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Evaluating ice sheet model performance over the last glacial cycle using paleo data

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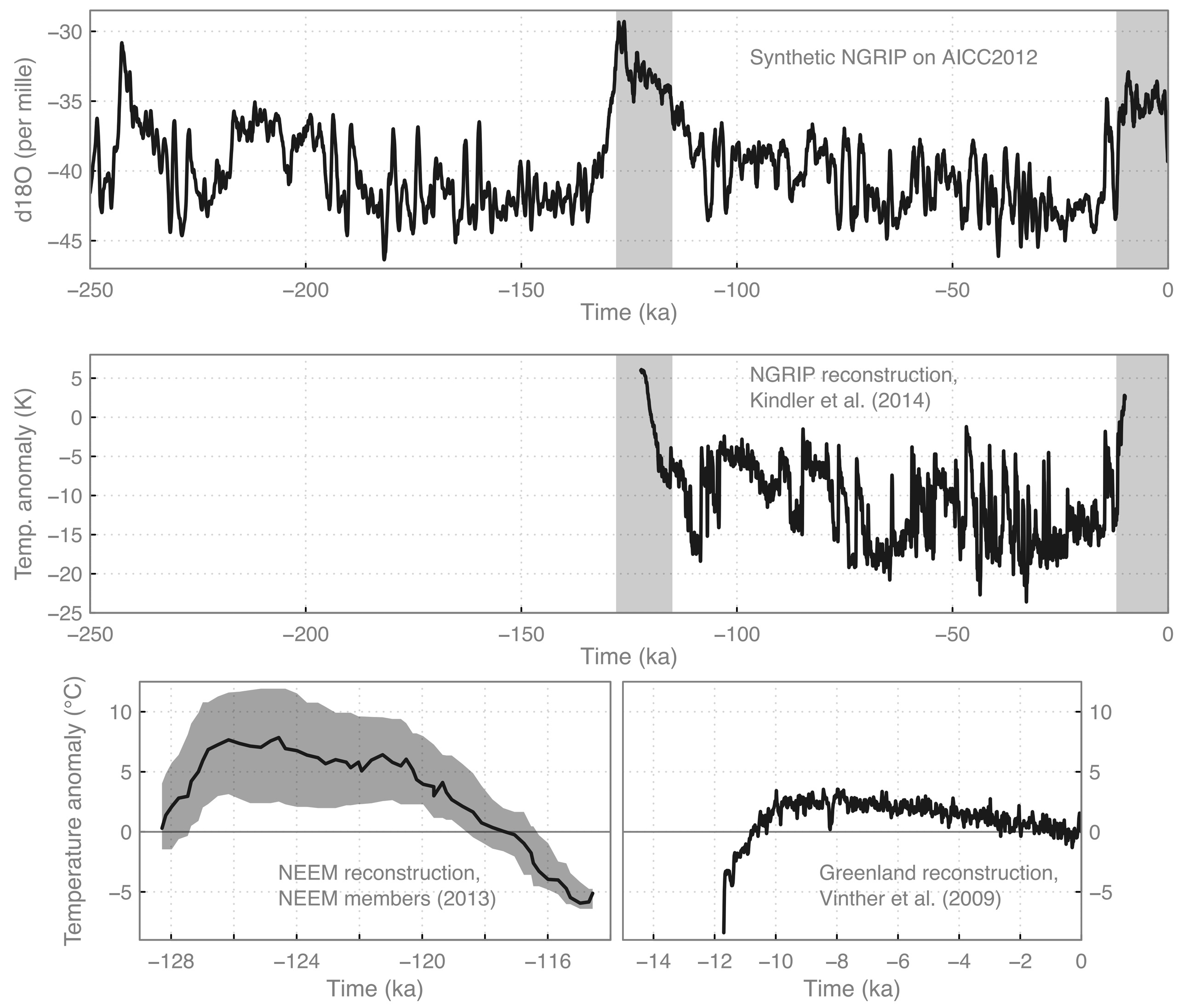
Abstract

