Reconstruction of large-scale atmospheric circulation and data assimilation in paleoclimatology

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Paleoclimate proxy data, such as tree rings, corals and ice cores, and also long instrumental records, have been used to reconstruct local and large-scale past climate. Large-scale reconstructions employ statistical upscaling methods, which exploit the fact that the local and large-scale climate are linked. Past climate has also been simulated with numerical models. A systematic combination of proxy- and simulation-based palaeoclimate estimates, either through consistency tests or through data assimilation, can reduce the uncertainty. The scale mismatch between local proxy data and numerical models, which typically have a resolution of at least several hundred kilometers, can be addressed by using upscaled proxy data, or by downscaling of GCM data to the local-scale. Here we present an example for upscaling, namely a reconstruction of the Antarctic Oscillation (AAO), and an assimilation method that have been developed as part of DEKLIM.

Upscaling
Upscaling involves fitting statistical models, which are mostly regression-based, between the local proxy data and the large-scale climate. Model fitting is usually based on the overlap period between proxy and instrumental data, and stability of the statistical relationships throughout the reconstruction period has to be assumed. Upscaling methods have been used to reconstruct numerous climate features, including global- to regional-scale temperatures (e.g. Mann and Jones 2003, Esper et al. 2002, Luterbacher et al. 2004), and the strength of atmospheric circulation modes (e.g. Cook et al. 2002, D'Arrigo et al. 2003). Such reconstructions are important to estimate natural climate variability (Houghton et al. 2001), and have also been compared to numerical simulations (e.g. Jones et al. 1998, Zorita et al. 2004).

For the Southern Hemisphere, gridded data exist only since the middle of the 20th century, namely the NCAR/NCEP and ECMWF ERA40 reanalyses. Thus even short reconstructions back to the beginning of the 20th century are useful. Here we consider the main mode of extratropical circulation in the Southern Hemisphere, the AAO. To obtain a high-quality reconstruction we used station pressure records to reconstruct the temporal evolution of the strength of the AAO, the Antarctic Oscillation Index (AAOI). This builds on the station-based reconstruction of the Austral Summer (NDJ) AAOI of Jones and Widmann (2003), who also produced a longer reconstruction using tree-ring width chronologies. The reconstructions have now been extended to cover the four standard seasons.

The Austral Autumn (MAM) AAO and the AAOI reconstruction are shown in Fig. 1. The circles represent the locations and relative statistical weights of the stations used to reconstruct the AAOI by means of principal component regression. Based on validation with independent data 50% of the variability of the ERA40 AAO is captured by the reconstruction and the reduction of error is 0.58. The uncertainty due to potential instabilities of the statistical relationship can not be quantified, that due to the variance not explained by the regression is represented in Fig. 1b by the confidence intervals.
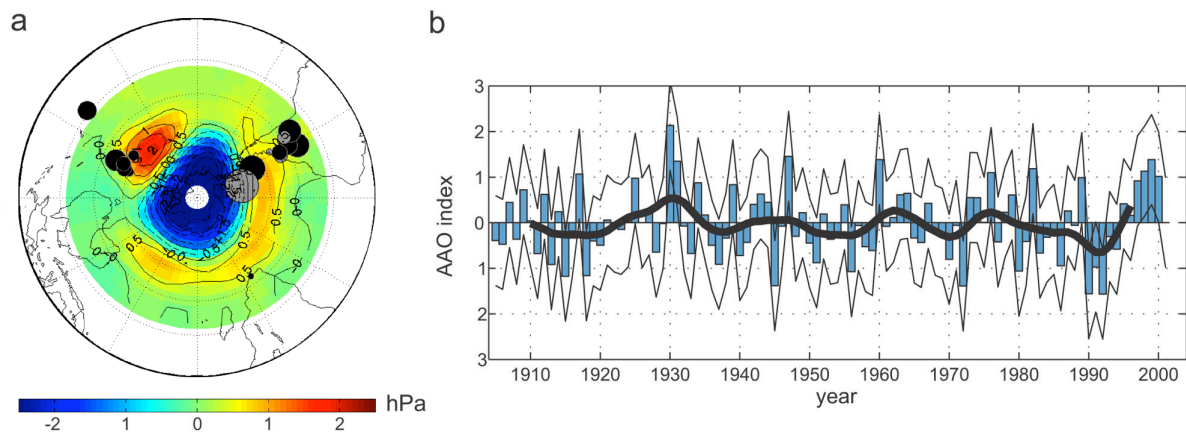
Figure 1a: the MAM Antarctic Oscillation pattern (EOF1 of detrended ERA40 SLP) and the station regression weights for normalised station SLP used for the AAOI reconstruction. Colours and isolines show the pressure change in hPa for AAOI +1. The station regression weights are dimensionless and are given by the circle area. The grey filled circles denote negative values; the black filled circles positive values.

Figure 1b: the reconstructed MAM AAOI. Bars show the reconstruction, and the solid black line is the 11 year filtered mean using a Hamming window. The thin lines show the 95% confidence interval.

