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Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet

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Abstract. *Since 2007, there has been a series of surface melt records over the Greenland Ice Sheet (GrIS), continuing the trend towards increased melt observed since the end of the 1990s (**Fig. 2a**). The last two decades are characterized by an increase of negative phases of the North-Atlantic Oscillation (NAO) favoring warmer and drier summers than normal over GrIS (**Figs. 1, 2b**). In this context, we use a Circulation Type Classification (CTC) based on daily 500hPa geopotential height to evaluate the role of atmospheric dynamics in this surface melt acceleration. The interannual melt variability is gauged here by the June-July-August (JJA) mean temperature from reanalyses at 700hPa over Greenland (**Fig. 2a, 4**). Analogous atmospheric circulations in the past show that ~70% of the 1993-2012 warming at 700hPa over Greenland has been driven by changes in the atmospheric flow frequencies (**Fig. 2e**). The occurrence of anticyclones centred over the GrIS has doubled since the end of 1990s, which induces more frequent southerly warm air advection along the Western Greenland coast and over the neighbouring Canadian Arctic Archipelago (CAA) (**Figs. 1, 3, 4**). These changes in the NAO modes explain also why no significant warming has been observed these last summers over Svalbard, where northerly atmospheric flows are twice as frequent as before (**Fig. 1, 4**). Therefore, the recent warmer summers over GrIS and CAA cannot be considered as a long-term climate warming but are more a consequence of NAO variability affecting atmospheric heat transport. Although no global model from the CMIP5 database projects subsequent significant changes in NAO through this century (**Fig. 5**), we cannot exclude the possibility that the observed NAO changes are due to global warming as a consequence of the Arctic sea-ice loss.*

- *The 3 main circulation types found by our automatic CTC are :*
  - *a type (n°1) close to the JJA climatology induced by neutral NAO conditions.*
  - *a cyclonic type (n°2) induced by positive NAO conditions and occurring 30% of the JJA time in average.*
  - *an anticyclonic type (n°3) gauged by negative NAO phases (see **Fig. 1**).*
- *Over the last two decades, there has been a significant frequency increase (15% => 40%) of daily circulations classified as anticyclonic Type 3 (**Fig. 2c**). Such a circulation change is mainly centred over Greenland (**Fig. 3**).*
- *By using analogue flows which occurred during the 1961-1990 summers, we have reconstructed the recent climate and the analogues explain ~ 70% (resp. ~65%) of reanalysis-based 1993-2012 (resp. 1983-2012) JJA warming at 700hPa (**Fig. 2e**). As for the CTC, our similarity index (i.e. the euclidean distance between both Z500 surfaces) is used to select the most similar Z500 surfaces to a given day*
- *The warming pattern of **Fig.4** is well reproduced by the analogues but the temperature increase is underestimated.*
- *The part of the trend not explained by the analogues results from the global warming gauged here by the global annual 2m temperature. By adding the ``anthropogenic'' signal to the analogues-based signal induced by changes in the general circulation, we are able to reconstruct most of the current JJA T700 variability over Greenland (**Fig. 2e**).*
- *The CMIP5 GCMs seem to suggest that these atmospheric circulation anomalies result from the natural variability and not from global warming because the GCMs do not project changes in NAO (**Fig. 5**). However, observational evidence for 2007-2012 suggests there may be a link between Arctic sea-ice loss and enhanced high pressure over Greenland (Overland et al., 2012).*

