Clim. Past Discuss., 6, 659–679, 2010
www.clim-past-discuss.net/6/659/2010/

Climate of the Past Discussions

Clustering climate reconstructions

G. Bürger

Pacific Climate Impacts Consortium, Victoria, Canada

Received: 31 March 2010 – Accepted: 1 April 2010 – Published: 21 April 2010

Correspondence to: G. Bürger (gbuerger@uvic.ca)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A systematic coherence analysis is presented for the set of the most prominent millennial reconstructions of Northern hemispheric temperature. The large number of mutual coherences underwent a clustering analysis that revealed five significant, mutually incoherent ("inconsistent") clusters. The use of multiple proxies seems to be causing the clustering, at least in part, but not in an easily definable, physical way. Alternatively, a multidimensional scaling is performed on the same set of coherences. This results in a graphic, two-dimensional rendering of the reconstructions whose geometry (location and distance) is given by the coherences. Both approaches offer complementary ways in dealing with the inconsistencies.

1 Introduction

How inconsistent do two models have to be in order to dismiss at least one of them? – For example, if model M1 purports that at least 60% ± 5% of all crows are green and model M2 purports 55% ± 5% are red, then, using classic logical and arithmetical reasoning, the models are inconsistent and at least one model *must* be dismissed as being wrong. (Of course, both can be wrong.) But what happens if the uncertainty is slightly larger (10% instead of 5%)? And are these arguments still valid in times of "reasoning under uncertainty" (Shafer and Pearl, 1990; Parsons, 2001) and an emergence of "paraconsistent" logics (Priest, 2000, 2002; Arieli, 2008)?

Such questions may arise when investigating the modeling – or reconstructing – of past millennial Northern hemispheric (NH) temperature. They arose in me, at least, in an attempt to understand the reconstructions of the latest IPCC report (Jansen et al., 2007; Fig. 6.10), of which the following extend back to the year 1000: (Jones et al., 1998; Mann et al., 1999; Briffa, 2000; Esper et al., 2002; Mann and Jones, 2003; Moberg et al., 2005; d'Arrigo et al., 2006). The figure in that report displays an overlap of the 1σ and 2σ uncertainty bands of the reconstructions, weighted accordingly, that approximates the "most likely" temperature for any given year. In the present study I am going to define a notion of "consistency" that is suited to these reconstructions, based on time series coherence. I have for completeness also included the reconstructions (Crowley and Lowery, 2000) and (Mann et al., 2008), making a total of ten reconstructions listed in Table 1. In statistical terms, the mentioned IPCC figure entails what is known as a "probability mixture model" (McLachlan and Peel, 2000), with all sub-models weighted equally. The reconstructions are thus tacitly considered as mutually consistent, and conflicting variations between any two of them are not resolved but instead add to an overall uncertainty of a unique, albeit unknown NH temperature.

That all reconstructions are weighted equally is mainly due to the lack of better evidence. Many verification attempts (Briffa et al., 1988; Mann et al., 1998, 2008; Rutherford et al., 2005; Wahl et al., 2006) suffer from insufficient independent verification data, which severely obscures the corresponding statistics (Bürger, 2007; Christiansen et al., 2009). This lack of data can partly be evaded by using the synthetic data of a climate simulation, where "pseudo" proxies, which are temperature grid points degraded by noise, are used to track temperature (Von Storch et al., 2004; Mann et al., 2005; Lee et al., 2008; Christiansen et al., 2009). The variance of the noise, or the signal-to-noise ratio (SNR), is determined from local temperature-proxy correlations. According to these studies, none of the tested methods revealed a performance conclusive enough to provide reliable temperature estimates for the entire millennium, at least not for the appropriate setting, that is, a small proxy network with a low SNR. It should be noted, moreover, that the reported performance measures are likely too optimistic anyway, as the local temperature-proxy error model – independent white noise – has been shown to be inadequate (Bürger et al., 2006; Bürger, 2007); see also (Von Storch et al., 2006).

