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Climate of the Past
Discussions

Interactive comment on "Long-term variations in Iceland–Scotland overflow strength during the Holocene" *by* D. J. R. Thornalley et al.

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We thank Nathalie Fagel for her review, which has lead us to improve our manuscript. Below we provide our response to specific queries and comments raised.

FAGEL: "General comment The ms presents the Holocene evolution of a major deep water overflow in Northern North Atlantic (ISOW). The grain size distribution of 11 sediment cores collected in Iceland basin was analysed to determine the sortable silt, i.e. a proxy for current strength. The database is complete with previous measurements on two cores. The full dataset is used to produced a stacked Holocene record of the ISOW strength. The reconstruction is further compared with climate model simulations in order to evidence the main forcing factors. The topic and approach of the ms are interesting. However for my point of view the interpretation is too rapid and does not

give sufficient credit to the numerous previous studies dedicated to the similar problematic, i.e reconstruction of deep circulation changes over the Holocene in North Atlantic. Basic but important sedimentological information must be present in order to attest the continuous sedimentation deposition in area often characterised by strong deep current. I have also many comment on the figures 1 and 5. Finally I'm not shure that CP is the most suitable journal to publish such dataset since most of the interpretations are related to paleoceanography. Based on my expertise, it is difficult to estimate if the results derived from the climate model simulations are sufficient new to be published in CP. I leave this question open. . .Wathever my feeling is that the ms requests a stronger discussion before any publication in CP."

REPLY: We should emphasise at the outset that our paper focuses specifically on the strength of the overflow rather than the more general area of reconstruction of deep circulation changes in the North Atlantic. In our study we use sites as close to the I-S overflow source as possible with a proxy that responds to flow strength. In our revised manuscript we have provided additional information regarding earlier studies that bear on the topic of palaeocurrent reconstruction of ISOW during the Holocene in both the 'previous studies' and 'discussion' sections (including an additional figure to aid the interpretation of the datasets) – see detailed comments below. We also provide further sedimentological information, including the addition of a new figure showing the age models for the cores, which demonstrate continuous and near linear sedimentation rates for the cores throughout the Holocene. A brief perusal of the contents of CP will show that it is a highly appropriate journal for this manuscript, which is closely aligned to the 'aims and scope' of CP. Our study provides marine proxy method development, application, and model-based interpretation to understand palaeo-climate and thus matches three of four main subject areas covered by the journal

FAGEL: "Here are below specific comments : Title – OK Abstract – OK Introduction – OK but I would not say that " we have limited knowledge of the long term behaviour of the overflows " (see line 16). Indeed many publications concern the Holocene evolution of deep circulation, Even quantitative reconstructions of overflow strength are limited, previous studies give some clues on North Atlantic overflows (DSOW, ISOW, NSOW, DSO). I would suggest to enlarge the state of the art in the next section and the discussion in order to better integrate relevant publications (see some suggestions below)."

REPLY: The overflows and the more general 'deep circulation' are not one and the same. However, in our statement regarding 'limited knowledge', we simply were intending to draw attention to the fact that we do not yet have a comprehensive understanding of the Holocene behaviour of the overflows, as well as the fact there is very little direct physical evidence of changes in overflow strength during the Holocene. We fully acknowledge the efforts made by previous workers (including several studies by the co-authors) to explore this topic, and in our revised manuscript we have now included additional references to such previous work as suggested (see below).

FAGEL: "Previous studies This section is too short. Taking into account the problematic, I suggest to expand it in order to present a more exhaustive state of the art. Here are some suggestions of publications with relevant results for the ISOW behavior. Line 19 - Fagel and Mattielli (2011) have combined mineralogy with radiogenic isotopes (Nd & Pb) to trace sediment provenance. Event indirect, such approach has allowed to evidence significant reorganization of paleocirculation of the deep North Atlantic components in the eastern Atlantic basins: mainly the reorganizations for the Iceland-Scotland OverflowWater (ISOW) and the Norwegian Sea OverflowWater (NSOW). For instance they evidenced that the Late Holocene Optimum period was characterised by enhanced particles driven by ISOW. At 6 kyr BP a pronounced shift in the geochemical isotopic ratio evidence a major change in particle supplies driven by the deep current. This period coincides in Nordic Seas with the end of the Holocene Climate Optimum [e.g., Rousse et al., 2006]. After a period characterized by minor variation, Rousse et al. [2006] emphasized increased oceanic instability linked to climate variations, from 6 kyr in core MD99 – 2275, North Iceland (water depth 440 m). The variability, deduced