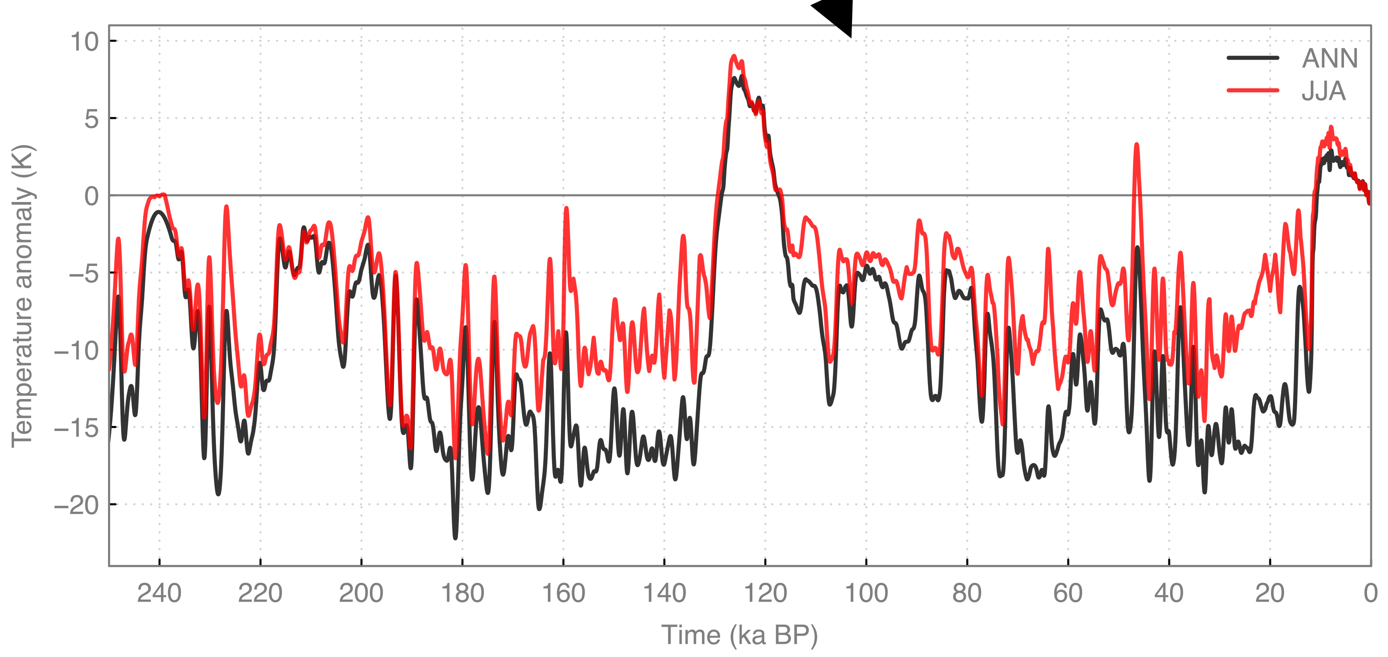
Estimating the past evolution of ice sheets is important for improving our understanding of their role in the Earth system and for quantifying their contribution to sea-level changes. Limited but significant paleo data and proxies are available to give insights into past changes. Meanwhile, models can be used to provide a mechanistic picture of ice sheet changes. Combined data-model comparisons are therefore useful exercises that allow models to be confronted with real-world information and lead to better understanding of the mechanisms driving changes. In turn, models can potentially be used to validate the data by providing a physical explanation for observed phenomena. We use an ensemble of simulations of the Greenland ice sheet (GrIS) to highlight common problems and potential opportunities in this context.

Simulating the GrIS over the last glacial cycle

Ice sheet models that are not coupled to a global climate model need to be driven by an approximation of past climate changes. Here we used the most recent data sources and time scales available to reconstruct temperature changes over the last 2 glacial cycles over Greenland. Combining this "hybrid" paleo proxy curve with a model-based estimate of seasonality changes, we generated monthly temperature anomalies for forcing the ice sheet model.

We then performed an ensemble of simulations, in which we independently rescaled temperatures during the Eemian, the glacial period and the Holocene over a wide range in order to test the impact of the imposed climatic forcing on the resulting simulated ice-sheet evolution. The GrIS was simulated using the coupled climate – ice sheet model REMBO-SICOPOLIS.