With verification being thus poor, debates about competing approaches to climate reconstruction, such as regional curve standardization (Briffa et al., 1992; Esper et al., 2002), or different variants of regression (Von Storch et al., 2004; Mann et al., 2005) remain largely undecided.

If such “unilateral” validation approaches fail, bilateral analyses may offer some guidance to assess millennial climate reconstructions. I am aware of only one systematic analysis of such kind. (Juckes et al., 2007) calculate cross correlations of six reconstructions, four of which are also considered here. But their analysis has a number of caveats. For example, the corresponding low-pass filtered versions (21-year running mean) have been described as “highly correlated”, but no significance analysis has been supplied that would put “high” into context. Moreover, their estimates are optimistically biased as they include the instrumental period which was used for calibration.

I follow a similar approach here by systematically analyzing the mutual consistency of the ten reconstructions of Table 1. To avoid the “synchronization” effect from the calibration, the analysis will be based exclusively on pre-instrumental variations. Additionally, *spectral coherence* is used to measure the mutual consistency of the reconstructions. Estimates of coherence and corresponding uncertainties rely on little more than very general stationarity assumptions (Brillinger, 2001) and therefore present a better protection against, e.g., spurious significance (Granger and Newbold, 1974). This should provide a more stringent criterion to judge the mutual consistency of any two series.

Using a distance measure that is based on coherence, aggregated across relevant frequencies, a clustering analysis is performed on the set of reconstructions. This results in a structured view of the reconstructions, with any two clusters being *inconsistent*. Based on the same distance metric, a multi-dimensional scaling (MDS) analysis of the ten reconstructions is performed. In two dimensions, a very graphic rendering of the reconstructions is obtained that may already be useful for, e.g., detecting outliers, and may help to design new reconstructions from the ones given. And it may ultimately lead to a better logical understanding, as indicated above, of what has actually been reconstructed.

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2 Clustering reconstructions

The following coherence analysis establishes statistically whether corresponding co-variations represent coherent behavior or just pure chance. The analysis is constrained to reconstructed data prior to 1850, to ensure that the estimated coherence is not inflated by calibrating effects from the instrumental period. All reconstructions are rescaled to have zero mean and unit variance.

We use the multitaper spectral estimator (Percival and Walden, 1993). Coherence, κ, as a spectral measure depends on frequency, f. An appropriate summary measure is given by the quantity

$$\overline{\kappa} = 1/0.2 \int_{0 \leq f \leq 0.2} \kappa(f)df, \tag{1}$$

representing the average coherence in the spectral band $0 \leq f \leq 0.2$, which means variability above 5 years. This is the time scale where significant temperature-proxy interaction is to be expected (Cook et al., 1998, 2000, 2004; Biondi et al., 2001; d'Arrigo et al., 2001; Briffa et al., 2002; Gray et al., 2003, 2004; Wilson et al., 2007). Table 2 shows the complete set of mutual coherences $\overline{\kappa}$ for the millennial reconstructions. Of all $\binom{10}{2} = 45$ pairs, only a small fraction (7) turns out to be significantly nonzero, indicating nonrandom behavior. Among these, the pairs dA06, Br00 and dA06, Es02 (abbreviations from Table 1) stick out with values of 0.65 and 0.6; and, adhering to what can be called the transitive law of coherence, Br00, Es02 follow with $\overline{\kappa} = 0.55$.

