processes additionally amplify these trends [3,4].

The Arctic region further exhibits a strong variability on time scales from days to seasons. Synoptic weather systems such as cyclones and anticyclones are related to air mass exchanges with the mid-latitudes [5,6] and air mass transformations within the Arctic [7,8], and are thus key drivers of Arctic variability.

In this study it is our goal to analyze the change of **Arctic seasonal variability** as well as the role of weather systems in a warming climate by using large-ensemble climate model data.

METHOD

For this analysis we use large-ensemble data of the CESM1 climate model [9,10]. Simulations are performed using the RCP8.5 emission scenario. 6-hourly output is available for four different periods:

S2000: 1990-2000 [**105** ensemble members]
S2040: 2031-2040 [**40** ensemble members]
S2070: 2061-2070 [**40** ensemble members]
S2100: 2091-2100 [**105** ensemble members]

To account for varying climatological and surface conditions, we differentiate between distinct geographic Arctic sub-regions and surface types (open ocean and sea ice). The seasonal variability in these sub-regions is analysed in the phase space spanned by the **seasonal-mean anomalies of 2m-temperature (*T*) and precipitation (*P*)**.

Climate change in the *T-P* phase space

Seasonal mean

- Substantial regional and seasonal differences in magnitude of overall warming and wettening
- Particularly large *T* increase in seasons and regions with strong sea ice loss
- Extremely warm seasons in S2000 rank among the coldest seasons / become unrealistic in S2100

Inter-annual variability

- Increase in *P* variability over Arctic Ocean and reduction in *T* variability in the Kara and Barents Seas in winter
- Changes related to increase in seasonal cycle and interannual variability of sea-ice concentration as well as increasing moisture transport towards high latitudes [11]