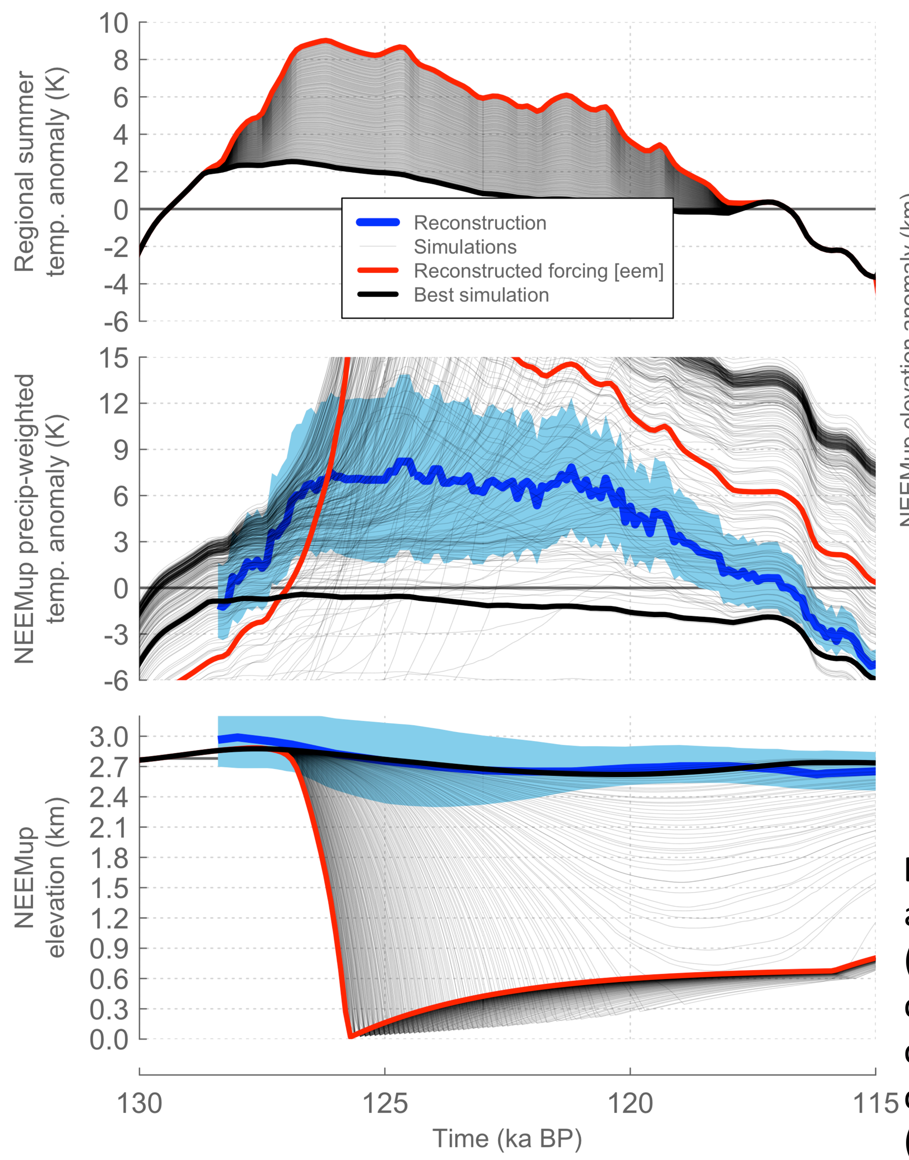
Above: Four paleo archives were merged to produce a "hybrid" estimate of Greenland temperature anomalies over the last 2 glacial cycles. The archives were assumed to give precip-weighted annual mean temps. Monthly temperature anomalies were generated by combining the hybrid curve with changes in seasonality modeled by CLIMBER-2. **Right**: Resulting annual and summer mean hybrid temperature anomaly time series from the hybrid "reconstruction".

