Supplementary Information: Greenland temperature and precipitation over the last 20,000 years using data assimilation

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S1 Accumulation records

Our aim is to develop simple, reproducible accumulation histories that are independent of temperature and water isotope assumptions and span the probable range of uncertainty. We use existing estimates for two sites (GISP2 and NEEM), but for three other sites (GRIP, NGRIP, and Dye3) we use one-dimensional ice-flow modeling to estimate the thinning function and convert measured layer-thickness into accumulation. Each core requires different ice-flow assumptions due to the different glaciological settings. Below we first describe the modeling approach used and then describe the reasoning for the ice-flow parameters chosen for each core.

S1.1 Model

We use a transient, one-dimensional, ice-flow model to calculate the cumulative vertical strain, termed the thinning function. We represent the vertical velocity profile using the Dansgaard and Johnsen (1969) formulation both because of its ubiquity in calculations of thinning for Greenland ice cores (Dahl-Jensen et al., 2003; Rasmussen et al., 2013; Dahl-Jensen et al., 1993) and it's simplicity:

$$w(z) = -(\dot{b} - \dot{m} - \dot{H})\psi(z) - \dot{m} \tag{1}$$

where z is the height above the bed in ice-equivalent meters (i.e. the firn has been compacted to ice), $\dot{b}$ is the accumulation rate, $\dot{m}$ is the melt rate, $\dot{H}$ is the rate of ice-thickness change, and $\psi(z)$ is the vertical velocity shape function computed as:

$$\psi(z) = \frac{f_B z + \frac{1}{2}(1-f_B)\frac{z^2}{h}}{H - \frac{1}{2}h(1-f_B)} \text{ for } h \geq z > 0 \tag{2}$$

$$\psi(z) = \frac{z - \frac{1}{2}h(1-f_B)}{H - \frac{1}{2}h(1-f_B)} \text{ for } H \geq z > h \tag{3}$$

following Dahl-Jensen et al. (2003) where h is the distance above bedrock of the Dansgaard and Johnsen (1969) kink height, f_B is the fraction of the horizontal surface velocity due to sliding over the bed, and H is the ice thickness. We assume no ice thickness change, $\dot{H} = 0$, and the f_B and $\dot{m}$ are constant in time with $\dot{b}(t)$ and $h(t)$ being functions of time.

The model is initially run with a constant accumulation history at the modern accumulation rate, and a thinning function is produced. The thinning function is then used with the measured layer thickness to infer a temporally-variable accumulation history. The model is then run with the temporally-variable accumulation history to produce an updated thinning function. This thinning function is then used with the measured layer thickness to infer the final accumulation history. The solution converges without additional iterations needed.

S1.2 NEEM

We use the accumulation reconstruction for the NEEM ice core from Rasmussen et al. (2013). Through the use of several different reconstruction methods, they developed a mean accumulation record with a two standard-deviation uncertainty envelope. We use their mean as our "moderate" record for the main reanalysis, the high end of their uncertainty envelope as our "high" estimate, and the low end of their uncertainty envelope as our "low" estimate.

S1.3 GISP2

The GISP2 ice core is located about 26 km from the ice divide at Summit, Greenland. The upper column of ice experiences vertical strain rates associated with flank flow, while ice close to the bed originated near the ice divide where vertical strain rates differ (Cuffey and Clow, 1997). The last 20,000 years of time is contained within the top two-thirds of the total ice thickness leading to a greater certainty in the vertical strain rates required to convert measured layer thickness into accumulation.

We use the accumulation reconstruction for the GISP2 ice core from Cuffey and Clow (1997) that coincides with their simulated 100 km retreat of the ice-sheet margin over the last 14,000 years. This reconstruction contains some uncertainty due to the vertical strain rates and margin-retreat scenario, but it is only weakly sensitive to changes in either one (Cuffey and Clow, 1997). Given these low uncertainties, we use this single accumulation record for our main, high, and low scenarios.

The Cuffey and Clow (1997) accumulation reconstruction is on an earlier depth-age scale (Alley et al., 1993; Meese et al., 1994; Bender et al., 1994). We transfer it onto the GICC05 depth-age scale by interpolating the GICC05 ages onto the accumulation depths and recalculating accumulation using:

$$A_{new} = A_{old}\frac{\lambda_{new}}{\lambda_{old}} \tag{4}$$

where A is accumulation, λ is the layer thickness, 'old' refers to the original depth-age scale from Cuffey and Clow (1997) and 'new' refers to the GICC05 depth-age scale. This approach accounts for errors in the depth-age scale while assuming the thinning function, with respect to depth, remains the same as the original record.

