Recent changes in summer Greenland blocking captured by none of the CMIP5 models

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Abstract. Recent studies note a significant increase in high-pressure blocking over the Greenland region (Greenland Blocking Index, GBI) in summer since the 1990s. Such a general circulation change, indicated by a negative trend in the North Atlantic Oscillation (NAO) index, is generally highlighted as a major driver of recent surface melt records observed on the Greenland Ice Sheet (GrIS). Here we compare reanalysis-based GBI records with those from the Coupled Model Intercomparison Project

5   5 (CMIP5) suite of global climate models over 1950-2100. We find that the recent summer GBI increase lies well outside the range of modelled past reconstructions (Historical scenario) and future GBI projections (RCP4.5 and RCP8.5). The models consistently project a future decrease in GBI (linked to an increase in NAO), which highlights a likely key deficiency of current climate models if the recently-observed circulation changes continue to persist. Given well-established connections between atmospheric pressure over the Greenland region and air temperature and precipitation extremes downstream, e.g.

10 over Northwest Europe, this brings into question the accuracy of simulated North Atlantic jet stream changes and resulting climatological anomalies over densely populated regions of northern Europe as well as of future projections of GrIS mass balance produced using global and regional climate models.

1 Introduction

Previous work notes strongly increasing mid-tropospheric high pressure over the Greenland region in summer over the past 2-3

15 decades (Fettweis et al., 2013; Hanna et al., 2013, 2014, 2015, 2016, 2018; McLeod and Mote, 2016). It is unknown to what extent this increased Greenland blocking, as measured through the Greenland Blocking Index (Fang , 2004; Hanna et al., 2013, 2014, 2015, 2016, 2018), has been triggered by low-level regional warming promoted by surface feedbacks (e.g. increased snow- and ice-melt, and Arctic regional sea-ice losses) as opposed to atmospheric dynamical (jet stream) changes; some recent studies (e.g. Francis et al. (2015)) suggests a slower-moving, more meridional northern polar jet stream, which may encourage

20 more frequent and intense blocking over Greenland. However, both of these mechanisms are likely to have played a role and moreover may well feed back off each other (Hanna et al., 2018). Increased Greenland blocking is a major contributor to the recent surface melt acceleration over the Greenland Ice Sheet (GrIS) because it favours the advection of relatively warm sub-tropical airmasses (Fettweis et al., 2013; Delhasse et al., 2018) and promotes sunnier and drier weather conditions that enhance the melt-albedo feedback (Hofer et al., 2017). Changes in Greenland blocking are also important for mid-latitude weather and

climate because they perturb the North Atlantic atmospheric polar jet stream, where increased (decreased) blocking diverts the jet southwards (northwards) (e.g. Hanna et al. (2018)). Further recent work (Overland et al., 2012, 2015; Hanna et al., 2016; Hanna et al. , 2017) highlights Greenland as a key region linking the Arctic Amplification of global warming (Overland et al., 2017) with mid-latitude extreme weather, although such links are intermittent, itinerant and state-dependent, competing with

5   a multitude of other climate forcings (Hall et al., 2015; Overland et al., 2016). Previous work using climate-model projections to simulate NAO changes under sustained global warming conditions to 2100 finds a general slight – although not necessarily significant - trend towards a more positive future summer NAO (Gillett et al. , 2013; Fettweis et al., 2013). This contrasts with the observed trend towards a significantly more negative summer NAO since around 1990 (Hanna et al., 2015). However, although there is a strong antiphase between NAO and GBI changes (Hanna et al., 2013), this statistical relationship is of course

10   not perfect, and no similar model results of GBI changes have so far been presented. Therefore here we review current climate model simulations of Greenland Blocking to see whether they capture the recent observed GBI changes, as a measure of how realistic these models may be for projecting future Greenland and North Atlantic regional atmospheric circulation changes.

2   Methods and datasets

We calculated two "observed" GBI series based on NCEP/NCAR v1 Reanalysis 500 hPa geopotential height data (Kalnay et al.,

15   1996). The first, which we here call GB1, is a simple area-weighted mean over 60–80°N, 20–80°W and follows previous work (Hanna et al., 2013, 2014, 2015, 2016, 2018). We define a second GBI series, GB2, by subtracting the area-weighted mean GPH500 over the 60–80°N whole hemispheric zonal band from the area-weighted mean GPH500 over the standard GBI region defined above. This is to allow for projected strong future Arctic warming raising geopotential heights over Greenland, which might mean that a future increasing GB1 mainly reflects increased atmospheric temperatures (Belleflamme et al., 2013)

20   rather than a relative regional enhancement in blocking, where the latter is more directly depicted using GB2. The results of these calculations are shown in Figure 1 and show good agreement of trends and variability in both GB1 and GB2 changes for the recent record. Therefore we use GB2 for the rest of our analysis.

