Author Comment - N.J. de Winter et al. – 16 Januari 2014

Dear Climate of the Past Editorial Board, dear Reviewers,

We thank Nicholas Thibault and Fabienne Giraud very much for their thoughtful review of our manuscript.

Nicholas Thibault's major points of criticism are the following:

Stratigraphic constraints. We agree that the discussion of the magneto-and biostratigraphy is an important part of the context of our study that we did not address it enough in the previous version. The addition of stratigraphic constraints does not lead to any significant change in the main content and outcome of our manuscript, but inclusion of the constraints does provide independent support for our interpretation.

We include the magneto- and bio-stratigraphic constraints of DSDP Site 516F where available. Note that the magnetobiostratigraphy was also mentioned by Park et al. (1993) in their references/footnotes. We further included a paragraph on the remarkable cyclostratigraphic study of Herbert and d'Hondt (1990) of deep-sea cores of late Cretaceous to early Paleogene age from the South Atlantic, including cores 87 to 110 from Site 516, using digitized sediment color as proxy for carbonate content. All their records reveal a dominant precession control, and the short ~100-kyr eccentricity cycle is often expressed by bundling of 4-6 precession related cycles. These patterns are very similar to the ones observed in the color and MS records of the longer interval that we studied, and support our interpretation of the precession and eccentricity related variations.

We would like to add a paragraph like the following to an improved manuscript:

"Part of the upper Cretaceous at Site 516F was subjected to a detailed cyclostratigraphic study by Herbert and d'Hondt (1990), which revealed the influence of precession and eccentricity. To study sub-Milankovitch climate variability, Park et al. (1993) selected the interval between 1145 and 1166 meters below seafloor (mbsf). This interval was placed by Weiss (1983) in the *Globotruncana arca* and *G. ventricosa* Zones, based on the successive first occurrences (FO) of the nominate species. He positioned the Campanian base at the *G. arca* FO, but this boundary is now provisionally placed at the bottom of C33r in GTS2012 (Ogg and Hinnov, 2012). In the meantime the planktonic foraminiferal biozonal scheme has been significantly modified (Petrizzo et al., 2011; Ogg and Hinnov, 2012), largely because of the marked diachronous nature of events such as the *G. ventricosa* FO (Petrizzo et al., 2011). The magnetostratigraphy of the Upper Cretaceous at Site 516F was studied by Hamilton and Suzyumov (1983). Based on the common identification of the Cretaceous/Paleogene boundary, they showed that the magnetic polarity sequence identified at Site 516F could be correlated to the magnetostratigraphy of the Gubbio section of Alvarez et al. (1977). This correlation shows that the succession ranges from Chron 34 to 29 and that the interval studied by Park et al. (1993) falls within C33r and belongs to the early Campanian. At that time, Site 516 was located at a paleolatitude of ~ 30° S, and the South Atlantic Ocean was a smaller, much more confined ocean basin than at present."

Significance levels. We added significance envelops to the Blackman-Tukey spectra as suggested (see revised Figure C1 and C2 below). Further, we compute Lomb Scargle periodograms (Figure C5) and corresponding significance levels using the REDFIT software (Schulz and Mudelsee 2002), and also plot a wavelet analysis (Figure C4) with confidence levels (using the software of Torrence and Compo 1998). According to the Lomb-Scargle peridogram, main spectral peaks of the precession and sub-Milankovitch cyclicity (0.16 m period) are significant at the 80% level, which is often used in paleoclimatic studies. Further, wavelet analysis shows significant spectral features in this period range locally (see Figure C4). The peaks in the ~100-kyr eccentricity band are statistically not significant at the 80% CL (Figure C5), but this is not surprising as the eccentricity influence most likely stems from the eccentricity modulation of the precession amplitude, reason why eccentricity does not show up in a precession spectrum, but enters the record mainly through non-linear responses, as also outlined by Park et al. (1993). The eccentricity influence is, however, visible in the L* wavelet spectrum that we include here (Figure C4); around 1154 m significant spectral power in the eccentricity band (> 2m period) is present. Further confidence for the existence of the spectral periods of 22, 50, 90, 160 and 250 cm come from band pass filtering, filters match the pattern seen in the proxy data well (see figures 1 and 5 of the original manuscript) suggesting a nonrandom relationship. Because of the good fit between filters and proxy data we are confident that cycles in the (a*, L*) records are really present, despite the relatively low significance of the corresponding spectral peak (see revised figures C1 and C2).

As records are investigated in depth and not in time, all techniques for TIME series analysis have to be taken with caution, as changing sedimentation rates will unavoidably lead to less distinctive and thus significant spectral peaks.

