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# Supplementary Materials for

## Disappearing landscapes: The Arctic at +2.7°C global warming

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## Materials and Methods

### *Global Warming Levels (GWLs)*

To analyze the Arctic climate at pre-industrial conditions, +1.5ºC and +2.7ºC of global warming, we use a 'global warming level (GWL) sampling' approach (*56*) to select representative data samples for a given GWL from simulations of the Coupled Model Intercomparison Project phase 6 (CMIP6) (*84*). For each model simulation in the analysis, we identify the year in which the 20-year moving average global surface air temperature first exceeds a given anomaly relative to 1850-1900. We then include the 20-year period around that year in the data sample. Thereby, the timing of the 20-year periods may differ for different realizations of the same model due to internal variability, but the temperature averaged over the selected period in each simulation is consistent with the target GWL. For the pre-industrial conditions, we always use the 20-year period 1860-1879.

The underlying data and methodological details differ for the climate variables considered.

### *Temperature*

For the analysis of Arctic temperatures, we use daily surface air temperature data from a 50-member ensemble of historical and SSP5-8.5 scenario simulations of the MPI-ESM1.2-LR model (*85*), which is among the best performing CMIP6 models in representing Arctic near-surface temperatures and their spatio-temporal variability (*86*). We select data samples for the different GWLs as described above. Since the GWL samples from the SSP5-8.5 simulations are subject to transient warming, we remove the warming trend from the surface air temperature time series of each ensemble member in the GWL sample by subtracting the linear trend of the ensemble mean time series for each day and grid cell. We then compute the daily Arctic mean temperature over the spatial domain north of 66°N, compute the anomalies relative to 1850-1900, and remove the mean seasonal cycle. In Fig. 1, we show the probability distribution of these daily Arctic surface air temperature anomalies of the data samples for pre-industrial conditions, +1.5ºC, and +2.7ºC for the entire year and individual seasons. A more in-depth analysis based on multiple models is provided by Giesse et al., 2024 (*9*).

### *Sea-ice*

For the analysis of Arctic sea-ice area, we use September Northern Hemisphere sea-ice area from the same 50-member ensemble of MPI-ESM1.2-LR historical and SSP5-8.5 scenario simulations as for temperature. Climate models commonly simulate a lower sensitivity of Arctic sea-ice loss to global warming than has been observed (*16*). To match the simulated sensitivity with the observed one while maintaining the modeled internal variability, we perform a bias correction of the model data, following Niederdrenk and Notz (2018) (*86*): We calculate the linear regression between the ensemble mean September Arctic sea-ice area and global surface temperature anomaly for the observational period 1953-2016 and take the observed regression line from Niederdrenk and Notz (2018) based on merged sea-ice area estimates from HadISST and the NSIDC sea ice index combined with the observational estimate of global-mean temperature evolution from HadCRUT4 (*86*). We then subtract the positive or negative bias of the ensemble mean sea-ice area as a function of temperature anomaly from the time series of sea-ice area in each ensemble member. This results in a sea-ice sensitivity that is identical between the model ensemble mean and the observational record while maintaining the internal variability of the model simulations. When the sea-ice area falls below zero as a result of the bias correction, we set it to zero. From the bias-corrected sea-ice area data, we select the GWL samples as described above. We further detrend the time series of each ensemble member within the GWL samples by subtracting the ensemble mean.

In Fig. 2a, we show the corrected September sea-ice area and its inter-annual variability for pre-industrial conditions, +1.5$^o$C, and +2.7$^o$C, visualized by circles with a size corresponding to the sea-ice area of a given probability (color-coded) according to the sea-ice area distribution in the GWL sample. The outer, underlying circle represents the Arctic Ocean area (14.06 million km$^2$).

### ***Greenland***

For the analysis of Greenland melt area, we use daily surface air temperature data over Greenland from a 40-member ensemble of historical and SSP5-8.5 scenario simulations of the ACCESS-ESM1.5 model (*87*). The ACCESS-ESM1.5 model is chosen because the derived pattern of annual melt days over Greenland in the observational period agrees well with that derived from passive microwave data provided by NSIDC (https://nsidc.org/ice-sheets-today).

We select the GWL samples as described above and detrend the surface air temperature time series of each ensemble member in the GWL sample by subtracting the linear trend of the ensemble mean time series at each day and grid cell. Then, for each year and ensemble member, we count the number of melt days in each grid cell as the number of days with a surface air temperature above 0$^o$C. Based on the average number of melt days per year, we then calculate the area of Greenland that experiences more than 0, 1, ..., 100 days of melting.

In Fig. 2b, we show the area that experiences a given number of melt days as color-coded circles of corresponding size for pre-industrial conditions, +1.5$^o$C, and +2.7$^o$C. The outermost circle represents the entire area of Greenland (2.1 million km$^2$)

### **Permafrost**

For the analysis of surface permafrost area, we use Northern Hemisphere permafrost area from historical and SSP5-8.5 scenario simulations of 13 CMIP6 models from Steinert et al. 2023 (*83*, *88*). In contrast to the other variables, we use a multi-model ensemble instead of a single-model large ensemble as the internal variability of permafrost area is small compared to the model uncertainty. From the data provided by Steinert et al. (2023) (*83*), we use surface permafrost area defined as the area where the active layer thickness is less than 3 m. We further select only those models whose 1997-2014 average permafrost area is within the range of present-day estimates of 10.1 to 19.6 million km$^2$ (*24*, *88*) and additionally remove three models (E3SM-1-0, E3SM-1-1-ECA, GISS-E2-1-H) due to lack of surface air temperature data availability. This results in a selection of 13 CMIP6 models, each with a single realization.

For each model simulation, we select GWL samples as described above and calculate the average surface permafrost area over the resulting 20-year periods. In Fig. 2c, we show the permafrost area and its model uncertainty for pre-industrial conditions, +1.5$^o$C, and +2.7$^o$C, visualized by circles with a size corresponding to the permafrost area of a given probability (color-coded) according to the permafrost area distribution over all models. The outer, underlying circle represents the land area north of 45°N (41.68 million $km^2$).

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