We also calculate a related air temperature parameter, TA2, which is defined as the mean free atmosphere temperature for the standard GBI region minus that over the hemispheric zonal band of 60-80°N. TA2 is calculated using monthly temperature

25   data at the 850, 700 and 500 hPa pressure levels from the monthly outputs as follows:

$$TA2 = (T850 + T700 + T500)/3 \qquad\qquad\qquad (1)$$

We use all available Coupled Model Intercomparison Project 5 (CMIP5) model outputs (run r1i1p1) for which both RCP4.5 and RCP8.5 scenarios are available (i.e. 36 models listed in supplementary material) to simulate GB2 and TA2 changes over 1950–2100. All time series are smoothed using a 20-year running mean to emphasise long-term trends and variability linked to

30   climate change, and to enable physically meaningful comparison of CMIP5 model output with the NCEP/NCAR v1 Reanalysis-based record which we use as a reference. Comparisons with the new centennial-timescale reanalysis, 20CRv2c (Compo et al.,
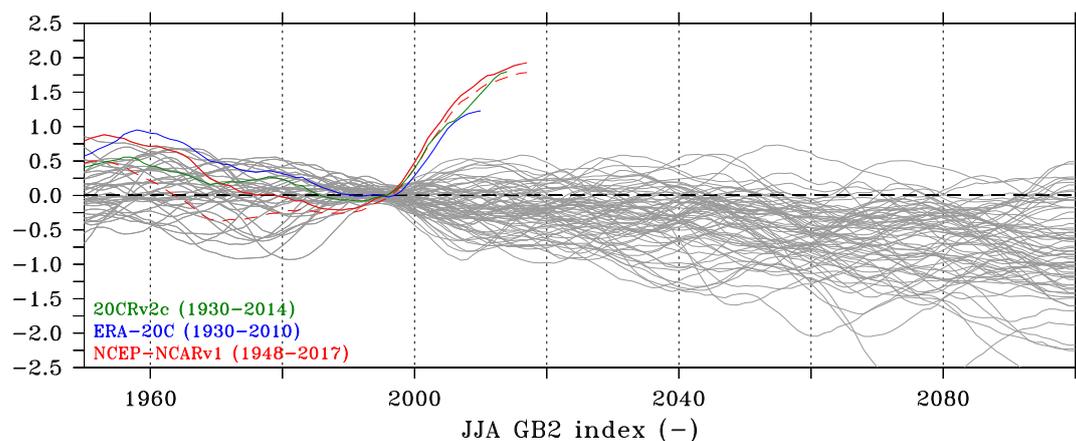
Figure 1. Time series of JJA GB2 index over 1950-2100 as simulated by NCEP/NCAR v1 reanalysis (red line), by 20CRv2c reanalysis (green line), by ERA20C reanalysis in blue as well as simulated by all the CMIP5 models (grey lines) for which both RCP4.5 and RCP8.5 scenarios are available. For the CMIP5-based time series, the Historical scenario is used over 1900-2005 and both RCP4.5 and RCP8.5 afterwards. A 20-year running mean has been applied to smooth the time series, and values have been normalised (average = 0 and standard deviation = 1) using 1986-2005 as reference period. The NCEP-NCARv1 based GB1 index is also shown (dashed red line).

2011) and ERA20C (Poli et al., 2016), are also added. However, as only surface data have been assimilated in these products, these reanalyses show biases in the free atmosphere, in particular in the summer free atmosphere temperature for which significant biases were found over Greenland by Fettweis et al. (2017) with respect to NCEP/NCAR v1 which is the only reanalysis shown here that assimilates soundings. This explains why the results of these long centennial reanalyses are slightly

5   different from those obtained using the NCEP/NCAR v1 Reanalysis, even though of course all three reanalyses represent exactly the same climate system. Finally, although 20CRv2c and ERA20C cover the whole of the last century, comparison with the observed record is limited here to 1950–2017 because this is the common period covered by the three reanalyses and because, as shown by Belleflamme et al. (2015), the general circulation of these centennial reanalyses diverges before 1940 over Greenland.

10   Finally, GB(X) and TA2 data are normalised using the recommended 1986–2005 recent past reference period (Hock, 2018). All data and results used herein refer to the standard meteorological summer (JJA) season only.

3   Results

NCEP Reanalysis data since 1970, as well as both of the centennial reanalyses, show an increase in GB2 and normalised positive GB2 anomalies with a maximum reached at the beginning of the 2010's, which clearly exceed GB2 values projected
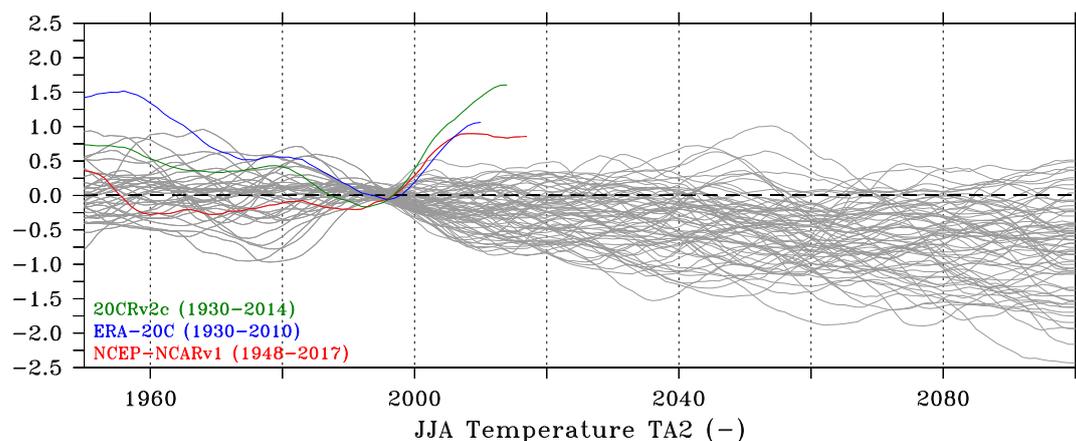
Figure 2. Similar to Figure 1 but showing TA2 (defined in Eq. 1).

