Clim. Past Discuss., 11, 5049–5071, 2015 www.clim-past-discuss.net/11/5049/2015/ doi:10.5194/cpd-11-5049-2015 © Author(s) 2015. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Climate of the Past (CP). Please refer to the corresponding final paper in CP if available.

Late Cretaceous (Late Campanian– Maastrichtian) sea surface temperature record of the Boreal Chalk Sea

N. Thibault¹, R. Harlou¹, N. H. Schovsbo², L. Stemmerik³, and F. Surlyk¹

¹Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark

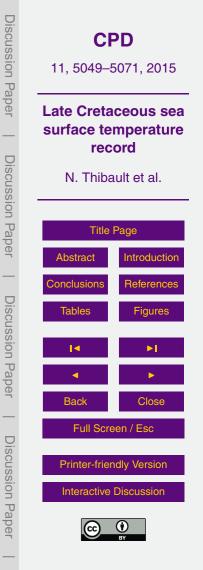
²Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350 Copenhagen K, Denmark

³Statens Naturhistoriske Museum, University of Copenhagen, Øster Voldgade 5–7, 1350 Copenhagen K, Denmark

Received: 26 September 2015 - Accepted: 16 October 2015 - Published: 3 November 2015

Correspondence to: N. Thibault (nt@ign.ku.dk)

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



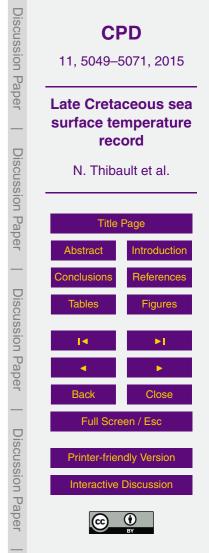
Abstract

The last 8 Myr of the Cretaceous greenhouse interval were characterized by a progressive global cooling with superimposed cool/warm fluctuations. The mechanisms responsible for these climatic fluctuations remain a source of debate that can only be resolved through multi-disciplinary studies and better time constraints. For the first time, we present a record of very high-resolution (ca. 4.5 kyr) sea-surface temperature (SST) changes from the Boreal epicontinental Chalk Sea (Stevns-1 core, Denmark), tied to an astronomical time scale of the late Campanian–Maastrichtian (74 to 66 Myr). Well-preserved bulk stable isotope trends and calcareous nannofossil palaeoecological patterns from the fully cored Stevns-1 borehole show marked changes in SSTs.

- These variations correlate with deep-water records of climate change from the tropical South Atlantic and Pacific oceans but differ greatly from the climate variations of the North Atlantic. We demonstrate that the onset and end of the early Maastrichtian cooling and of the large negative Campanian–Maastrichtian boundary carbon isotope
- excursion are coincident in the Chalk Sea. The direct link between SSTs and δ^{13} C variations in the Chalk Sea reassesses long-term glacio-eustasy as the potential driver of carbon isotope and climatic variations in the Maastrichtian.

1 Introduction

Superimposed on the long-term cooling trend of the latest Cretaceous, two benthic
 foraminiferal positive oxygen isotope excursions have been documented in the early and late Maastrichtian at low and mid-latitudes of the North and South Atlantic, Indian Ocean and central Pacific (Barrera and Savin, 1999; Friedrich et al., 2009). These positive excursions, which likely reflect bottom water cooling, have been tentatively correlated to 3rd order sea-level falls and associated with changes in the mode and direction of thermohaline oceanic circulation, possibly caused by the build-up of small ephemeral Antarctic ice sheets (Barrera and Savin, 1999; Miller et al., 1999). Alterna-



tively, these climatic changes have been associated with shifts in the source of deep water formation from low to southern high latitudes, linked to the opening of deep-sea gateways in the South Atlantic (Friedrich et al., 2009; Robinson et al., 2010). In addition, the latest Maastrichtian was characterized worldwide by a brief greenhouse warming

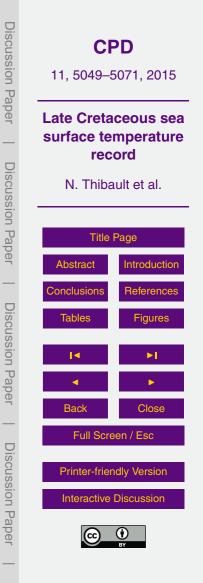
- ⁵ pulse, linked to Deccan volcanism (Li and Keller, 1998a; Robinson et al., 2009). This latter event is well-recorded in oxygen isotopes of benthic foraminifera but is poorly expressed in their planktonic counterparts (Li and Keller, 1998a, b; Barrera and Savin, 1999; Abramovich et al., 2003). Nevertheless, changes in the marine plankton community at the end of the Maastrichtian suggest a drastic, but as yet poorly constrained, increase in global sea-surface temperatures (SSTs, Abramovich et al., 2003; Thibault
- and Gardin. 2010).

Regionally divergent climatic patterns have been previously underlined in the Maastrichtian. In the southern South Atlantic, cooling is gradual, pronounced and only interrupted by the end-Maastrichtian warming (Barrera and Savin, 1999; Friedrich et al.,

- ¹⁵ 2009). In the North Atlantic, an apparent overall warming is inferred from low-resolution planktonic foraminiferal δ^{18} O data, while climate was globally cooling in all other oceanic basins (MacLeod et al., 2005). These regional differences emphasize the need for well-calibrated high-resolution data from different basins, and from open ocean and epicontinental seas in order to provide a reliable picture of past climates. Data from the
- ²⁰ mid-latitude Boreal epicontinental Chalk Sea are particularly critical as this basin was connected to the North Atlantic Ocean to the West, to the Tethys to the southeast and possibly to the Arctic Ocean to the North (Fig. 1).

To investigate climate change in the Boreal Chalk Sea, we generated a calcareous nannofossil temperature index (NTI) and a new record of 1932 bulk carbonate stable

isotopes across the late Campanian–Maastrichtian of the Stevns-1 core, Denmark. The sedimentology and stratigraphy of Stevns-1 are described in detail in Rasmussen and Surlyk (2012) and Surlyk et al. (2013). Carbon isotope stratigraphic correlations with ODP Site 762C have been used to tie the Stevns-1 record to the astronomical time scale of the late Campanian–Maastrichtian (66 to 74.5 Myr, Fig. 2).