Length of records. As far as the length of the records is concerned we mainly followed the Park et al. (1993) paper as we would like to compare our results with theirs. The longer MS record covers ~750 kyr, which is long enough to test and portray the short eccentricity, obliquity and precession related cycles, although it is admittedly short for eccentricity related variations. The combined shorter intervals contain 20 to 30 semi-precession and Heinrich-frequency band cycles, which is sufficient for statistical analysis. Moreover these intervals were selected by Park et al. (1993) as they reveal the sub-Milankovitch variability best. We refrained from extending the length of the records, also because our cyclostratigraphic interpretation is now independently supported by including the information from magnetobiostratigraphic constraints and the cyclostratigraphic study of Herbert and d'Hondt (1990) of deep marine cores from the upper Cretaceous to lower Paleogene of the South Atlantic; the addition of this confirmation makes the results of our study much less hypothetical than in the original manuscript.

Further, upward extension of the record is complicated by the lack of recovery of DSDP Site 516F, core 111 (Barker et al., 1983), while cores 110 up to 89 were included in the cyclostratigraphic study of Herbert and d'Hondt (1990) that is consistent with our interpretation as far as the dominance of precession and eccentricity in terms of Milankovitch control is concerned. In addition, visual inspection revealed that the sub-Milankovitch (0.16 m) cycles that are the main subject of the present study and that of Park et al. (1993) are nearly absent in cores 110 to 89 (Barker et al., 1983; Herbert and D'Hondt, 1990).

<u>**Detailed comments**</u>:

Title. We prefer to stick to the wording Heinrich frequency band; we deliberately avoided using the terms Heinrich cycles and Heinrich events as we would like to have a provocative title to attract the attention of the paleoclimate community that studies true Heinrich cycles/events at the young Quaternary end of the time scale. In our opinion this usage is justified as we do suggest that the origin of Heinrich cycles may lie with precession forcing at low latitudes (i.e., between the tropics) that operates independently from ice ages.

Results. Magnetostratigraphic constraints have been added and independently confirm our cyclostratigraphic interpretation (see also above).

Issues with cyclostratigraphy:

Sub-Milankovitch variability. The sub-Milankovitch cycles are manifested in the spectra of the long records (Figures C1, C4 and C5). The shorter intervals were selected for further study and for comparison with the results of Park et al. (1993), because they reveal the sub-Milankovitch variations best. As usually, confidence envelopes are calculated for Blackman Tukey powerspectra, we include these (revised Figures C1 and C2), and also Lomb-Scarle periodograms with confidence levels (Figure C5). Further, we applied wavelet analysis with significance levels (Torrence and Compo 1998) in addition to the power spectra to 1) confirm the sub-Milankovitch variability 2) obtain a strong validation of the existence of the eccentricity related cyclicity.

Beside the visible observation of the data, also wavelet analysis (Figure C4) shows that the most significant short term variations (here interpreted to represent sub-Milankovitch-variability) occur from ~1151-1156 m depth. The short selected intervals are long enough to portray the sub-Milankovitch cyclicity as the associated spectral peaks are significant at least locally in the wavelet analysis, and partly also for the whole data set (see Figure C4). As stated above, also the match between the filters and data are strong support for a nonrandom relationship between filtered periods/frequencies and data.

Depth to time conversion. We would like to refrain from including a depth to time conversion in the figures directly, as this is valuable information but not the topic of the manuscript. Further, and depth to time conversion would rely on a cyclostratigraphic interpretation. We include the magnetobiostratigraphic constraints; biostratigraphic constraints (Weiss, 1983) in a text section dealing with the straitigraphical context (see main comment # 1 above). The outcome of the wavelet analysis does not indicate significant changes in sedimentation rate. The inferred obliquity cyclicity in a* could indeed have been used for this purpose, but the interpretation of this cycle may be subject to debate. An alternative approach would be to assign ~20 kyr to each of the precession related cycles in the short intervals, but again it is our impression that this will not add much to the outcome of our ms.

Additional remarks:
We did not have the intention to provide a complete list of papers that detected sub-Milankovitch in the Mesozoic and Paleozoic in the reference list. However, we do not mind to include these in the discussion of a revised manuscript. We agree that this may contribute to the context in which our manuscript is placed, and would follow this suggestion.

The following is in response to Fabienne Giraud's comments:

Figures. In response to the comments by Fabienne Giraud we had a critical look at the composition of our figures. We agree that there has been a mistake in the inclusion of supplementary figures A1 and A2, resulting in them being similar. We will change figure A1 so it matches its caption (see revised figure C3 below).

The reason why figure 3 and figures A1 and A2 are similar is that figures A1 and A2 are supplementary figures and contain records that are not discussed in the text (Si and Ca). We excluded these records from figure 3 to make the figure more straight-forward to interpret.

