Climate of the Past

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Discussions

On-line and off-line data assimilation of palaeoclimate proxy data into a GCM using ensemble member selection

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Abstract

Different ensemble-based data assimilation (DA) approaches for palaeoclimate reconstructions have been recently followed, but no systematic comparison among them has been attempted. We compare an off-line and an on-line ensemble-based method, with the testing period being the 17th century, which led into the Maunder Minimum. We use a low-resolution version of Max Planck Institute for Meteorology's model MPI-ESM, to assimilate the PAGES 2K continental temperature reconstructions. In the off-line approach the ensemble for the entire simulation period is generated first and then the ensemble is used in combination with the empirical information to produce the analysis. In contrast, in the on-line approach the ensembles are generated sequentially for sub-periods based on the analysis of previous sub-periods. Both schemes perform better than the simulations without DA. The on-line method would be expected to perform better if the assimilation led to states of the slow components of the climate system that are close to reality and the system had sufficient memory to propagate this information forward in time. In our comparison, which is based on analysing correlations and differences between the analysis and the proxy-based reconstructions, we find similar skill for both methods on continental and the hemispheric scales. This indicates either a lack of control of the slow components in our setup or a lack of information propagation on decadal timescales. Although the skill is similar and the on-line method is more difficult to implement, the temporal consistency of the analysis in on-line method makes it in general preferable.

1 Introduction

Reconstructing the climate of the past is crucial for quantifying and understanding natural climatic change, which in turn is essential for detecting anthropogenic climate change, as well as for the validation of climate models that are used to provide future climate projections. As the instrumental meteorological records are too short to esti-

mate low-frequency variability, reconstructions based on climate proxy data or numerical simulations are used for this purpose. However, both approaches are associated with substantial uncertainties. In principle, the best state estimates can be expected by employing data assimilation (DA) techniques, which systematically combine the empirical information from proxy data with the representation of the processes that govern the climate system given by climate models. Although DA is a very mature field in numerical weather prediction, the specific problem in palaeoclimatology is different and the methods cannot be directly transferred (e.g. Widmann et al., 2010; Hakim et al., 2013). DA is an emerging research area and can be considered as one of the key challenges in palaeoclimatology.

There are two types of proxy-based reconstructions, those for large-scale, e.g. continental or hemispheric averages (e.g. Moberg et al., 2006; PAGES 2K Consortium, 2013) and spatial field reconstructions (e.g. Briffa, 2000; Crowley and Lowery, 2000; Jones and Mann, 2004; Mann et al., 2008). Proxy-based estimates of climate variability contain considerable uncertainties: different proxies usually represent different seasons, different statistical methods used in the reconstructions lead to different results, and non-climatic factors influence the proxies. Moreover, the poor spatial coverage of the climate proxies leads to errors in hemispheric or continental means and even larger errors in full-field reconstructions. The climate states provided by standard model simulations are spatially complete and provide an independent estimate which can be checked for consistency with the proxies, on both large and regional scales. However, the simulations also have errors, e.g. systematic model biases and errors in the climate forcings or in the response to them. Additionally, interannual to decadal temperature variations have a large random, non-forced component and thus agreement of simulations and observations is very unlikely on these timescales. The forcings do not precisely determine the temporal evolution of the climate, in particular on regional scales. Ensemble simulations are indispensable in order to better assess the internal variability for periods within the last millennium (Jungclaus et al., 2010).

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Data assimilation combines the two previous methods to find estimates that are both consistent with the empirical knowledge and with the dynamical understanding of the climate system. It uses the empirical data after the construction of the model to either estimate, correct or select the system state (e.g. Hakim et al., 2013; Bronnimann et al.,
5 2013), or to systematically improve some model parameters (e.g. Annan et al., 2013). Here, we consider the case of state estimation, where DA aims to capture the real-world random, non-forced variability in a simulation and to provide information for variables for which no empirical estimates exist.

Attempts to assimilate proxy data into models include different approaches, such
10 as the selection of ensemble members, forcing singular vectors, and pattern nudging (e.g. Widmann et al., 2010). Ensemble member selection techniques, like the one implemented here, are based on the selection of simulations from an ensemble that are closest to the empirical evidence on climate. A general advantage of these techniques is that they are easy and straightforward to implement, and they are the most fre-
15 quently used methods by the community. Goosse et al. (2006) were the first to use this method for palaeoclimate research, employing a simplified global 3-D climate model. An updated version was employed by Goosse et al. (2010), using a more advanced 3-D Earth-System Model of Intermediate Complexity (EMIC), along with a set of 56 proxy series derived from a comprehensive compilation of Mann et al. (2008). In the
20 first case, the best model analog was selected by comparing the simulations with proxy-based temperature reconstructions after the completion of the simulations, an approach called off-line DA. In the second case a new ensemble was generated at each step of the assimilation procedure, starting from the best simulation selected for the previous period, an approach called on-line DA. The revised method offered dy-
25 namical consistency between best model analogs of different periods, while the former benefited from its computational simplicity. Both methods showed positive reconstruction skill, particularly at the regional scale in areas with high data coverage. The off-line method was also employed by Crespin et al. (2009) to analyse the fifteenth century Arctic warming.

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In addition to the above method, where a single simulation having the best fit to the data is chosen during the assimilation ("degenerate particle filter"), another approach employs weights for each member of the ensemble, calculated after the comparison with the proxies and generating a probabilistic posterior distribution ("particle filter").

5   The technique was applied by Annan and Hargreaves (2012), who used a simple likelihood weighting algorithm and involved off-line assimilation, performing thus all the DA after the completion of the ensemble integration. In the "particle filter" methods, more than one member proceeds to the next assimilation step after the first filtering. The most unlikely ensemble members (particles) are being stopped and the highly likely

10 particles are being copied proportionally to their likelihood. The same "probabilistic posterior distributions" technique was used by Goosse et al. (2012). The outcomes of the approach led to distributions with larger overlaps with the proxy-based reconstruction. The method has also been used by Mairesse et al. (2013) to reconstruct the climate of the mid-Holocene (6 kyr BP).