More systematically, a hierarchical clustering analysis (Hastie et al., 2001) is applied to Table 2, using as a distance metric the term

$$\mathrm{d} = 1 - \overline{\kappa}. \tag{2}$$

Starting from each single reconstruction as a cluster, new clusters may be formed recursively from any given set of clusters by merging the two nearest (most coherent)

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clusters, the distance of any two clusters being taken as the maximum of *all* member distances ("complete linkage"). If that distance is smaller than the distance corresponding to the level of κ significance in Eq. (2) (from the 99% level), the two clusters are called *consistent* and merged to form a new cluster. A looser criterion of forming clusters is "single linkage" where maximum distance is replaced by minimum distance. But in that case, two clusters are merged if only *any* two members are significantly coherent, and so clusters are populated with mutually incoherent members (reconstructions) which should be avoided after all. Therefore, single linkage clustering is generally dropped from this analysis. The clustering process is shown in Fig. 1, the resulting group of internally coherent but mutually incoherent clusters signified by different colors. The height of a node is given by the distance of its two constituents. Five clusters are so obtained: {Br00, Es02, dA06}, {MJ03, Mo05}, {CL00, Jo98}, {Ma08L, Ma08}, and {Ma99}.

A more graphic representation of the reconstruction clustering is obtained from using multidimensional scaling (MDS) (Hastie et al., 2001). In MDS, the ten reconstructions are mapped onto a low (here two) dimensional Euclidean space, so as to optimally represent the distance matrix of Table 2 as Euclidean distances between the mapped points. The result is shown in Fig. 2. Br00 occupies the center of the plot, with relatively moderate (albeit mostly inconsistent) distances to the other reconstructions; dA06 is similar. In this display, Ma08L appears as the most "excentric" reconstruction, followed by CL00, Ma99, and Mo05. Ma08L and Ma99 show the greatest distance, that is, of all pairs they are maximally inconsistent. Note that all five clusters are well represented in the plot (which is not too surprising as that is exactly the purpose of MDS).

Figure 3 displays the reconstructed time series grouped by cluster. Cluster {Br00, Es02, dA06} shows warm conditions at about the years 1000, 1400 and 1550, and cooler conditions from 1200 to 1350 and at 1450 and 1600. Cluster {MJ03, Mo05} is, like all remaining clusters, dominated by a fairly strong negative trend. On top of that there is an extended cooling in the 17th century, followed by much warmer conditions in the 18th century. Not much variability is in cluster {CL00, Jo98}, only the apparent negative trend which seems stronger for CL00. The series are weakly coherent. Finally, the clusters {Ma08L, Ma08} and {Ma99} are both characterized by little variability, interrupted by sporadic outbreaks of strong cooling (1350, 1450, 1700) that might be related to volcanic events.

To exemplify the inter- and intra-cluster coherence I have plotted in Fig. 4 typical coherence spectra from the clusters {Br00, Es02, dA06}, {MJ03, Mo05}, {Ma08L, Ma08}, and {Ma99}, together with the 90%, 95%, and 99% confidence band of no coherence (which is known to be independent of frequency). Br00 and dA06 are significantly (99%) coherent on all timescales, whereas MJ03 and Mo05 are coherent at the lower frequencies ($f \leq 0.2$) only. An extreme case of cross-cluster inconsistency are the two most distant reconstructions Ma99 and Ma08L, which are nowhere coherent except at very small frequencies, signifying their common negative trend.

A potential cause of the cluster incoherence may lie in the different target areas of the reconstructions. For example, Br00 reconstructs the NH extratropical land temperature only, while Mo05 is targeted at the entire NH. Inspecting Table 3 shows that in fact the five clusters are nicely lined up with their respective target configurations, with the exception of {Ma08, Ma08L} which are distinguished by using sea surface information. But this characterization is not unique as, e.g., {MJ03, Mo05} and {Ma99} are incoherent but share the same targets. Moreover, the different targets are not so different in the first place, as Table 4 shows: a millennial climate simulation (Gonzalez-Rouco et al., 2003) shows that the various target areas are strongly coherent for the relevant time scales >5y, with $\overline{\kappa} \sim 0.95$ or d $\sim$0.05.

If the different target areas cannot sufficiently account for the different clusters, having a sufficiently even type and processing of proxies seems to lead to coherent reconstructions. This applies to the cluster {Br00, Es02, dA06}, all whose reconstructions are based on tree rings and a similar technique (age band decomposition and regional curve standardization) to retain low-frequency information for the proxy standardization.

