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Discussions

Interactive comment on "Natural periodicities and north–south hemispheres connection of fast temperature changes during the last glacial period: EPICA and NGRIP revisited" *by* T. Alberti et al.

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First of all, we would like to thank the two Referees for their insightful comments.

Introductory remarks

Before giving our answers to all the points raised by the Referees, it is worth to remark that, following the suggestions of Referee #1, we have carried out again our analysis on a longer time interval (20 – 120 kyr BP) of more recent versions of the EDML

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(EPICA community members, 2006, 2010; Bazin et al, 2013) and NGRIP (NorthGRIP community members, 2004; Bazin et al, 2013) δ^{18}O data, both synchronised using the more recent AICC2012 age scale (Veres et al., 2013; Bazin et al., 2013). The results obtained using the new, longer time series are similar to those shown in the first version of the paper and this represents, in our opinion, an indication of the robustness of our results which are improved by the application to the longer time series. If it will be asked to us to submit a revised version, we will use in it the results obtained by performing our analysis on the new data-sets. In order to briefly illustrate these updated results, we include to this reply a few figures which refer to the analysis of the new data-sets.

In Fig. 1 the results of the EMD significance test performed on the IMFs of the new data-sets are reported. The two plots show the normalized IMF square amplitude E_j vs. period T_j for the EMD significance test applied to the EDML (upper panel) and NGRIP (lower panel) IMFs. The dashed lines represent the 99th percentile spread function line. 15 and 17 IMFs are obtained for the new EDML and NGRIP data-sets respectively. More IMFs are obtained with respect to the first version, as the new data-sets have more points and cover a longer time interval. The significant modes are $j = 5 - 14$ and $j = 4 - 16$ for the EDML and NGRIP data respectively.

The dynamics of the DO events is reconstructed by the sum of the $j = 6 - 10$ NGRIP IMFs (which have characteristic periods between 0.7 kyr and 3.3 kyr), while the modes $j = 11-16$ are used for reconstructing the longer time scale evolution. For EDML, using the same characteristic period range as NGRIP (0.7 – 3.3 kyr) the modes $j = 5-8$ are used to reconstruct the short time scale dynamics, and the $j = 9 - 14$ modes are thus used for the long time scale reconstruction. In Fig. 2 the δ^{18}O original data (black lines), the short time scale (red lines) and the long time scale (blue lines) reconstructions are shown for the EDML (upper panel) and NGRIP (lower panel) data-sets. An offset corresponding to the temporal mean of the δ^{18}O original data was applied to the IMF sums to allow visualization in the same plot.

Fig. 3 displays the potentials $U(z)$ calculated from the new data (black curves and error

bars) using the method described in the paper and polynomial best fits (red dashed curves) for NGRIP reconstructions at short (panel a) and long (panel c) time scales, and for EDML reconstructions at short (panel b) and long (panel d) time scales. It is worth to remark that the potentials show the same qualitative behaviour as those calculated in the first version of the paper.

The cross correlation coefficients between EDML and NGRIP short time-scale (top panel) and long time-scale (bottom panel) EMD reconstructions are shown in Fig. 4. Similarly to the results of the first version of the paper the cross correlation coefficient between the short time scale reconstructions displays oscillations with many peaks of comparable amplitude at both negative and positive lags. Therefore, in this case it is not possible to identify the leading and the following signal. On the other hand, a clear correlation peak, with a maximum value of ≈ 0.73 is found in the cross correlation coefficient between the long time scale reconstructions at a lag of $\Delta = 3.05 \pm 0.19$ kyr, with the EDML signal leading that of NGRIP. This result is again similar to that obtained from the analysis of old data. It should be noted that using the new data, the correlation is even clearer than with previous data, as a single peak is found, moreover we also developed, motivated by one of the Referee # 2 comments, a procedure by which we were able to estimate an uncertainty (0.19 kyr) on the correlation lag (see below replies to Referee # 2 major content issues number 4 and 11).

The answers to all the Referees' comments are given below.