15 Other ensemble-based DA approaches include the use of the Kalman filter including the explicit treatment of time-averaged observations. The off-line approach of DA was advanced by Bhend et al. (2012), through the assimilation of proxy data into a high-resolution general circulation model (GCM). The ensemble square root filter (EnSRF), a variant of the ensemble Kalman filter, was used to update the ensembles with cli-

20 mate proxy information. An off-line scheme was used at the DA, since the use of an atmosphere-only GCM rather than a coupled atmosphere–ocean GCM left no possibility for information propagation on long timescales. In other words, an on-line DA scheme would not have benefitted the reconstruction skill, apart from leading to temporal consistency of the analysis. Dirren and Hakim (2005) examined the case where

25 only time-averaged observations are available. Their algorithm constitutes a natural extension of the ensemble Kalman filter, and reduces to the ensemble Kalman filter in the limit of zero time averaging (Dirren and Hakim, 2005). Huntley and Hakim (2010) applied the new algorithm to test the method in a simple atmospheric model. Similarly, Pendergrass et al. (2012) tested two idealized models, which captured adequate cli-

mate variability related to the palaeoproxies. In order to identify initial conditions, an ensemble Kalman filter technique was applied to the two models.

An advantage of the on-line compared to the off-line ensemble-based DA methods is the temporal consistency of the simulated states. The off-line approach on the other hand is computationally less complicated and can also be computationally cheaper if one uses simulations that already exist. The question we address in this paper is whether the on-line reconstruction is closer to the proxy-based reconstructions compared to the off-line version. This depends on the memory of the slow components of the climate system, such as the ocean. If these propagate the information contained in the assimilated proxy data forward in time on decadal timescales, the on-line approach is expected to perform better. If, on the other hand, the chaotic nature of the system dominates and the predictability of the system is limited, the computationally easier off-line method would be sufficient. GCMs exhibit up to decadal predictability in the North Atlantic and the ocean predictability can in turn lead to atmospheric predictability. The extent of decadal predictability and the relevant mechanism behind are not yet clear and many studies have recently been performed on these topics (e.g. Steiger et al., 2014; Hawkins and Sutton, 2009a, b; Keenlyside and Ba, 2010).

In this paper, we compare two ensemble-based DA approaches, an off-line and an on-line method, to reconstruct the climate for the period 1600–1700 AD, which led into the Maunder Minimum. This is a period for which many proxy studies and model simulations exist, and which is interesting due to the large temperature variations exhibited in the transition to the prolonged cold period of the Maunder Minimum (about 1645 AD to 1715 AD). We employ ensemble simulations with the Max Planck Institute for Meteorology's General Circulation Model MPI-ESM, and specifically a low-resolution version of the MPI CMIP5 model. The proxy temperature reconstructions of the PAGES 2K project are used in our assimilation.

The structure of the paper is as follows: in Sect. 2, we review the model characteristics and the proxy datasets used, and give the details of our methodology. Section 3 gives the results of the validation of the off-line and the on-line DA approaches and

a first comparison of them, while in Sect. 4, we draw conclusions and discuss the benefits of each approach.

2 Experimental design

2.1 Model simulations

We used the Max Planck Institute for Meteorology Earth System Model (MPI-ESM), comprising of the general circulation models ECHAM6 (Stevens et al., 2013) for the atmosphere and MPIOM (Marsland et al., 2003) for the ocean. ECHAM6 was run at T31 horizontal resolution (3.75° × 3.75°), with 31 vertical levels, resolving the atmosphere up to 10 hPa. MPIOM was run at a horizontal resolution of 3.0° (GR30) and 40 vertical levels. The OASIS3 coupler was used to couple the ocean and the atmosphere daily without flux corrections. The land surface model was JSBACH (Raddatz et al., 2007) and no ocean biogeochemistry model was employed. The model is a low-resolution version of the model used for the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations.

The simulations described here are based on a simulation covering the last millennium (850–1849 AD) following the "past1000" protocol of the Paleo Model Intercomparison Project Phase 3 (Schmidt et al., 2011). Prescribed external forcing factors are reconstructed variations of total solar irradiance (Vieira et al., 2011), volcanic aerosols (Crowley and Unterman, 2012), concentrations of the most important greenhouse gases (Schmidt et al., 2011), and anthropogenic land-cover changes (Pongratz et al., 2008). A long control simulation with constant pre-industrial (1850 AD) boundary conditions was also conducted and the past1000 simulation was started after a 700 year long spin-up with constant 850 AD boundary conditions.

The high computational cost restricted us to running 10 ensemble members for each experiment. This choice is consistent with Bhend et al. (2012) who found that ensembles of size 10 or more can be successful in finding a simulation moderately close to

the proxies, and that considerable skill in regions close to the assimilated data can be found for ensembles of 15 members or more, while larger sizes are needed for areas further away. The ensemble members have been generated by slightly varying values of an atmospheric diffusion parameter. The method leads to a fast divergence of the different simulations and an adequate ensemble spread, not only in surface variables like the 2m or sea-surface temperature, but also in deeper ocean variables, such as the AMOC – Atlantic meridional overturning circulation. The selected ensemble generation method does not directly introduce any disturbance in the ocean, which may limit the capability of the assimilation scheme. For this reason, a different way of generating ensembles was also tested, namely the lagged-ocean initialization method, generating the ensemble members by using different ocean initial conditions, based on different dates close to the original starting date of the generation. The similarity in the output of the two methods however, and the fact that the lagged-ocean initialization method could produce unobserved forcings for some simulations, led us to choose the atmosphere-only disturbance.