S1.4 GRIP

The GRIP ice core was drilled about 2 km from the true summit of Greenland. The basal temperature is well below freezing (Dahl-Jensen et al., 1998) and thus the melting term in the vertical velocity calculation can be neglected. Despite no Raymond arch being imaged with ice penetrating radar, phase sensitive radar (Gillet-Chaulet et al., 2011) revealed a vertical velocity profile influenced by the divide (i.e., the Raymond effect, Raymond, 1983). This indicates that the present divide position has not been stable long enough for a Raymond arch to develop (Marshall and Cuffey, 2000). The englacial vertical velocity profiles of Gillet-Chaulet et al. (2011) are not at the GRIP site and cannot directly inform our choice of profile. Because GRIP is not directly beneath the ice divide and the divide position has likely not been stable, we use a vertical velocity profile that is transitional between a typical flank profile and a divide profile; this is represented with a Dansgaard-Johnsen kink height of 0.4, which we use from 5 ka to present. Prior to 5 ka, we use a typically flank flow value of 0.1 assuming that the divide position is more than one ice thickness (3 km) away. The onset of divide flow at 5 ka is guided by 1) the inference of Vinther et al. (2009) of small surface elevation change around Greenland after 5 ka suggesting the ice sheet had reached a more stable configuration and 2) the duration of divide flow that could exist without a Raymond arch becoming visible. We use this as our moderate accumulation history and note that it is not sensitive to 1,000 year changes in the onset times of the divide flow.

The divide-like vertical velocity profiles causes more vertical strain near the surface of the ice sheet. Thus, an accumulation reconstruction that uses divide-like flow produces higher accumulation values. To develop the high and low scenarios, we use the divide-like kink height of 0.4 and the flank-like kink height of 0.1, respectively.

S1.5 NGRIP

The NGRIP ice-core site is located approximately 300 km north of GRIP along the central ridge of the Greenland Ice Sheet, where the high geothermal flux leads to a significant basal melt rate of approximately 7.7 mm a^{-1} (Dahl-Jensen et al., 2003). This melt rate should be included in the vertical velocity profile even though its primary influence is near the bed; the melting also suggests the possibility that basal sliding contributes to the surface horizontal velocity. Dahl-Jensen et al. (2003) found an optimal fit to the depth-age relationship with the parameters $h = 0.45$, $f_B = 0.135$, $\dot{m} = 7.7$mm a^{-1}, and $\dot{b} = 0.19$ m a^{-1}. Gkinis et al. (2014) used the diffusion length of water isotopes to infer that these parameters produce too much thinning in the early Holocene, and suggested a linear correction of 25% less thinning to a depth of 2,000 m. A kink height of 0.45 is typically appropriate for ice-flow that is experiencing divide-like flow conditions. It would be unusual to have divide-like flow in a location with significant melt, as the Raymond effect is suppressed by basal sliding (Raymond, 1983; Pettit et al., 2003). We find that a kink-height of 0.2 reproduces the thinning function inferred by Gkinis et al. (2014) quite closely and is more easily interpreted dynamically because this value is expected for a site experiencing typical non-divide flow. The inverse method for inferring optimal model parameters as used by Dahl-Jensen et al. (2003) could be led astray by the assumption of direct scaling between accumulation and water isotopes.

For all scenarios, we use a melt rate of 7.7 mm a^{-1}. There may be small variations in the basal melt rate due to changes in the surface temperature and accumulation forcing and flow over bedrock with a different geothermal flux (Dahl-Jensen et al., 2003); however, any variations in the basal melt rate have a limited impact on the thinning inferred for the upper portion of the ice column. We use a kink height of 0.2 for our moderate scenario. For the high scenario, we use the original values of Dahl-Jensen et al. (2003). For the low scenario, we use a kink height of 0, which is equivalent to using a basal sliding fraction of 1, essentially the Nye model (Nye, 1963).