2 Methods

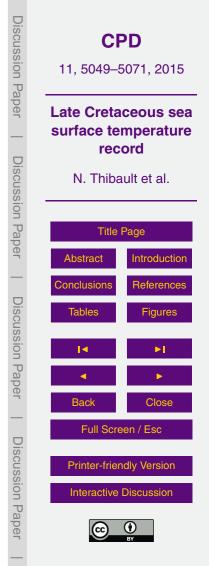
25

2.1 Age model

The age model is based on the correlation of magnetostratigraphic records at Sites 762C and 525A and carbon isotope curves of Stevns-1, 762C and 525A as presented in Thibault et al. (2012a). Numerical ages are derived directly from the correlation with 5 the astronomically calibrated Site 762C (Fig. 2). A small hiatus characterizes the K-Pg boundary interval in the Stevns-1 core. Another hiatus is suspected at the boundary between the Sigerslev and Højerup Members situated 2.2 m below the base Danian. Based on the comparison of global climatic trends, it is estimated here that together, these two hiatuses correspond approximately to the last 150 kyr of the Cretaceous (see Sect. 3.3). For simplification of the age-model, a total gap of 150 kyr was accounted for at the top of our record and the uppermost sample of the Maastrichtian was assigned an age of 66.15 Myr, considering an age of 66 Myr for the K-Pg boundary as in Thibault et al. (2012a). The late Campanian-Maastrichtian succession of Stevns-1 accounts for a total duration of ca. 8.15 Myr with an inferred average sedimentation rate of 5.5 cm kyr⁻¹ over the entire interval. This gives an average resolution of ca. 100 kyr for the 89 samples analyzed for nannofossil palaeoecology and ca. 4.5 kyr for the isotopic data. This oxygen isotopic dataset is the highest resolution record so far published for this interval.

20 2.2 Isotopic measurements and palaeotemperature reconstruction

Oxygen and carbon isotopic ratios of bulk carbonates were measured on a micromass isoprime spectrometer. Analytical precision is calculated to 0.1 ‰ for δ^{18} O and 0.05 ‰ for δ^{13} C. Sea-surface temperature estimates (Fig. 3) are based on Anderson and Arthur (1983) for bulk carbonates of Stevns-1 and Eq. (1) of Bemis et al. (1998) for foraminiferal data of Site 525A, using a $\delta^{18}O_{sw}$ of Late Cretaceous seawater of -1.0‰ SMOW for an ice-free world. Resulting average SST estimates of ca.15.5°C



in the early Maastrichtian of Denmark is in agreement with the global compilation of Zakharov et al. (2006). In addition, we provide temperature estimates for the bulk carbonate of Stevns-1 using an average $\delta^{18}O_{sw}$ of Late Cretaceous seawater of -0.5% SMOW (Fig. 3) assuming glacio-eustatic variations in the range of 25–75 m in the Maastrichtian by comparison with the extent of coincident $\delta^{18}O_{sw}$ and sea-level variations in the Oligocene to early Miocene (Billups and Schrag, 2002).

2.3 Calcareous nannofossil data

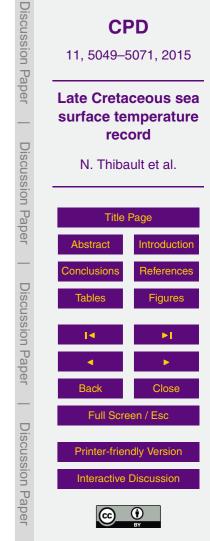
A total of 89 nannofossil slides were prepared following the method described in Thibault and Gardin (2006). Slides were analyzed for quantitative counts. Preservation of the assemblage is moderate in all samples. Relative abundances have been calculated for a total of more than 400 specimens. The nannofossil temperature index (NTI) was calculated as the ratio between warm-water taxa and the sum of warm-water and cool-water taxa identified in the assemblage (see Sect. 3).

3 Results and interpretations

15 3.1 Calcareous nannofossils

Results from the nannofossil analysis are focused here primarily on potential temperature changes as expressed in the nannofossil assemblage through the abundance of cool- and warm-water taxa. *Ahmuellerella octoradiata*, *Gartnerago* spp., *Kamptnerius magnificus*, and *Nephrolithus frequens* are considered as high-latitude taxa, and

- Arkhangelskiella cymbiformis sensu lato has a greater affinity to cool-waters (Wind, 1979; Thierstein, 1981; Pospichal and Wise, 1990; Watkins, 1992; Lees, 2002; Thibault and Gardin, 2006, 2010). Watznaueria barnesiae is ubiquitous in Cretaceous assemblages. Several studies have demonstrated that this is a low-nutrient indicator (Erba et al., 1992; Williams and Bralower, 1995). However, during the Maastrichtian, vary-ing abundances and patterns of migration of this anasis in mid- and high latitudes.
- ²⁵ ing abundances and patterns of migration of this species in mid- and high-latitudes



have mainly been linked to temperature changes (Watkins, 1992; Sheldon et al., 2010). Sheldon et al. (2010) and Thibault et al. (2015) have shown that warm intervals in the Boreal Chalk Sea are characterized by an increase in abundance of *W. barnesiae*. Cool-water taxa and *W. barnesiae* clearly show opposite long-term trends through-

- ⁵ out the studied succession and highlight three warm intervals in the late Campanian, mid-Maastrichtian and latest Maastrichtian, and two cool intervals in the early and late Maastrichtian (Fig. 3). The palaeoecological affinity of *Ahmuellerella regularis* is unknown and this species has shown to be common both in the tropical and mid-latitude areas. However, in the Stevns-1 core, intervals with lower abundances of high-latitude
- taxa and higher abundances in *W. barnesiae* also show enrichments in *A. regularis* (Fig. 3). Therefore, in this study, this species was grouped together with *W. barnesiae* among the warm-water taxa. The Nannofossil Temperature Index (NTI) was calculated as follows:

NTI = (% W. barnesiae + % A. regularis)/[(% A. cymbiformis s.l. + % A. octoradiata

+ % Gartnerago spp. + % K. magnificus + % N. frequens)

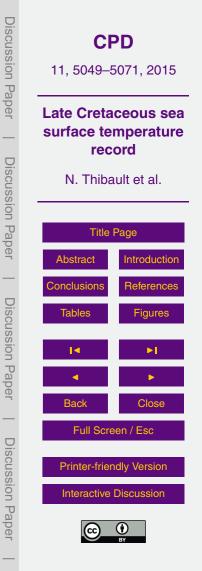
+ (% W. barnesiae + % A. regularis)].

15

3.2 Validation of Stevns-1 bulk δ^{18} O as a proxy for Late Cretaceous SSTs

The nannofossil chalk of the Danish Basin is a very pure carbonate. Carbonate content of the analyzed bulk rock samples is generally over 95% in all analyzed samples. Scanning electron microscope images of the chalk show numerous calcareous nannofossils with dissolution phenomenon, few recrystallization and small carbonate micro-particles, which likely come from the breakdown of nannofossils (Fig. 4). Recent experiments have shown reduced coccolithophore interspecific differences and less carbon and oxygen-isotope fractionation in large and slow growing species with higher ambient carbon availability, which is expected in the sea water of periods with

high CO₂ concentrations such as the Cretaceous (Rickaby et al., 2010; Bolton et al., 2012; Hermoso et al., 2014). Due to its limited diagenetic alteration, the nannofossil



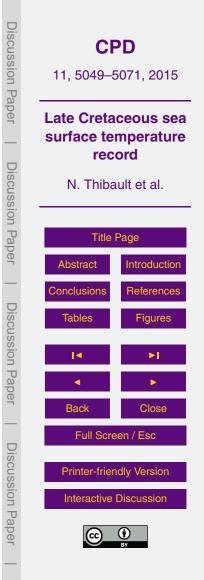
(1)

chalk of Stevns-1 may thus draw a reliable picture of sea-surface water environmental conditions.