Reply to Referee #1

Replies to major points:

1. We agree with the Referee that the relation of our results with bipolar seesaw models should be considered. In particular, our cross-correlation analysis shows

a clear positive correlation peak at a lag of $\Delta \approx 3$ kyr, with the Antarctic leading with respect to Greenland, when long time scale reconstructions are used. It should be noted that using the new data, the correlation is even clearer than with previous data, as a single peak is found. It is worth to remark that no clear correlations lags are identified using the short time scale reconstructions associated with the DO occurrence. Therefore, the EMD filtering procedure is able to identify dynamical features of the climate evolution at different timescales which have not been underlined in previous works. As explained in more detail in point 7 we think that while a direct comparison with previous bipolar seesaw models (Stocker 2003, Barker 2011) is not possible at this stage, the long time scale dynamics and the associated correlation found through our analysis could be explained by building up specifig seesaw models more focused on the study of the long time scale range.

Concerning the Referee's question "Lead-lag analysis on the kyr-time scale therefore needs to define exactly, which points of the records in the north and south are analysed, ..." we remark that the correlation was calculated using all the points of the short and long time scale reconstructions obtained from the EMD decomposition of the original time series.

We cannot answer to the following Referee's comment, since probably some words are missing at the beginning of the sentence, making it unclear: "is a global signal, there exisit an interhemispheric gradient, but rapid changes in should be seen at the same time in both hemispheres.".

The above discussion and a brief outline of the main points of the papers about seesaw models suggested by the Referee will be included in the new version of the paper.

2. As suggested by the Referee, we have considerably extended the analysed time series to the interval between 20 and 120 kyr BP. We consider this interval (excluding the present interglacial $0 - 20$ kyr BP) since this is the interval in which

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significant temperature changes, that are the focus of the present work, are ob-
served.

3. We followed the suggestion of the Referee and performed again our analysis
using the more recent AICC2012 age scale (Veres et al., 2013; Bazin et al., 2013)
both for EDML (EPICA community members, 2006, 2010; Bazin et al, 2013) and
NGRIP (NorthGRIP community members, 2004; Bazin et al, 2013) data-sets (see
also the introductory remarks).

4. We agree with the Referee that is questionable to report an EMD mode periodicity
comparable to the length of the time series. We will indicate only periods which
are sufficiently shorter than the time series length in the revised version of the
paper.

5. We agree with the Referee that we should have discarded the 1st EMD mode
for EPICA, but we included it because it lays almost on the spread function line.
Anyway, in performing again our analysis on the new, longer data-sets we applied
rigorously the significance criterion and considered only the modes above the
spread function line (see the introductory remarks and Fig. 1).

6. We will follow the Referee's suggestion and will replace "EPICA" with "EDML"
throughout the text in the revised version of the paper.

7. According to the Referee's suggestion we will add references to the more recent
papers about lead-lag analysis (Barker et al. 2011; Veres et al. 2013).

Concerning the meaningfulness of our method and the role of the bipolar seesaw,
we remark that our correlation analysis is based on the EMD decomposition of
empirical data-sets referring to Antarctic and Greenland. Therefore, in our opin-
ion, the question is not if our method is meaningful but, rather, if our results about
the correlation between the EDML and NGRIP signals could be explained in the
framework of bipolar seesaw models. About this last issue, as already pointed

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out above in point 1, we think that the long time scale dynamics and the associated correlation found through our analysis could be explained in the framework of seesaw models. But, since the correlation lag ($\approx$ 3 kyr) obtained from our analysis is quite different from the characteristic thermal timescale (about $1 - 1.5$ kyr) of previous bipolar seesaw models (Stocker 2003, Barker 2011) it would be necessary to build up a thermal seesaw model starting from our EMD filterd long time scale series to properly investigate the question raised by the Referee.

8. According to the Referee's suggestion we will move the mathematical descriptions about the Kernel Density Estimator and the corresponding uncertainty (equations (12)-(16)) to an appendix.

9. The use of empirical EMD functions, characterised by time-dependent amplitude and phase, allows to overcome some limitations of Fourier analysis. Fourier analysis requires linear systems and periodic or stationary data, and its application to non-linear, non-stationary data can produce misleading results for the following reasons.

a) The Fourier uniform harmonic components do not carry local information: many components are needed to build up a solution that corresponds to non-stationary data thus resulting in a energy spreading over a wide frequency range. As a consequence the energy/frequency distribution of non-linear and non-stationary data is not accurate.

b) Fourier spectral analysis uses linear superposition of sinusoidal functions, thus several components are mixed together in order to reproduce deformed waveforms, local variations, or the fictitious periodic boundary conditions imposed by the analysis.

c) Sinusoidal functions are usually far from being eigenfunctions of the phenomenon under study for non-linear/non-stationary data.