We agree that the power spectra of Al and Ti/Al in figure 4 need better discussion. These power spectra were added to show differences in the expression of cycles in Ti and Al, which are indicators for different terrestrial fluxes, and therefore serve as illustration in the discussion whether the sub-Milankovitch cycles are quadruplets.

As mentioned above, significance levels are included for the Blackman Tukey spectrum figures (C1 and C2, see below).

Comments and response:

1. "In the methods, please explain your choices for the point moving average applied to the raw records."
   In the methods part, it is suggested to explain the choice for the smoothing (point moving average) of the record.

- This is a helpful comment to make our manuscript more clear. Our choice of the moving average smoothing is intended to smooth the record somewhat, but to keep the important features in the record. Depending on the proxy and purpose the window size of the running average is adjusted.

2. "In the figure 1, you draw the raw L record but also the point moving average applied to the records. When you make your comments, please define which record you speak about, because it's really not clear."
   Fabienne Giraud points out that it is not always clear if we refer to the records itself or the smoothed records.

- Also this is a fair point; in the revised manuscript we clarify this for every record we refer to. In the methods and results, we will add more careful explanations of the point moving averages discussed, including why specific pma's are included in the discussion.

3. "On the raw record (L) I cannot see the minima at more or less 50 cm, and when looking for this cycle in the L*10 record, I can see it in some parts of the record, but I'm not agree that there is a well-defined minima of the 50 cm cycle. More or less well defined between 1145 and 1151 and between 1159 and 1163 cm."
   It is noted that the minima at about 50 cm are not always seen in the raw records, but are only clear from 1145-1151 and 1159 and 1163 cm.

- We agree that the ~50 cm cycle is easier distinguished in the 10 pma of L*, which is why we include this point moving average in figure 1A. We think that the 50 cm cycle is still very much present in the interval between 1151 m and 1159 m. The reason why it might be less clearly distinguished is that the 0.16 m cycle is expressed in this interval, causing three minima per 50 cm cycle. The 10 pma is therefore less prone to pick up one peak per 50 cm cycle.

4. “Can you please define what you call bundles and then bundles 3-5?”
   The meaning of the term “bundles” is unclear.

- With bundles of 3 to 5 minima we mean to describe how, in the record, groups of 3 to 5 minima in L* are observed with more space between the groups than between minima within the groups. This is an important point that we can clarify. In the revised manuscript we highlight these bundles in a supplementary figure (Figure A1 and A2).

5. “I just can see minima from 1152 to 1156.”
   It is noted that the minima in L* can only be observed in the interval between 1152 and 1156 mcd.

- We agree that the minima in this interval are best developed, but all intervals named in the text are characterized by bundles of distinct minima in L*. In a revised manuscript we can highlight these minima, e.g. in a supplementary figure similar to figure 1A.

6. “Values decrease from 1159 to 1162, and it seems to me clear.”
   Fabienne Giraud comments on the incorrect way the sentence on lines 3 and 4 of page 7 is formulated.

- This sentence indeed may require more careful formulation. With this sentence we mean to express that no distinct cyclicity is observed in this interval of the a* record. We rephrase this sentence to “The uppermost interval of the a* record is marked by decreasing values and less obvious cyclic variations” to make this clear.

7. “Your spectra, especially for a, show that the sampling frequency is not sufficient as you can see an increase of your spectrum towards the values of 0.33.”
   It is noted that our powerspectra show that our sampling density is insufficient for out discussion.

- We do not agree that the power spectrum for a* shows that our sampling frequency is insufficient. Confidence intervals will are included to the figures to illustrate this. Further, we used filters of the discussed frequencies/periods to demonstrate the real existence of these frequencies/periods by comparing data to filters.

8. “Can you please add the confidence interval for both spectra.”

- We supply confidence envelopes for the Blackman Tukey method (revised figures C1 and C2) and also include Lomb Scargle spectra (Figure C5) and wavelet plots (Figure C4).

9. “What is the resolution of the measurements for the short records? It is indicated for long records (1.5 cm) but not for shorter records. Is it the same?”

- The short records were measured at the same resolution as the long records. We will add a note of this to our revised manuscript. Further, we will make data openly accessible after publication.

10. “after the comments of Fig. 3

    A comment is made on the order in which figures are discussed in the Results section.

- Figure 3 is named here to allow for comparison between the magnetic susceptibility record and its Blackman-Tukey spectrum. Also, Figure 3 is introduced here to allow for comparison between magnetic susceptibility and elemental abundance, which is important in section 4.2 of the manuscript.