It should be noted that choosing a narrower spectral band, such as for example $0 \leq f \leq 0.1$, that is, decadal and longer, does not alter the dendrogram of Fig. 1 substantially. Similarly, the 95% significance level (d=0.61) yields identical clusters, while under the 90% level (d=0.65) clusters {Br00, Es02, dA06} and {MJ03, Mo05} merge.

3 Discussion

By avoiding the (calibrating) instrumental period, and by using a fairly robust spectral measure for low-frequency performance, the above coherence analysis has uncovered several inconsistencies among the group of millennial reconstructions that figured prominently in the latest IPCC report and elsewhere. An immediate lesson from this is that simple visual inspection of smoothed time series, grouped and overlaid into a single graph, can be very misleading. For example, the two reconstructions Ma99 and Ma08L, which have previously been described to be in "striking agreement" (cf. Mann et al., 2008), turned out to be the most incoherent of all in our analysis.

The most obvious, pragmatic, response to the inconsistencies is to inspect the methods and try to improve and harmonize them. But as I have pointed out, without a functioning, uncontroversial verification procedure this will not lead very far.

Having therefore to live, for now, with pairwise inconsistent reconstruction clusters there is more than one way to interpret the coherence results meaningfully. Two complementary views regarding the "true" NH temperature are possible, depending on the focus lying on the clustering or on the MDS:

a) five inconsistent clusters each representing a possible truth

b) ten independent approximations of an otherwise unknown truth

ad a) With no obvious means at hand to dismiss any of the five inconsistent reconstructions, one would have to deal with derivations involving inconsistent statements.

As mentioned in the beginning, this requires a non-standard approach to the logical discourse, perhaps along the lines of, e.g., (Arieli, 2008).
ad b) This viewpoint, which may be somewhat more realistic than a), is closer to the conventional approach where all reconstructions are seen as approximations to a single, true temperature curve. However, the error metric is fundamentally different here. The conventional metric would operate on the reconstructed temperatures themselves and construct a real temperature average. The view suggested here (mainly through Fig. 2) is that the best estimate of truth is near the "center" of the reconstructions in the MDS rendition. But this rendition is non-physical, or not directly physical, as the MDS dimensions are not related to the original temperature series in a simple way. Least-squares approaches do not work here, so that estimating the center by simple temperature averaging is impossible. That center represents a compromise of the reconstructions, in the sense that it would be, on average, maximally coherent with all of them. It is likely to be "close" to Br00 and Ma08, and may be found by prudently merging techniques and proxies from both approaches. If not, one would probably have to resort to trial and error.

One may as well choose to neglect the reported incoherences. But then the following, and likely more, semantic subtleties from the inconsistent reconstructions have to be resolved:

- Can they *skillfully* represent NH temperatures?
- Can they lie within a *common uncertainty* bound?
- If they come to an identical *conclusion* – such as the non-existence of a Medieval Warm Period, what does it mean for that conclusion?

Using inconsistent reconstructions to approximate the temperature curve has one particular visual consequence. Whether overlaying them in one figure or forming an average, the result tends to be a cancellation of larger amplitudes as inconsistency means here to be indistinguishable from random covariations. Together with the mentioned synchronization through the instrumental calibration period, such "synthesis" figures automatically resemble a hockey-stick.

It was shown that the target area plays only a minor role. Furthermore, if type and processing of proxies are sufficiently even, coherent reconstructions are produced. If that is true in general, the main source of reconstruction inconsistency is the use of mixed types of proxies ("multi-proxies"), and their role for temperature reconstruction should be revised. One should systematically check whether "uni"-proxy reconstructions tend to be more coherent than multi-proxy reconstructions, and if so, which types of proxies actually create the inconsistencies.

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Table 1. The ten reconstructions used in this study, with target season and proxy type.