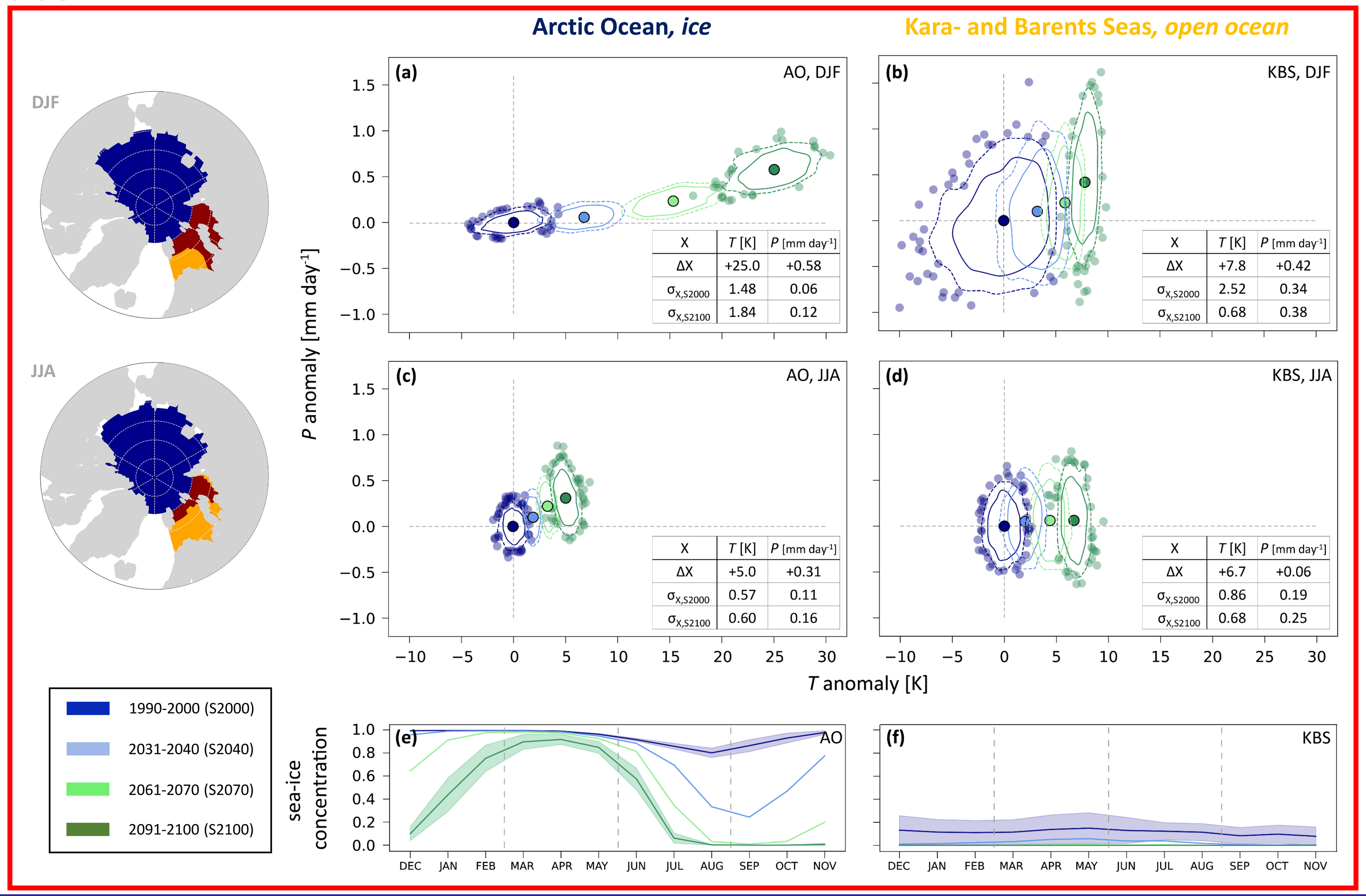

Figure 1: Seasonal-mean anomalies of *T* (in K) along the x-axis and *P* (in mm day^{-1}) along the y-axis in the region of (a, c) the Arctic Ocean with $SIC_{clim} \geq 0.5$ (blue area in the map) and (b, d) in the region of the Kara- and Barents Seas with $SIC_{clim} < 0.5$ (orange area in the map) in (a, b) DJF and (c, d) JJA. Colored dots show mean anomalies per period and solid (dashed) lines include 80% (95%) of all seasons. Outlier seasons are shown for the S2000 and S2100 period. Tables show change in the seasonal mean between S2000 and S2100 (ΔX) as well as the standard deviation of anomalies in S2000 ($\sigma_{X,S2000}$) and S2100 ($\sigma_{X,S2100}$) for both *T* and *P*. Panels (e) and f) show monthly-mean sea ice concentration for all four periods in the respective sub-regions.

CESM1 vs. CMIP6 models

- Distributions of simulated *T* and *P* anomalies relative to S2000 for CESM1 and CMIP6 models largely overlap in almost all seasons and regions
- Models mainly differ relative to changes in seasonal mean values between S2000 and S2100
- Good agreement regarding changes in *T* and *P* variability