- The NTI and δ^{18} O values of Stevns-1 show similar trends for the late Campanian– Maastrichtian (Fig. 3). In order to test the correlation between low-resolution nannofossil and high-resolution isotopic data, both 7 and 21 point running averages were run over δ^{18} O values. Correlation was tested for the resulting values of the 89 samples in common. The R^2 Pearson coefficient of correlation between the NTI and the δ^{18} O is 0.60 for the 7 point running average and increases up to 0.69 for a 21 point running average. This suggests temperature as the dominant factor controlling the observed variations in the δ^{18} O of Stevns-1. Little influence of diagenesis is reinforced by the lack 10 of correlation between δ^{18} O and δ^{13} C data of this core (Thibault et al., 2012b). The timing and magnitude of long-term δ^{18} O changes at Stevns-1 match those recorded in benthic foraminiferal data at Site 525A (Li and Keller, 1998a, b) as well as δ^{18} O variations observed in planktonic foraminifer Globotruncana arca from the late Campanian to the mid-Maastrichtian (Friedrich et al., 2009) (Fig. 5). Average seawater palaeotem-15 perature estimates of 15.5 °C in the early Maastrichtian of the Danish Basin is also in agreement with the global compilation of Zakharov et al. (2006) while considering a $\delta^{18}O_{sw}$ of Late Cretaceous seawater of -1.0 % for an ice-fee world. The preservation
- of δ^{18} O trends, the good correlation with the NTI and the consistent palaeotemperature estimates argue against the influence of prominent early diagenetic alteration in the chalk of Stevns-1. The δ^{18} O record of Stevns-1 can thus be used as a proxy to describe Late Cretaceous SSTs in the Chalk Sea.

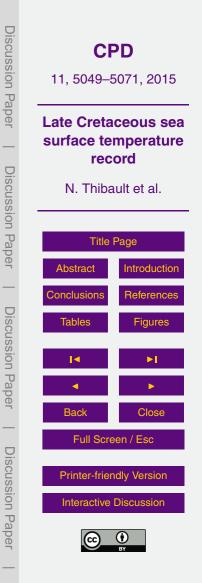
3.3 Climatic trends

Calcareous nannofossil and δ¹⁸O data from Stevns-1 suggest the following climatic
 evolution in the Chalk Sea: from 73.8 to 72.8 Myr, a late Campanian climatic warm optimum with SSTs between ca. 19 and 20 °C, followed by a late Campanian–early Maastrichtian progressive cooling of 3.5 °C (Fig. 5). From 72.8 to 71 Myr, cooling occurs in two major phases, interrupted by a ca. 600 kyr long stable period. These two



long cooling steps are characterized by rapid temperature drops, two of which can also be observed in the NTI at 72.8 and at 72–71.8 Myr. A cool climate mode with slight oscillations in SSTs around 15.5 °C is recorded between 71 and 69.8 Myr. The transition between the early Maastrichtian cooling and mid-Maastrichtian warming is character-

- ⁵ ized by a rapid 1.5 °C increase in SSTs lasting ca. 300 kyr at 69.8–69.5 Myr. The mid-Maastrichtian warming trend is characterized by SSTs oscillating around 16.5 to 17 °C between 69.5 and 68.4 Myr. This trend is followed by a late Maastrichtian cooling of 1 °C during which minimal SSTs around 15.5 °C at 67.9 Myr are reached. A concomitant sharp decrease in δ^{18} O and increase of the NTI delineate the end-Maastrichtian warm-
- ¹⁰ ing from ca. 66.3 Myr up to the K–Pg boundary. This last warming episode accounts for a total of 2°C in the Boreal Realm and occurs in two rapid (< 100 kyr) steps of 1°C each at ca. 66.3 and 66.2 Myr (Fig. 5). The K–Pg boundary clay is not present in the Stevns-1 core, which suggests a small gap across the K–Pg boundary interval. This small gap is only local as small basins are developed across the K–Pg boundary. Sections through
- these basins show a complete development of the K–Pg succession, whereas sections between the basins contain a small gap spanning the boundary transition and in the order of several tens of centimetres, i.e. < 30 kyr (Surlyk et al., 2006). In addition, the presence of a double incipient hardground at the base of the Højerup Member situated 4 to 5 m below the K–Pg boundary at Stevns Klint suggests another potential hiatus
- within the uppermost Maastrichtian interval (Surlyk et al., 2006). These small gaps in Stevns-1 partly hinder observation of a globally characterized short cooling event immediately before the K–Pg event (Li and Keller, 1998a; Thibault and Gardin, 2010; Punekar et al., 2014; Thibault and Husson, 2015). The duration of this end-Cretaceous cooling episode has been estimated to be of the order of 100 to 120 kyr and is followed
- ²⁵ by a ca. 30 kyr short pulse of warming in the Tethys (Punekar et al., 2014; Thibault and Husson, 2015). A sharp decrease in the relative abundance of *W. barnesiae* and in the NTI situated within the Højerup Mb. suggests that the onset of the last end-Cretaceous cooling episode is present in the core (Fig. 3). Therefore, the cumulated uppermost Maastrichtian gap in the Stevns-1 core is of a limited extent, corresponding

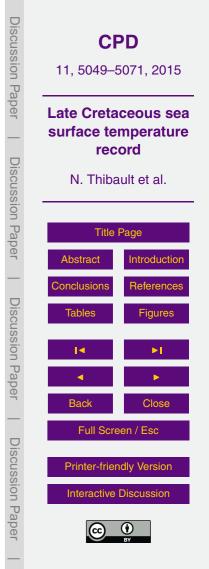


to less than 150 kyr of the latest Cretaceous and most of it probably corresponds to the double incipient hardground.

4 Discussion

Despite regional differences between the South Atlantic and the Chalk Sea, climatic
trends generally match well (Fig. 5). Except for the North Atlantic, low and mid latitudes of all other oceanic basins show the same climate modes (Barrera and Savin, 1999; MacLeod et al., 2005). Differences in climate trends between the Chalk Sea and the North Atlantic are difficult to reconcile with their tight connection and multiple gateways across submerged parts of UK and the Paris Basin (Fig. 1). However,
Maastrichtian water masses at the location of Stevns-1 could have been influenced by Tethyan northwestward currents as suggested by the direction of large channels in seismic profiles offshore Stevns Klint and further north in the Danish Basin (Lykke-Andersen and Surlyk, 2004; Esmerode et al., 2007; Surlyk and Lykke-Andersen, 2007). Climatic trends from Stevns-1 correlate with δ¹⁸O trends of benthic foraminifers