from magnetic mineral properties, was mainly associated with the renewed activity of the paleo-Irminger Current in relation with periods of enhanced NADW [Knudsen and EirÄśksson, 2002]. Mayewski et al. [2004] also evidenced in cores from Iceland Shelf strong fluctuations in grain size parameters after 6 kyr. In Iceland Basin (ODP980, Feni drift, 2179 m), Oppo et al. [2003] reported a long-term reduction in NADW contribution beginning at 6.5 kyr. Those long-term records all demonstrated that a major change in the regional oceanography took place at 6 kyr, most likely in relation with, as suggested by Rousse et al. [2006], the neoglacial cooling of the surface waters observed in the Denmark Strait [see also Bond et al.,1997]."

REPLY: On balance we agree with the referee that this section was perhaps too short in the original submission and we did not provide sufficient direction to certain previous studies that contribute to the background of the present Iceland-Scotland (I-S) overflow focussed work. We are aware of the references identified in the referees comments and accordingly, have revised the manuscript to provide an additional paragraph where we discuss the general climate trends in the North Atlantic region over the Holocene including many of these references.

We now also more fully outline the findings of studies that have examined deep water changes in the North Atlantic, including the work by Fagel and Mattielli (2011), which synthesises much of their earlier work, work by Oppo et al 2003, Hillaire-Marcel et al 2001, and Hoogakker et al 2011. We simply wish to provide a concise overview of hypothesised changes in the deep circulation of the North Atlantic so that the reader can place our new results in context. We again emphasise that the primary focus of our study is the physical flow speed changes of the Iceland-Scotland (I-S) overflow and we do not wish to divert the reader with a protracted review of all earlier literature on the various hydrographic changes of the deep North Atlantic downstream of our study site.

Fagel's comments are of broad interest but we also observe that cores in shallow water to the north of Iceland do not record signals that have a close link with the subject of our paper, namely the strength of the overflow that descends to depths in excess of 1000 m within a few hundred km to the south west.

We also note that Oppo et al 2003 do not infer a long-term reduction in NADW contribution beginning at 6.5 kyr. Rather, they state “The most pronounced feature of the Holocene is a trend of decreasing relative NADW contribution that began at about 6.5 kyr and culminated with a minimum at around 5 kyr.” There is then an abrupt increase in benthic d13C back to ‘pre-event’ values by ∼4.5 ka. The benthic d13C data of Oppo et al do not show a pronounced long-term decline in NADW; values persist at ∼1-1.2 per mil, with pronounced millennial scale events at 9.3, 8.0, 5.0 and 2.8 ka. Moreover, recent work has suggested that benthic d13C changes at this site are likely controlled by changes in LSW production. Also, benthic d13C can be controlled by many factors including changes in its preformed value (i.e. that of the surface waters form which it is derived) as well as changes in the d13C of the entrained surface and subsurface waters, as well as local remineralisation (e.g. Hall et al 2004, Thornalley et al . 2010, Paleoceanography). Given these uncertainties and our focus on the physical changes in the over flow strength we have chosen not to include any extended discussion of these data.

FAGEL: “Line 15 – In their paper Kissel et al. [2009] interpreted the decreasing trend of the mineral magnetic content in 6 cores from Iceland Basin as a decrease of the ISOW strength over the Holocene. However, they already noticed that their hypothesis was inconsistent with the short-term variations derived from deep-sea proxies [Bianchi and McCave, 1999; Oppo et al., 2003; Hall et al., 2004; Praetorius et al., 2008]. The geochemical observations in Fagel and Mattielli (2011) in cores from Iceland Basin are rather in favor of a continuous depletion of the detrital supply after the Holocene optimum. It is important to to present in this ms the earlier discussions and contradictions.”

REPLY: As already discussed, the studies of Bianchi and McCave, 1999; Hall et al., 2004 and Praetorius et al., 2008 each relied on a single core sites and were therefore unable to fully constrain changes in the strength and depth of the I-S overflow, thus

these records are unlikely to provide a robust record of the overall long-term changes in overflow strength. Indeed, our current study, which incorporates the results of Hall et al 2004 and Praetorius et al 2008, rather demonstrates the impact of a depth migration of the faster flowing axis of the overflow on the downstream palaeocurrent records and reconciles these data sets.