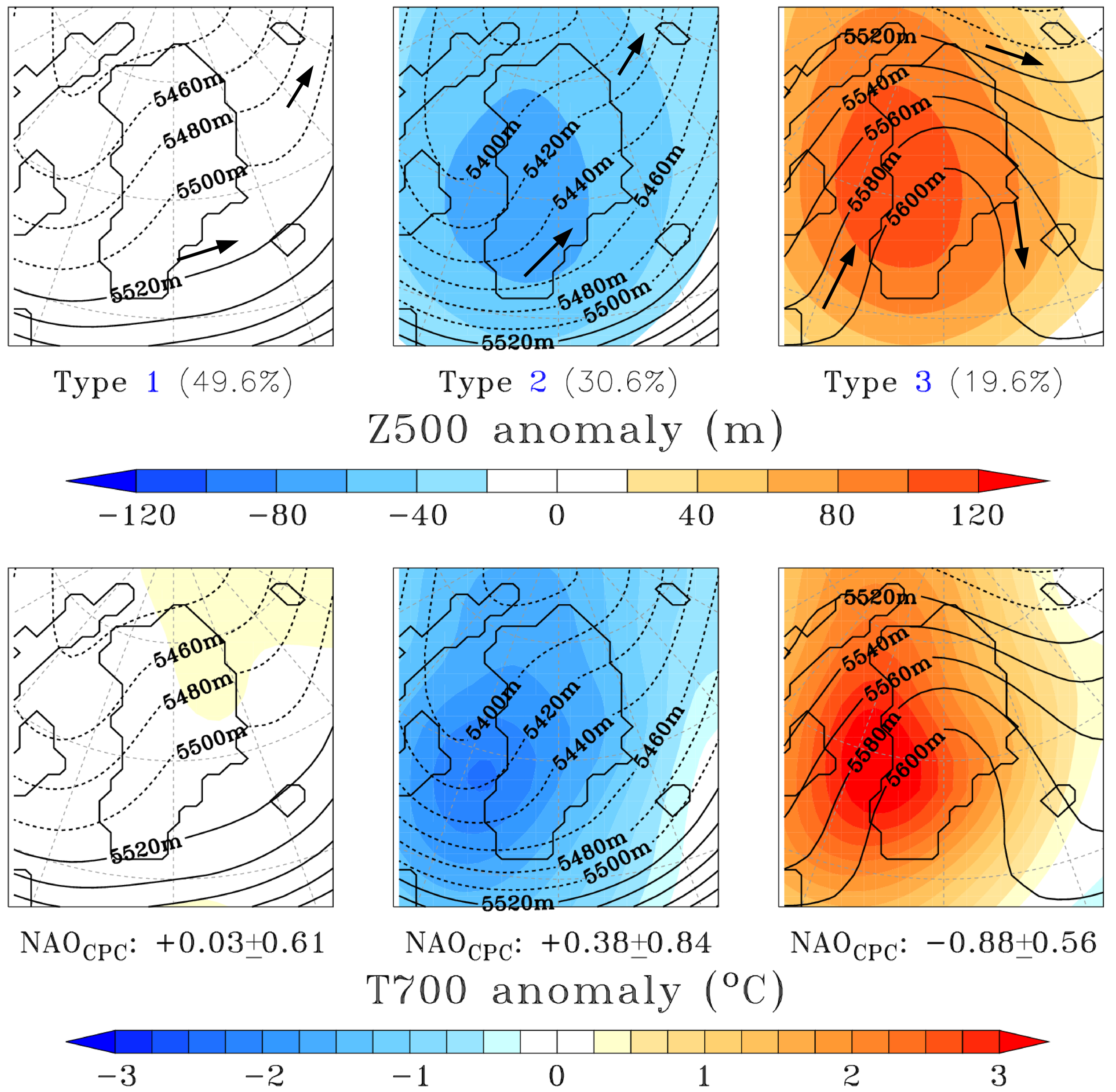

Fig. 1 **(Top)** The geopotential height at 500hPa (Z500) average over the days categorized into the 3 circulation types minus the JJA Z500 average over the whole period 1958–2012. For each circulation type, the proportion of days contained in that class compared to the 5060 days of the 1958–2012 JJA months is indicated in brackets. (**Below**) The lower panels show much the same but for the temperature at 700 hPa (T700). The daily mean NAO index from Climate Prediction Center (CPC) when the considered circulation type occurs is listed. Both Z500 and T700 fields come here from the NCEP-NCAR reanalysis.