2.2 Proxy datasets

For our assimilation procedure, we used the "2k Network" of the IGBP Past Global Changes (PAGES) proxy datasets. The PAGES project used a global set of proxy records and produced temperature reconstructions for seven continental-scale regions (PAGES 2K Consortium, 2013). The dataset covers different periods during the last millennium for each continent, and specifically the years 167–2005 AD for Antarctica, 1–2000 AD for the Arctic, 800–1989 AD for Asia, 1001–2001 AD for Australasia, 1–2003 AD for Europe, 480–1974 AD for North America and 857–1995 AD for South America. It has been produced by nine regional working groups, who identified the best proxy climate records for the temperature reconstruction within their region, using criteria they had established a priori. The techniques followed by the majority of the groups were either the "composite plus scale" (CPS) approach for the adjustment of the mean and variance of a predictor composite to an instrumental target (e.g. Mann

et al., 2008, 2009), or regression-based techniques for the predictors, including principal component pre-filters or distance weighting (PAGES 2K Consortium, 2013). The dataset of individual proxies consists of 511 time series that include ice cores, tree rings, pollen, speleothems, corals, lake and marine sediments as well as historical documents of changes in biological or physical processes. The reconstructions have annual resolution, apart from North America, which is resolved in ten- and thirty-year periods.

2.3 Selection of the best ensemble members

We simulated the period 1600–1700 AD using the standard forcings for this period. The initial conditions were those of the last day of the year 1599 AD, taken from a transient forced simulation starting in 850 AD. We performed ensemble experiments of 100 year duration. In the off-line experiment, in the first year (1600 AD), the ten ensemble members used slightly different values of an atmospheric diffusion parameter. For each member, the simulation period was divided into 10 year intervals, and the decadal means of the 2m temperature were calculated for each of the Northern Hemisphere continents. Using a root mean square (RMS) error-based cost function, the model outputs were compared to the proxy-based continental temperature reconstructions, averaged over the respective 10 year periods. The ensemble member that minimized the cost function in each decade was selected as the best simulation for that period. The same process was followed for all the decades within the analysis period, so that in the end we obtained the analysis, by merging the best members of each decade.

The selection of the "optimal" simulation of the ensemble for each decade of the simulation period was done after the calculation of the following cost function:

$$CF(t) = \sqrt{\sum_{i=1}^{k} \left(T_{\text{mod}}^k(t) - T_{\text{prx}}^k(t) \right)^2} \tag{1}$$

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where k are the Northern Hemisphere continents, namely the Arctic, Asia, Europe and North America, $T^k_{\text{mod}}(t)$ is the standardized modelled decadal mean of the temperatures in each Northern Hemisphere continent and $T^k_{\text{prx}}(t)$ is the standardized proxy-based reconstruction for the decadal mean of the temperatures in each Northern Hemisphere continent. The algorithm filters out the particles that are considered poor representations of the actual state, by throwing away the ones that are less consistent with the proxies and promoting the best fitting particle. We include the data of the Northern Hemisphere alone in the cost function, in an effort to reduce the degrees of freedom of the system and make it easier to find good analogues with our small ensemble size. Moreover, the Southern Hemisphere is affected by bigger uncertainties and is reconstructed by less dense proxy networks.

The reason for basing the cost function on standardized simulated and proxy-based temperatures is to remove systematic biases between the model and the proxy-based reconstructions, and to avoid that continental temperatures with differing variance do not contribute equally to the analysis. The standardized model and proxy time-series were calculated by subtracting the 850–1850 AD means of the model output and the proxies from the 1600–1700 AD raw model output and proxies respectively, and dividing by the respective standard deviations, based on the decadal averages for the 850–1850 AD period. The datasets were not weighted according to the size of the different regions, as we consider all continents to be equally important. We also decided against weighting on the base of the errors of the proxy datasets, as the different methods followed by each of the PAGES 2K groups make the errors not directly comparable. Moreover, the errors of the continental reconstructions are of similar order and thus error weighting would only have a small effect.

In the on-line experiment, a ten-member ensemble was generated for the first year of the analysis period, by introducing small perturbations in the atmospheric diffusion field. Simulations with 10 year duration were run. Using the same cost function as the one used in the off-line experiment, the temperature decadal means of the model outputs were compared to the PAGES 2K continental proxy reconstructions. In contrast to

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the off-line method, the selected member for that period, i.e. the one that minimized the cost function, was used as the initial condition for the subsequent simulation. A new ensemble consisting of 10 members was performed for the second decade, starting from the previous best member's final conditions and having slightly varying values of the

5   atmospheric diffusivity parameter in the different members. The same procedure was repeated until the year 1700 AD

The comparison of the two experiments is based on the proximity to the proxy-based reconstructions. We note however that it is not the aim of DA to exactly reproduce the assimilated empirical information, since these have errors. Ideally, a validation of

10 different DA methods would be based on a comparison with the true and spatially complete temperature field, but as this is not available, a validation based on proximity to the assimilated information is a useful first step to investigate whether the on-line and off-line approaches perform differently.

3   Results and discussion

15 We assimilate the PAGES 2K temperature reconstruction for the period 1600 AD to 1700 AD, which led into the Maunder Minimum. The Maunder minimum (1645 AD to 1715 AD) was characterized by a large reduction in the number of sunspots and hence a reduction in solar radiation, and corresponds to the middle part of the Little Ice Age. The PAGES 2K reconstructions exhibit a cooling in all the continents except Antarctica

20 for this period, being in agreement with previous studies. Fossil coral evidence suggests that El Nino-like conditions prevailed during the 17th century (Jones and Mann, 2004).

Having a good chance to find a close analogue of an atmospheric state requires a large number of ensemble members, if the state space has a high dimension. Van

25 Den Dool (1994) found that to find an accurate analogue for daily data over a large area, such as the Northern Hemisphere, one needs daily data from a period of about 10^{30} years. According to Van Den Dool (1994), using a shorter library, like the current li-

braries of only 10–100 years of data, analogues can be found only in just 2 or 3 degrees of freedom (e.g. Bretherton et al., 1999). In our case, by using only the continental averages of the Northern Hemisphere as targets for the assimilation process, we have a low number of degrees of freedom for our cost function (less than 3). This makes the detection of a good analogue much more likely with our small ensemble size of 10 members. The performance of the two schemes was assessed by computing the correlation and the root-mean-square (RMS) error for each Northern Hemisphere (NH) continent between the simulated and the proxy-based reconstructions of the 2 m air temperatures.