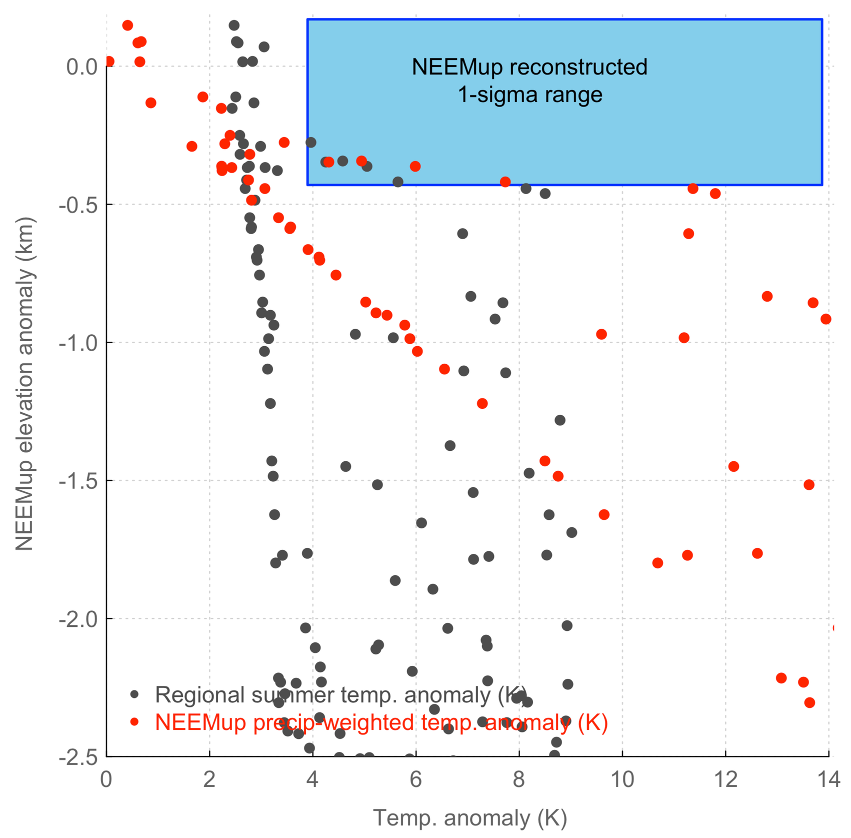
Test 1: Eemian interglacial temperature and elevation

Peak Greenland summer temperature anomalies during the Eemian have been proposed to range from 0.5-6.5 K above today (Bakker et al., 2013; Capron et al., 2014), leading to a retreat of the GrIS. Meanwhile temperature anomalies at the NEEM ice core have been reconstructed with a range of 8±4 K, with a corresponding minimum NEEM ice sheet elevation of -130±300 m below today.

To test our model against this reconstruction, we scaled the peak temperature anomalies of our hybrid curve to give a range of 1.0-8.0 K, overlapping with both the model- and NEEM-estimated temperature anomalies.

Result: No combination of climatic forcing and NEEM (upstream) elevation changes can be simulated that are consistent with the 1-sigma estimates from the reconstruction. Indeed high peak temperatures or small elevation changes are possible in the model, but not both simultaneously.