Symbol	Reference	Season	Proxies
Br00	Briffa, 2000	Summer	trees
dA06	d'Arrigo et al., 2006	Annual	trees
Es02	Esper et al., 2002	Annual	trees
MJ03	Mann and Jones, 2003	Annual	multi-proxy
Mo05	Moberg et al., 2005	Annual	multi-proxy
CL00	Crowley and Lowery, 2000	Annual	multi-proxy
Jo98	Jones et al., 1998	Summer	multi-proxy
Ma08L	Mann et al., 2008	Annual	multi-proxy
Ma08	Mann et al., 2008	Annual	multi-proxy
Ma99	Mann et al., 1999	Annual	multi-proxy

Table 2. Mutual coherence κ between millennial (1000 to 1850) reconstructions, averaged over frequencies ≥ 5y. Significant values (κ ≥0.47 as the 99% level) are highlighted.

$\overline{\kappa}$	Br00	dA06	Es02	MJ03	Mo05	CL00	Jo98	Ma08L	Ma08	Ma99
Br00	1									
dA06	**0.65**	1								
Es02	**0.55**	**0.6**	1							
MJ03	0.4	0.38	0.44	1						
Mo95	0.46	0.41	0.42	**0.54**	1					
CL00	0.38	0.35	0.31	0.32	0.33	1				
Jo98	0.42	0.4	0.36	0.31	0.27	**0.54**	1			
Ma08L	0.3	0.28	0.22	0.35	0.31	0.28	0.25	1		
Ma08	0.42	0.36	0.36	**0.48**	0.42	0.32	0.27	**0.48**	1	
Ma99	0.37	0.34	0.38	0.38	0.31	0.34	0.44	0.26	0.3	1

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Table 3. Target area for reconstructions.

	Br00	dA06	Es02	MJ03	Mo05	CL00	Jo98	Ma08L	Ma08	Ma99
NH				■	■			■	■	■
NH extratropics	■	■	■			■	■			
land + sea				■	■	■	■		■	■
land	■	■	■					■		

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Table 4. Coherence between target areas as simulated by ECHO-G Erik.

$\overline{\kappa}$	NH	NH extratropics
land + sea	0.93	0.89
land	0.90	0.91

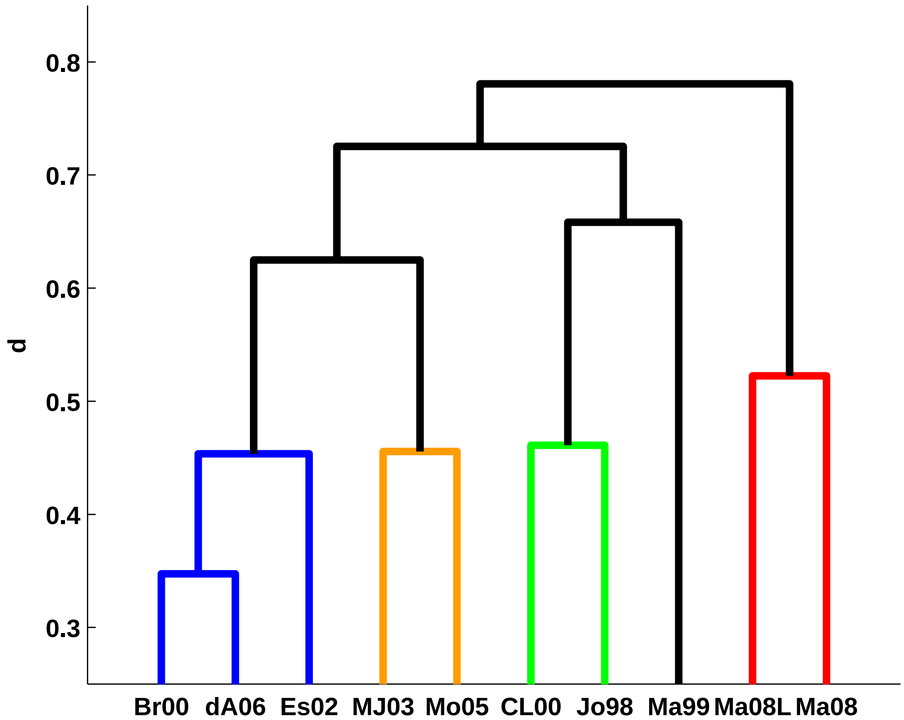

Fig. 1. Dendrogram of reconstructions, with distance metric d based on coherence κ (see text). Each node immediately below the 99% significance level of d=0.525 corresponds to a significant cluster, signified by the coloring.