S1.6 Dye3

As discussed in the main text, reconstructing the accumulation rate at Dye3 is significantly more challenging than for the other interior ice-core sites. Ice of 20 ka age is much closer to the bed at Dye3 than at the central Greenland core locations, and has been strained to less than 10% of its original thickness. Complicating matters further, Dye3 was drilled at a site where the current surface velocity is 11 m yr^{-1}; the early Holocene ice has thus flowed many tens of kilometers (Whillans et al., 1984), possibly through significant accumulation variations (Reeh et al., 1985). Dye3 also has a more pronounced difference in ice fabric between the Holocene and glacial ice (Thorsteinsson et al., 1999; Montagnat et al., 2014). To develop the thinning function, we first compute the vertical velocity profile based on the horizontal strain measured with borehole tilt observations (Gundestrup and Hansen, 1984). These produced an accumulation history with an accumulation rate at the onset of the Holocene (11.7 ka) that is less than half of the modern accumulation rate. We consider this to be a low estimate, as the current velocity profile is strongly influenced by the location of the transition between the glacial and Holocene ice. We create a moderate scenario by approximately matching the accumulation rate around 7 ka with the past 1 ka accumulation rate; this uses a kink height of 0.2 which is typical for flank sites. We create a high scenario where we set the accumulation history at 11 ka approximately equal to the past 1 ka. The resulting accumulation histories vary significantly more than those for the interior cores because of the much greater uncertainty in the flow model.

We have not attempted to correct the accumulation history for advection because of the large uncertainties in both the flow path and the pattern of accumulation in the past. We note that we have low confidence in the Dye3 accumulation reconstructions; we include them because they are the only information from southern Greenland.

S2 Extension of the Dye3 depth-age scale to 20 ka

Here we explain the method we use to determine a Dye3 depth-age scale from 11.7 ka to 20 ka. Following the cross-correlation maximization procedure from Huybers and Wunsch (2004), we match the δ^{18}O record from Dye3 to the δ^{18}O record from NGRIP during this time interval. First we pick approximate tie points between the two δ^{18}O records. We emphasize placing tie points in the middle of high-magnitude, abrupt signals, such as the warming into the Bolling-Allerod, because these sigmals are most likely to be coherent across the ice sheet. Next we pick signals found in both δ^{18}O records regardless of magnitude and rate of change. We interpolate the depth-age scale between all the picked signals, including the tie points. We do this to achieve a close initial alignment of the two records, which gives us an initial correlation coefficient of 0.69 between the Dye3 and NGRIP δ^{18}O records. We then use the algorithm developed by Huybers and Wunsch (2004) to adjust the Dye3 depth-age scale to achieve a better alignment between these records. As input into the algorithm, we provide an age uncertainty estimate for each tie point and the amount of compression or extension each section between tie points is allowed to undergo. This latter constraint prevents both tie points from crossing and unrealistic changes in the implied accumulation rates. The updated depth-age scale output by this procedure gives a slightly higher correlation coefficient of 0.71.

S3 Importance of including a southern Greenland ice core

The Dye3 ice core is an important source of information for capturing southern Greenland climate. For example, we find that posterior ensemble mean compares quite well to independent (excluded) proxy records in central-northern Greenland, like NGRIP δ^{18}O; however, the equivalent for Dye3 shows a worse comparison, especially in the glacial (Fig. S1). This implies that the northern ice cores are uninformative for southern Greenland climate and/or the prior covariance structure does not properly convey information from northern ice cores to southern Greenland. The former demonstrates a need for data in southern Greenland, while the latter suggests a need for more climate-model simulations.

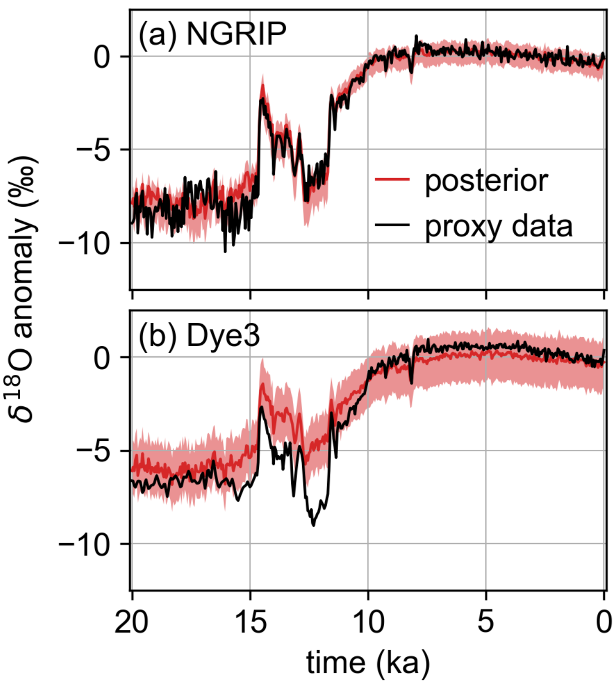

Figure S1. Comparison of the posterior (red) ensemble mean and 5^{th} to 95^{th} percentile shading to excluded proxy records (black) for (a) the NGRIP δ^{18}O record and (b) the Dye3 δ^{18}O record. We find that the proxy network is able to better capture northern-central proxy records like NGRIP than the southern Greenland record, Dye3, especially in the glacial period.

