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Climate of the Past Discussions

Interactive comment on "Land–sea coupling of Early Pleistocene glacial cycles in the southern North Sea exhibit dominant Northern Hemisphere forcing" *by* Timme Donders et al.

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Donders, T.H. et al. We thank the reviewers for their constructive and specific comments and will use them to improve the interpretation and data representation. Here we provide a first reply to the comments and indicate where we plan to make adjustments, and provide additional information to support our interpretations. We feel that with extension of the discussion and added detail as indicated below we are able to meet the concerns of all reviewers.

Reviewer Stijn de Schepper comment: Validity of age model: While the presented work is underpinned by previously published papers and insights into depositional environ-

ment (papers by Kuhlmann and co-authors), aspects of the age model can be questioned. The authors rely here on the G/M reversal and the X-event for constraining the age of their studied interval (L152–155). Kuhlman and Wong (2008) discuss in fact 4 different possible interpretations of the pmag. It seems very questionable to me that the very short-lived X-event (2.420–2.441 Ma, Cande and Kent, 1995) can be detected in the sedimentary record of a shallow sea by measuring the magnetic signal of discrete samples (Kuhlman and Wong, 2008). This event does not show up in u-channeled, high-resolution pmag records of the North Atlantic (e.g. Hoddell and Channell 2016; Channell et al 2016), neither has it been tied to the LR04 Marine Isotope Stratigraphy. The dinocyst bioevents generally point to the Plio-Pleistocene, but the events are not well-recognised (e.g. Barssidinium, M. choanophorum) or not calibrated (e.g. I. multiplexum) outside the North Sea Basin. This questions the age assigned to these events and thus also the age model. Using additional/different tiepoints that have been calibrated outside the North Sea Basin could provide more credibility to the age model used (see below). Based on these concerns about the age model, it remains uncertain 1) whether the cycles visible in the gamma-ray reflect the interval MIS102–96 and 2) whether these are truly, consecutive (i.e. no erosional events in between) G-IG cycles.

Reply: The comments regarding the age model focus on three aspects; the validity of the paleomagnetic signal and, consequently, the completeness and correct assignment of the stratigraphy at A15-3/4 to MIS 102-96, and the use of the dinocyst biozonation. Firstly, based on the combined stratigraphic and detailed 3D seismic interpretations and overall fine grained (clays to silts) deposits all point to a continuously aggrading system in the interval we report. There is evidence of small hiatuses above (first around 2.1 Ma) and significant hiatuses below (intervals within the Early Pliocene and Miocene, particularly the Mid Miocene Unconformity) the selected interval, which is why we excluded these intervals in this publication. Indeed, in the excluded intervals erosional surfaces (beside the obvious MMU) are well recognizable in the seismic property data (Kuhlmann and Wong, 2008), where the high-resolution 3D volume resolves e.g. (iceberg) scour marks and truncated clinoforms. The seismic data thus serve as

an important control on our stratigraphic interpretation. In the intervals with erosive signals, the associated palynological signals point to much more shallow and near terrestrial conditions that are typically associated with erosive conditions (Kuhlmann et al., 2006a)

