

1 **Wind regime changes in the Euro-Atlantic region driven by Late-Holocene Grand**
2 **Solar Minima**

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36 **Keywords:** Solar Activity, Atmospheric Circulation, Varves, Diatoms, Climate Change.

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54 **Abstract:**

55 **Understanding atmospheric response to radiative forcing, including the intensity and**
56 **distribution of wind patterns is critical as this might have important implications in the**
57 **coming decades. Long-term episodes of reduced solar activity (i.e. Grand Solar Minima,**
58 **GSM) have triggered rapid climate change in the past, recorded in proxy-based records,**
59 **including varved sediments from Meerfelder Maar, Germany, where the Homeric GSM**
60 **(~2800 years ago) was studied. This study reconstructs windy conditions during the**
61 **same GSM from Diss Mere, another varved record in England, to support the solar-wind**
62 **linkage in the North Atlantic-European region. We use diatoms as proxies for windiness**
63 **and support the palaeolimnological and palaeoclimate interpretation with a multi-proxy**
64 **approach, including sedimentological, geochemical, and biological (chironomids and**
65 **pollen) evidence. The diatom assemblage documents a shift from *Pantocsekiella***
66 ***ocellata* dominance to *Stephanodiscus parvus* and *Lindavia comta*, indicating a shift to**
67 **more turbulent waters from $\sim 2767 \pm 28$, linked to increased windiness. This shift is**
68 **synchronous with changes in ^{14}C production, linked to solar activity changes during**
69 **the GSM. Both proxy records reflect a rapid and synchronous atmospheric response**
70 **(i.e. stronger winds) at the onset and during the GSM in the North Atlantic and**
71 **continental Europe. In order to test whether this solar-wind linkage is consistent during**
72 **other GSMs and to understand the underlying climate dynamics, we analyse the wind**
73 **response to solar forcing at the two study sites during the Little Ice Age, a period that**
74 **includes several GSMs. For this, we have used a reconstruction based on a 1200-year-**
75 **long simulation with an isotope-enabled climate model. Our study suggests that wind**
76 **anomalies in the North Atlantic-European sector may relate to an anomalous**
77 **atmospheric circulation in response to long-term solar forcing leading to north-**
78 **easterlies modulated by the East Atlantic pattern.**

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81 Introduction:

82 Solar activity has trended toward weaker solar cycles in the last four decades. Solar Cycle
83 (SC) 24 (2009-2020) was below-average and SC 25 is expected to be weak. The prediction
84 of future cycles comes with high uncertainty and some studies have suggested that the Sun
85 is approaching a Grand Solar Minima (GSM) (Lean et al. 1997; Maycock et al. 2015), while
86 the Solar Cycle Prediction Panel suggests SC 25 (2021 ~ 2032) might be the end of the current
87 weakening (Nandy 2021). Reductions in total solar irradiance may only have a small influence
88 on average global surface temperature (Maycock et al. 2015), however, there has been a
89 contemporaneous decrease in ultraviolet solar irradiance (Lean et al. 1997), which could
90 influence Northern Hemisphere regional winter climate through top-down mechanisms
91 modulating modes of climate variability (Matthes et al. 2006; Woollings et al. 2010; Gray et al.
92 2010; Ineson et al. 2015). In northern-central Europe, persistent low solar activity is likely
93 associated with anomalously cold winters on multidecadal timescales (Ineson et al. 2015) and
94 tropospheric blocking events, likely associated with a more negative Arctic Oscillation index
95 (Maycock et al. 2015), in the absence of other controlling factors. Long-term solar forcing does
96 not, however, have an impact on North Atlantic Oscillation (NAO) (Ortega et al. 2015; Maycock
97 et al. 2015), but instead, the East Atlantic pattern (EA) (Sjolte et al. 2018), the secondary mode
98 of atmospheric circulation in the North Atlantic region. On the other hand, reanalysis data
99 suggest wind speeds over western Europe are affected by the EA modulating the influence of
100 the NAO (westerlies) on regional wind patterns (Zubiate et al. 2017). Thus, when NAO and
101 EA have opposite indices there are positive wind anomalies over Ireland, the UK and central
102 Europe (Zubiate et al. 2017). As such, decadal-scale variations of surface wind may be
103 influenced by the variability in the dominant spatial climate patterns in the region, which define
104 the main climate modes, for example the NAO, EA and Scandinavian pattern, Atlantic
105 Multidecadal Variability (Zeng et al. 2019; Hernández et al. 2020). In addition, statistical
106 models for wind series of the last 40 years reveal a reversal in global terrestrial stilling since
107 2010, with potentially significant impacts for Europe (Zeng et al. 2019). This decadal-scale