11. “Difficult to see the higher frequency variations!”

    It is noted that the higher frequency variations are difficult to observe the higher frequency variations in the figures provided.

- The higher frequency cycles are indicated in Figure 3 by vertical lines, and are quite visible in the figures in our opinion. As mentioned above, this may have not been clear enough in the previous manuscript version.

12. “The comments are not clear and really difficult to follow when reading the figures! No comments about the spectra of Ti/al and Al presented in figure 4?”

    It is correctly noted that Figure 4 needs more careful discussion.

- See above, in the “Figures”-paragraph; we agree that figure 4 needs more careful discussion.

13. “I do not understand the differences between figs 3 and A2; only Ca and SI are new in A2; for the rest it's the same with a different caption! What is surprising is L. In both figures, it is called L (5pma) but it 's not the same record on the figure!”
14. “What is the difference between Figs. A1 and A2? I do not see any differences between these two figures except the caption.”

    Both these comments indicate that there is confusion over the difference between Figure 3 and Figures A1 and A2.

- See ´Figures” paragraph: Figure A1 will be revised (see Figure C3 below) and Figure 3 is indeed a simplified version of the figures A1 and A2. However, L* (5 pma) is the same record in all figures, the L* axis is reversed in figures A1 and A2 while it is not reversed in Fig. 3.

15. “It is the first time you speak about the 2.5 m cycle : why in the discussion and not in the results?”

- The 2.5 m cycle in L* is described in the results. (p. 7, line 10)

16. “Sediment color is in part correlated with sediment composition. What is your interpretation concerning L and a?”

    A question is raised about the depositional origin of out L* and a* signals. This comment is very helpful, and we agree that some discussion about the origin of the color signals will improve our manuscript.

- The L* data correlates inversely with the magnetic susceptibility and most elemental abundance data (see Fig. 3 of the original manuscript, see also Giosan et al., 2002). Therefore lightness (L*) data can be interpreted as a proxy for the concentration of non-carbonate and non-silica matter (exported from the water column) representing terrestrial input. The redness (a*) data may represent the hematite content, but this is speculative. The a* data lack the high frequency sub-Milankovitch variability, therefore this proxy has a different and not as straight forward origin as the L*.

A publication by Giosan et al. (2002) points out that, as our data suggests, the brightness of the sediment is correlated to the carbonate content of the sediment. The hue (shown in part by the a* index) of the sediment is determined predominantly by the hematite content of the sediment and the relative abundance of Fe^{2+} and Fe^{3+} in clay minerals (Giosan et al., 2002).

17. "There are recent studies showing that the Early to Mid Campanian represented a major transition in deep-ocean history and circulation, with the establishment of a new mode of circulation dominated by southern component water. I think that an accurate consideration of the paleoceanography of the Atlantic for this time period must be taken into account. See papers of Robinson et al (2010) in geological society of America, Robinson and Vance (2012) in paleoceanography, Martin et al (2012) EPSL..."

- In a revised manuscript version we will provide a more detailed discussion of the paleoceanography and climate of the Late Cretaceous and their influence on the L* and a* signals. The suggestions of useful publications in Fabienne Giraud's comments will prove very helpful in writing this paragraph on paleoceanography.

  However, according to the Drilling Report (Barker et al., 1983), Park et al. (1993) and our observations there is no reason to assume a major change in depositional environment occurred during the time interval studied in this research.

To be added in the manuscript:

As suggested, we included Lomb-Scargle spectra (figure C5) and wavelet spectra (figure C4) for the L* and a* of the longer interval. Especially the L* wavelet spectrum reveals the expression of short eccentricity as power maxima in the precession frequency band. We did not add amplitude spectrograms as these do not provide much extra information in addition to the Blackman Tukey, Lomb-Scargle and wavelet spectra.

Methods:

We use wavelet analysis including a significance test was applied using the software provided by C. Torrence and G. Compo, this software is available at URL: http://paos.colorado.edu/research/wavelets/. See Torrence & Compo, 1998 for a description of the methods behind the program used. Prior to wavelet analysis, data were detrended and normalized using a Morlet mother wavelet. Power spectra were generated using the Redfit program (Schulz & Mudelsee 2002, version 3.8e) based on the (bias-corrected) Lomb-Scargle Fourier transform. A Welch window is used. Results for the confidence levels are based on 1000 simulations.