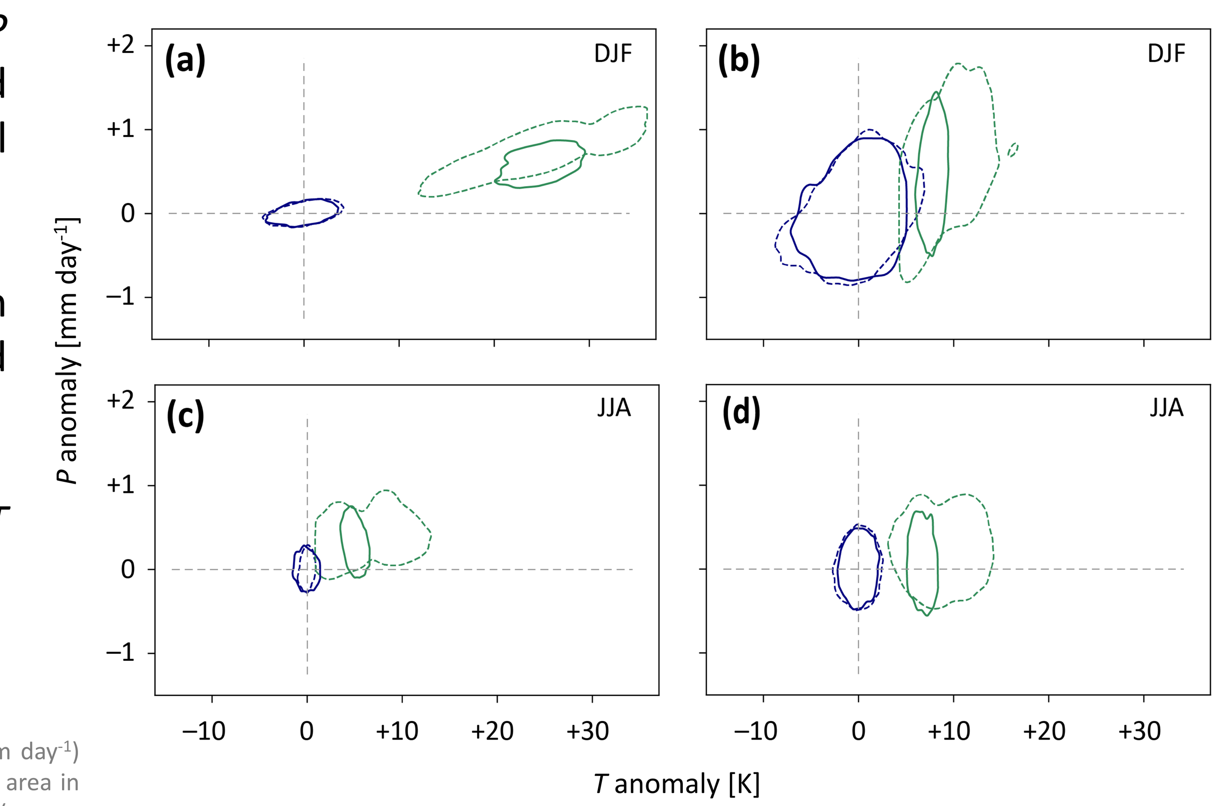

Figure 2: Same as Fig. 1 for S2000 and S2100. Contours contain 95% of all seasons for CESM1 (solid lines) and 16 multi-member CMIP6 models (dashed lines). Anomalies are calculated relative to the mean over all seasons in S2000 for CESM1 and the respective model in CMIP6.

Want to know more?
→ Hartmuth et al., 2023
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Application of large-ensemble data: changes in synoptic processes

Role of weather systems for extreme seasons (CESM1)

- ***P* extremes** driven by **colocated anomalies** in cyclone/anticyclone occurrence, while ***T* extremes** driven by **large-scale dipole patterns**
- Large-scale patterns largely unaffected by global warming