- at Site 525A (Walvis Ridge, South Atlantic), which represents the highest resolution record on separated foraminifers for this time interval (Li and Keller, 1998a, b; Friedrich et al., 2009) (Fig. 5). SSTs in the Chalk Sea followed the same evolution as intermediate and deep-waters of the South Atlantic, Indian Ocean and central Pacific (Barrera and Savin, 1999). However, the record of most planktonic foraminifers in these basins fails to clearly depict the trends in sea-surface waters (Barrera and Savin, 1999). Stevns-1 bulk δ¹⁸O and calcareous nannofossil assemblages, as well as δ¹⁸O values of *G. arca* at Site 525A indicate that climatic modes recorded in late Campanian–Maastrichtian intermediate and deep waters affected sea surface waters
- in a similar fashion (Fig. 5). Changes in Maastrichtian nannofossil assemblages in the tropical Atlantic and Pacific oceans delineate the same climatic trends in sea-surface waters (Thibault and Gardin, 2006, 2010). Migration patterns in planktonic organisms throughout the late Campanian–Maastrichtian strengthen this interpretation (Watkins,



1992; Thibault et al., 2010). When comparing δ^{18} O values of planktonic foraminifers *Rugoglobigerina rugosa* and *Globotruncana arca* at Site 525A across the early Maastrichtian cooling, it appears that data from the latter species show a better consistency with variations observed in the benthic foraminiferal record and in the bulk of Stevns-1

⁵ (Fig. 5). This suggests that δ^{18} O values of *R. rugosa* likely reflect underestimated and smoothed SST variations in the late Campanian–Maastrichtian interval, whereas data acquired on *G. arca* reflect a more faithful picture of primary Late Cretaceous South Atlantic SSTs. Potential diagenetic overprint, the presence of numerous pseudo-cryptic ecophenotypes of *Rugoglobigerina* and vital effect associated to photosymbiosis can ¹⁰ be invoked to explain this discrepancy in the δ^{18} O values of *R. rugosa* (Abramovich et al. 2002) Explanation (Abramovich)

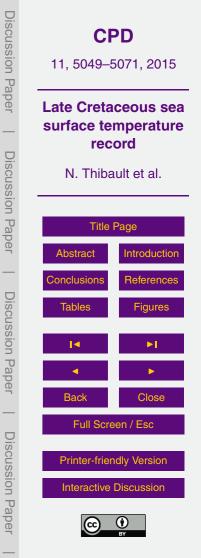
et al., 2003; Falzoni et al., 2014).

25

Despite these similarities, regional differences are nevertheless apparent across the early Maastrichtian cooling event between Stevns-1 (palaeolatitude: 45° N) and Site 525A (palaeolatitude: 36° S). A short warming pulse occurs in the middle of this interval

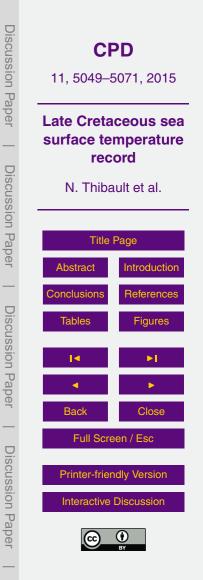
- at Site 525A (Fig. 5). This pulse is very poorly recorded at Stevns-1 through a number of outlying data points with lighter values between -252 and -272 m (Fig. 3) and through slightly lighter values in the 2 standard deviation envelope of Stevns-1 between 70.45 and 70.85 Myr (Fig. 5). The nannofossil assemblage of Stevns-1 does not appear to show any warming in this interval. However, a similar short pulse of warming has been
- ²⁰ recorded during the early Maastrichtian cooling through lighter values of the bulk δ^{18} O accompanied by a slight enrichment in *Watznaueria barnesiae* in the Skælskør-1 core (SW Sjælland, Denmark, Thibault et al., 2015).

Comparison of the Stevns-1 δ^{13} C and δ^{18} O data sheds new light on the relationship between the large negative carbon isotope excursion (CIE) of the Campanian– Maastrichtian boundary interval and the early Maastrichtian cooling. The onset of progressive cooling at 72.8 Myr coincides exactly with the onset of the decrease in δ^{13} C values while the onset of the early Maastrichtian warming mode is broadly coeval to the top of the recovery in δ^{13} C values at 69.5 Myr (Fig. 3). It was recently shown that the negative δ^{13} C excursion predates the δ^{18} O increase with a lag of about 600 kyr at



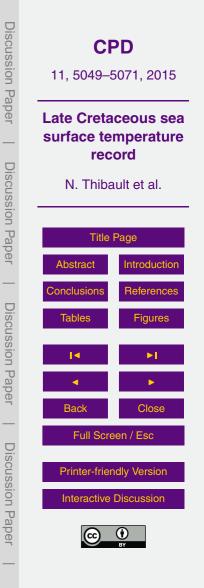
Sites 525A and 690 (Weddell Sea, Southern Ocean) (Friedrich et al., 2009). In contrast, our new high-resolution dataset actually supports synchroneity between the CIE and the positive δ^{18} O excursion of this interval. Isotopic data from Site 525A neither confirm or refute this observation because data from the onset of the excursion at 73 Myr are lacking. However, the return to a mid-Maastrichtian warm mode at 69.5 Myr is coincident with a rapid increase in the δ^{13} C of benthic and planktonic foraminifers at Site 525A (Fig. 2). Therefore, it is possible that the lag between the two signals is a Southern Ocean phenomenon. Decoupling between the two signals can, however, be highlighted at Stevns-1 elsewhere in the record. For example, the stepwise decrease in

- 10 δ^{13} C between 73 and 71 Myr appears to be decoupled from the δ^{18} O record (Fig. 3). Here, maximum cooling occurs between 71.5 and 69.5 Myr during a progressive rise in δ^{13} C values. This decoupling remains to be explained, but with respect to the onset and termination of δ^{18} O and δ^{13} C excursions, our results argue for a direct cause and effect scenario in the Chalk Sea. Decoupling and lead–lag relationships between
- these two proxies has been used as an argument to rule out Maastrichtian glaciation and a subsequent drop in sea level as a likely scenario for these two isotopic excursions (Friedrich et al., 2009). On the contrary, our results tend to show consistency with a glacio-eustatic scenario as previously supported by Barrera and Savin (1999) and Miller et al. (1999). Despite the fact that Kominz et al. (2008) used the Geologic
- ²⁰ Time Scale 2004 with the K–Pg and Campanian–Maastrichtian boundaries at 65.5 and 70.6 Myr, respectively, comparison of the timing of the two cooling episodes appears to match fairly well with that of the two major lowstands in the New Jersey margin sea-level curve (Kominz et al., 2008; Fig. 5). Haq (2014) recently identified six 3rd order sea-level cycles in the late Campanian–Maastrichtian interval bounded by se-
- quence boundaries (SBs) KCa7, KMa1, KMa2, KMa3, KMa4 and KMa5, among which KMa2 and KMa5 at 70.6 and 66.8 Myr, respectively, are considered as major cycle boundaries. Considering the great uncertainty in the estimated ages of Haq's SBs, the timing of major SBs KMa2 and KMa5 at 70.6 and 66.8 Myr corresponds well to a position within the two lowstands of the New Jersey record and within the cooling



episodes highlighted at Stevns-1 (Fig. 5). Although no direct evidence of glaciation, such as dropstones and ice-rafted debris, have been found in the late Campanian–Maastrichtian of the Southern Ocean (Price et al., 1999), examination of diatom-rich sediments from the Alpha Ridge, and palynomorph records from southeastern Aus-