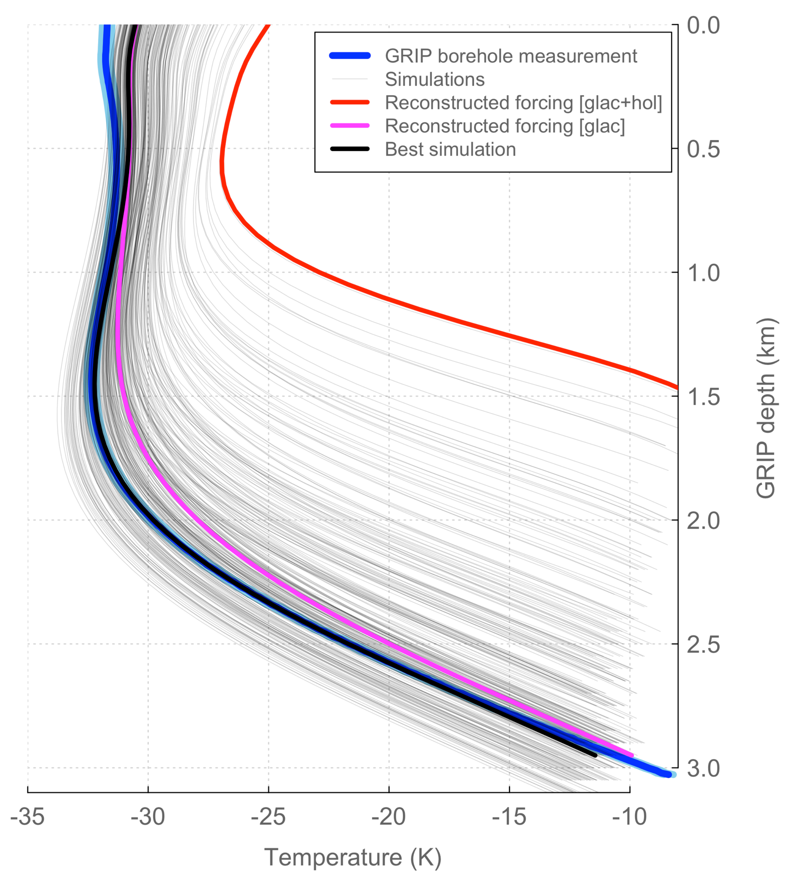


Left: Time series of the summer average forcing applied in the model (top), and the resulting NEEM (upstream) local temp. anomalies and elevation changes (middle and bottom). **Top**: Simulated combinations of max. temp. and elevation anomalies compared with the reconstructed range for NEEM (upstream).

Test 2: borehole temperatures

To test the thermodynamic initialization of our model as a function of the climate, we forced it with reconstructed temperature anomalies as estimated from the NGRIP ice core (Kindler et al., 2014) along with perturbations to find a best fit.

Result: Using the reconstruction directly results in an ice sheet that is several K too warm in the interior. Applying colder glacial and Holocene temperature anomalies gave better agreement with measurements.



