Centennial to millennial variability of greenhouse climate
across the mid-Cenomanian event

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S1. Background of the studied interval

The age model of the studied interval (141 to 146 m of the Iona-1 core, ~96.42 to 96.83 Ma; Figure DR2) in the MCE is determined by the study of Eldrett et al., (2015a,b) through cyclostratigraphic study combined with high resolution zircon U-Pb isotopic dating. The carbon isotope study demonstrates that 141 to 144 m interval is during the MCE whereas 144-146 m is within 200 k.y. before the MCE (Figure DR2). The studied interval consists of marl and limestone couplets that are influenced by precession (Eldrett et al., 2015a,b). The Alpha Method (Ma et al., 2020) was developed to determine the time distribution in different facies by assuming that the (compacted) sedimentation accumulation rates (SRs) are facies dependent. Then the SRs can be calculated by comparing to the frequency modulation of the precession in the astronomical model. The SRs for the marl and limestone in the studied interval are shown in Table DR1 and Figure DR2b.

Grayscale data (Figure DR2e) for the studied interval is extracted from core-slab photographs of the Iona-1 core (Figure DR2d). The bentonite layers (red bars in Figure DR2c) are removed from the data before analysis since they represent nearly instantaneous events that should be excluded. See Eldrett et al. (2015a, 2015b) for additional details on the grayscale analyses.

S2. Time series analysis of the grayscale of the marls

A consistent cycle of ~2 mm is shown in the time series analyses of marls M1-M3 and M6-M10 (Figure DR3, Table DR2). M4 and M5 are excluded because of potential hiatuses in these two marls (Ma et al., 2020). All of these frequencies achieve a significance level of >99.5% (M1, M2, M7-10) and >99% (M3, M6) in harmonic F-testing. The significance level of the of ~2 mm component in M6
is lower than 95%, due to increased noise/signal ratio compared to other marls. In M2, M6, M7, M8 and M9, components around ~2 mm are in a narrow band, ranging from 1.98 to 2.36 mm. The ~2 mm component in M1, M3 and M10 ranges from 1.83 to 2.57 mm; this may be caused by a relatively large variation in the thickness of the laminae pairs. The otherwise consistent ~2.1 mm component in these 8 marlstone beds is comparable to the average thickness of the laminae pairs in each marl (Table DR1), which suggests a similar origin of the laminae pairs and similar sedimentation rates across the 8 marls and M11. Based on the time represented by the marls (Table DR1), the time for the ~2-mm component is ~200-year that is similar to the de Vries cycle. The cycles ranging from 0.7-1.1 mm in the marls (Figure DR3, Table DR2), may be associated with the ~70-100 year Gleissberg cycle.

S3. Micropaleontology

We provide here a detailed description of the micropaleontology observed limestones L12 and L11, and marlstone M11.

L12: Calcispheres (r-strategists) bloomed in oligo-mesotrophic, high temperature, high salinity, carbonate-rich ecosystems on Cretaceous shelves (Adams et al., 1967). Beds dominated by tightly-packed calcispheres (Figure DR5) are therefore interpreted as very carbonate-rich, shallow shelf environments with warm, euhaline, and meso-oligotrophic surface waters. These environments were likely relatively isolated, as true oceanic waters (lower temperature, salinity, and carbonate content) would have been adverse to calcisphere populations (Dias-Brito, 2000). The calcisphere assemblage is dominated by Pithonella sphaerica (mean = 86%) and Rotaliporids were commonly not observed, both of which are consistent with inner-middle neritic water depths (Dias-Brito, 2000).
M11: Whereas there are very fine-scale changes from bed to bed (described below), the overall section was likely a stressed, eutrophic setting with dysoxic to anoxic bottom waters in a relatively restricted marine basin. The high dominance of globular, surface-dwelling planktonics – particularly juveniles and Heterohelicids – with a nearly complete lack of benthic foraminifera and the consistent presence of sedimentary pyrite supports this interpretation and suggests that the Oxygen Minimum Zone (OMZ) was vertically expanded well up onto the shelf. Water depths were likely middle neritic throughout, with few beds showing signs of slightly deeper waters (middle-outer neritic) and more marine influence.