- ⁵ tralia and Seymour Island support the development of winter sea ice in the Arctic Sea and around Antarctica, and the waxing and waning of ephemeral Antarctic ice sheets at that time (Gallagher et al., 2008; Davies et al., 2009; Bowman et al., 2013). The development of ephemeral ice sheets in Antarctica can explain the δ^{18} O excursions through a drop in seawater δ^{18} O accompanied by a global cooling of water masses
- (Barrera and Savin, 1999; Li and Keller, 1999). Sea-level changes could trigger the onset and termination of the late Campanian–early Maastrichtian CIE by shifting calcium carbonate accumulation and organic-matter burial from shelf to open-ocean areas (Barrera and Savin, 1999; Friedrich et al., 2009). The occurrence of the CIE and the early Maastrichtian cooling have been recently explained mainly by a global change in
- the source of intermediate and deep-water masses and the onset of deep-water formation in the Southern Ocean, favoured by the opening of tectonic gateways (Robinson et al., 2010; Koch and Friedrich, 2012). However, a reorganization in the global oceanic circulation is actually compatible with a glacio-eustatic scenario and could have been triggered both by tectonics and glaciation. In such a scenario, changes in the sea-
- ²⁰ water $\delta^{18}O_{sw}$ within a range of 25 to 75 m glacio-eustatic variations may have followed a rather similar evolution as for the Oligocene–Miocene interval (Billups and Schrag, 2002). Palaeotemperature calculations should progressively and cyclically shift from an equation that assumes a sea-water $\delta^{18}O(\delta^{18}O_{sw})$ of -1% to potential $\delta^{18}O_{sw}$ down to ca. -0.5% (Billups and Schrag, 2002). Minimum temperatures of 15.5°C for the SSTs
- ²⁵ of the Boreal Chalk Sea during the early and late Maastrichtian coolings could thus be underestimated and may rather be around 17.5 °C (Figs. 3 and 5).



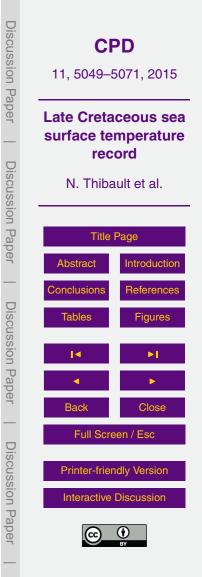
5 Conclusions

High-resolution bulk stable isotopes and calcareous nannofossil data from the fully cored Stevns-1 borehole provide fundamental insights into the late Campanian-Maastrichtian climate of the Boreal Chalk Sea, Our results show that the evolution ⁵ of SSTs in the Boreal Chalk Sea parallel that of bottom-water temperatures at low and mid-latitudes of the North and South Atlantic, Indian Ocean and central Pacific. Two major cool intervals are highlighted at 71.6-69.6 (lower Maastrichtian) and 67.9-66.4 Myr (upper Maastrichtian). The onset and end of the late Campanian-early Maastrichtian negative CIE are coincident with the onset of cooling in the late Campanian and with the onset of the mid-Maastrichtian warming, respectively. These data reopen the possibility 10 of a Maastrichtian glacio-eustatic scenario, supporting a causal relationship between changes in eustatic sea level and major shifts in Late Cretaceous δ^{13} C as previously suggested by Jarvis et al. (2002). Assuming that the early and late Maastrichtian coolings were caused by glaciation, palaeotemperature estimates should be calculated with two different equations using either a $\delta^{18}O_{sw}$ of -1% during warm episodes or a $\delta^{18}O_{sw}$ of ca. -0.5 ‰ during cool episodes. In such a scenario, the full extent of the early Maastrichtian SST cooling would thus be 4°C rather than 6°C. Finally, the two sharp stepwise 1 °C increases in SSTs of the Chalk Sea at 66.3 and 66.2 Myr are con-

sistent with the second main phase of the Deccan volcanic episode in a series of rapid pulses of flood basalt volcanism and associated release of greenhouse gases (Chenet et al., 2009).

The Supplement related to this article is available online at doi:10.5194/cpd-11-5049-2015-supplement.

Acknowledgements. Funding for this study was provided by the Danish Natural Science Research Council, the Natural Science Faculty, the University of Copenhagen and the Carlsberg



Foundation. We thank C. V. Ullmann, J. Moreau, M. Ruhl, and D. Husson for fruitful discussions and two anonymous reviewers for their suggestions.

References

- Abramovich, S., Keller, G., Stüben, D., and Berner, Z.: Characterization of late Campanian
- foraminiferal depth habitats and vital activities based on stable isotopes, Palaeogeogr. Palaeocl., 202, 1–29, 2003.
 - Anderson, T. F. and Arthur, M. A.: Stable isotopes of oxygen and carbon and their application to sedimentologic and environmental problems, in: Stable Isotopes in Sedimentary Geology, edited by: Arthur, M. A. et al., SEPM Short Course Notes, 10, 1–151, 1983.
- Barrera, E. and Savin, S. M.: Evolution of late Campanian–Maastrichtian marine climates and oceans, in: Evolution of the Cretaceous Ocean-Climate System, edited by: Barrera, E. and Johnson, C. C., GSA Special Paper, 332, 245–282, doi:10.1130/0-8137-2332-9.245, 1999.
 - Bemis, B. E., Spero, H. J., Bijma, J., and Lea, D. W.: Reevaluation of the oxygen isotopic composition of planktonic foraminifera: experimental results and revised paleotemperature equations, Paleoceanography, 13, 150–160, doi:10.1029/98PA00070, 1998.
- equations, Paleoceanography, 13, 150–160, doi:10.1029/98PA00070, 1998.
 Billups, K. and Schrag, D. P.: Paleotemperatures and ice volume of the past 27 Myr revisited with paired Mg/Ca and ¹⁸O/¹⁶O measurements on benthic foraminifera, Paleoceanography, 17, 3-1–3-11, doi:10.1029/2000PA000567, 2002.

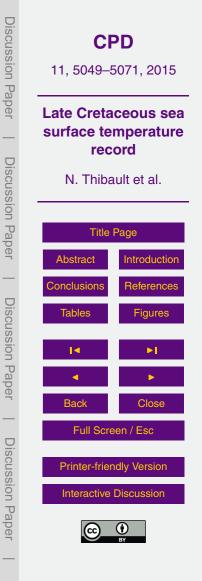
Bolton, C. T., Stoll, H. M., and Mendez-Vicente, A.: Vital effects in coccolith calcite: cenozoic climate- pCO_2 drove the diversity of carbon acquisition strategies in coccolithophores?, Pa-

- leoceanography, 27, doi:10.1029/2012PA002339, 2012.
- Bowman, V. C., Francis, J. E., and Riding, J. B.: Late Cretaceous winter sea ice in Antarctica?, Geology, 41, 1227–1230, 2013.