The work by Kissel et al. 2009 has recently been superseded by Kissel et al., 2013, which we now include and discuss. This work demonstrates that their original findings in 2009 were not caused by a depletion of the detrital supply of magnetic grains, and are best explained by changes in flow strength. Their results are therefore in excellent agreement with our data, and we have included a plot of their data along with our new results in the revised manuscript. These datasets are also in excellent agreement with modelling results that have examined long-term changes in deep water formation in the North Atlantic (Renssen et al 2005). We suggest together these provide extremely robust evidence for a decline in I-S overflow strength over the past ∼6 ka

As also suggested by the referee, we discuss the apparent contradictions of earlier work. Notably, the declining trend over the past ∼6 ka displayed by sortable silt data (this study and Hoogakker et al., 2011) and magnetic grain data from numerous sites along the pathway of ISOW (Kissel et al. 2009, 2013), supported by modelling studies, is at odds with the conclusion of Fagel and Mattielli (2011) of a persistent strong ISOW over the past 6 ka, based on the constant high relative abundance of volcanic derived clays from the Mid-Atlantic Ridge (MAR) provenance over this interval. First, we argue that given relative mineral abundance data alone, it is not possible to directly infer weakening of the flow of any one specific water mass (e.g. a decrease in relative abundance of clay from one particular provenance may be caused by an increase in supply from other sources, and vice versa). Second, we suggest that changes in the clay provenance data may be influenced by additional factors unrelated to deep circulation such as the production and delivery of clays from different provenances e.g. caused by weathering changes and the off-shelf delivery of clays, perhaps in response to climatic changes such as neoglaciation, and for example, the increased oceanic instability on the Iceland shelf after ∼6 ka (Rousse et al 2006), highlighted by Fagel and Mattielli (2011). Third, the sites examined by Fagel and Mattielli (2011) are situated at the southern end of Gardar Drift and the Charlie Gibbs Fracture Zone, i.e. distal to the I-S overflow and may therefore be sensitive to other processes downstream of the immediate overflow.

FAGEL: "Some additional references : Bilodeau et al. (1994), Benthic foraminiferal assemblages in Labrador Sea sediments: Relations with deep-water mass changes since the deglaciation, Can. J. Earth Sci., 31, 128– 138. Fagel, N., C. Hillaire-Marcel, M. Humblet, R. Brasseur, D. Weis, and R. Stevenson (2004), Nd and Pb isotope signatures of the clay-size fraction of Labrador Sea sediments during the Holocene: Implications for the inception of the modern deep circulation pattern, Paleoceanography, 19, PA3002, doi:10.1029/2003PA000993. Giraudeau et al (2004), Timing and mechanisms of surface and intermediate water circulation changes in the Nordic Seas over the last 10,000 cal years: A view from the North Iceland shelf, Quat. Sci. Rev., 23(20 – 22), 2127 – 2139, doi:10.1016/j.quascirev.2004.08.011. Giraudeau et al. (2010), Millennial-scale variability in Atlantic water advection to the Nordic Seas derived from Holocene coccolith concentration records,Quat. Sci. Rev., 29(9 – 10), 1276 – 1287, doi:10.1016/j.quascirev.2010.02.014. Hillaire-Marcel et al. (2001), Absence of deep water formation in the Labrador Sea during the last interglacial period, Nature, 410,1073–1077. Knudsen and J. EirÄśksson (2002), Application of tephrochronology to the timing and correlation of palaeoceanographic events recorded in Holocene and late Glacial shelf sediments off north Iceland, Mar. Geol.,191, 165 – 188, doi:10.1016/S0025- 3227(02)00530-3. Kuijpers et al., (2003), Late Quaternary sedimentary processes and ocean circulation changes at the southeast Greenland margin, Mar. Geol.,195, 109– 129. Mayewski, P. A., et al. (2004), Holocene climate variability, Quat. Res.,62(3), 243 – 255, doi:10.1016/j.yqres.2004.07.001. Rousse et al. (2006), Holocene centennial to millennial-scale climatic variability: Evidence from high-resolution magnetic analyses of the last 10 cal kyrs off North Iceland (core MD99

– 2275), Earth Planet. Sci. Lett., 242, 390 – 405, doi:10.1016/j.epsl.2005.07.030. Solignac et al. (2004), Holocene sea-surface conditions in the North Atlantic - Contrasted trends and regimes between the eastern and western sectors (Labrador Sea vs. Iceland Basin), Quat.Sci. Rev., 23, 319–334."