3.1 Validation of the off-line DA scheme

Despite the fact that the cost function for the selection of the best members was based on standardized data, we demonstrate the performance of the two schemes using the non-standardized, but unbiased model output (absolute anomalies). This is because the latter represents the actual assimilated temperatures that come out of the model, which can be compared with other studies. The validation of the off-line DA scheme shows a clear improvement of the simulated reconstruction for the period under consideration, presenting higher correlations between model and proxies for all the continents of the Northern Hemisphere and lower root mean square errors for the analysis compared to the individual members. The analysis was formed by merging the best members of each decade together. Figure 1 shows the Northern Hemisphere continents' decadal mean temperatures for the 17th century for the 10 ensemble members, the proxy-based reconstructions and the off-line DA analysis. The analysis for all the NH continents is closer to the proxies than any of the individual ensemble members. This result is not trivial, as the cost function only minimizes the RMS error with respect to all NH continents.

Figure 2 shows the comparison of the proxy-based and simulated reconstructions for the direct average of the Northern Hemisphere, as well as the Northern Hemisphere mean. The direct average of the four NH continental temperatures in the simulations

makes use of the same sea-land masks and seasonal representativity as the ones employed by the proxy reconstructions. Hence, it is directly comparable to the proxy datasets, which are only available as continental means. The NH mean on the other hand is the true spatial average temperature of the whole Northern Hemisphere. We

5 show this time-series as it is the usual mean temperature given in most climate studies, despite the fact that in our comparison it not the direct equivalent of the proxy-based reconstructions (the proxy time-series in the two cases are the same). The correlations between the analysis and the proxies are relatively high for all the NH continents (0.56 for the Arctic, 0.78 for Asia, 0.79 for Europe and 0.89 for North America). Since the cost

10 function includes all the NH continents, the correlation is maximum for the Northern Hemisphere direct average (0.94), while the correlation for the Northern Hemisphere mean is also high (0.92). These values are much higher than the correlations of the individual members with the proxies, and also higher than the correlation of the ensemble mean with the proxies (0.73).

15 The RMS error of the simulated time-series for each continent provide a quantification of the local agreement between the model and the proxy-based reconstructions. It is calculated based on the decadal mean differences of the model and the proxy time-series for each continent. Figure 3 shows the RMS errors for the individual members, the ensemble mean and the analysis of the four Northern Hemisphere continents. The

20 RMS errors are either minimal or among the lowest for the analysis compared to all other members. The result is even more obvious when considering the RMS errors for the direct average of the Northern Hemisphere, where the analysis had clearly the lowest value (not shown). The fact that the RMS error of the ensemble mean is lower than the error of most of the individual members indicates the influence of forcings in

25 some continents. However, a better estimate can be still obtained from the DA analysis, which means that internal variability is important too, especially for Europe, North America and the direct average of the NH.

The assessment of the performance of the off-line DA scheme using the standardized data produced very similar correlations and RMS errors to the ones found when

using the absolute anomalies and presented above. For the Southern Hemisphere, it is more meaningful to assess the performance of the method using the standardized data, as the RMS error only has a meaning with this approach. Not using the standardized outputs in this case would result in non-comparable scales because of the different standard deviations between model and proxies. In contrast to the good skill of the scheme in the Northern Hemisphere, the agreement between the analysis for the Southern Hemisphere (SH) and the proxy-based reconstructions is not good, as expected from the fact that SH data are not included in the cost function. It is noteworthy that the PAGES 2K record for Antarctica shows less cooling than the NH records during the seventeenth century. As the NH cooling during this period has been mainly attributed to solar and volcanic forcings (Jones and Mann, 2004), this indicates a weaker sensitivity of Antarctica to these forcings, presumably due to the large fraction of ocean in the SH and the high albedo of Antarctica.

3.2 Validation of the on-line DA scheme

The on-line DA scheme was also successful, improving the skill of the analysis time-series compared to the individual members. However, the scheme presented very similar correlations between the DA analysis and the proxy-based reconstructions with the ones found with the off-line approach, and no major improvements to the RMS errors, both on the continental scales and the direct averages. The NH continents' decadal mean temperatures for the 17th century, for the 10 ensemble members, the proxy-based reconstructions and the on-line DA analysis are displayed in Fig. 4 and show the good proximity of the analysis to the empirical reconstruction. Even better agreement is exhibited by the direct average of the four Northern Hemisphere continents and the Northern Hemisphere mean, as illustrated in Fig. 5. Validation of the absolute anomalies reveal that correlations between analysis and proxies are high for all the NH continents (0.79 for the Arctic, 0.76 for Asia, 0.79 for Europe and 0.81 for North America). The correlation is again the maximum for the Northern Hemisphere direct average (0.93), and the Northern Hemisphere mean, (0.92). Similarly to the off-line

DA scheme, the above values are much higher than the correlations of any individual member with the proxies, as well as higher than the correlation of the ensemble mean with the proxies (0.67).

The RMS errors for the analysis of the NH continents are among the lowest compared to the different members, as shown by Fig. 6. This is also the case for the direct average of the NH continents and the NH mean, to an even greater extent compared to the respective individual members (Fig. 7). Specifically, the RMS errors between the analysis and the proxies in the on-line DA scheme are 0.18 for the Arctic, 0.21 for Asia, 0.16 for Europe and 0.18 for North America. The RMS error for the direct average of the four Northern Hemisphere continents is 0.19.

The construction of our cost function on the base of decadal mean temperatures of the NH, means that the analysis is not expected to be more skilful than the individual members when considering the hundred-year average. The 17th century average temperatures for the NH continents are presented in Fig. 8, and indeed do not exhibit the best agreement between the analysis and the proxy-based reconstructions in all the regions, although this is the case for some continents (the Arctic and Europe).