by any GCM using both RCP4.5 and RCP8.5 as well as in the recent past GCM-based reconstructions using the Historical
scenario. Here, 20-year running means of GB2 time series are shown but the same conclusions can be drawn using either
30-yr or 3-yr running mean times series (see supplementary material). Likewise we find a recent marked increase in observed
(reanalysis-based) TA2 that is not replicated in any of the CMIP5 models: the latter show an overall reduction in GB2 and TA2,

5   i.e. simulating fewer blocking events and weaker warming over Greenland compared with the rest of the Northern Hemisphere
(See Figure 2).

The disparity between the latest NCEP1 GB2 anomalies ($\sim +2$) and TA2 anomalies ($\sim +1$) indicates that the observed
GB2 increase is unlikely to be fully driven by the Greenland regional free atmosphere temperature (TA2) increase, and there
is also a recent (2010s) flattening off of TA2 while GB2 continues to increase. This leads us to invoke remote forcing from

10 North Atlantic polar jet-stream changes advecting more southerly airmasses over Greenland as being partly responsible. This
effect is not shown in the CMIP5 model simulations, which project a near-uniform ratio of the normalised TA2 decreases to the
normalised GB2 decreases. Finally, we note that while the NCEP/NCAR v1 based time series of TA2 ends with more stable
(although still extreme) positive anomalies over the last couple of years, GB2 anomalies continue to increase over recent years
and are not well simulated by any of the GCM-based time series.

15 **4   Discussions and conclusions**

Here we have shown that CMIP5 climate models do not adequately simulate the recent Greenland blocking increase since
they project both a recent past and future decrease in Greenland blocking. We also note that the current observed blocking
anomalies are significantly higher than simulated by any GCM for either current climate or future projections. Such models

typically underestimate the magnitude of recent (since mid-1990s) Greenland warming, while previous work already suggested they are also not particularly effective at representing some key properties of North Atlantic jet-stream and blocking patterns (Davini and Cagnazzo, 2014; Davini et al., 2016; Hall et al., 2015).

The recent record rise in Greenland summer blocking may be influenced by the coincident positive phase of the Atlantic

5 Multidecadal Oscillation (AMO), which is related to a more negative Summer NAO (Sutton et al., 2012; Folland et al., 2009) and therefore a more positive GBI. Since we are currently near the peak in the (80-year) AMO cycle, this effect could reverse in the next few decades, although – given the other drivers mentioned above – we consider this more likely to slow down the rate of GBI increase rather than result in decreased Greenland Blocking. Also, intrinsic atmospheric dynamics (internal variability) may have contributed to the recent GB2 increase, although there is likely to be a significant external forcing

10 element too arising through Arctic/Greenland temperature feedbacks (Hanna et al., 2016, 2018). There is an issue of how well climate models capture internal variability in the GBI and NAO (Deser et al., 2017), and internal variability may result in different GBI trends in model output and observations for any given period of up to a few decades. However, the scale of the recent observed GBI change is well outside that represented in any of the CMIP5 models, and we do not subscribe to the view that most multi-decadal changes in these circulation patterns are mainly due to internal variability rather than being externally

15 forced. Our findings underscore the limitations of the climate models in representing high-latitude blocking, and so we question how realistic is model representation of North Atlantic circulation changes and therefore hence European climatology: most notably winter temperature and windstorms and summer precipitation. Also the GCM-forced projections may underestimate future GrIS surface mass balance decreases by a factor of two, independently of the precise timing and amplitude of global warming, if the recent observed circulation changes continue to persist in summer (Delhasse et al., 2018). Model-observation

20 discrepancies and thus model fidelity may, of course, be partly addressed in CMIP6 but clearly this is far from certain and meanwhile CMIP5 represents the current 'state of the science'. Given the recent rapid changes in Arctic climate and Greenland Ice Sheet dynamics – which were not well predicted 15-20 years ago – it is therefore essential that future climate modelling efforts focus on improving their representation of blocking, as this is a key aspect of mid-high latitude cryosphere-climate dynamics and change.

25 *Data availability.* Time series are available through a simple email request to the authors.

Competing interests. The authors declare that they have no conflict of interest.

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