For the reported MIS102-96 interval, the typical cyclic pattern of the gamma ray is traceable across several wells in the central part of the entire southern North Sea (see Kuhlman et al. 2006ab as well as in the seismic interpretations presented in our supplementary data). Crucially, the Pmag has been measured first by a continuous paleomagnetic downhole logging tool, Geological High-resolution Magnetic Tool (GHMT) by Schlumberger, in wells A15-3 and B16-1 (see description in Kuhlmann et al., 2006a), which is a rarely available tool and therefore an important addition to the interpretation. This continuous signal is present in two wells in the same log zone and has subsequently been verified by discrete samples taken from continuous cores in well A15-3 (Kuhlmann et al., 2006a), and the interpretation relies on the combined signal from borehole logging and core measurements. Secondly, owing to the coastal proximity, the thickness of the North Sea succession and therewith sedimentation rates of the investigated interval is far higher than any North Atlantic site, which greatly increases the chance of recovery of the X-event. Our approximately 250 kyr record is represented by an sediment thickness from over 160 m of fine-grained sediment. While the independent position of the X-event is not included in i.e. the LR stack, there is additional recent evidence that supports our interpretation. Noorbergen et al. (2015) has carried out a detailed study of a land-based section (Noordwijk well) that represents approximately the same interval as our 15-3/4 study. The Noordwijk record contains both palynology and detailed stable isotope stratigraphy, and it includes a direct correlation with the A15-3 well, including the quantitative abundance signals on palynology. At this site, carbonate preservation was much better and more sample material was available, providing a much more complete benthic isotope record. Based on the Noordwijk data, Noorbergen et al (2015) established a tuning to LR04, which is valid for A15-3/4 as well. The 4 options for paleomagnetic interpretation in Kuhlman and Wong (2008) pointed at

by the reviewer, are already presented in Kuhlmann et al. (2006a), and represent the theoretical ties when only Pmag data would be considered. The key to our record is an integrated Pmag, isotope stratigraphic, seismic stratigraphic and palynological biozonation that exclude the other options and all converge on the present interpretation. We recognize that the evidence from the Noordwijk well (Noorbergen et al, 2015) was insufficiently represented in our manuscript and we will incorporate this study in our discussion to strengthen our interpretation, and we will refer to the available evidence on hiatuses.

The bioevents in the North Sea basin, specifically the acmes, indeed have a clear regional character, but within the basin allow a high resolution well correlation (Kuhlmann et al., 2006b). While the age model and bioevents have been discussed in Kuhlmann et al. (2006a) and are used for this publication, their validity is significantly strengthened by the tuning approach of Noorbergen et al. (2015). That paper describes the occurrence of I. multiplexum in both the A15-3 well and Noordwijk well, which has been tied to an acme in MIS 97/98 in this basin. Based on the comments, we have reviewed the dinocyst events and the suggested inclusion of the additional markers strengthens our interpretation. In the revision we will provide an updated table with the age of the events used and update the age-depth model where needed. This revision is not expected to alter the interpretations of the MIS102-92 interval.

Comments reviewer: The leads/lags between climate proxies and sea level are not so clearly visible as the authors claim in the abstract and conclusions. The leads/lags are not clearly demonstrated on a figure, or more importantly using statistical techniques.

Reply: Lead –lags signals that we infer are based on the G-IC cycle (MIS 98-97-96) in our record that is best resolved in all available proxies. A statistical approach would require multiple of these successions with similar sampling resolution which, unfortunately, is not available. The stratigraphic record is not fully cored, but only in part (see fig 2) and part of the proxies (palynology and organic geochemistry) supplemented by side wall cores. The strength and value of the record is in the expanded nature and

good reflection of both marine and terrestrial signals, which is a rare occasion. Based on the available evidence we infer a lead-lag relation of (crucially) signals that are all coming from the same source material. While the overall climate signal between land, sea surface and sea level is indeed in phase ("vary in concert"), there are small lead –lags relations in the data that we point to, we will highlight these different aspect more extensively in the revised manuscript in such a way that it is clear that no exact duration of the phase lag has been inferred yet (this would require a more continuous record).

Comment reviewer: What is the effect of using cutting samples (caving, reworking) on your interpretations?

Reply: The effect of the cuttings is very minimal as the majority of the samples is from cores or side wall cores (which are intact samples obtained after drilling). The cuttings are used here to increase resolution of the palynological samples, and are based on larger chips that have been cleaned before treatment. Importantly, no PDC (power drill bit) has been used so the cutting material has not been ground into a fine paste as is a common practice in many recent wells. The expanded sediment package helps limit the caving problems as the time resolution is high. We will provide a table with exact sample type and proxy, but we can state that all organic and carbonate proxies have been measured on core or sidewall cores and the key conclusions are not depending on cutting material. Other wells in the region that have been studied (by TNO Geological Survey of the Netherlands), internal reports) on cutting material could be correlated confidently to A15-3/4, and independently verified by 3D seismic interpretations.