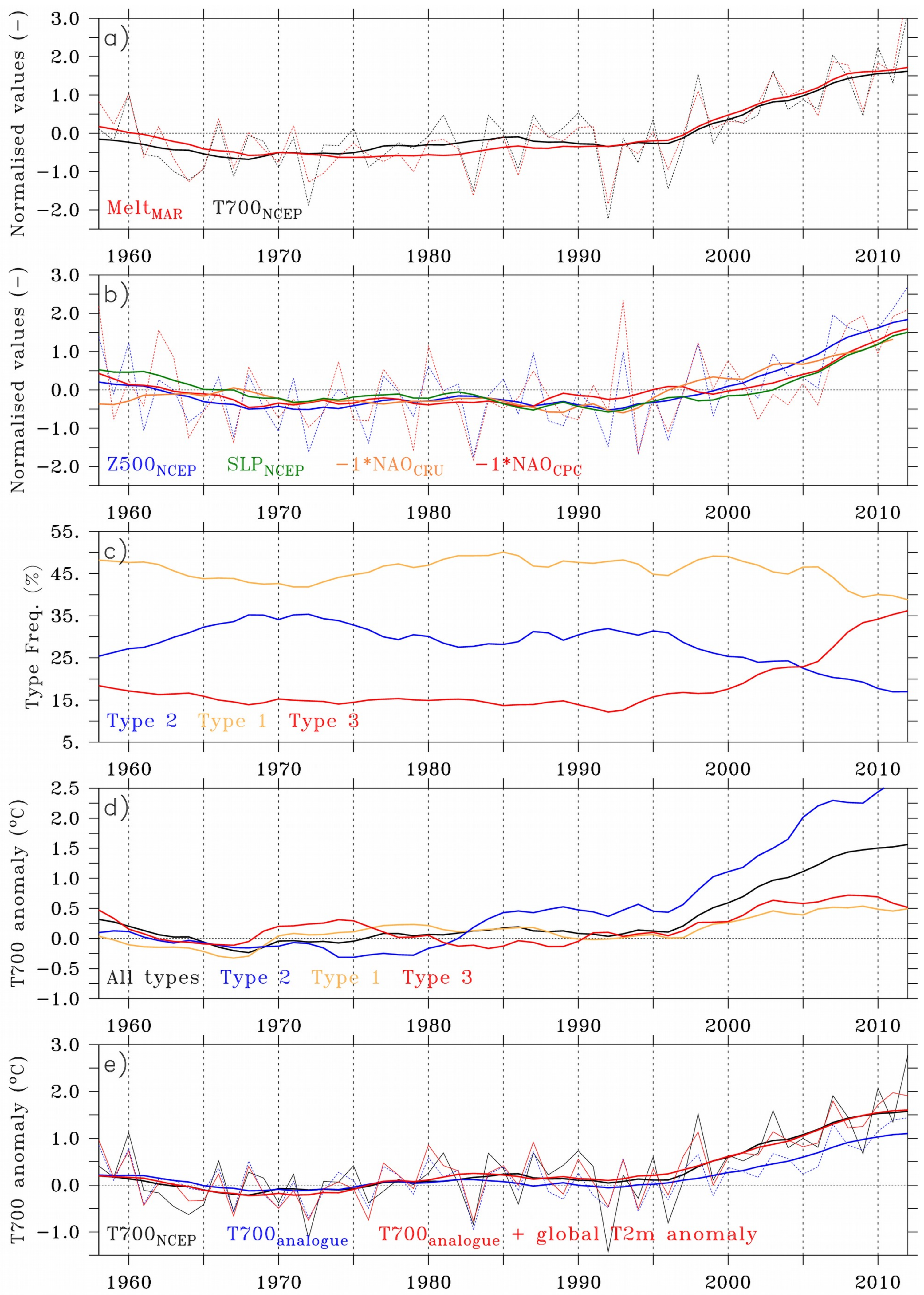

Fig. 2 **(a)** Normalised time series of the annual GrIS melt amount simulated by MAR (in red) and of the JJA Temperature at 700 hPa (T700) averaged over the area covering Greenland (20°W≤longitude≤70°W and 60°N≤latitude≤85°N) from the NCEP-NCAR reanalysis (in black). The smoothed lines show the 10-yr running mean of the time series. **(b)** Normalised time series of the JJA geopotential height at 500hPa (Z500) averaged over the area covering Greenland (in blue), of the JJA sea level pressure (SLP) (in green), of the Z500 based NAO index (in red) from CPC and of the SLP-based NAO index (in orange) from the Climate Research Unit (CRU). Here, the sign of the NAO indexes time series has been changed to be consistent with the other time series. **(c)** Evolution (in percentage) of the number of occurrences of each circulation class shown in Fig. 1 for each summer from 1958 to 2012. A 10-yr running mean is applied here. **(d)** Time series in °C of the JJA T700 anomaly averaged over the area covering Greenland (in black) and of the T700 anomaly averaged over the days contained in each type of the CTC. Only 10-yr running means are shown here. **(e)** Time series in °C of the JJA T700 averaged over the area covering Greenland (in black), of the analogues-based T700 (in blue) and of the analogues-based T700 plus the anomaly of the global annual NCEP-NCAR 2m-temperature (in red) compared with the 1961–1990 mean.