Chenet, A.-L., Courtillot, V., Fluteau, F., Gérard, M., Quidelleur, X., Khadri, S. F. R., Sub-

barao, K. V., and Thordarson, T.: Determination of rapid Deccan eruptions across the Cretaceous–Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section, J. Geophys. Res., 114, B6103, doi:10.1029/2008JB005644, 2009.

Davies, A., Kemp, A. E. S., and Pike, J.: Late Cretaceous seasonal ocean variability from the Arctic, Nature, 460, 254–258, 2009.



Erba, E., Castradori, F., Guasti, G., and Ripepe, M.: Calcareous nannofossils and Milankovitch cycles: the example of the Gault Clay Formation (southern England), Palaeogeogr. Palaeocl., 93, 47–69, 1992.

Esmerode, E. V., Lykke-Andersen, H., and Surlyk, F.: Ridge and valley systems in the Up-

- ⁵ per Cretaceous chalk of the Danish Basin: contourites in an epireic sea, in: Economic and Palaeoceanographic Significance of Contourite Deposits, edited by: Viana, A. R. and Rebesco, M., Geological Society of London Special Publication, 276, 265–282, 2007.
- Falzoni, F., Petrizzo, M. R., Huber, B. T., and MacLeod, K. G.: Insight into the meridional ornamentation of the planktonic foraminiferal genus *Rugoglobigerina* (Late Cretaceous) and
 implications for taxonomy, Cretaceous Res., 47, 87–104, 2014.
- Friedrich, O., Herrle, J. O., Cooper, M. J., Erbacher, J., Wilson, P. A., and Hemleben, C.: The early Maastrichtian carbon cycle perturbation and cooling event: implications from the South Atlantic Ocean, Paleoceanography, 24, PA221, doi:10.1029/2008PA001654, 2009.

Gallagher, S. J., Wagstaff, B.E:, Barid, J. G., Wallace, M. W., and Li, C. L.: Southern high

latitude climate variability in the Late Cretaceous greenhouse world, Global Planet. Change,
 60, 351–364, 2008.

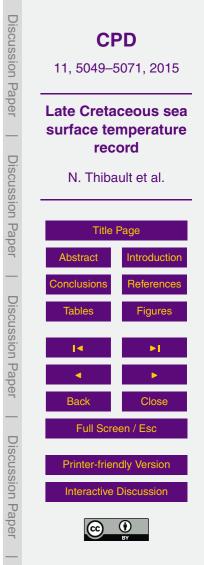
Haq, B. U.: Cretaceous eustasy revisited, Global Planet. Change, 113, 44–58, 2014.

20

- Hermoso, M., Horner, T. J., Minoletti, F., and Rickaby, R. E. M.: Constraints on the vital effect in coccolithophore and dinoflagellate calcite by oxygen isotopic modification of seawater, Geochim. Cosmochim. Ac., 141, 612–627, 2014.
- Jarvis, I., Mabrouk, A., Moody, R. T. J., and de Cabrera, S.: Late Cretaceous (Campanian) carbon isotope events, sea-level change and correlation of the Tethyan and Boreal realms, Palaeogeogr. Palaeocl., 188, 215–248, 2002.

Koch, M. C. and Friedrich, O.: Campanian-Maastrichtian intermediate- to deep-water changes

- in the high latitudes: benthic foraminiferal evidence, Paleoceanography, 27, PA2209, doi:10.1029/2011PA002259, 2012.
 - Kominz, M. A., Browning, J. V., Miller, K. G., Sugarman, P. J., Mizintsevaw, S., and Scotese, C. R.: Late Cretaceous to Miocene sea-level estimates from the New Jersey and Delaware coastal plain coreholes: an error analysis, Basin Res., 20, 211–226, 2008.
- ³⁰ Laskar, J., Fienga, A., Gastineau, M., and Manche, H.: La2010: a new orbital solution for the long-term motion of the Earth, Astron. Astrophys., 532, A89, doi:10.1051/0004-6361/201116836, 2011.



5064

- isotopes, Mar. Geol., 161, 171-190, 1999. Lykke-Andersen, H. and Surlyk, F.: The Cretaceous-Paleogene boundary at Stevns Klint, Den-10
 - mark: inversion tectonics or sea-floor topography?, J. Geol. Soc. London, 161, 343-352, 2004.
 - MacLeod, K. G., Huber, B. T., and Isaza-Londoño, C.: North Atlantic warming during global cooling at the end of the Cretaceous, Geology, 33, 437-440, 2005.
 - Markwick, P. J. and Valdes, P. J.: Palaeo-digital elevation models for use as boundary condi-15 tions in coupled ocean-atmosphere GCM experiments: a Maastrichtian (late Cretaceous) example, Palaeogeogr. Palaeocl., 213, 37-63, 2004.
 - Miller, K. G., Barrera, E., Olsson, R. K., Sugarman, P. J., and Savin, S. M.: Does ice drive early Maastrichtian eustasy?, Geology, 27, 783-786, 1999.
 - Pospichal, J. J. and Wise Jr., S. W.: Calcareous nannofossils across the K-T boundary, ODP 20 Hole 690C, Maud Rise, Weddell Sea, in: Proc. Ocean Drill. Program. Sci. Results, 113, 515-532, 1990.
 - Price, G. D.: The evidence and implications of polar ice during the Mesozoic, Earth-Sci. Rev., 48, 183-210, 1999.
 - ²⁵ Punekar, J., Mateo, P., and Keller, G.: Effects of Deccan volcanism on paleoenvironment and planktic foraminifera: a global survey, in: Volcanism, Impacts, and Mass Extinctions: Causes and Effects, edited by: Keller, G. and Kerr, A. C., GSA Spec. Pap., 505, 91-116, 2014. Rasmussen, S. L. and Surlyk, F.: Facies and ichnology of an Upper Cretaceous chalk contourite drift complex, eastern Denmark, and the validity of contourite facies models, J. Geol. Soc.
 - London, 169, 435–447, 2012. 30

1998b.

Rickaby, R. E. M., Henderiks, J., and Young, J. N.: Perturbing phytoplankton: response and isotopic fractionation with changing carbonate chemistry in two coccolithophore species, Clim. Past, 6, 771-785, doi:10.5194/cp-6-771-2010, 2010.

- Lees, J. A.: Calcareous nannofossils biogeography illustrates palaeoclimate change in the Late Cretaceous Indian Ocean, Cretaceous Res., 23, 537-634, 2002.
- Li, L. and Keller, G.: Abrupt deep-sea warming at the end of the Cretaceous, Geology, 26, 995-998, 1998a.