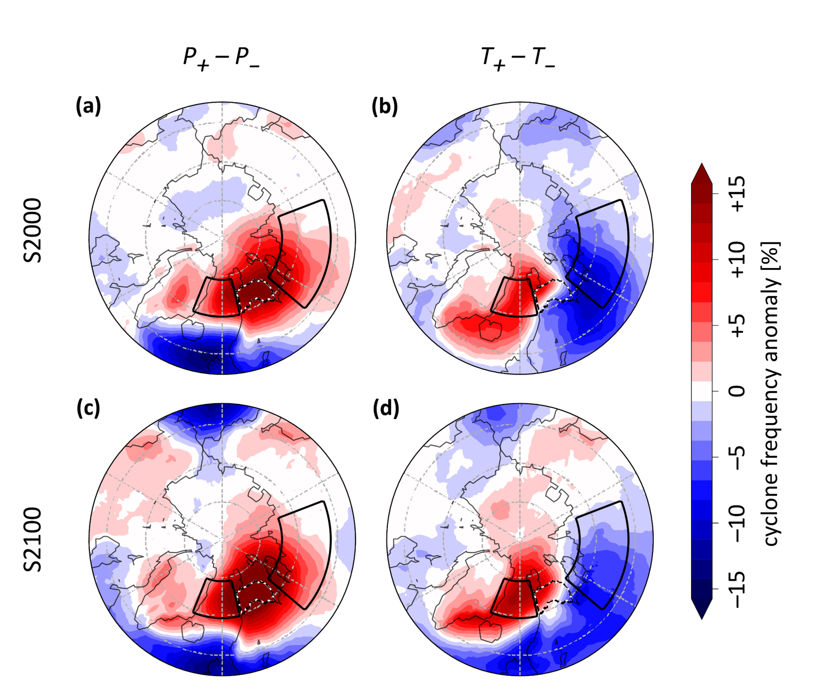

Figure 3: Differences in seasonal-mean cyclone frequency anomaly composites for DJF in the ice-free part of the Kara and Barents Seas (black-white contour) for extremely (a, c) wet (P_+) – dry (P_-) and (b, d) warm (T_+) – cold (T_-) seasons in (a, b) S2000 and (c, d) S2100.

Arctic moisture transport (CESM2)

Master thesis project by Sven Voigt, ETH Zurich (supervised together with Iris Thurnherr)

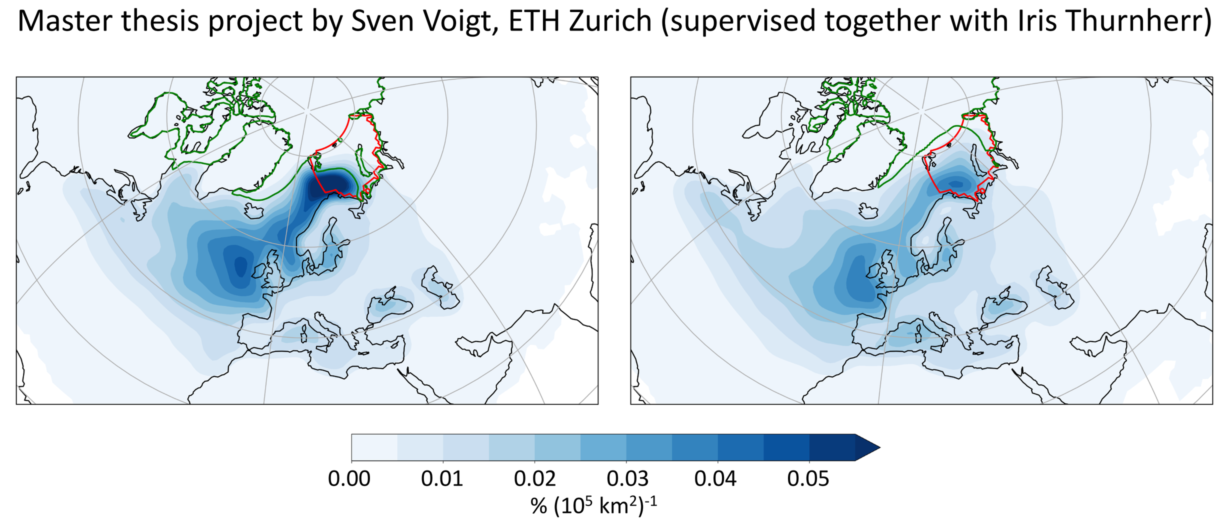

Figure 4: Mean moisture source areas for the Kara and Barents Seas (red contour) for DJF in (left) present-day and (right) future CESM2 simulations. Ensemble mean sea ice edge in each climate state is shown by solid green line.

- Increasing contribution of local moisture sources linked to sea ice retreat
- Increasing contribution of remote moisture sources (e.g., subtropical North Atlantic, Mediterranean) which can be associated with changes in cyclone and anticyclone frequency

SUMMARY

- **Regionally dependent changes** in seasonal temperature and precipitation variability are closely linked to **local sea-ice evolution**.
- Seasons ranking among the warmest in present-day climate are soon projected to rank among the coldest or **become unrealistic**.
- **Robust dynamical relationship** between weather system frequency and seasonal extremes **persists in warming climate**.
- Compared to a range of CMIP6 models, **CESM1 performs well** regarding trends in seasonal-mean *T* and *P*, and variability thereof.

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