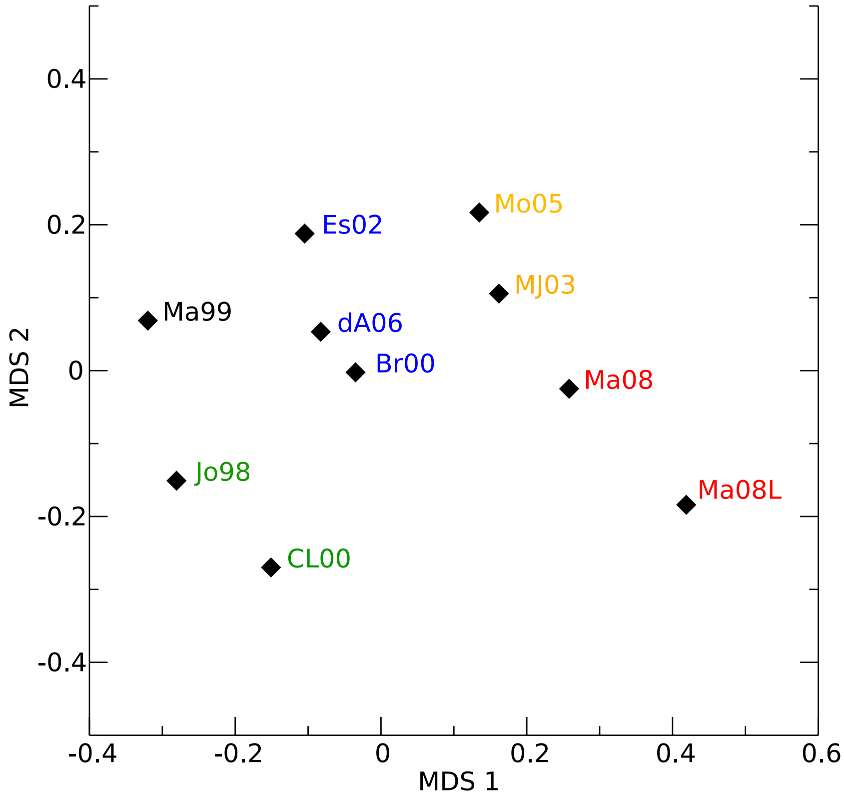

Fig. 2. MDS image of the ten climate reconstructions, based on mutual coherence. The five colors represent the five inconsistent clusters, {Br00, Es02, dA06} (blue), {MJ03, Mo05} (orange), {CL00, Jo98} (green), {Ma08L, Ma08} (red), and {Ma99} (black).