5 Li, L. and Keller, G.: Maastrichtian climate, productivity and faunal turnovers in planktic foraminifera in South Atlantic DSDP sites 525A and 21, Mar. Micropaleontol., 33, 55-86,

surface temperature Li, L. and Keller, G.: Variability in Late Cretaceous and deep waters: evidence from stable record Discussion Paper N. Thibault et al. **Title Page** Abstract Introduction Conclusions References **Discussion** Paper Tables Figures Back Close Full Screen / Esc **Discussion** Paper **Printer-friendly Version** Interactive Discussion

Discussion

Pape



11, 5049–5071, 2015

Late Cretaceous sea

- Robinson, N., Ravizza, G., Coccioni, R., Peucker-Ehrenbrink, B., and Norris, R.: A high resolution marine 1870s/1880s record for the late Maastrichtian: distinguishing the chemical fingerprints of Deccan volcanism and the KP impact event, Earth Planet. Sc. Lett., 281, 159–168, 2009.
- ⁵ Robinson, S. A., Murphy, D. P., Vance, D., and Thomas, D. J.: Formation of "Southern Component Water" in the Late Cretaceous: evidence from Nd-isotopes, Geology, 38, 871–874, 2010.
 - Sheldon, E., Ineson, J., and Bown, P.: Late Maastrichtian warming in the Boreal Realm: calcareous nannofossil evidence from Denmark, Palaeogeogr. Palaeocl., 295, 55–75, 2010.
- ¹⁰ Surlyk, F., Dons, T., Clausen, C. K., and Higham, J.: Upper Cretaceous, in: The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea, edited by: Evans, D., Graham, C., Armour, A., and Bathurst, P., The Geological Society, London, 213–233, 2003.
 - Surlyk, F., Damholt, T., and Bjerager, M.: Stevns Klint, Denmark: uppermost Maastrichtian chalk, Cretaceous–Tertiary boundary, and lower Danian bryozoan mound complex, B. Geol.
- ¹⁵ Soc. Denmark, 54, 1–48, 2006.

20

25

30

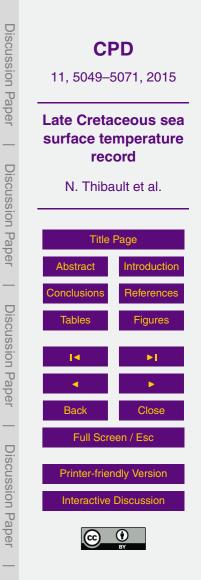
- Surlyk, F. and Lykke-Andersen, H.: Contourites drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin, Sedimentology, 54, 405–422, 2007.
 - Surlyk, F., Rasmussen, S. L., Boussaha, M., Schiøler, P., Schovsbo, N. H., Sheldon, E., Stemmerik, L., and Thibault, N.: Upper Campanian–Maastrichtian holostratigraphy of the eastern Danish Basin, Cretaceous Res., 46, 232–256, 2013.
- Thibault, N. and Gardin, S.: Maastrichtian calcareous nannofossil biostratigraphy and paleoecology in the Equatorial Atlantic (Demerara Rise, ODP Leg 207 Hole 1258A), Rev. Micropaleontol., 49, 199–214, 2006.

Thibault, N. and Gardin, S.: The calcareous nannofossil response to the end-Cretaceous warm event in the Tropical Pacific, Palaeogeogr. Palaeocl., 291, 239–252, 2010.

Thibault, N. and Husson, D.: Climatic fluctuations and sea surface water circulation patterns at the end of the Cretaceous era: calcareous nannofossil evidence, Palaeogeogr. Palaeocl., doi:10.1016/j.palaeo.2015.07.049, 2015.

Thibault, N., Gardin, S., and Galbrun, B.: Latitudinal migration of calcareous nannofossil *Micula murus* in the Maastrichtian: implications for global climate change, Geology, 38, 203–206, 2010.

Thibault, N., Husson, D., Harlou, R., Gardin, S., Galbrun, B., Huret, E., and Minoletti, F.: Astronomical calibration of upper Campanian–Maastrichtian carbon isotope events and calcare-



ous plankton biostratigraphy in the Indian Ocean (ODP Hole 762C): implication for the age of the Campanian–Maastrichtian boundary, Palaeogeogr. Palaeocl., 337–338, 52–71, 2012a.

- Thibault, N., Harlou, R., Schovsbo, N., Schiøler, P., Minoletti, F., Galbrun, B., Lauridsen, B. W., Sheldon, E., Stemmerik, L., and Surlyk, F.: Upper Campanian–Maastrichtian nannofossil
- ⁵ biostratigraphy and high-resolution carbon-isotope stratigraphy of the Danish Basin: towards a standard δ^{13} C curve for the Boreal Realm, Cretaceous Res., 33, 72–90, 2012b.
 - Thibault, N., Anderskouv, K., Bjerager, M., Boldreel, L. O., Jelby, M. E., Stemmerik, L., and Surlyk, F.: Upper Campanian–Maastrichtian chronostratigraphy of the Skælskør-1 core, Denmark: correlation at the basinal and global scale and implications for changes in sea-surface temperatures, Lethaia, 48, 549–560, doi:10.1111/let.12128, 2015.
- Thierstein, H. R.: Late Cretaceous nannoplankton and the change at the Cretaceous–Tertiary boundary, in: The Deep Sea Drilling Project: a Decade of Progress, edited by: Warme, J. E., Douglas, R. G., and Winterer, E. L., SEPM Special Publication, 32, 355–394, 1981.

10

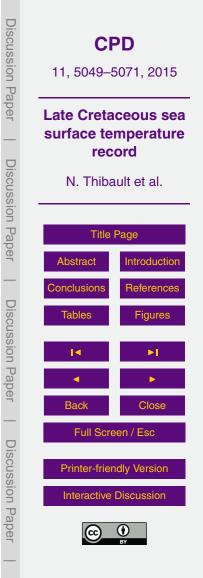
- Watkins, D. K.: Upper Cretaceous nannofossils from Leg 120, Kerguelen Plateau, Southern Ocean, Proc. Ocean Drill. Program Sci. Results, 120, 343–370, 1992.
- Williams, J. R. and Bralower, T. J.: Nannofossil assemblages, fine-fraction stable isotopes, and the paleoceanography of the Valanginian–Barremian (Early Cretaceous) North Sea Basin, Paleoceanography, 10, 815–839, 1995.

Wind, F. H.: Maestrichtian–Campanian nannofloral provinces of the southern Atlantic and Indian

Oceans, in: Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment, edited by: Talwani, M., Hay, W. W., and Ryan, W. B. F., AGU, Maurice Ewing. Ser., 3, 123–137, 1979.

Zakharov, Y. D., Popov, A. M., Shigeta, Y., Smyshlyaeva, O. P., Sokolova, E. P., Nagendra, R., Velivetskaya, T. A., and Afanasyeva, T. B.: New Maastrichtian oxygen and carbon isotope record: additional ovidence for warm low latitudes. General J. 10, 347–367, 2006

record: additional evidence for warm low latitudes, Geosci. J., 10, 347–367, 2006.