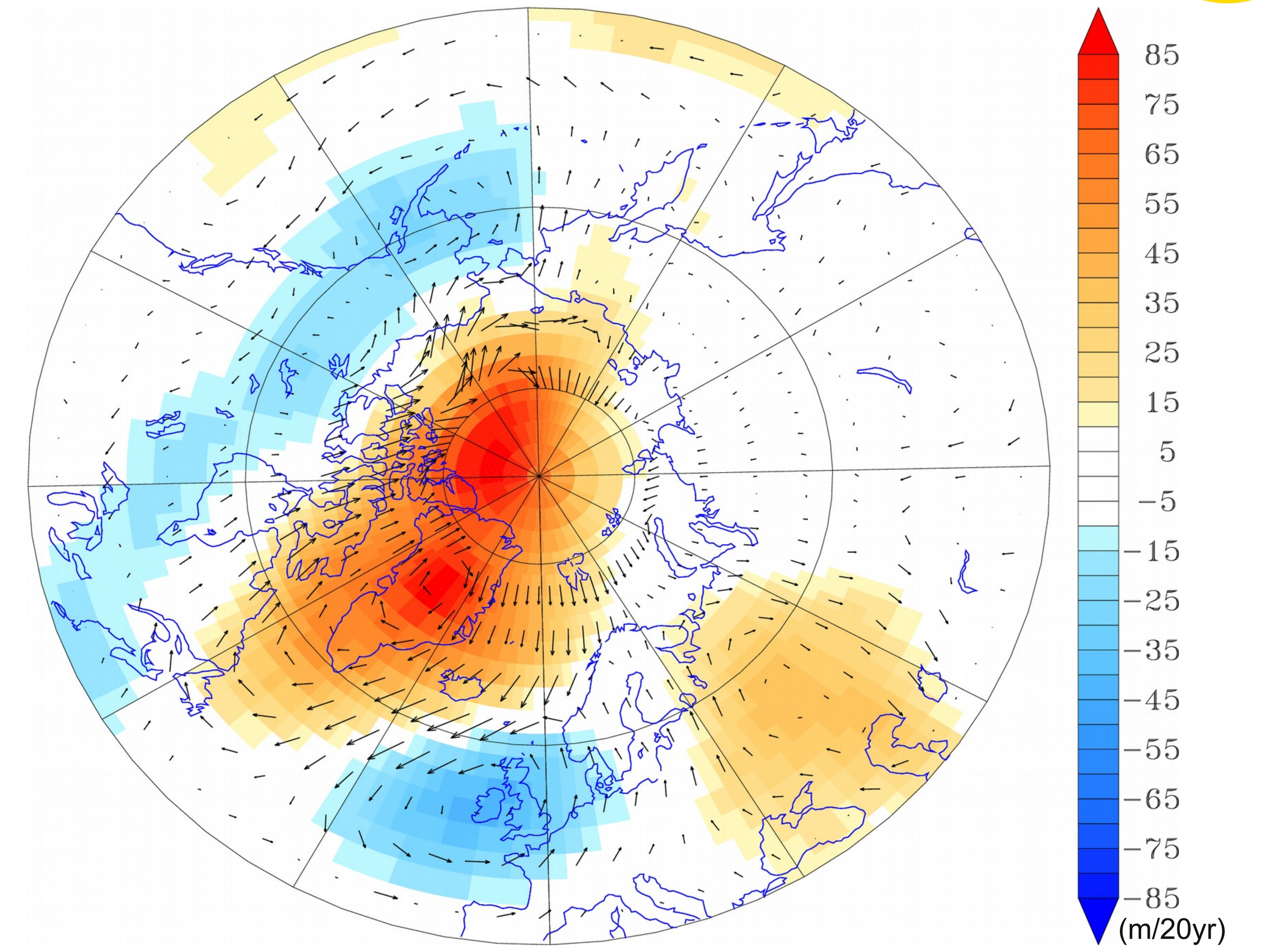

Fig. 3 The JJA geopotential (in background) and wind (vector) changes at 500hPa from 1993 to 2012 based on a linear regression using the NCEP-NCAR reanalysis.