3.3 Comparison of the two DA schemes

As previously noted, both DA schemes perform better than the simulations without DA. Not much difference appears between the two of them. In seven out of the 10 decades of the testing period, a lower cost function for the best member and the ensemble mean is found when using the on-line method, but the differences with the off-line approach are very small (Table 1), not allowing any robust statements about one method being better than the other. The respective ensemble mean (EM) cost functions are also shown in the table. Table 2 shows the Northern Hemisphere RMS errors between simulations and proxy-based reconstructions for the analysis and the ensemble mean of the two data assimilation schemes. The correlations and the RMS errors, at the continental scale and the averages of the NH, are very close to each other. The differences between the on-line and the off-line NH direct average and mean temperatures for the

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17th century are displayed in Fig. 9, where none of the two analyses can be deemed as better in following the proxy-based reconstruction. The proximity of the analyses of the two methods can also be seen in Fig. 10. The figure displays the analyses of the on-line and the off-line DA methods for the 2 m mean temperature (anomalies w.r.t. the

5   1961–90 AD mean) and 500hPa geopotential height (anomalies w.r.t. the 1961–90 AD mean) of the decade 1640–49 AD We see some similar patterns emerging, e.g. cool Barents Sea and warm NW Atlantic. An interesting question to answer is whether we would see differences in the performances of the two schemes if we included circulation indices from proxies. It could also be interesting to examine if it could be useful to

10   include more proxy information from the ocean (e.g. the North Atlantic), to get a better estimate of the ocean state.

    In our setup, it appears that either no information propagation on the decadal timescales exists, or insufficient control of the ocean state affects the two DA methods. In the first case, if there is no information propagation through the slow components of

15   the climate system, then the on-line DA scheme cannot be expected to perform better than the off-line one in any setup that compares the two schemes. In the second case, different reasons may have influenced our setup, and a different setup could produce different conclusions that favour the on-line DA scheme.

    A first explanation of the equal skill of the two methods would be that the decadal res-

20   olution of the cost function indicates very little predictability in the atmosphere–ocean system. The ocean predictability is not leading to significant atmospheric predictability, in other words the slow components of the climate system do not have enough memory to propagate the information contained in the assimilated proxy data forward in time on decadal timescales. Atmospheric processes in this case seem to play a more impor-

25   tant role in the assimilation compared to the oceanic processes. Moreover, even in the case of a mistaken ocean state, the 2 m-air temperature reconstruction might still be unaffected if the atmospheric processes are indeed more significant than the ocean ones.

However, we cannot be sure that the ocean has got no ability and memory to propagate the information forward on multi-year timescales. If this is not the case, a different setup could produce different conclusions that could prove the on-line DA scheme more skilful than the off-line one. Reasons for which the on-line DA is not better than the off-line DA in following the proxy-based reconstructions in our setup but could be more skilful in a different setup could be various. Firstly, the insufficient control of the ocean state could be due to the small ensemble size. If the ensemble size is too small to find a member that is close to the true climatic state, there will be no added skill by propagating this misleading information forward in time. A second reason for the initial state of the ocean not being accurately enough determined throughout the on-line assimilation could be that the selection of the best member was based on the atmospheric temperature state. A correct atmospheric state cannot guarantee that the ocean state is also determined correctly. A differently defined cost function, considering for example the global or direct average of the PAGES 2K continental reconstructions or different timescales could also change the performance of the two schemes. Another aspect that could have influenced our approaches is the proxy datasets. The use of proxies with the minimum possible noise would give a better chance to the on-line approach to capture the true climatic state. Finally, the use of a full particle filter rather than a degenerate one might produce a bigger ensemble spread for the ocean, giving again a better possibility to the on-line DA scheme to capture the true ocean state more closely.

4   Conclusions

Two main approaches have so far been employed to reconstruct the past climate: empirical and dynamical methods. Direct assimilation of proxy-based reconstructions into climate model simulations addresses the weaknesses of the two methods. Here, we have compared two ensemble-based DA schemes, an off-line and an on-line one, with the test case corresponding to the climate of the period leading into the Maunder Minimum, i.e. 1600–1700 AD

The two DA schemes outperform the simulations without DA. The correlations between simulations and proxy-based reconstructions for the analyses of the DA schemes were higher than the correlations of the individual members, whilst the RMS errors were lower. The RMS errors of the ensemble means are lower than the errors of most of the individual members, indicating the influence of forcings in some continents, but the DA analyses perform better, implying that internal variability is important too. No big difference was found between the two approaches. The majority of the cost functions for the best member and the ensemble mean of the on-line DA method were found to be slightly lower than the ones of the off-line DA method, but the correlations and the RMS errors, at both the continental and the hemispheric level were very close to each other. The results suggest that either no information propagation on the decadal timescales exists, with insignificant predictability for the climate system, or insufficient control of the ocean state affects the two DA approaches.

These results raise the question of which approach should be preferred in the future. In some cases, since the reconstruction skill of the on-line approach is not improved compared to the off-line equivalent, it would appear natural to use the less complicated off-line approach to DA, especially when computationally less expensive alternatives of off-line DA schemes can be used, for example when employing simulations that already exist. The temporal consistency of the simulation is eliminated in these cases though, which does not happen in the on-line approach. In the majority of the cases, and especially in the cases where the computational cost of the two methods is equal, the on-line approach should be preferred, as a result of the temporally consistent states that it provides.

Yet, we cannot be sure through these experiments whether a different setup could produce a better agreement for the on-line DA. Validation is only done with respect to the proximity to the proxy-based reconstructions, which is only a first step. We do not validate against the unknown true climate, as this would require pseudoproxy studies, which are beyond the scope of this paper. A differently defined cost function or different performance measures could also alter the comparison. Special care must be taken to

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Table 1. Best cost functions for the off-line and the on-line DA schemes, for the decades 1 (1600–1609) to 10 (1690–1699). The respective ensemble mean (EM) cost functions are also shown.

Decade	Off-line Best	On-line Best	Off-line EM	On-line EM
1	1.47	1.47	2.53	2.53
2	1.44	1.55	1.96	2.00
3	0.51	0.45	1.31	0.86
4	1.71	2.10	2.39	2.49
5	0.72	0.60	1.57	1.14
6	1.04	0.50	1.65	0.95
7	0.53	0.49	1.22	0.97
8	0.62	0.38	1.66	1.62
9	1.72	0.66	2.28	2.21
10	1.46	1.45	1.97	1.93

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Table 2. Northern Hemisphere RMS errors between simulations and proxy-based reconstructions for the analysis and the ensemble mean of the two data assimilation schemes.