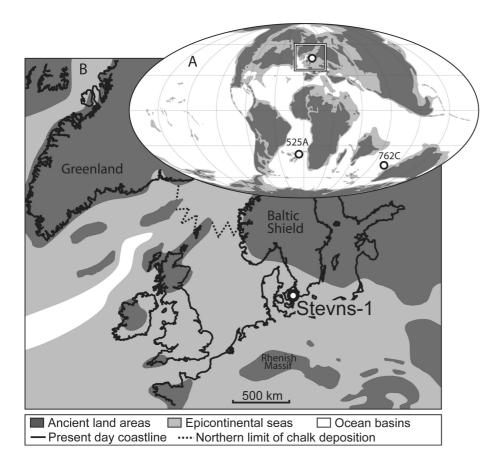
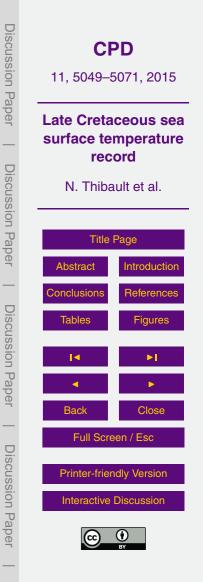
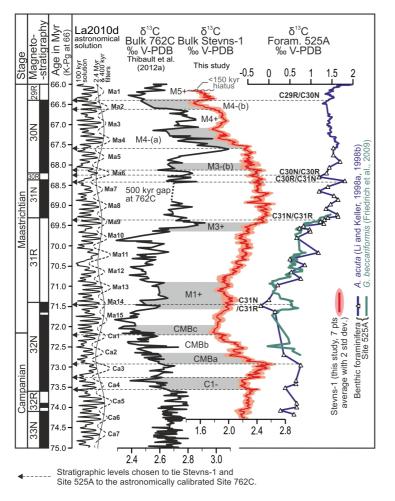
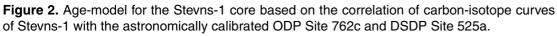
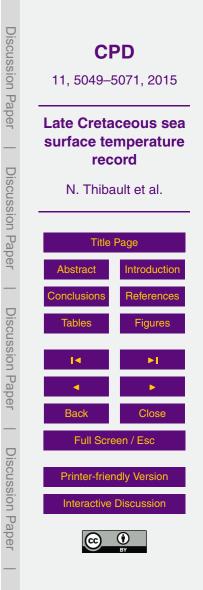


Figure 1. (a) Palaeogeographic reconstruction for the Maastrichtian (66 Myr) showing location of the Boreal Chalk Sea (square) and key localities discussed in the text (after Markwick and Valdes, 2004, modified). **(b)** Palaeogeographic reconstruction of the Boreal Chalk Sea for the Maastrichtian with location of Stevns-1 (after Surlyk et al., 2003, modified).









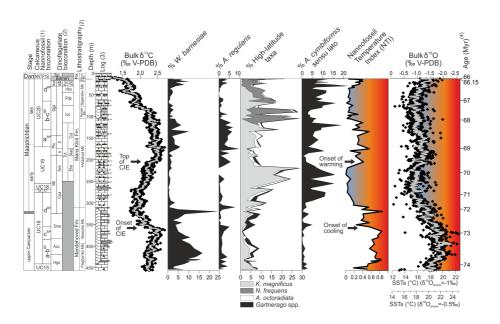
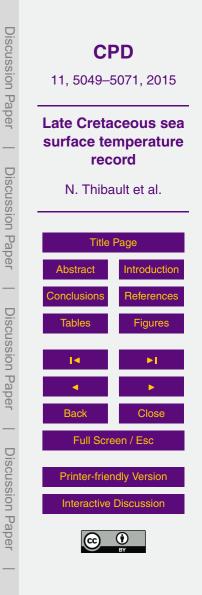


Figure 3. Calcareous nannofossil climatic data and bulk stable isotopes of Stevns-1. Background colours delineate cool and warm climatic trends in the Chalk Sea. (1) Thibault et al. (2012b). (2) Surlyk et al. (2013) for details of the dinoflagellate biozonation and lithostratigraphy. (3) Rasmussen and Surlyk (2012) for the full sedimentological description of the Stevns-1 core. (4) Age model after Thibault et al. (2012a) and correlation of Fig. 2.



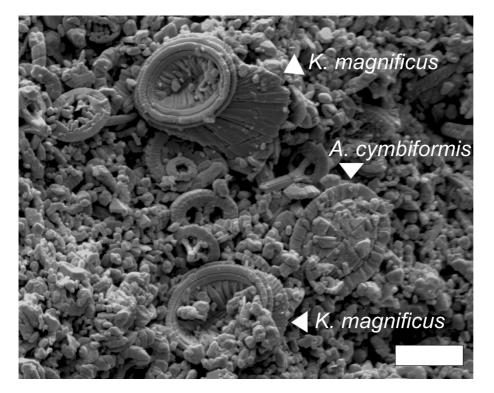
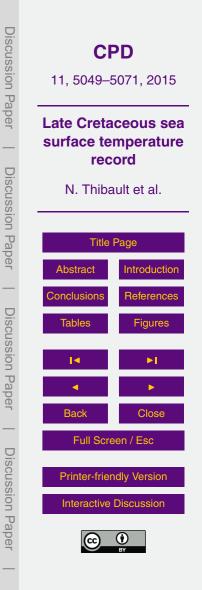
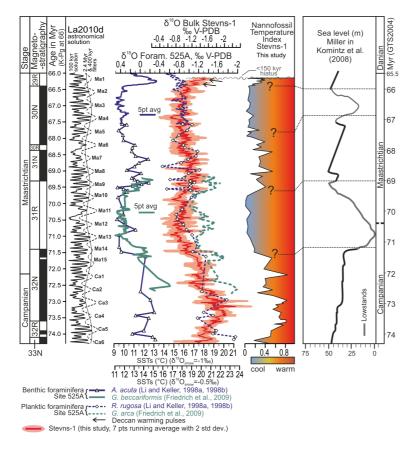


Figure 4. SEM picture of the Stevns-1 chalk. Sample 6146 (late Maastrichtian cooling episode, nannofossil subzone UC20b-c^{BP}, depth: 73.91 m). Two of the main cool-water nannofossils taxa are shown. Bar is 10 μ m.





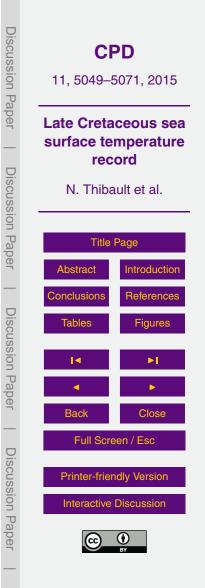


Figure 5. Stable oxygen isotope and calcareous nannofossil data of Stevns-1 compared to data on foraminifers of South Atlantic DSDP Site 525A. The age scale is based on the correlation of carbon isotope curves between Stevns-1, DSDP Site 525A and the astronomically calibrated ODP Site 762C. La2010d: astronomical solution from Laskar et al. (2011). Benthic and planktonic foraminiferal stable isotope data from Li and Keller (1998a, b) and Friedrich et al. (2009).