To evaluate whether each ice core is informative for southern Greenland climate, we compute the difference in evaluation metrics – correlation coefficient (Δ r), coefficient of efficiency (Δ CE), and root mean squared error (Δ RMSE) – between two sets of iterations when evaluated against Dye3, the only southern Greenland ice-core record. These two sets of iterations are: 1) ten iterations that exclude one proxy record, and 2) ten iterations that include all proxy records. We subtract the latter (all records) from the former (excluding one record), such that if the excluded proxy record is informative of southern Greenland climate, then the difference will be negative for r and CE and positive for RMSE.

To test the extent to which information from each core is spread to southern Greenland, we compute the change in ensemble variance (Δ variance) in southern Greenland for each set of iterations and average over time. To compute Δ variance, we divide by the iterations that include all proxy records, such that the result is fractional change in variance with a larger values indicating that more information is spread from the proxy record to southern Greenland. For this analysis, we focus on the change in variance for a region around Kangerlussuaq (65°N to 68.7°N and 48.5°W to 52.5°W), which does not overlap the location of Dye3.

We compute each "Δ" value as a mean over the Holocene to create a fair comparison between the proxy records that span different time periods; however, we find that the implications of this analysis are insensitive to averaging over just the Holocene or the full 20,000 years.

We find that our reconstruction of southern Greenland temperature and precipitation generally improves with the inclusion of any of these ice-core records; however, it improves the most with the inclusion of the Dye3 records (Fig. S2). In addition, the Dye3 records result in the greatest change in ensemble variance in the Kangerlussuaq region (Fig. S2).