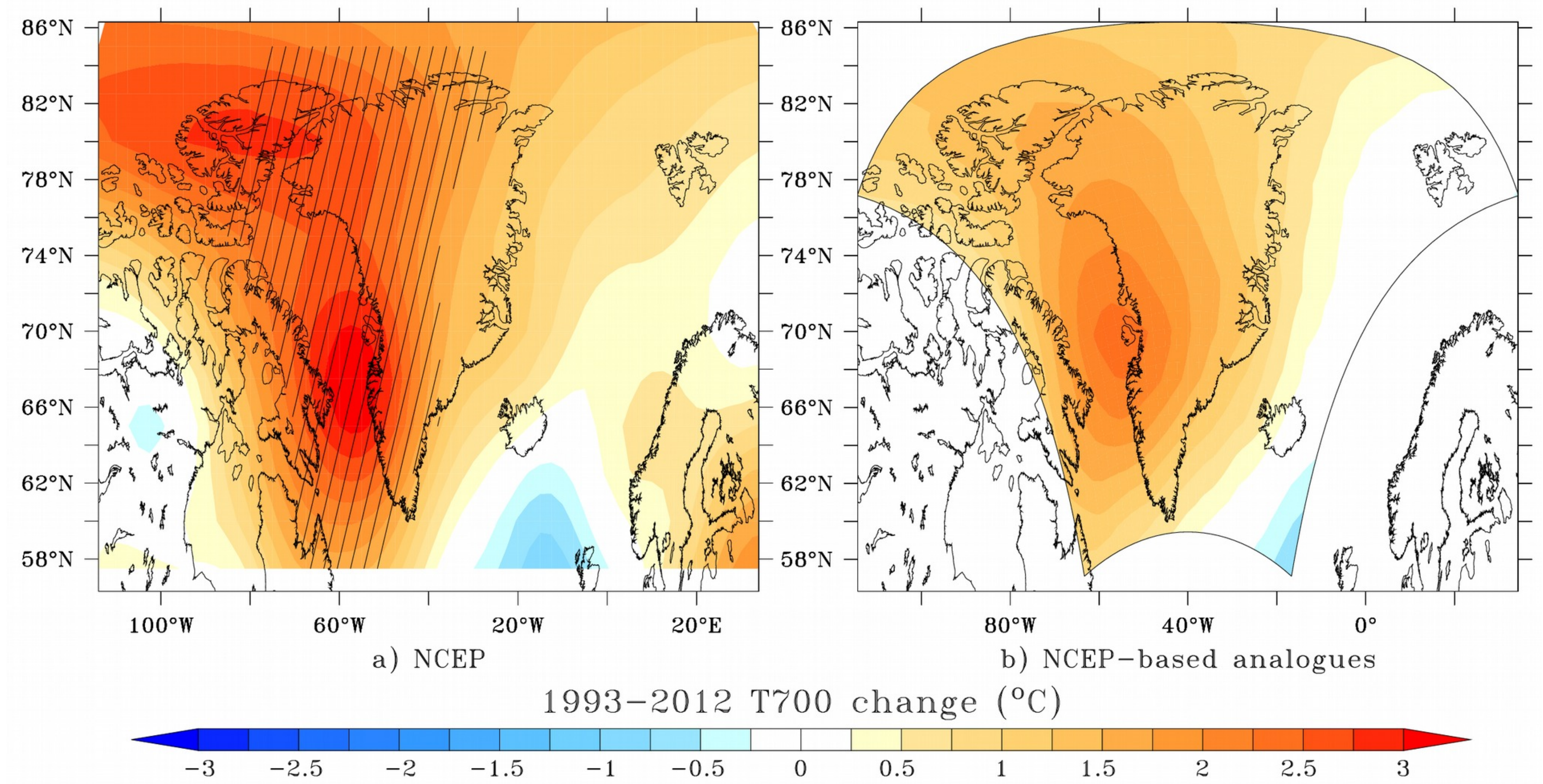

Fig. 4 **(a)** The JJA T700 changes (°C/20yr) over 1993–2012 based on a linear regression using the NCEP-NCAR reanalysis. The areas where the changes are two times above the 1961–1990 JJA T700 standard deviation are hatched. **(b)** The same as (a) but derived using the NCEP-NCAR-based T700 analogues.