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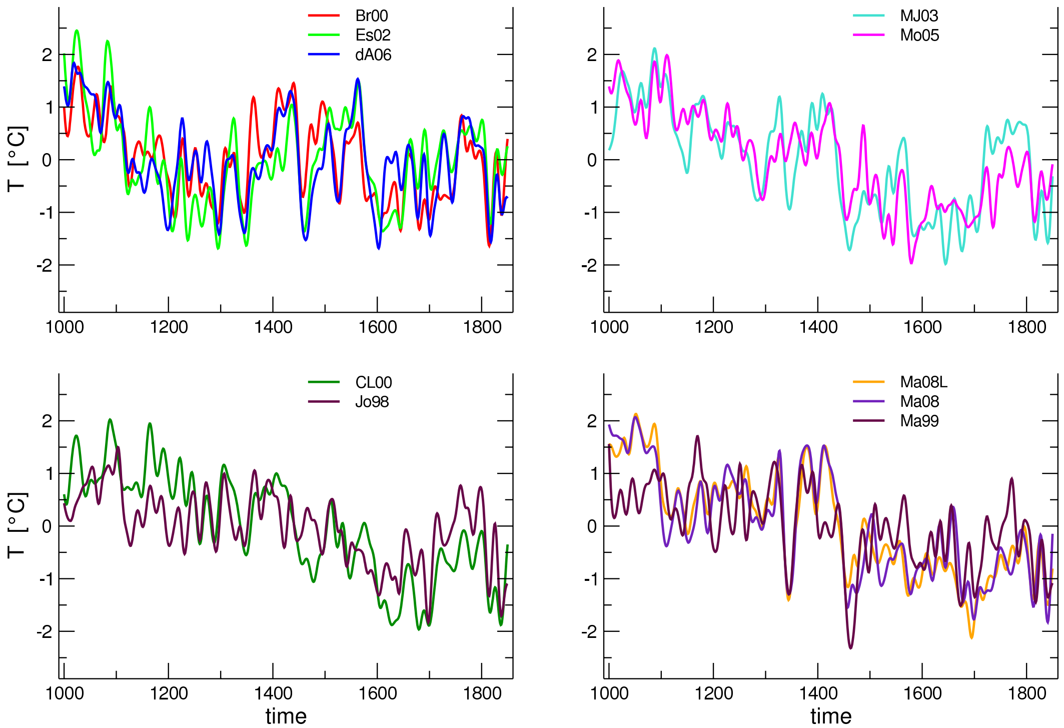

Fig. 3. The five clusters of reconstructions (smoothed).

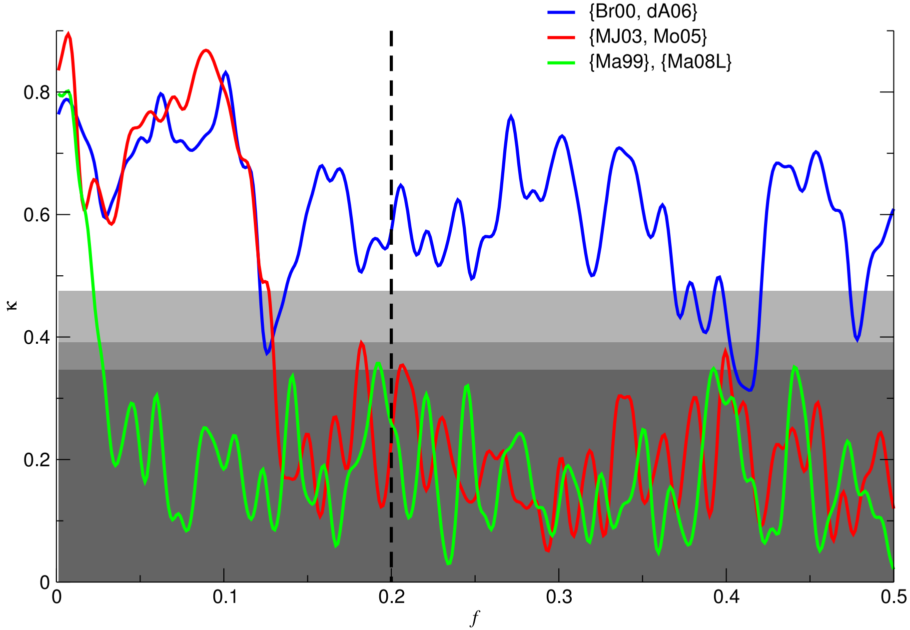

Fig. 4. Intra- and inter-cluster coherence spectrum (smoothed). The gray areas mark, from dark to light gray, the 90%, 95%, and 99% significance level. The vertical dashed line indicates the frequency threshold below which reconstructions are compared for clustering.

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