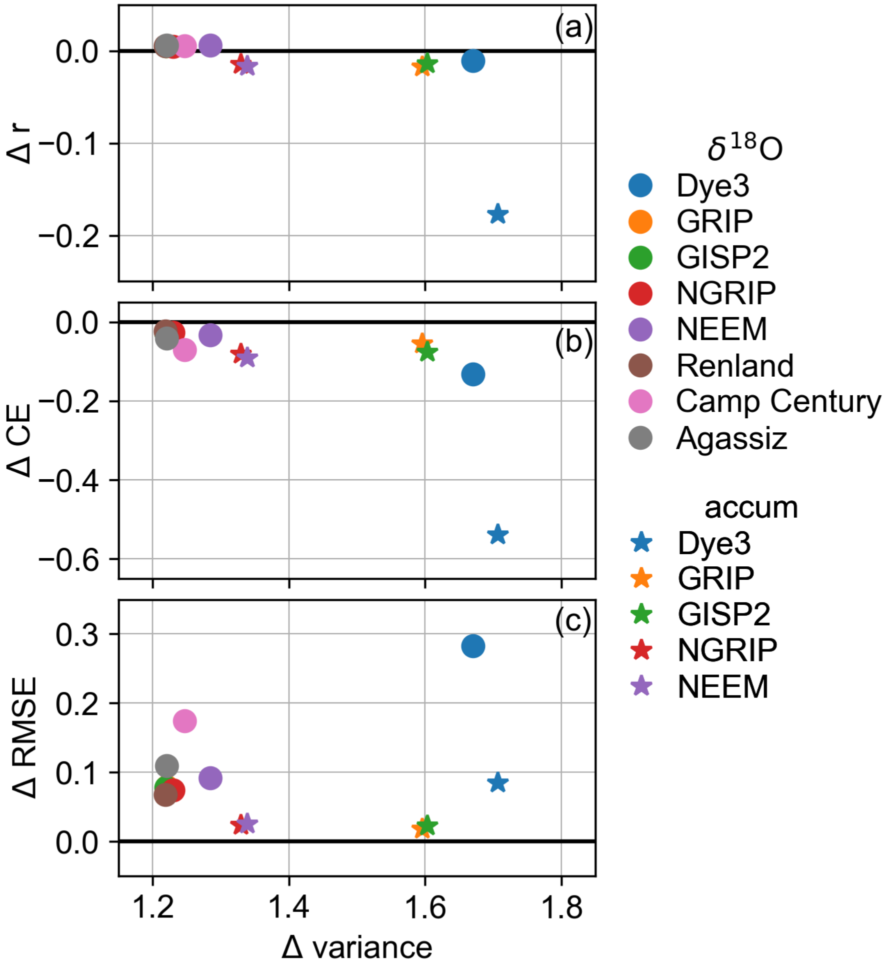

Figure S2. Relative importance of each ice-core record for reconstructing southern Greenland climate. On the absicissa is the change in posterior ensemble variance (Δ variance) in the Kangerlussuaq region, which indicates how much information is spread from a proxy record to that region. Higher values indicate more information has reached the region. On the ordinates are changes to skill metrics at the Dye3 ice-core site, which indicate whether proxy records are valuable for reconstructing southern Greenland climate. (a) shows results for the correlation coefficient (r), (b) shows results for the coefficient of efficiency (CE), and (c) shows results for the root mean square error (RMSE). Negative values of r and CE and positive values of RMSE indicate that the proxy record improves the reconstruction at the Dye3 site. The proxy record under consideration is indicated by colors (for the site) and symbols (for the proxy variable). Note that Δ RMSE values are in units of ‰ for δ^{18}O and are unitless for accumulation.

S4 Improvement of the reanalysis over the prior ensemble

In Sect. 4.1, we present an evaluation of our main reanalysis using independent proxies and based on four skill metrics, correlation coefficient (r), coefficient of efficiency (CE), root mean square error (RMSE), and ensemble calibration ratio (ECR).

Each of these skill metrics is described in detail in Sect. 2.3. We evaluate over three time periods, the full overlap of the reanalysis and the proxy record, a late-glacial period (20-15 ka), and period in the Holocene (8-3 ka).

Here, we show the magnitude of the change in each skill metric from the prior to the posterior ensemble (Figs. S3 and S4). We find that for all skill metrics the greatest changes coincide with an improvement of the reanalysis over the prior. Where the skill metrics show a lack of improvement, the changes tend to be small. For both temperature and precipitation, the largest changes in r occur for the full evaluation time period, while for CE and RMSE the largest changes occur during the shorter evaluation periods. The ECR is less consistent, with the greatest improvements for temperature occurring in the full and late-glacial evaluation periods, and the greatest improvements for precipitation occurring just in the late glacial.