L11: There is a relatively sharp transition at top of M11 out of the “Black Shale” type environment back into a setting similar to the L12. Assemblages with tightly packed calcispheres are interpreted much the same – a very carbonate-rich, oligo-mesotrophic, shallow shelf environment with warm, high salinity surface waters. The calcisphere assemblage is dominated by P. sphaerica (mean = 81%) with only secondary Pithonella ovalis (mean = 19%) and two single specimens of Bonetocardiella conoidea. In conjunction with a near absence of rotaliporids, this suggests that water depths were relatively shallow in this section (inner-middle neritic), as they were in the basal limestone section.

The limestone layers (L11 and L12) are dominated by radiolarian and calcispheres, while M11 is dominated by planktonic foraminifera (Figure DR5). Beds with diverse assemblages of radiolaria, foraminifera, and calcispheres may represent intermittent incursions of marine surface waters and/or
regional upwelling events. Either of these scenarios would reduce carbonate productivity and surface water temperature and salinity, enhance primary productivity, and mobilize sedimentary silica, all of which would favor the development of mixed radiolarian/foraminifera populations and hinder calcsphere populations.

S3. Data availability

All data and code used in the analyses for this paper are openly available at:

https://github.com/Demerara/Ma2022Geology
Figure DR1. Paleogeographic map illustrating the plate tectonic framework and foreland basin setting of the Cretaceous (late Cenomanian) Western Interior Seaway (KWIS) at the margin of the subsiding Gulf of Mexico Carbonate Shelf (modified from Ron Blakey and the Colorado Plateau Geosystems Inc.). The gray lines show the present-day state boundaries of the United States. The red star indicates the location of the Iona-1 core. ETB: East Texas Basin; MB: Maverick Basin; SB: Sabinas Basin.
Figure DR2. Measurements for 141-146 m of the Iona-1 core. (a) Precession bandpass filter (rectangular window; 0.9-1.45 cycle/m) of the grayscale data from Eldrett et al. (2015b). (b) Reconstruction of sedimentation rates with the Alpha Method (Ma et al. 2020) for L1 to L12 and M1 to M11. (c) Lithology and sedimentological code. (d) Core photograph. (e) Grayscale data. Note: (a)-(e) share the same depth and age scale in (a); the age scale is estimated based on Eldrett et al. (2015a) and Ma et al. (2020) and is not linear. (f) Carbon isotope data (Eldrett et al., 2015a) of the Iona core from 42 to 153 m with shaded area showing the OAE2 and MCE events; dashed lines indicate the position of the limestone/marl couplets in (d).
Figure DR3. Spectral analysis of the grayscale stratigraphic series of M1-M3 and M6-M10. All the labeled significant frequencies (vertical dotted lines) have >99.5% (M1, M2, M7-10), >99% (M3, M6) F-test significance levels. These frequencies are listed in Table DR.2. In all panels, The X-axis is the frequency (cycle/mm), and the left Y-axis is the log power of the MTM spectrum (black curves); the right Y-axis is the F-test significance level (red).
Figure DR4. Thin section of the Iona-1 core (its position is in Figure DR6) showing two scales of dark and light laminae. Magnified views of dark and light laminae can be seen in a and b which are also labeled in the yellow boxes on the thin section at the left. The dark laminae (a) mainly consists of organic matter, a few smaller juvenile-sized foraminifera, and calcite and silica cements, whereas the light laminae (b) are dominated by globular planktic foraminifera with a mix of juveniles and larger adult Whiteinellids and Hedbergellids and cemented calcispheres.
Figure DR5. Summary distribution chart of key microfossil groups in L11-M11-L12 with the core photo. The horizontal white bars vs. gray bars across the figure represent the light calcite-rich laminae vs. the dark calcite-poor laminae. Four groups of microfossils are plotted in this figure: foraminifera (blue names, mostly planktonic), siliceous microfossils (pink names, mostly radiolarian), calcisphere (green name) and collophane (dark green name). The units are counts otherwise indicated as “%”.
**Figure DR6.** Above: XRF-derived element count rates taken at 230-micron spacings along the core, and reported in counts per second. Below: Continuous thin section image of M11 with a stratigraphic scale in mm. The time scale at the bottom is based on ‘Alpha method’ time scale modeling by Ma et al. (2020) relative to the 80 mm position. The vertical gray shading indicates dark laminae. The horizontal red bar shows the core location of the thin section photomicrograph in **Figure DR4** (left is the upward direction of the thin section).
Figure DR7. Cross plots and Pearson r values of the selected XRF scanning data for the M11 interval. Symbols: black laminae = black circles, white laminae = gray circles. These data highlight the differences between white and black laminae. The elements analyzed are plotted in cross plots vs. Ca, where Si, K, Ti, Cr, Fe, Zn, V, S and Zr show negative correlations with Ca, whereas Mn and Sr show positive correlations with Ca. Fe and S exhibit positive correlations with V and Ni.
Figure DR8. PCA analysis on the major elements shown in Figure DR6: (a) principal component loadings; (b) screeplot; (c) sample (black dots) and elemental loading (red arrows) biplot of PC1 versus PC2.
Figure DR9. Spectral analysis of the PC2 time series shown in Figure 1 of main text. The numbers indicate wavelength in thickness (mm). From the top: $2\pi$ multitaper power spectrum with AR(1) noise model and significance levels, $2\pi$ multitaper amplitude spectrum, and F-test significance spectrum, with dashed horizontal line indicating 99% significance, time series and FFT spectrogram (moving window is 20mm).
Figure DR10. Spectral analysis of the PC1 time series shown in Figure 1 of main text. The numbers indicate wavelength in thickness (mm). From the top: $2\pi$ multitaper power spectrum with AR(1) noise model and significance levels, $2\pi$ multitaper amplitude spectrum, and F-test significance spectrum, with dashed horizontal line indicating 99% significance, time series and FFT spectrogram (moving window is 20mm).
Figure DR11. Spectral analysis of the grayscale time series shown in Figure 1 of main text. The numbers indicate wavelength in thickness (mm). From the top: $2\pi$ multitaper power spectrum with AR(1) noise model and significance levels, $2\pi$ multitaper amplitude spectrum, and F-test significance spectrum, with dashed horizontal line indicating 99% significance, time series and FFT spectrogram (moving window is 20mm).
**Table DR1.** Statistics for the marls from 141-146 m in the Iona-1 core (M4 and M5 are excluded). E and G are determined by the Alpha Method in Ma et al. (2020). F is calculated by E/C*1000.