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Revised Figures:

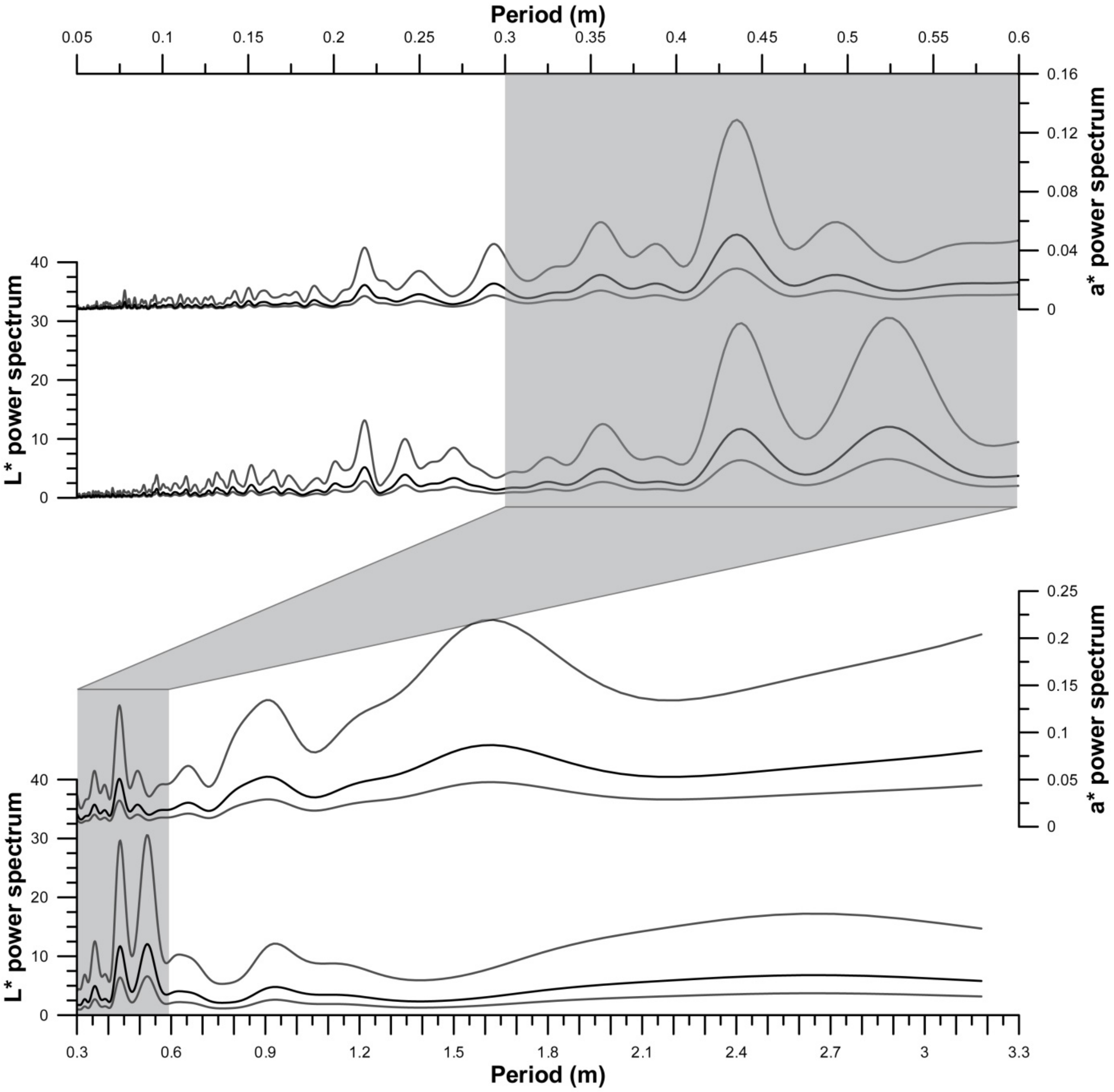