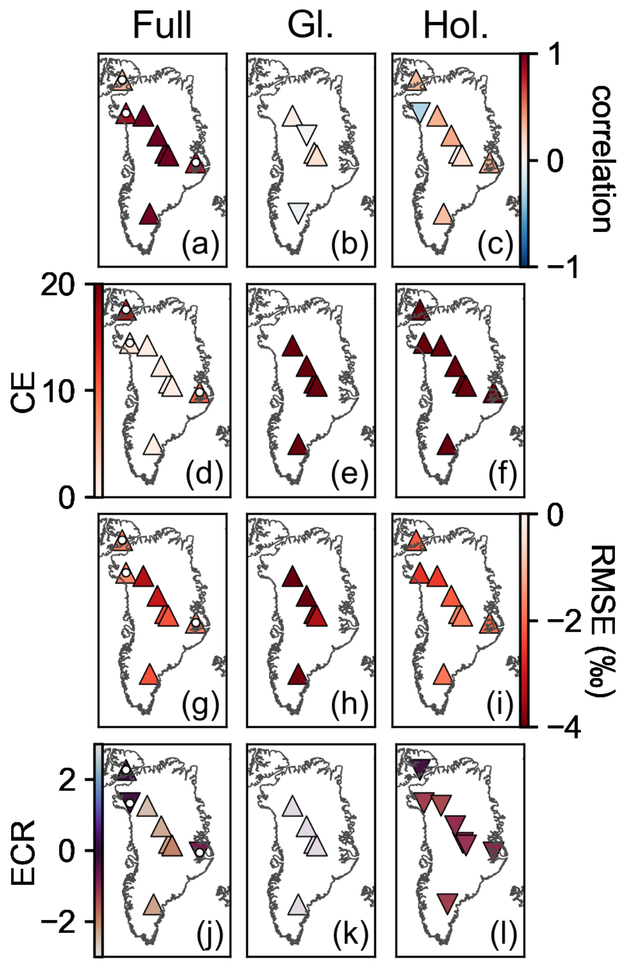

Figure S3. Change in skill metrics from the prior to posterior ensemble averaged over iterations and time for the temperature reanalysis. The first column (panels (a), (d), (g), and (j)) shows the skill-metric change for the full overlap (Full) between the proxy record and reanalysis. A white dot indicates evaluation against proxy records that overlap only the Holocene (11.7-0 ka). The middle column (panels (b), (e), (h), and (k)) shows the skill-metric change for a period in the glacial (Gl.) (20-15 ka), while the right column (panels (c), (f), (i), and (l)) is for a period in the Holocene (Hol.) (8-3 ka). The first row (panels (a)-(c)) reports the change in correlation coefficient, the second row (panels (d)-(f)) the coefficient of efficiency (CE), the third (panels (g)-(i)) the root mean square error (RMSE), and the fourth row (panels (j)-(l)) the ensemble calibration ratio (ECR). Triangle symbols pointing up indicate that the posterior ensemble evaluates better than the prior ensemble for that location and statistic. Triangle symbols pointing down indicate the opposite. We define better evaluation as correlation coefficient closer to 1, CE closer to 1, RMSE closer to 0, and ECR closer to 1.

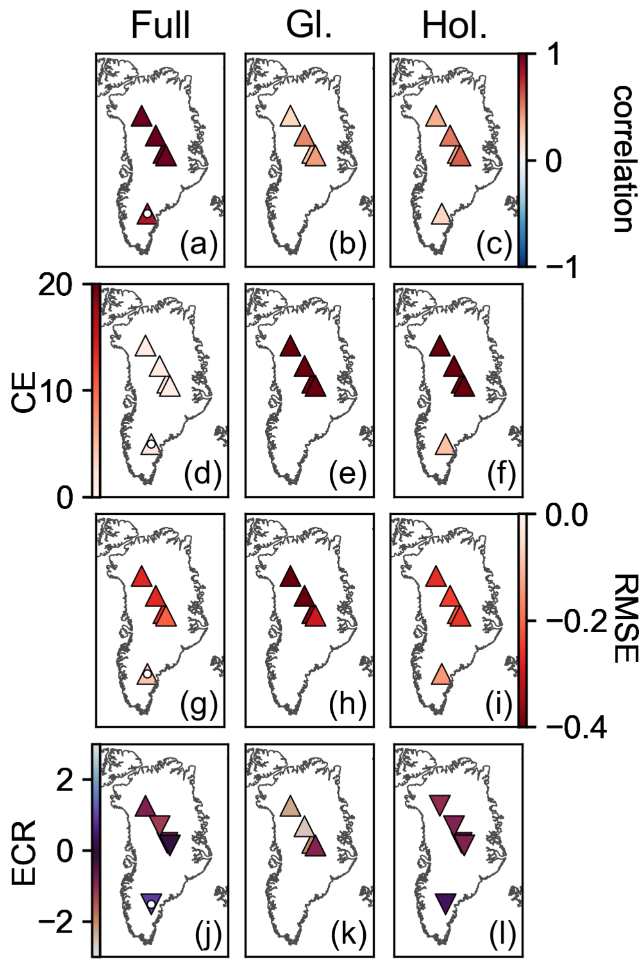

Figure S4. Change in skill metrics from the prior to posterior ensemble averaged over iterations and time for the precipitation reanalysis. The first column (panels (a), (d), (g), and (j)) shows the skill-metric change for the full overlap (Full) between the proxy record and reanalysis. A white dot indicates evaluation against proxy records that overlap only the Holocene (11.7-0 ka). The middle column (panels (b), (e), (h), and (k)) shows the skill-metric change for a period in the glacial (Gl.) (20-15 ka), while the right column (panels (c), (f), (i), and (l)) is for a period in the Holocene (Hol.) (8-3 ka). The first row (panels (a)-(c)) reports the change in correlation coefficient, the second row (panels (d)-(f)) the coefficient of efficiency (CE), the third (panels (g)-(i)) the root mean square error (RMSE), and the fourth row (panels (j)-(l)) the ensemble calibration ratio (ECR). Triangle symbols pointing up indicate that the posterior ensemble evaluates better than the prior ensemble for that location and statistic. Triangle symbols pointing down indicate the opposite. We define better evaluation as correlation coefficient closer to 1, CE closer to 1, RMSE closer to 0, and ECR closer to 1.

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