In these situations, when the data are far to be periodic, linear and stationary, an empirical decomposition such as the EMD provides a better description of the analysed phenomenon.

We will add this discussion to the revised version of the article.

Replies to minor points:

1. We will correct the indications of the ranges in the data-sets, as requested by the Referee.

2. The offset applied to the IMF sums in Fig. 5 of the paper is the temporal mean of the original time series and is added to the IMF sums in order to superimpose the corresponding curves to the original data and allow better visualization in the same plot. We will clarify this in the new version.

Reply to Referee #2

Replies to major content issues:

1. The issue about the justification of the use of the EMD formalism, especially compared to the Fourier analysis, was raised by the Referee #1 too. Our reply can be found above (see reply to Referee #1 major point number 9). As already stated previously, we will add this more detailed justification to the revised version.

2. We thank the Referee for letting us know about the paper by Solé et al. (2007a). Our results are not directly comparable to those of Solè et al. (2007a) for the following reasons. First of all they used different data-sets: GRIP δ^{18}O 100 kyr BP series, Vostok δD (deuterium) 400 kyr BP series, and EPICA δD (deuterium) 741

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kyr BP series. Moreover, they changed the sampling of the series (200 years for GRIP, 500 years for Vostok, and 3000 years for EPICA) before applying the EMD. Therefore, their results about oscillation patterns periodicities are related to larger time scales with respect to ours. Concerning the analysis, they directly compared single IMFs of different data-sets, by calculating phase differences in order to find common oscillation patterns between the data-sets. Conversely, we used the EMD as a filter, obtaining reconstructions by summing more IMFs, in order to separate the dynamics of DO events from the longer time scale evolution. When using reconstructions with more IMFs, of course it is not possible to calculate phase differences and the comparison is more properly performed by correlation analysis. Notwithstanding a direct comparison is not possible, in the new version of the paper we will reference the work by Solè et al. (2007a) as a previous application of EMD to ice core data.

3. In the first version of the paper it was not stated that "there is a constant resolution of 50 yr for both data sets", but it was specified that 100-yr and 50-yr averages were availabe for the EPICA and NGRIP data-sets respectively. Anyway, as suggested by Referee #1 (see the introductory remarks and our replies to her/his major points number 2 and 3), we performed again our analysis on longer data sets, synchronised on the more recent AICC2012 age scale (Veres et al., 2013; Bazin et al., 2013). These new data are not given with a constant time resolution and will be used for the new version of the article.

4. In the data files used for the first version of the paper there were no errors available. In the new data-sets the error on the age scale is available (Bazin et al., 2013). As far as the error propagation by the EMD method is concerned, this is not a trivial issue, since we are not aware about any discussion of the error propagation by the EMD in previous works. However, in order to test the robustness of our analysis, and especially the cross correlation results, we developed the following procedure. We used the error on the age scale to perform a Monte-

carlo algorithm in order to estimate the time error on the two reconstructions performed with the EMD. More specifically, we calculated 10^3 realizations of the long time-scale reconstructions varying randomly the age scale position of each data point within the error windows. Then, we calculated the corresponding 10^3 cross-correlations between the EDML and NGRIP long time-scale reconstructions and the peak positions for each of them. Following this procedure we obtained an estimate of ≈ 190 yr for the error on the position of the long time-scale cross correlation peak.

We will include the description of this procedure and of its results in the new version of the paper.

5. We agree with the Referee. In some cases, when local frequencies are too close, it happens that single IMFs consist of signals at different scales. This phenomelogy is well known as "mode mixing effect". As correctly stated by the Referee this is not crucial in our analysis, since we considered signal obtained by adding IMFs ranging in a wide range of timescales. According with the Referee's suggestion we will add to the paper a comment about the mode mixing in the IMFs.

6. In the new version of the paper, we will follow the Referee's suggestion by adding some material about the physical basis of the DO events and the difference between DO and Heinrich events. We will also add the suggested references (Broecker 1994; Burroughs 1992; Solé et al. 2007b).