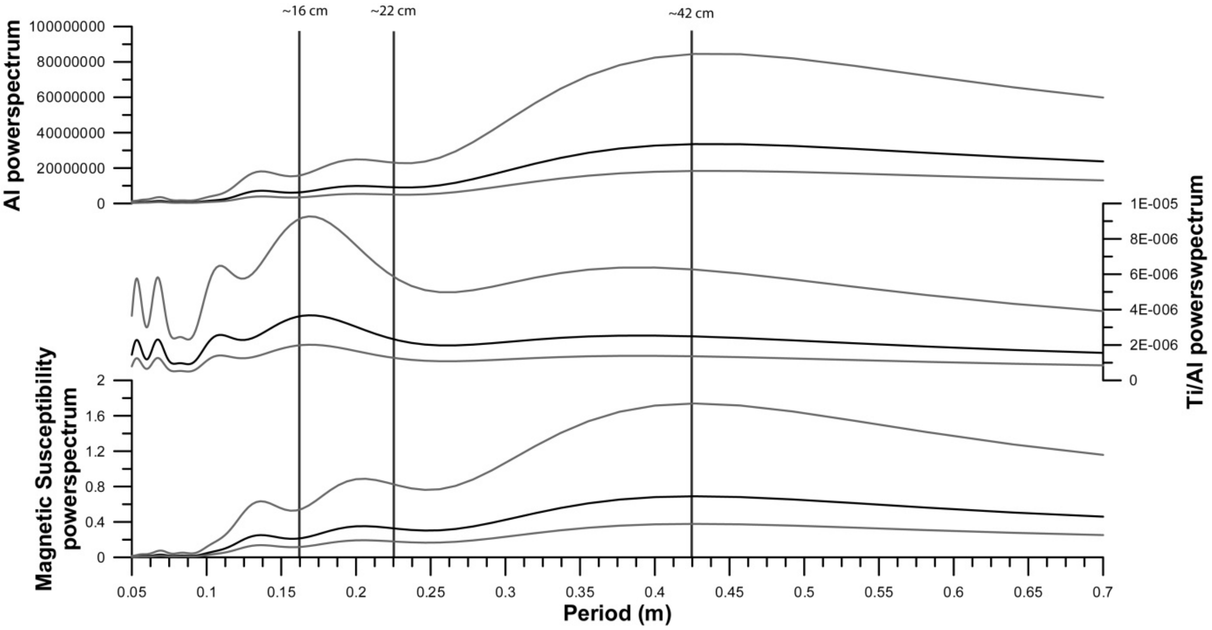
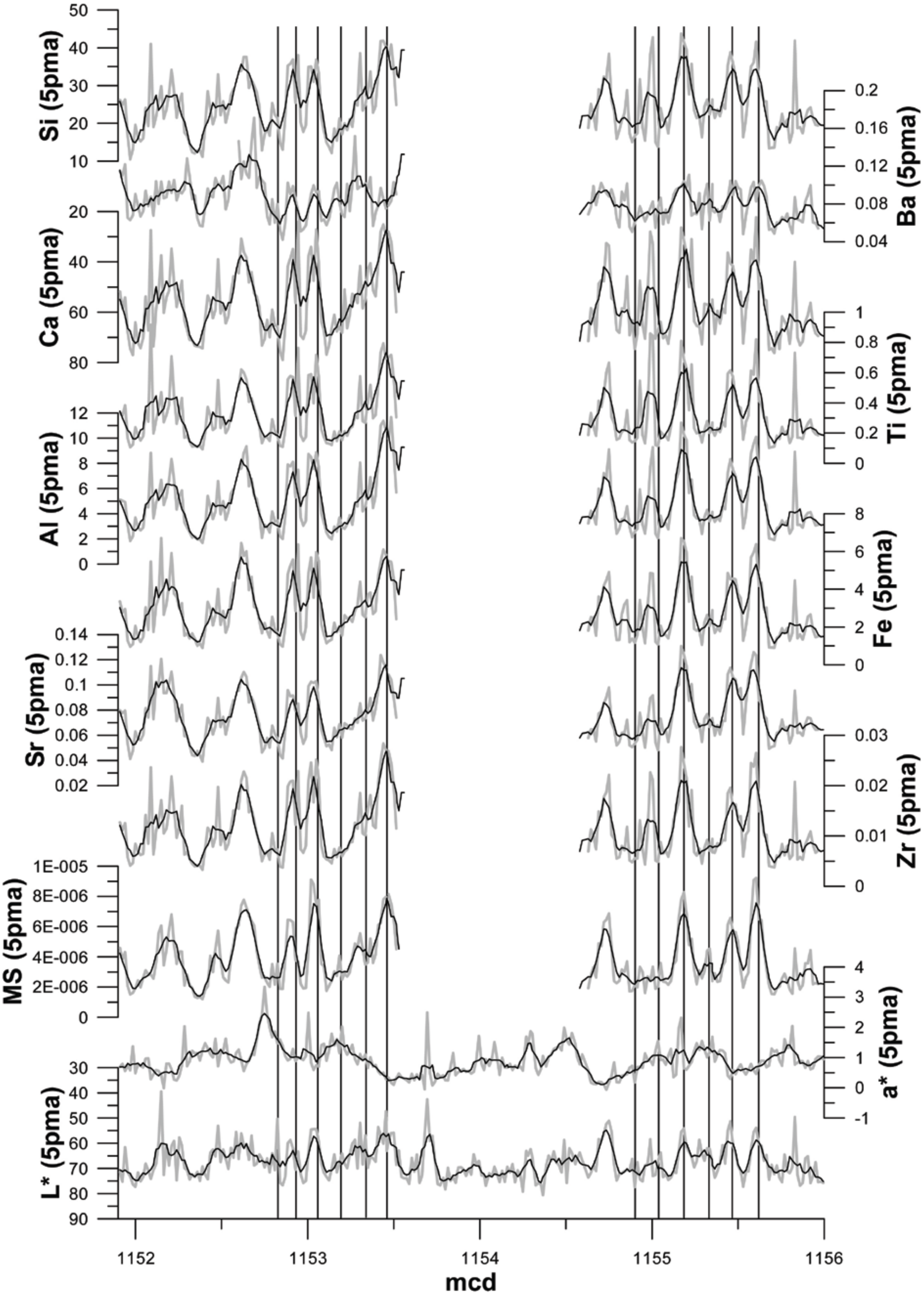