REPLY: We thank Fagel for these additional references, which we have added as appropriate to our revised manuscript.

FAGEL: "Method Lines 19-25 – The text is not clear. The proposed 1000-yr smoothing method must also be discussed according to the temporal resolution in the different proxy records. You should indicate what is the sampling resolution before you propose temporal average. The 14C ages are reported as supplement data but I think it is crucial to present the age models and their uncertainties. What about the sediment model deposition ? is there any hiatus in the record ? Remobilization of glacial sediments by the renewed ISOW at the end of the deglaciation was for instance observed by Kissel et al.(2009) in the same marine sector."

REPLY: We have not applied a smoothing to the records. We have simply calculated the mean and standard deviation of 1000 year 'windows or bins' so that we are able to statistically compare changes in the inferred flow speeds at different intervals. In the revised manuscript we have included the temporal resolution of the records (ranging from ∼100 year down to 500-1000 year resolution). We have also included a figure that shows the age models for each of the cores, which highlights a near linear sedimentation rate at each site over the Holocene (see attached Fig. 1). This strongly suggests that there are no prolonged hiatuses present within the archives. We are not aware of any a priori reason to suspect hiatuses are present in our cores located on Bjorn Drift. Each core is characterised by high Holocene sedimentation rates of silty-clay lithologies with no foraminifera sand lag deposits present, which we might expect if sufficient active winnowing was present to form a hiatus.

FAGEL: "Sensitivity test – ok Calibration As it is stated in the ms, a calibration with only

5 points is not very robust, it just gives a trend. Some additional information must be give about the sediment model deposition for those 5 locations (winnowing ? focusing ?). I'm surprised that they are so few available data. Using cruise report I would suggest to compile a regional map of bottom current strength to give a spatial representation of modern current strength in the study area. In parallel I assume they are more available grain size data on surface sediments from the Iceland basin ? Even the measurements were not performed using the same Sedigraph method, an estimation of sortable silt values may be calculated from raw grain size data. Even the current strength and the SS proxy is not measured at the same location, it could give some indication to support the calibration."

REPLY: The core-tops are mud-rich and, as demonstrated by our core top 14C dates, all 5 sites have late Holocene sediment. As discussed in the manuscript, long-term current meter measurements are required to compare to core tops, yet such data are indeed sparse in the Iceland Basin. This is because no one has focussed their coring on old current meter sites. The generality of a relationship between sediment size and current paths was shown regionally for the Argentine basin by Ledbetter (1986, Nature) but that sort of information does not enable a size-speed calibration. We are unsure as to what cruise report data would enable us to accurately reconstruct bottom current strength, other than seafloor observations and geostrophic flow speed calculations made by cruises specifically addressing this issue, which we have referenced (Shor, 1980; Bianchi and McCave, 2000). Contrary to the referee we don't feel it is appropriate, for the purposes of a calibration, to compare SS data and current strength data that are not recorded at the same site because of local topographic variations in flow speed, such as those discussed by Shor (1980) and van Aken (1995). As mentioned, more extensive, ongoing calibration work is being coordinated by co-author Nick McCave which will be presented in detail in a forthcoming dedicated manuscript; the focus of our paper is on long-term trends in the Holocene overflow. Our conclusions do not hinge on the precise calibration of SS, as we demonstrated in our original figure 4, by comparing the results obtained from normalized versus 'raw' data. The trends

remain robust.

FAGEL: "Result and Discussion 4.1 proxy Fig. 1 – Since modern ISOW only influences the sites deeper than 1300 m I would suggest to adapt the depth intervals (1200 to <1300 for the first group)."

REPLY: This is indeed the depths covered by the first group of cores (cores at 1.19 km, 1.24 km and 1.3 km).

FAGEL: "For 1375-1575m how do you explain the important error bars on the average profile? Some error bars are as important as the total range of variation for sortable silt proxy. Do the two records give unconsistent results?"

REPLY: The error bars are the 2 standard error of the 'binned' data. Since there are relatively few data for these cores, the standard errors are large. This also simply reflects the difficultly (and reduced reliability) of estimating uncertainty when there are only few data points. It is likely that the data are somewhat aliased by higher frequency variability. However, similar long-term trends are observed.