	Arctic	Asia	Europe	N. America	NH dir. aver.
Off-line DA analysis	0.24	0.19	0.18	0.13	0.20
On-line DA analysis	0.18	0.21	0.16	0.18	0.19
Off-line DA EM	0.23	0.19	0.24	0.18	0.21
On-line DA EM	0.22	0.21	0.24	0.19	0.22
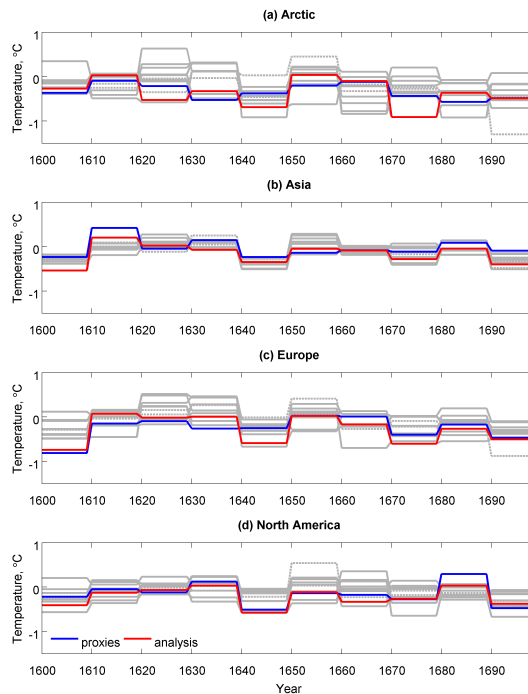
Figure 1. Continental decadal mean temperatures in the Northern Hemisphere for the 17th century, for the 10 ensemble members (gray lines), the proxy-based reconstructions (blue line) and the off-line DA analysis (red line).
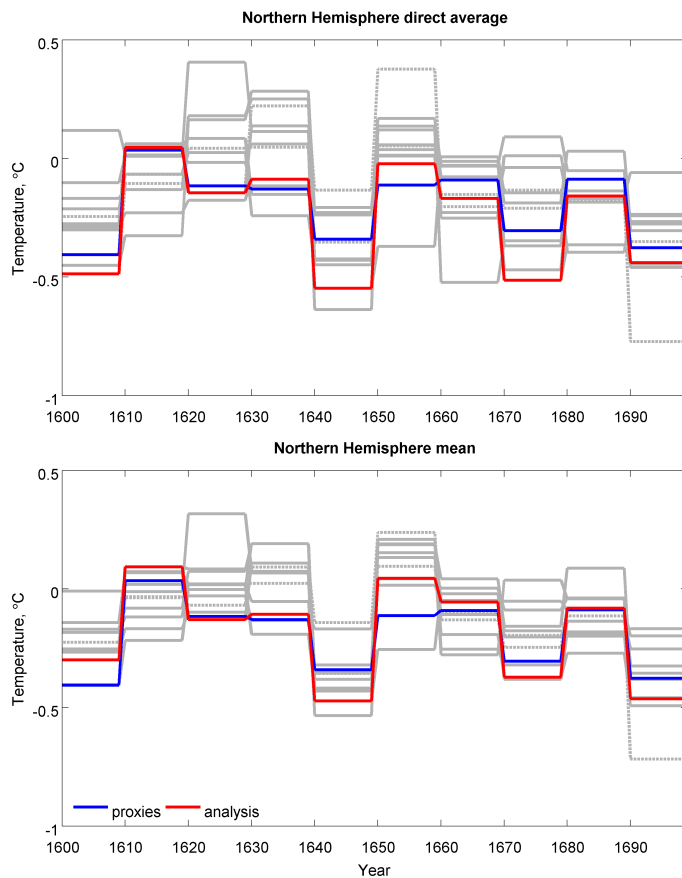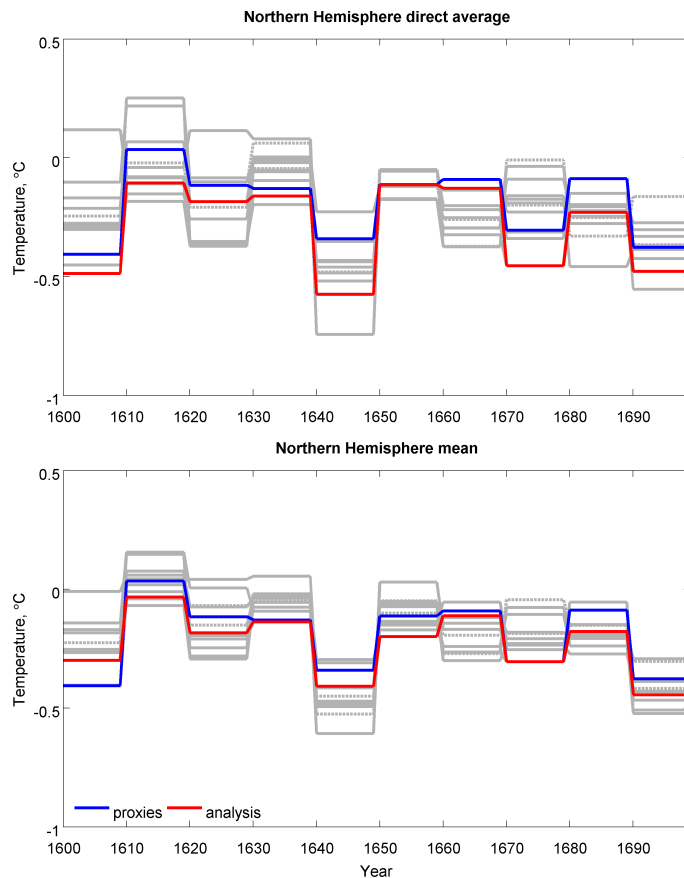
Figure 2. Direct average of the four Northern Hemisphere continental temperatures and NH mean for the 17th century, for the 10 