Figure C1: Blackman-Tukey powerspectra of L* and a* with 90% confidence level upper and lower boundaries (After Figure 2 in original manuscript).



Revised Figure C2: Blackman-Tukey powerspectra of magnetic susceptibility, Ti/Al and Al with 90% confidence upper and lower boundaries (After Figure 4 in the original manuscript).



Revised Figure C3: L*, a*, magnetic susceptibility and all XRF elemental abundances with 5 point moving averages plotted against composite depth (After Figure A1 in the original manuscript).

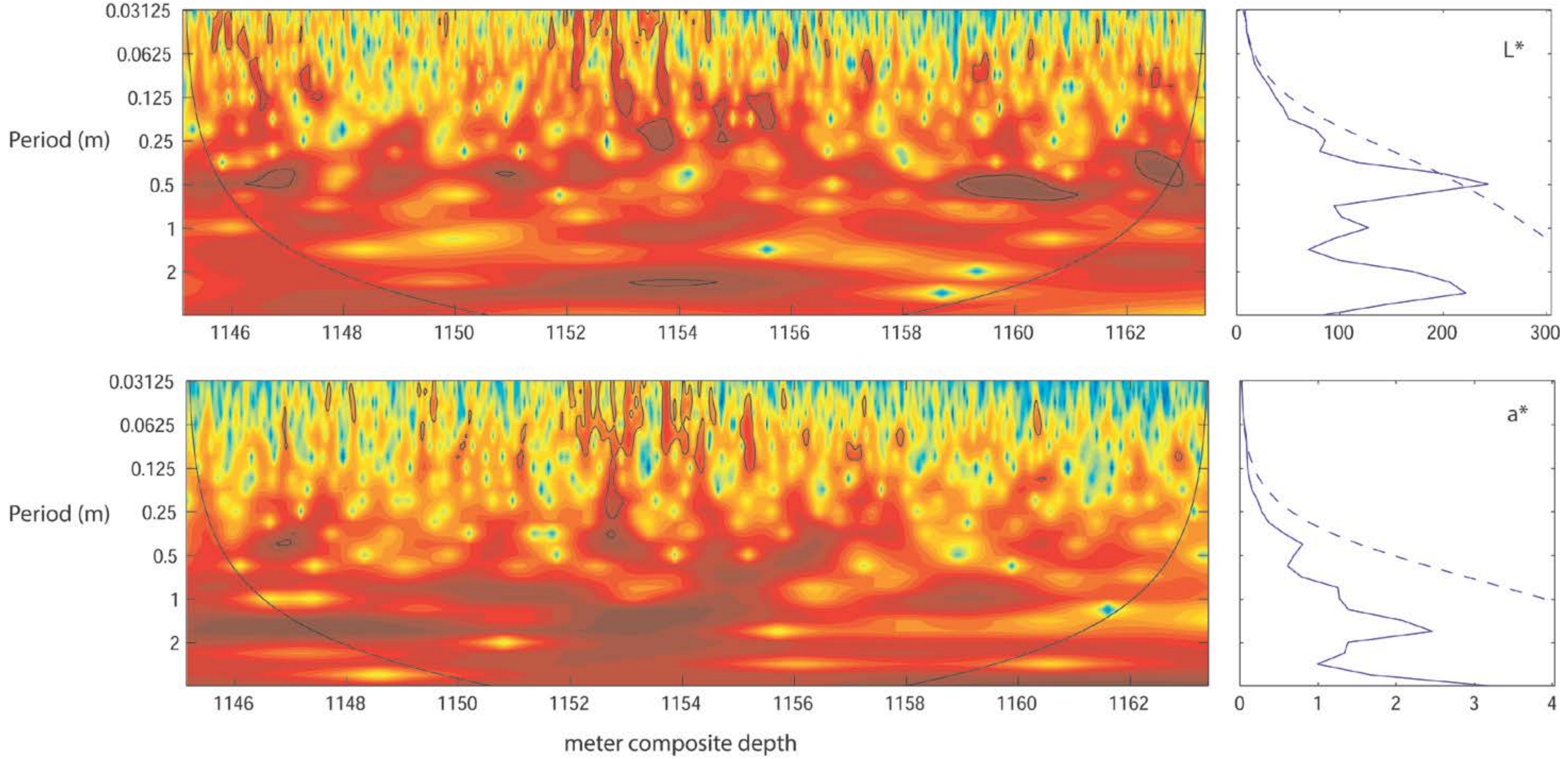


Figure C4: Wavelet plots of the long record of L* and a* showing the confidence of cyclicity per period