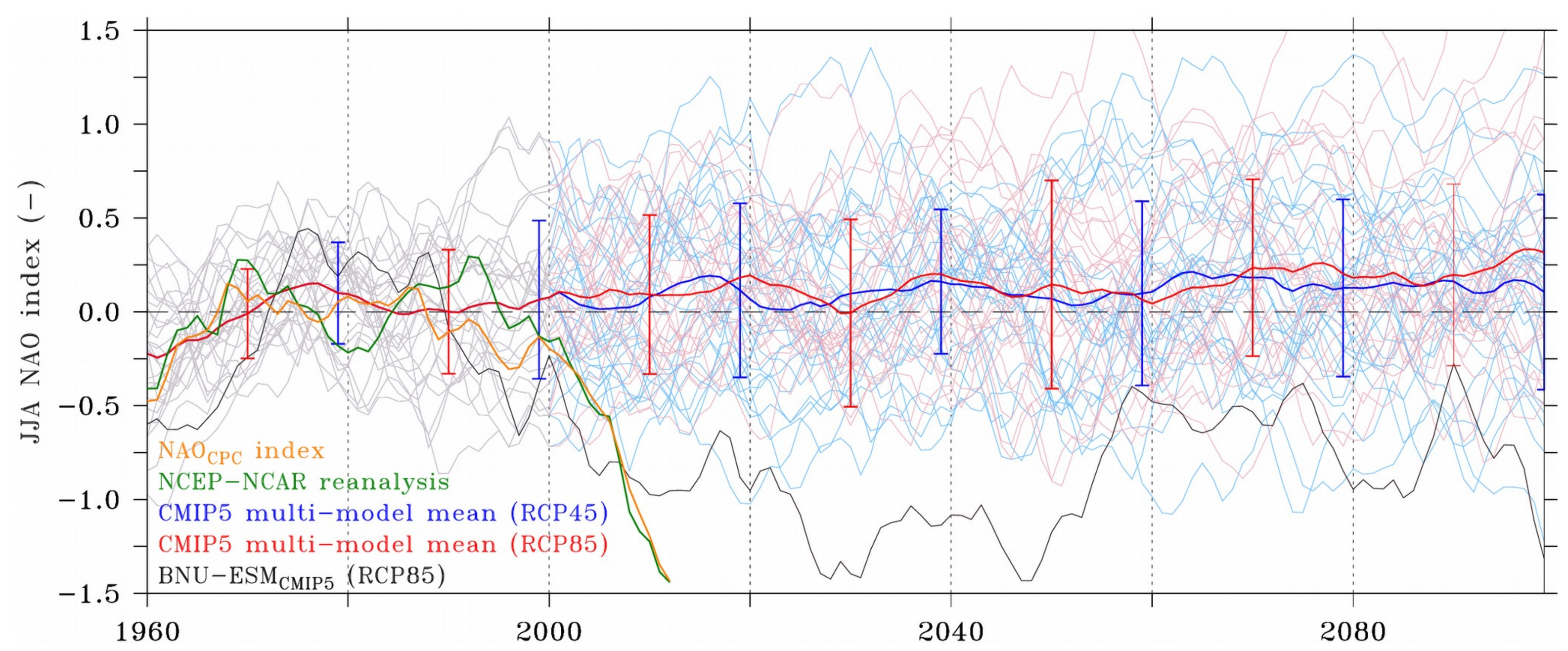

Fig. 5 Time series (10-yr running mean) of the JJA NAO index over 1960–2100. For the NCEP-NCAR reanalysis (in green) and the General Circulation Models (GCMs) from the CMIP5 database, the JJA NAO index is estimated as the standardized (over 1961–1990) difference of the JJA mean sea-level pressure between the Azores (27°W, 39°N) and Southwest Iceland (22°W, 64°N). For the CMIP5 GCMs, the historical scenario (in grey) is used for recent (1960–2005) climate conditions and future projections over 2006–2100 use RCP 4.5 (in blue) and RCP 8.5 (in red) scenarios. The CMIP5 multi-model mean (composed of 28 GCMs) as well as the standard deviation of the ensemble mean are also plotted in dark blue and red, respectively. The NAO time series simulated by the Chinese model BNU-ESM (using RCP8.5) is plotted in black. Finally, the JJA NAO index from CPC is plotted in orange for comparison.

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