ensemble members (gray lines), the proxy-based reconstructions (blue line) and the off-line DA analysis (red line).
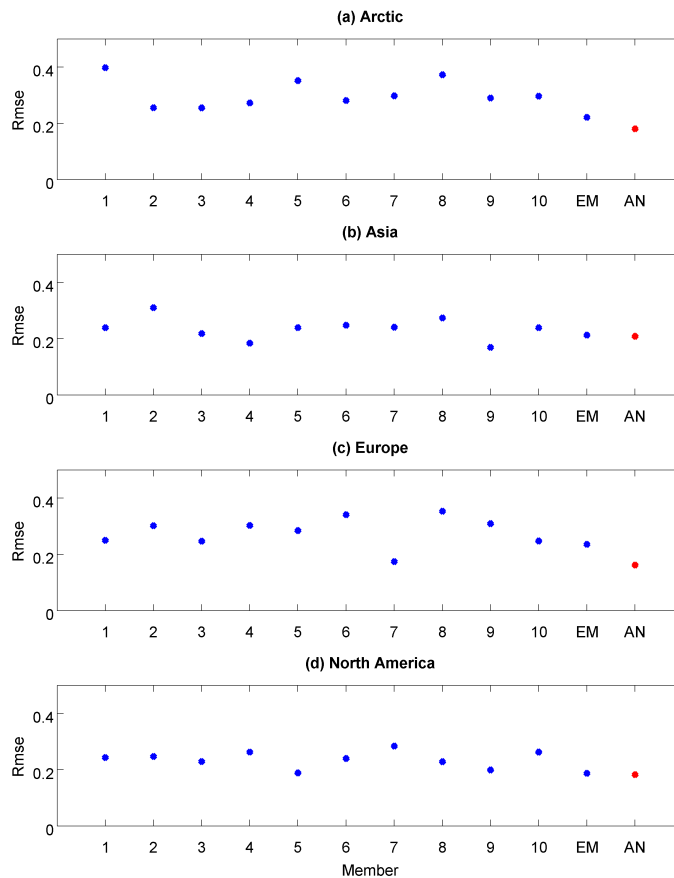
Figure 3. RMS errors for the four Northern Hemisphere continents for the 17th century, for the 10 ensemble members, the ensemble mean (EM) and the off-line DA analysis (AN).
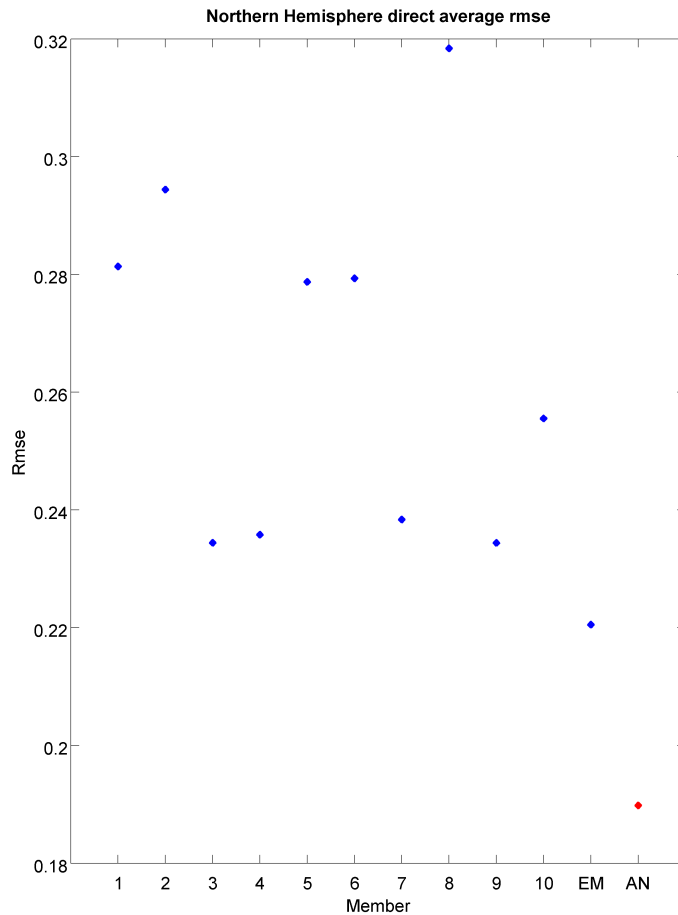
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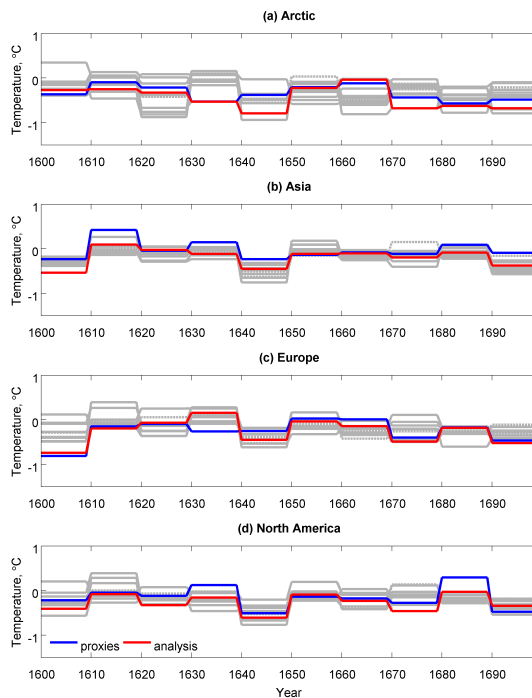
Figure 4. Continental decadal mean temperatures in the Northern Hemisphere for the 17th century, for the 10 ensemble members (gray lines), the proxy-based reconstructions (blue line) and the on-line DA analysis (red line).