| A  | B            | C            | D            | E                | F          | G            |
|----|--------------|--------------|--------------|------------------|------------|--------------|
| Marls | Thickness of marls (mm) | Number of laminae pairs in marls | Average thickness of laminae pairs (mm) | Durations of the marls (k.y.) | Time for each lamina pairs (year) | Sedimentation rate (cm/k.y.) |
| M1  | 344.41       | 160          | 2.15         | 40.691           | 255        | 0.85         |
| M2  | 561.63       | 260          | 2.16         | 63.073           | 243        | 0.89         |
| M3  | 183.52       | 81           | 2.27         | 21.501           | 266        | 0.85         |
| M6  | 175.21       | 80           | 2.19         | 18.614           | 233        | 0.94         |
| M7  | 233.84       | 105          | 2.24         | 24.085           | 230        | 0.97         |
| M8  | 537.86       | 257          | 2.10         | 58.878           | 229        | 0.91         |
| M9  | 151.66       | 68           | 2.22         | 16.641           | 243        | 0.91         |
| M10 | 165.51       | 85           | 1.96         | 16.751           | 198        | 0.99         |
| M11 | 192.52       | 90           | 2.14         | 18.933           | 210        | 1.02         |
Table DR2. Significant spectral peaks in the grayscale series of M1 - M3 and M6 - M10.