FAGEL: "Between 1575 and 1750m the individual trends do not record many fluctuations over the Holocene. What's your interpretation ? Between 1750-2250m the trends are different from one core to another. The figure needs to be deeper discussed in the text. Indeed the stacked curve mainly mimicts the average trend for the cores collected around 1.5 km. The other records are more variable. with a max. Does this depth corespond to the main axis of influence of ISOW ? The stacked curve is characterise by a maximum during the climate Holocene optimum and a progressive decline but a plateau is observed between 5 and 3 kyr BP, an interval consistent with deep current reorganisation (see Fagel and Mattielli, 2011 ; Fagel et al., 2004 and reference therein)"

REPLY: One of the key findings of our work is that it records the changing depth of the I-S overflow throughout the Holocene. It is hence difficult/inappropriate to interpret any one depth interval in isolation and we therefore refrain from interpreting results at any one depth, as suggested. For example, the relatively flat data for 1575-1750m can be explained by these sites being influenced by the lower edge of the shallow I-S overflow during the early Holocene. A peak in flow at these sites is recorded at ∼7 ka as the main flow of I-S overflow passes through this depth during its early Holocene deepening. Flow speed then decreases as these cores are located on the upper edge of the main flow of I-S overflow water through the remainder of the Holocene. To aid the reader visualise the changes in I-S overflow depth and strength through the Holocene, we have included in our revised manuscript (see attached Fig. 2) a contour plot of grain size changes with respect to depth through the Holocene. This more clearly shows the deepening of the main flow of I-S overflow during the early Holocene. We also provide additional text to help clarify the evolution of the I-S overflow through time at the various core depths. Those within the deepest group all show similar trends: weak early Holocene flow (albeit with some strengthening at ∼10 ka), peak flow at ∼6-7 ka and then a long term decline. We disagree with the referee's assertion that the stack mainly mimics the cores around 1.5 km. The cores at 1.5 km show peak values during the early Holocene (8-11 ka), whereas the stack has a later pronounced peak at 6-7 ka. As highlighted above, the stack is calculated by averaging the 'binned' data from all cores and is therefore representative of all depth groups. As also described in the manuscript, we also calculated a weighted stack (weighted according to the depth range of each interval), since the weighting was greatest for the deepest group, if anything, the weighted stack most strongly resembles this group. The uncertainty in our stack does not allow us to confidently assess whether there is a plateau at 3-5 ka or not. As reported in the original manuscript the data show a decline after 7 ka that can be described using a linear regression (n=8, R-squared =0.94, p<0.001), or as a monotonic trend with the rank correlation coefficient, Kendall tau=1, p<0.001.

FAGEL:"Figure 5 – Why do you not report the curves from Kissel et al (2009), Rasmussen et al .2002) and Hoogakker et al. (2011)? Those papers are cited in the text but it could be useful for the discussion to compare the Holocene record of ISOW strength, even some contradictions have been evidenced. The neoglacial trend is not

obvious from the benthic 13C profile (5f). We rather observe a sharp decrease than a stabilization."

REPLY: We have included the updated, new magnetic data of Kissel et al (2013) in our revised manuscript (attached Fig. 3). Rasmussen et al (2002) do not present time series, but three discrete time slice maps, which can therefore not be plotted as a time series. Given our observations suggesting the migration of ISOW depth through time we have avoided direct comparison to previous records based on a single core e.g. Hoogakker et al (2011) as this would rather negate one of our main conclusions: the importance of using a depth transect when investigating overflows. Because of the aforementioned complications in using benthic d13C to infer changes in the strength of deep water formation, we have removed the benthic d13C plot.

FAGEL:"4.2 model Figure 6 – The changes during the climate holocene optimum and the neoglacial have been already suggested in several papers (see suggested additional references). I would suggest to discuss deeper the discrepancies between the model and the proxy data (see the end of the section). Are the model trends consistent with other publications?"

REPLY: As discussed, the model trends are consistent with existing paleoclimate data, which we have cited. For further comments on the model aspects, we refer to our comments to Review 2.

FAGEL: "Conclusion – OK References – OK, all citations are listed. Hoping this review will help to improve the ms, Your sincerely, Nathalie Fagel"

Interactive comment on Clim. Past Discuss., 9, 1627, 2013.