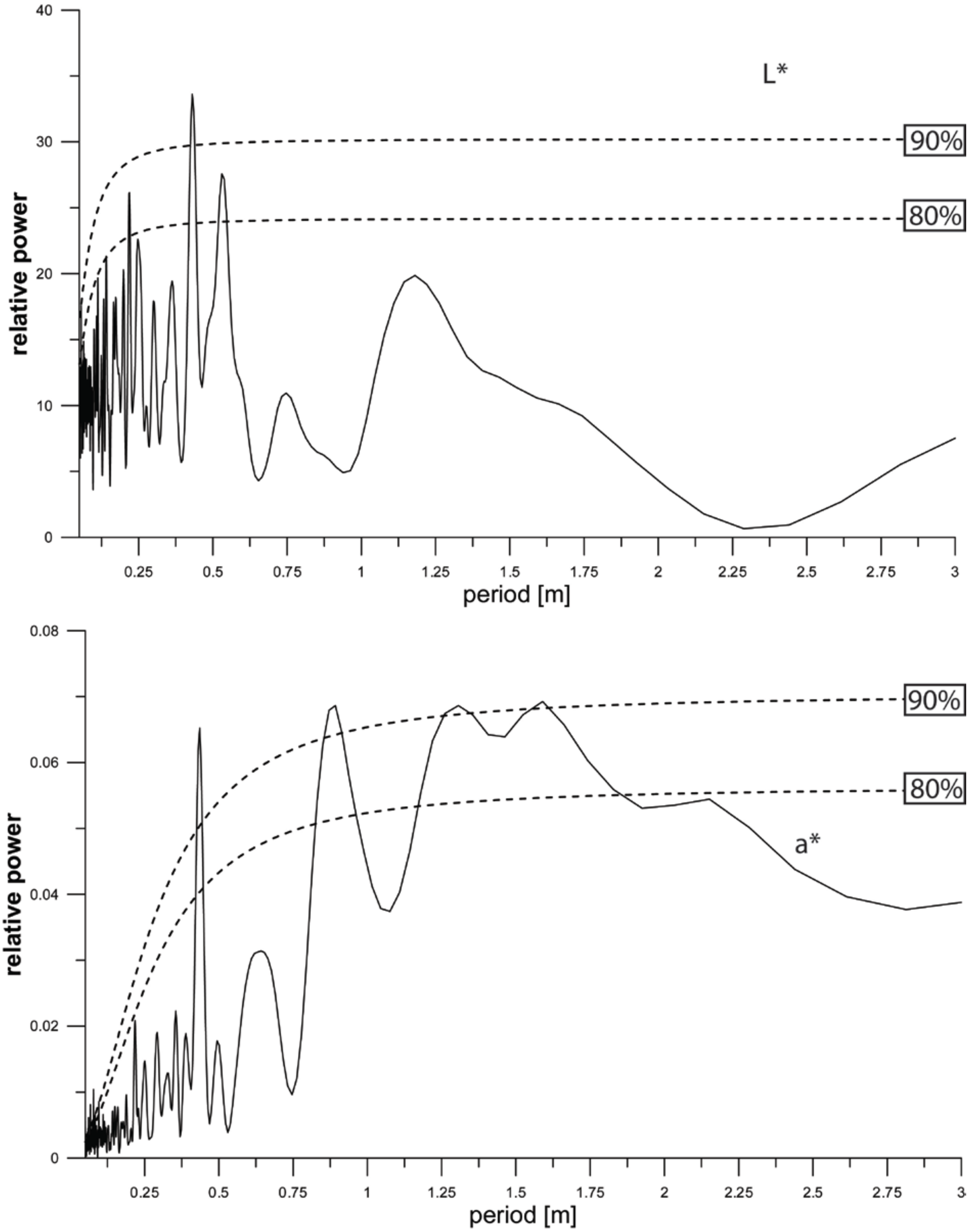


Figure C5: Lomb-Scargle periodogram of L* and a* long records including 80% and 90% confidence levels