Simulation types and data assimilation

Climate models range from simple energy balance models to coupled atmosphere-ocean General Circulation Models (GCMs), which feature complex representations of the fluid dynamics of the climate system. So far two types of GCM simulation have been used in paleoclimatology. Equilibrium runs simulate the internally generated variability of the atmosphere-ocean system and provide an estimate of the mean state and the natural variability consistent with temporally constant forcing factors. Transient experiments with forcing factors that vary in time can help to find the components of the climate variability that are linked to these forcings. An overview of such simulations for the last millennium can be found for instance in Widmann and Tett (2003). Because of internal variability the forcing factors do not completely determine the state of the system, and thus even a perfect GCM forced with all relevant factors will yield only one of many possible realisations of the climate that are consistent with the forcing, rather than the realisation that took place in the real world.

GCM simulations in assimilation mode attempt to also include part of the historic internally generated variability by taking into account empirical knowledge about the climate. Assimilation of observations from surface stations, balloon soundings, or satellites into atmospheric GCMs has been operationally employed for many years for numerical weather prediction, as well as to obtain atmospheric reanalyses. In these applications sophisticated methods are employed (for an overview see Swinbank et al. 2003). Data assimilation in GCMs has also been used for process studies and model validation, usually using the simpler nudging method, which directly forces the model states towards prescribed target values (e.g. Timmreck et al. 1999, Murphy 2000).

These methods require a relatively precise knowledge of the target state. To adapt the nudging method to paleoclimatic applications, where the climate state estimated from proxy data is more uncertain, the DATUN (Data Assimilation Through Upscaling And Nudging) has been developed (Von Storch et al. 2000, Jones and Widmann 2004). It consists of two steps. The first step is the estimation of large-scale climate states through upscaling as described above. The second step will employ a newly developed pattern nudging technique to nudge the model state towards the estimated large-scale states, for instance towards a specific amplitude of the Arctic or Antarctic Oscillation, without directly affecting components of the

climate state that are not constrained by proxy data, and without suppressing synoptic-scale variability.

In test experiments the ECHAM4 atmospheric GCM was nudged towards constant target amplitudes of the Arctic Oscillation (AO). Instead of directly nudging the model sea level pressure (SLP) towards the AO pattern (Fig. 2a), the relative vorticity of the wind field was nudged throughout the lower half of the troposphere towards the AO vorticity signal (Fig. 2b). The amplitudes of the vorticity pattern could be modified as desired (Fig. 2e/f), the SLP response to the nudging had the AO structure and the specified amplitude (not shown), and stormtracks were modified in a physically plausible way without being suppressed (Fig. 2 c/d). Experiments using a coupled atmosphere-ocean GCM and historic values of large-scale anomalies are in preparation.
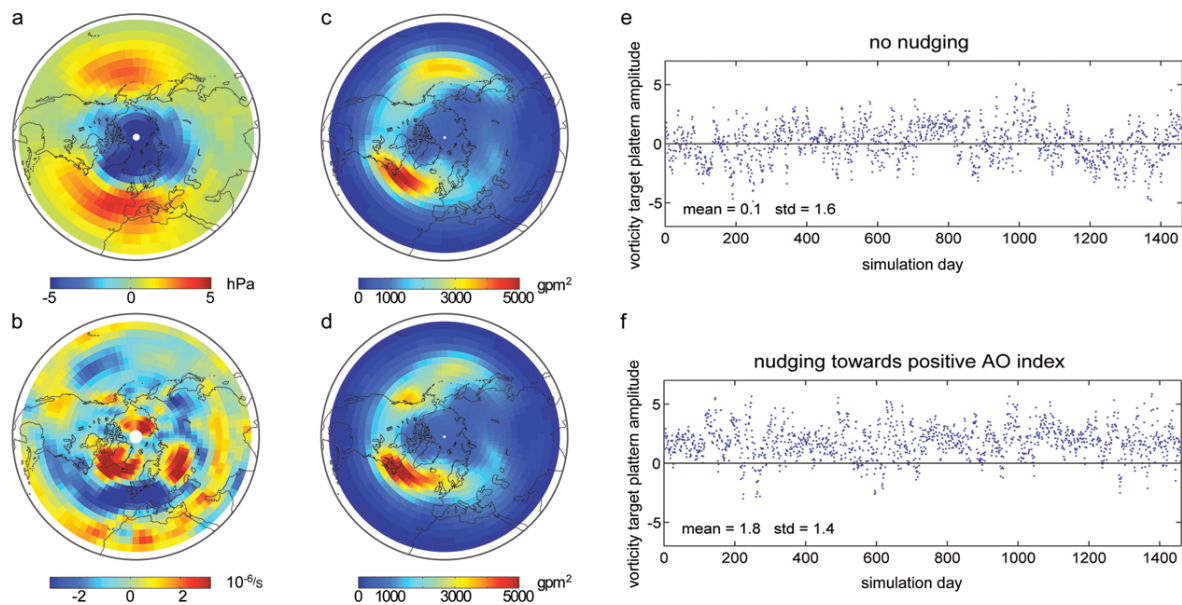

Figure 2a: the AO pattern in January (EOF1 of detrended NCEP Reanalysis SLP), the pressure change for a positive AOI of one standard deviation is shown. Figure 2b: the AO signal in January 850 hPa relative vorticity derived by regression, the vorticity change for a positive AOI of one standard deviation is shown . Figure 2c: stormtracks (2.5d – 6d filtered 500 hPa geopot. height) in a control run (without nudging). Figure 2d: as 2c but in a run nudged towards a positive AO state. Figure 2e: amplitudes of the vorticity pattern (2b) in a control run. Figure 2f: as 2e but in a run nudged towards a positive AO state.

Acknowledgements

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