7. As the Referee correctly understood, the Langevin model is actually used to ascertain the kind of climatic state transition which can be associated with temperature changes. Concerning the notation, $N(t)$ and $S(t)$ on page 1135 Eqs. (4)-(7), in the revised version it will be clarified that $N(t)$ (North) refers to NGRIP and $S(t)$ (South) to EPICA-EDML.

8. In order to calculate the error on $U(z)$, we first estimate the empirical probability density function (pdf) p_{emp} through the Kernel Density Estimator and the boot-

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strap procedure described in Section 4 (Eqs. (12)-(16)). We then use these estimates to perform error propagation in Eq. (11) to obtain the errors on $U(z)$. This will be specified in the text of the new version. We remark that the part of Section 4 between Eqs. (12)-(16) will be moved to an appendix by following the suggestion in point 8 by the Referee # 1.

9. We used the potential analysis developed by Livina at al. (2010), but following a different approach. More specifically, we performed the potential analysis on the EMD reconstructions of the EDML and NGRIP data-sets, using, in the new analysis, the time range 20–120 kyr BP. Livina et al. (2010) used only Greenland data-sets, in particular they considered the GRIP and NGRIP $\delta^{18}O$ series in the interval 0–60 kyr.

   Moreover we calculated the potential shape from the full time range of the EMD reconstructions, while they used sliding windows of varying length through each data-set to detect the number of climate states as a function of time.

   We will highlight these differences in the new version of the paper.

10. According to the Referee's suggestion, we will include in the new version of the paper some discussion about the possible physical mechanisms which could produce the observed correlation lag. In particular, we will mention the possible role of the Thermohaline Circulation (THC), the Antarctic Meridional Overturning Circulation (AMOC), and, following also the comments of Referee #1, the thermal bipolar seesaw mechanism.

11. As already discussed in point 4, we developed an ad hoc procedure in order to test the robustness of our cross correlation analysis with respect to the errors on the age scale.

Replies to major organization issues:

1. We will reorganize the paper by following the Referee's suggestions. In details, Section 2 and Section 3 will be combined in a single section and the present Section 3 "Empirical Mode Decomposition results" will be a subsection of the new (combined) Section 2 which will be entitled "Datasets and Empirical Mode Decomposition Analysis". A brief description of the paper organization will be added at the end of the Introduction.

2. With the reorganization described in the previous point, the main aims of the paper will be clearer. Furthermore, we will add a paragraph, at the end of the Introduction, explaining the two main aims of the paper.

3. From the methodological point of view, the main novelty is represented by the fact that we use EMD reconstructions to investigate the climate dynamics at different time scales and to highlight, through a potential analysis of the EMD reconstructions, some characteristics of the climate transitions. Conceptually, the main novelty are: 1) the presence of two different climate transitions occurring at different time scales; 2) the finding of a significant correlation between long time scale Antarctic and Greenland signals, with the first leading the second, at a lag of $\approx$ 3 kyr which was not found in previous works.

   We will extend the last Section of the paper, which will be entitled "Discussion and conclusions", by including a discussion part as suggested by the Referee, in order to clarify which are the main novelties of our work.

Replies to minor questions:

1. We will correct the typos indicated by the Referee.

2. The offset applied to the IMF sums in Fig. 5 of the paper is the temporal mean of the original time series and is added to the IMF sums in order to superimpose

the corresponding curves to the original data and allow better visualization in the same plot.