|     | M1             | M2             | M3             | M6             | M7             |
|-----|----------------|----------------|----------------|----------------|----------------|
|     | Period (mm)    | Period (year)  | Period (mm)    | Period (year)  | Period (mm)    | Period (year)  | Period (mm)    | Period (year)  |
| 215.26 | 25325          | 8.24           | 925            | 9.98           | 1174           | 5.52           | 587            | 7.90           | 815            |
| 1.75  | 206            | 3.78           | 425            | 2.45           | 289            | 1.77           | 188            | 4.09           | 422            |
| 1.53  | 181            | 3.67           | 412            | 2.35           | 276            | 1.10           | 117            | 2.27           | 234            |
| 1.37  | 161            | 2.82           | 317            | 2.16           | 254            | 0.90           | 96             | 1.89           | 194            |
| 1.30  | 153            | 2.32           | 261            | 1.12           | 131            | 0.81           | 86             | 1.39           | 144            |
| 0.91  | 107            | 1.98           | 222            | 1.09           | 129            | 0.71           | 76             | 1.16           | 120            |
| 0.84  | 99             | 1.42           | 159            | 0.90           | 105            | 0.70           | 75             | 1.04           | 107            |
| 0.83  | 98             | 0.71           | 79             | 0.51           | 60             | 0.50           | 53             | 0.70           | 72             |
| 0.83  | 97             | 0.69           | 78             |                |                | 0.69           | 72             |                |                |
| 0.82  | 97             | 0.69           | 77             |                |                |                |                |                |                |
| 0.72  | 85             | 0.68           | 76             |                |                |                |                |                |                |
| 0.72  | 85             | 0.62           | 69             |                |                |                |                |                |                |
| 0.62  |                | 69             |                |                |                |                |                |                |                |
| 0.52  |                | 59             |                |                |                |                |                |                |                |

|     | M8             | M9             | M10            |
|-----|----------------|----------------|----------------|
|     | Period (mm)    | Period (year)  | Period (mm)    |
| 20.07 | 2205           | 2.16           | 208            |
| 7.41 | 814            | 0.89           | 98             |
| 2.35 | 258            | 0.51           | 56             |
| 1.99 | 218            |                |                |
| 1.41 | 155            |                |                |
| 1.32 | 145            |                |                |
| 1.30 | 143            |                |                |
| 1.12 | 123            |                |                |
| 1.08 | 119            |                |                |
| 1.07 | 117            |                |                |
| 1.01 | 110            |                |                |
| 0.92 | 101            |                |                |
| 0.92 | 101            |                |                |
| 0.91 | 100            |                |                |
| 0.90 | 99             |                |                |
| 0.79 | 87             |                |                |
| 0.56 | 61             |                |                |
| 0.46 | 51             |                |                |
References

Adams, T.D., Khalili, M. and Said, A.K. 1967. Stratigraphic significance of some oligosteginid assemblages from Lurestan Province, northwest Iran. Micropaleontology, 13, 55-67.

Dias-Brito, D., 2000. Global stratigraphy, palaeobiogeography and palaeoecology of Albian–Maastrichtian pithonellid calcispheres: impact on Tethys configuration. Cretaceous Research, 21: 315-349.

Eldrett, J. S., Ma, C., Bergman, S. C., Lutz, B., Gregory, F. J., Dodsworth, P., Phipps, M., Hardas, P., Minisini, D., Ozkan, A., Ramezani, J., Bowring, S. A., Kamo, S. L., Ferguson, K., Macaulay, C., and Kelly, A. E., 2015a. An astronomically calibrated stratigraphy of the Cenomanian, Turonian and earliest Coniacian from the Cretaceous Western Interior Seaway, USA: Implications for global chronostratigraphy: Cretaceous Research, 56, 316-344.

Eldrett, J. S., Ma, C., Bergman, S. C., Ozkan, A., Minisini, D., Lutz, B., Jackett, S.-J., Macaulay, C., and Kelly, A. E., 2015b. Origin of limestone–marlstone cycles: astronomic forcing of organic-rich sedimentary rocks from the Cenomanian to early Coniacian of the Cretaceous Western Interior Seaway, USA: Earth and Planetary Science Letters, 423, 98-113.

Ma, C., Meyers, S.R., Hinnov, L.A., Eldrett, J.S., Bergman, S.C., Minisini, D., 2020. A method to decipher the time distribution in astronomically forced sedimentary couplets: Marine and Petroleum Geology, 118, 104399.