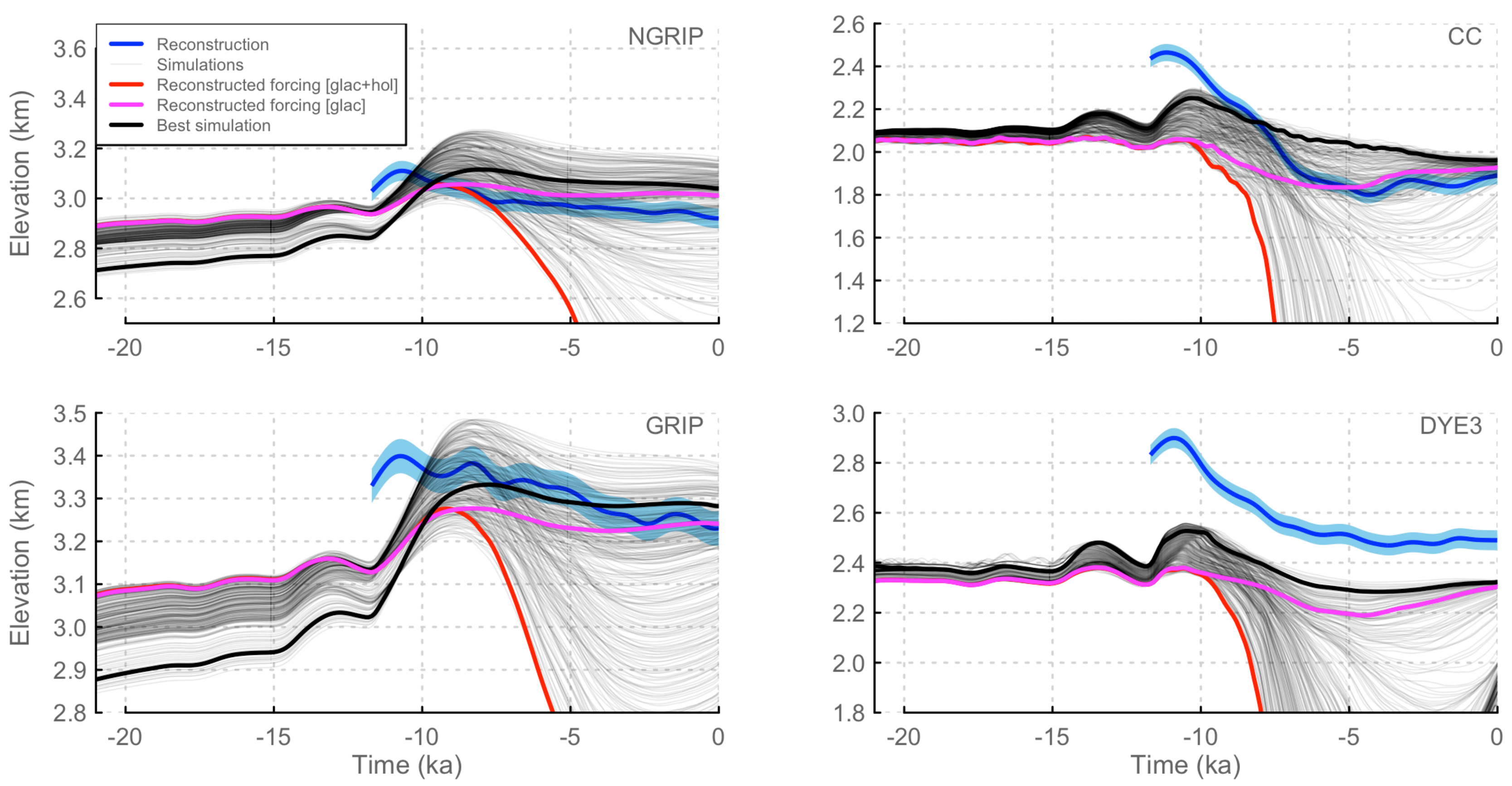
Left: Simulated borehole temperatures at GRIP compared with measurements. The ensemble included perturbations in the Eemian, glacial and Holocene temperature forcing.

Test 3: Holocene elevation changes

Vinther et al. (2009) reconstructed elevation changes during the Holocene at four GrIS ice cores, along with the regional temp. anomaly, which reaches its peak of 2.5 K (4 K in summer) at ~8 ka BP. The central ice cores NGRIP and GRIP enter the Holocene with elevations higher than today and decline until the present. In our ensemble, we varied the Holocene and glacial temp. anomalies over a wide range to see the sensitivity of the model.

Result: Applying the reconstructed temp. anomaly for Greenland results in unrealistically widespread melting of the ice sheet. Lower Holocene temperature anomalies provide better agreement, however the timing of growth in the interior is delayed in the model by ~2 ka.

Our model does not simulate shelf ice, nor did we impose a background uplift from the deglaciation of the Laurentide. However, the accumulation rate in the model fits well with the timing and magnitude of the reconstruction at GRIP. In this context, the simulations only show growth in the interior after entering the Holocene in contrast to the reconstructed elevations.



Above: Simulated time series of elevation anomalies at four ice core locations compared with reconstructions.

Conclusions

Transient ice-sheet model simulations of Greenland reproduce the large-scale behavior of the ice sheet as recorded in paleo proxies and arrive at a reasonable approximation of the present-day GrIS. But significant discrepancies exist that point to deficiencies in both the models and the data reconstructions. Significant effort should be focused on understanding and reducing these discrepancies.

Open questions:

- What is the best way to convert uncertain proxies into quantitative model forcing? What is the best way to validate the result?
- What physical processes are missing from the models that are needed to improve their performance?
- What factors are neglected in converting proxies into paleo constraints or forcing (eg, $d^{18}O$ => temps; total air content => elevation)?
- How can important temporal changes in seasonality and their impact on proxies properly be determined or accounted for?

References

Bakker et al., Climate of the Past, 2013
Capron et al., Quat. Sci. Rev., 2014
Kindler et al., Climate of the Past, 2014
NEEM Members, Nature, 2013
Vinther et al., Nature, 2009