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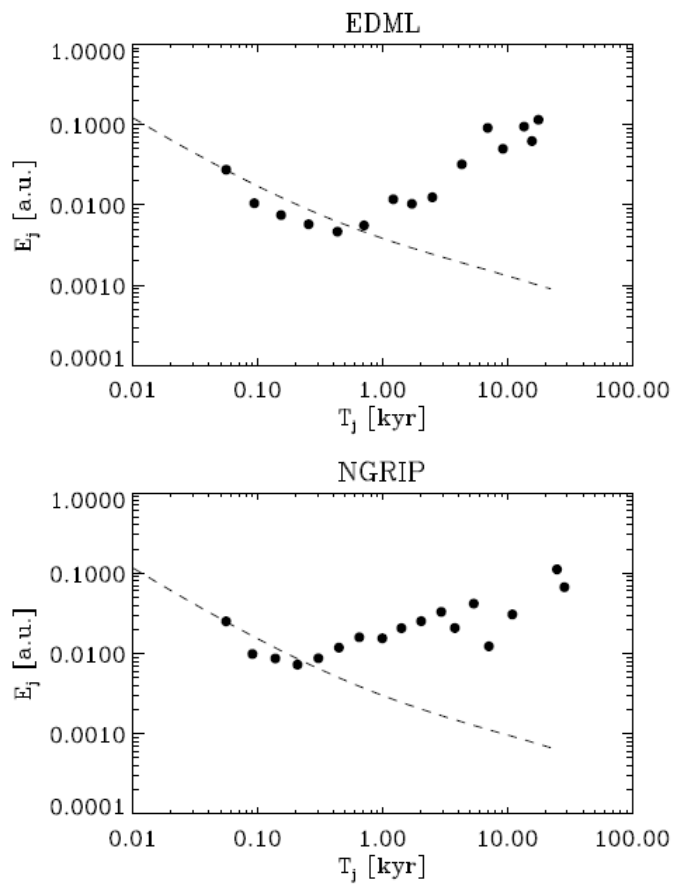
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Fig. 1. Results of the EMD significance test performed on the EDML (upper panel) and NGRIP (lower panel) IMFs (see text).
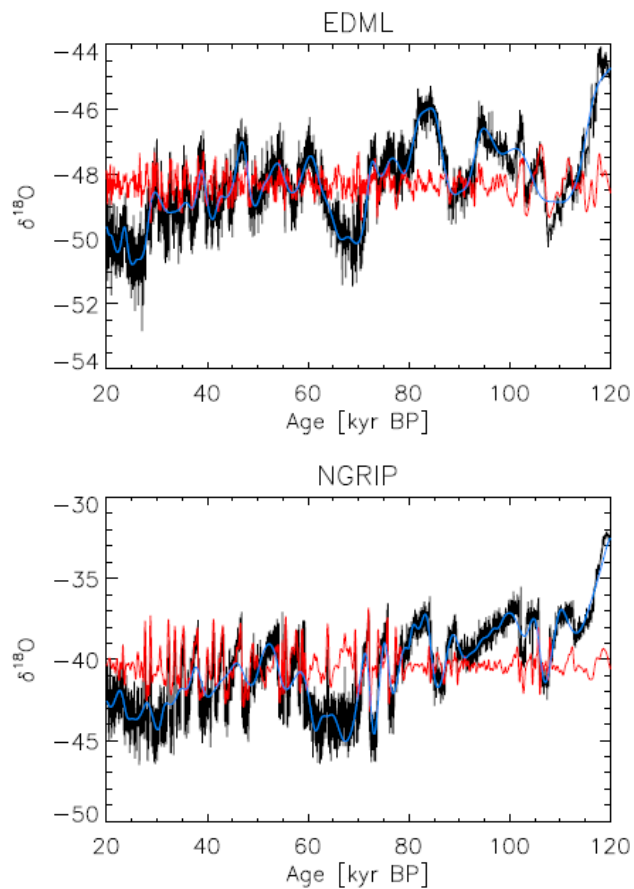
Fig. 2. Delta-O-18 data (black lines), short time scale (red lines) and long time scale (blue lines) reconstructions for the EDML (upper panel) and NGRIP (lower panel) data-sets.