Comment reviewer: Environmental signal from dinocysts; The 4 species used to indicate a warm water signal are all coastal, shallow water species

Reply: The reviewer is absolutely right that the 4 selected dinocyst taxa indicate coastal conditions. In fact this is our main purpose for displaying them, and conclusions based on their abundance refer to their indication of coastal conditions. Our climatic inter-

pretations rely on the cool water taxa as we tried to optimally separate the in-/offshore and climatic trends. The confusion is in our use of the phrase " . . . indicate generally warm, coastal waters", while we principally use them for the latter. We shall explain this point better in the revision. The principal source of the terrestrial palynomorphs is from the Eridanos paleoriver (as verified in a source area study by Kuhlmann et al., 2004). The detailed seismic interpretation provides further important control on the direction of river progradation. The component most sensitive to the T/M index related to differential transport processes, the bisaccate pollen, are here tested for their effect on the ratio by including and excluding them (Fig. 1). The resulting ratio with bisaccate pollen excluded is slightly lower, but the relation between both ratios is very strong and hence no indications for phases of differential transport are present. This additional figure will be included in the supplementary data.

Minor points by reviewer S. de Schepper

All suggested textual comments will be clarified and/or adjusted

The suggested use of the Gibbard and Lewin 2016 paleogeographic reconstruction will be considered, it will not alter the implications of our study

Comment L121 "different water types": water masses in Fig 1 refer mostly to the origin of the fresh water inflows

Comment L126–128 Please provide a timeframe Reply: the Eridanos delta was active during most of the Neogene and early Pleistocene, and progressively prograded towards the study site

Comment L157–162 comment on the depositional model;This model would get more credibility if this has also been demonstrated for late Pleistocene glacial/interglacial cycles. Would the SL drop of up to 60 m in these glacials (e.g. Miller et al. 2005; Bintanja et al. 2005) not provide a stronger control on the sedimentation (rather than hydrography)? Reply: the relation between grain size and G-IG cycles is regionally only

and valid as long as the site is permanently marine. Available foraminifera and seismic data indicate water depths of 300-100 m in the reported interval (Kuhlmann et al., 2006a; Huuse et al., 2001). In later glacial stages as the Eridanos system is abandoned and more extensive glaciations cover the Scandinavian shield and the Southern North Sea basin is either dry or very shallow this depositional system proposed by Kuhlmann and Wong (2008) is no longer valid. Also the study by Noorbergen et al (2015) on the Noordwijk well confirms that " . . . the finer grained intervals coincide with d18O maxima implying increased ice sheet volume and lowered eustatic sea levels."

Comment L165 How was the age model transferred to LR04 MIS? Reply: GR breaks were picked as inflection points of the LR04 MIS transitions; this will be clarified in the revision in the tie point table.

Comment L202 How was recrystallization and dissolution determined? Reply: Preservation was based on a visual inspection and assignment of a relative scale of 1-5 of preservation, after which the poorest 2 classes were discarded. The best preserved specimens (cat. 1) had shiny tests (original wall calcite) and showed no signs of overgrowth. Category 2 specimens showed signs of overgrowth but were not recrystallized and cat. 3 specimens were dull and overgrown by a thin layer of secondary calcite. Cat 4-5 specimens were discarded because primary calcite was (nearly) absent. While we are aware of the importance of SEM work for detailed preservational assessments the aim was to establish the phase relation with the GR cycles.

Comment L273 Why were there only relative abundances calculated? Reply: No lycopodium counts were available, needed for calculations of concentrations, due to part industry origin of the datasets (data produced by authors for industry purpose).