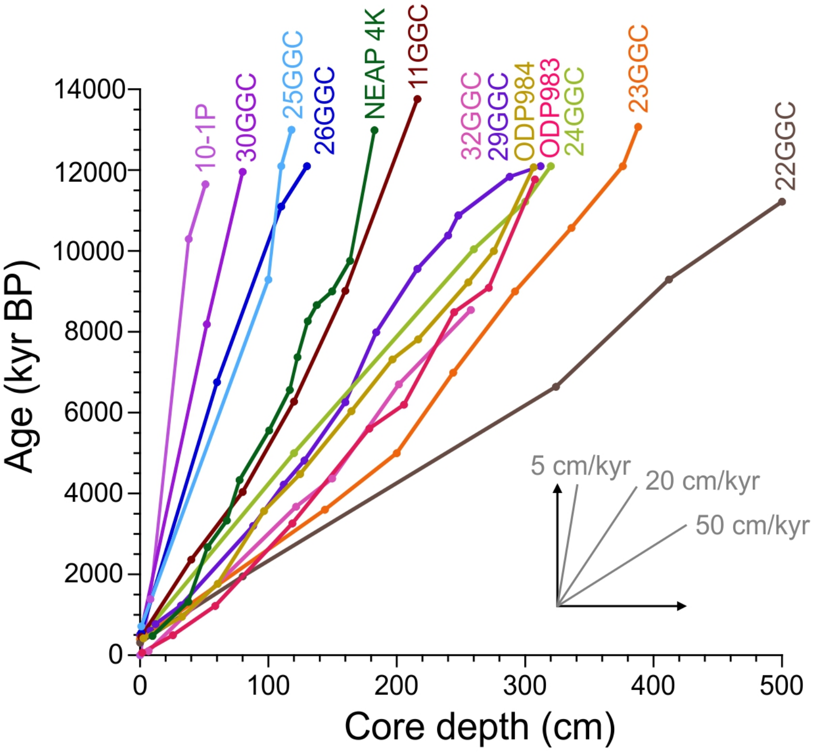

Fig. 1. Age models for sediment cores. See also Supp. Info.

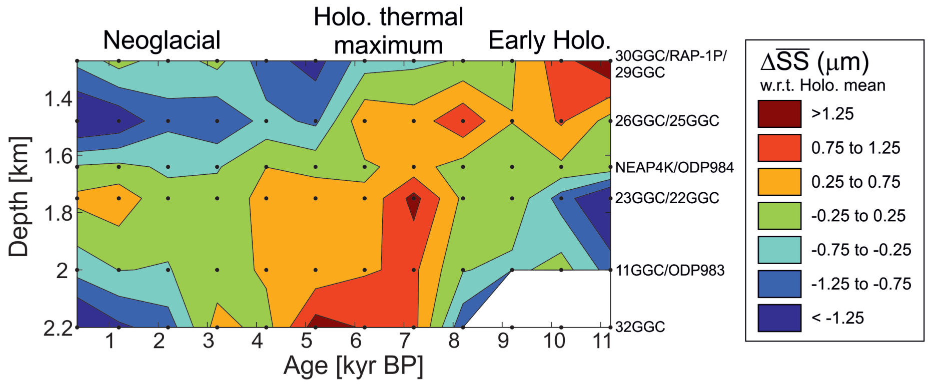

Fig. 2. Contour plot showing change in grain size (flow speed proxy) through time at different depths

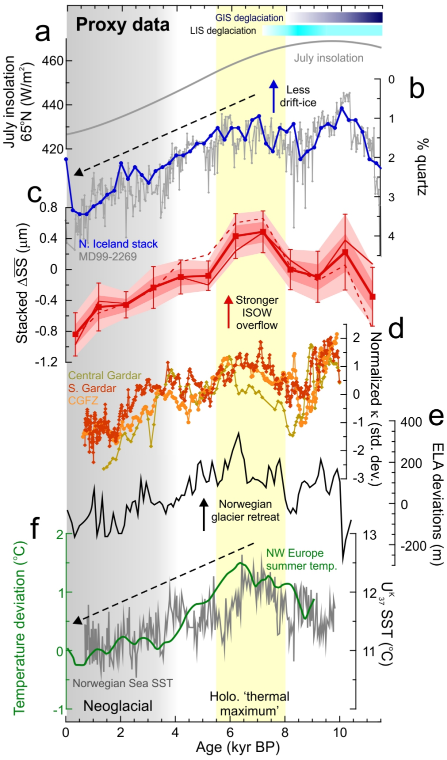

Fig. 3. Revised comparison of our I-S overflow stack to other climate records, now including in part (d) magnetic susceptibility data (proxy for ISOW strength) from Kissel et al 2013