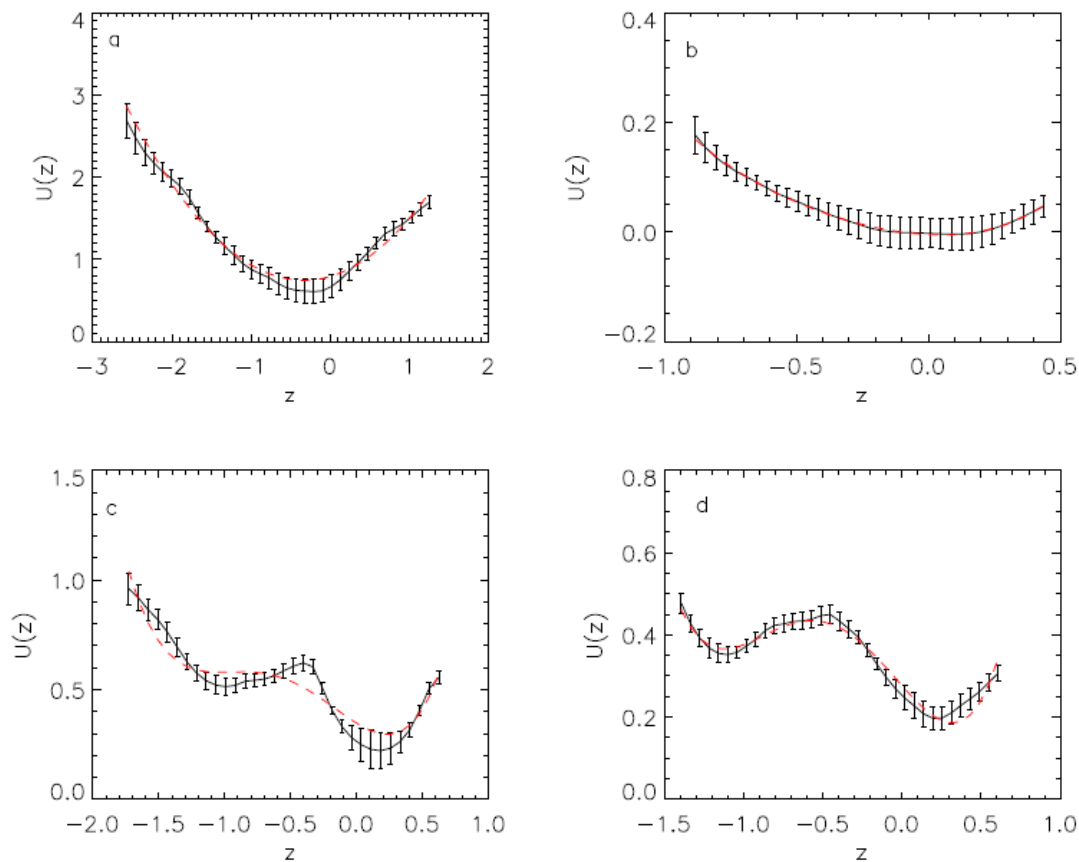
Fig. 3. Potentials U(z) calculated from the data (black curves and error bars) and polynomial best fits (red dashed curves) for NGRIP (panels a and c) and EDML (panels b and d) reconstructions (see text).
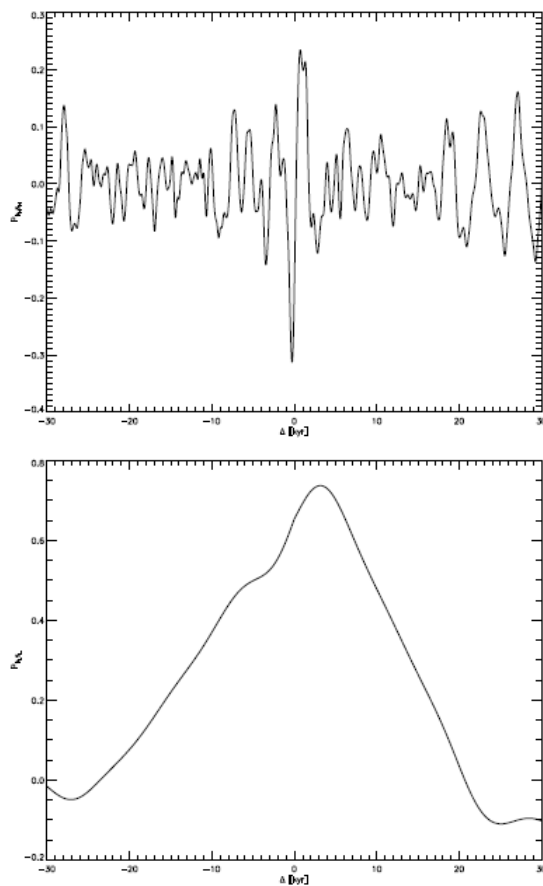
Fig. 4. Cross correlation coefficients between EDML and NGRIP short time-scale (top panel) and long time-scale (bottom panel) EMD reconstructions.