Comment: L359 not convincing Reply:reviewer referring to phrase 'The Cassidulina teretis δ18O (δ18Ob) confirms the relation between glacial stages and fine grained sediment as proposed by Kuhlman et al. (2006a,b)": Apart from our data, the benthic (δ18Ob) from the nearby Noordwijk well (Noorbergen et al., 2015) now independently

confirms the relation between glacial stages and fine grained sediment as proposed by Kuhlman et al. (2006a).

Comment L383 Which fresh water algae did you find? Reply: Pediastrum and Botryococcus (see supplementary data)

Comment: L401-402 What does the n-C23 Sphagnum biomarker indicate? Reply: development of boreal (moist/cool) climate and influx

Comment Chapter 6.1 is confusing. reply: we will revise the text for inconsistencies

Comment L434 Effect of SL on pollen is addressed here, but the effect of SL on the dinocyst record is not discussed in the MS. Reply: the coastal dinocyst index is especially included to document the combined influence of coastal progradation and sea level change. Due to the earlier confusion on the use as warm water indicators, this point was perhaps overseen by the reviewer.

Comment L485, L535 Onset/intensification have been used intermixed. Reply: valid point that we will adjust

Comment: L510 Speculation Reply: yes, but consistent with the effect of obliquity forcing

Comment L518 Severe cooling. Subjective comment. Reply: the cooling is relative to late Pliocene conditions and in that respect severe. We will specify more exactly the degree of cooling based on the brGDGT data that, although not always in phase with the other proxies, does give a temperature range for the G-IG cycles.

Comment: Please provide a list with the tiepoints. Reply: we will add this together with the MIS transitions, but all age tie points are reported in Kuhlmann et al, 2006ab

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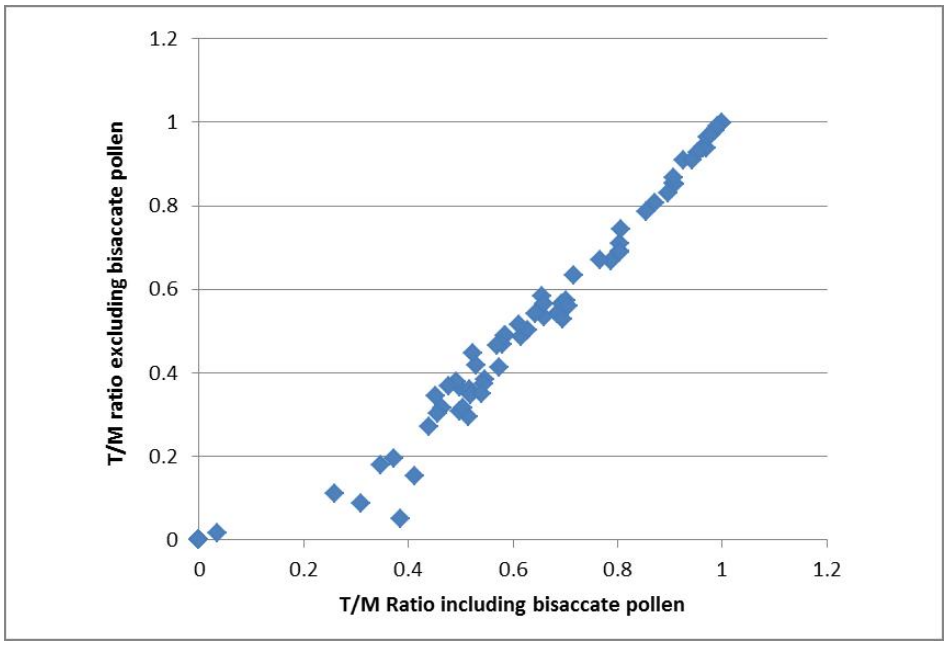

Fig. 1. Figure 1: terrestrial / marine palynomorph ratios with in- and exclusion of bisaccate pollen.