Figure 5. Direct average of the four Northern Hemisphere continental temperatures and NH mean for the 17th century, for the 10 ensemble members (gray lines), the proxy-based reconstructions (blue line) and the on-line DA analysis (red line).

Figure 6. RMS errors for the four Northern Hemisphere continents for the 17th century, for the 10 ensemble members, the ensemble mean (EM) and the on-line DA analysis (AN).

Figure 7. RMS errors for the direct average of the Northern Hemisphere for the 17th century, for the 10 ensemble members, the ensemble mean and the on-line DA analysis.
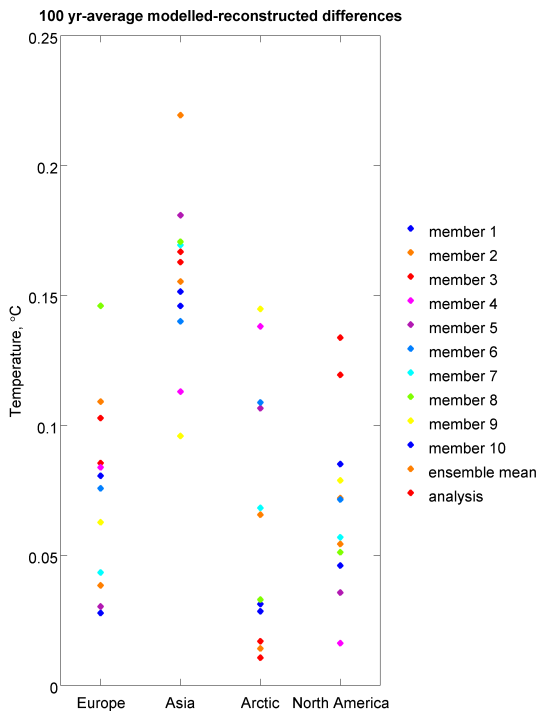
Figure 8. 17th century average temperatures for the four Northern Hemisphere continents.
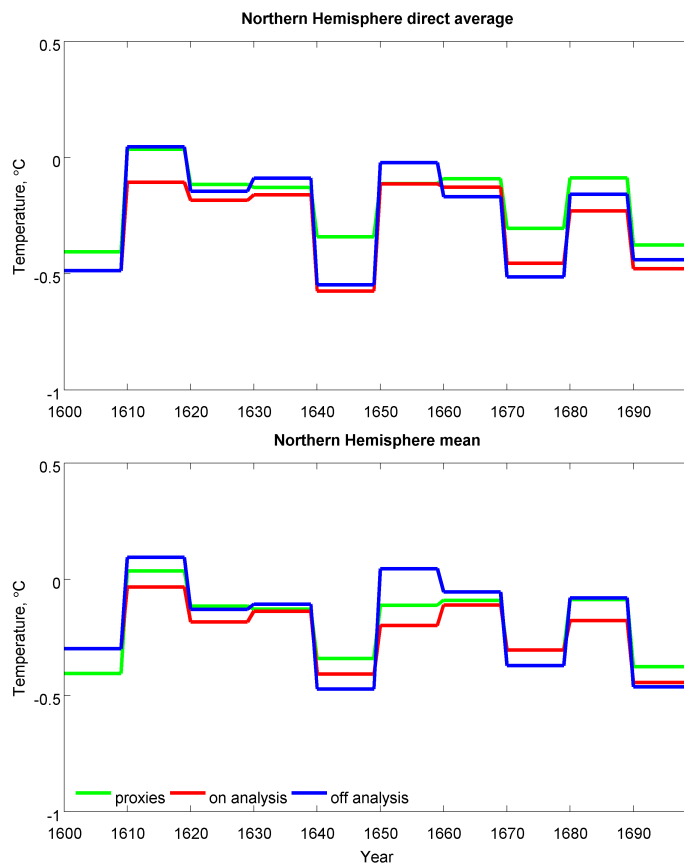
Figure 9. Decadal means of the on-line DA (red line) and off-line DA (blue line) analyses for the NH direct average and mean temperatures for the 17th century, compared to the proxy-based reconstructions (green line).

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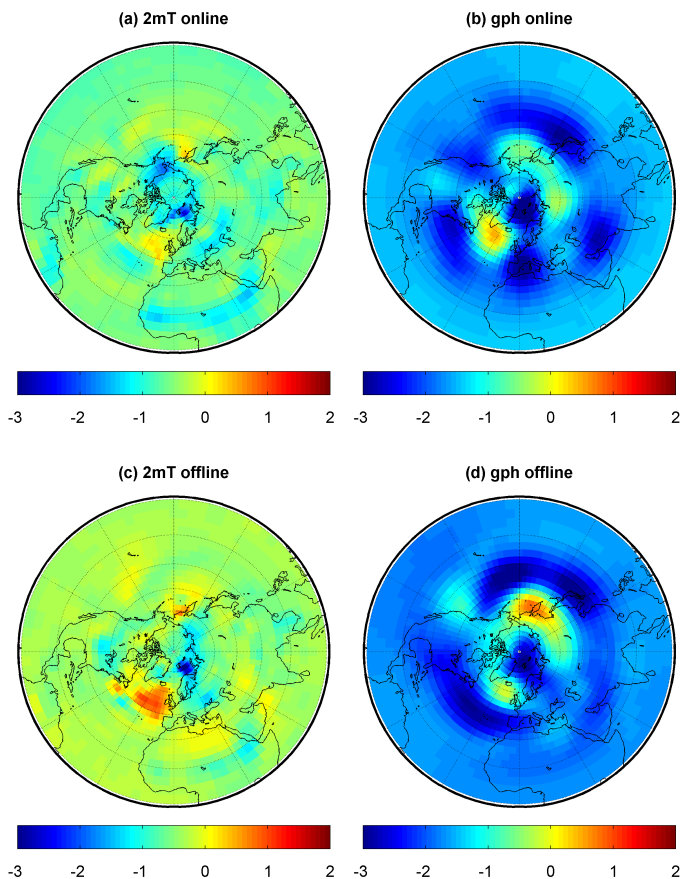
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Figure 10. Analyses of the on-line and the off-line DA methods for the 2 m mean temperature (anomalies w.r.t. the 1961–1990 AD mean) and 500 hPa geopotential height (anomalies w.r.t. the 1961–1990 AD mean) of the decade 1640–1649 AD.

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