108 shift to a positive trend of observed surface wind speeds coincides with the weak SC 24 and
109 25, suggesting enhanced windiness could continue, at least, for the next decade.

110 GSMS occur on centennial timescales (Usoskin et al. 2007), with the best studied (Dalton,
111 Maunder, Spörer and Wolf Minima) occurring during the Little Ice Age (LIA, AD 1300 - 1850)
112 (Brehm et al. 2021), a period also characterised by high volcanic activity (Miller et al. 2012).
113 Annually resolved ¹⁴C based reconstructions of solar reconstructions are now available for
114 earlier GSM's, specifically the Wolf (1279-1349 AD) and Oort Minima (1021-1060AD) (Brehm
115 et al. 2021). GSM are thought to potentially trigger notable cooling, particularly in Europe and
116 North America (Owens et al. 2017), although evidence for the climatic impact of GSM is
117 complicated by other factors, such as human modification of the environment and volcanic
118 forcing (Sigl et al. 2015). One important GSM prior to the last millennia was the Homeric
119 Minimum, which occurred ~2800 years ago (Stuiver and Kra 1986). It is not associated with
120 significant volcanic forcing (Zielinski and Mershon 1997), and has much less human impact,
121 that may influence climate proxy data. The period around the Homeric Minimum (~2800-2550
122 cal. BP) is divided into a higher amplitude initial event from ~2750-2635 cal. BP, that we
123 consider as the Homeric GSM, followed by a lower amplitude, secondary minimum between
124 2614 – 2594 cal. BP (Reimer et al. 2020). Additionally, it must be noted that at ~2610 cal. BP
125 there is a short-lived solar proton event, which triggered increased ¹⁴C production (Muscheler
126 et al. 2005; O'Hare et al. 2019; Reimer et al. 2020), however, this short-lived event is likely
127 not linked to longer-term changes in solar activity. LIA climatic reconstructions from proxies
128 and climate simulations report temperature and/or precipitation anomalies linked to low solar
129 activity (Luterbacher 2001; Luterbacher et al. 2001; Shindell et al. 2001; Mauquoy et al. 2002).
130 However, assessing past GSM influences on atmospheric changes, including wind intensity,
131 duration, and direction, requires highly resolved wind-sensitive records with annual to decadal
132 resolution. The annually laminated (varved) record from Meerfelder Maar, Germany (MFM;
133 50° 6'N, 6° 45'E) (Fig. 1.a) is a relatively rare record for this time period in Europe, showing
134 increased windiness for 199 ± 9 varve years, coincident with the Homeric GSM (Martin-

135 Puertas et al. 2012). This study suggested top-down mechanisms triggered a synchronous in-
136 phase response of atmospheric circulation to solar forcing (Martin-Puertas et al. 2012).
137 However, the use of a single site only provides evidence of the impact of the GSM in one
138 continental location and requires confirmation by additional highly resolved records, to allow
139 the testing of the regional expression of GSM and to preclude a coincidental relationship.

140 This new study presents a multiproxy record from the varved sediments of Diss Mere (52°
141 22'N, 1° 6'E), with the main goal of testing the hypothesis of a comparable solar-induced shift
142 in windiness in the British Isles during the Homeric GSM. The multiproxy study is built around
143 a diatom-based reconstruction of Diss Mere sediments. Diatoms are sensitive to a range of
144 environmental variables and can respond rapidly to changes in environmental conditions due
145 to their short life cycles (hours to days), making them excellent palaeoecological,
146 palaeoenvironmental and palaelimnological proxies (Kilham et al. 1986; Rioual et al. 2007;
147 Jones 2013). While they are used in a diverse range of studies, one way diatoms can be
148 employed is to infer changes in windiness, due to the specific requirements of some species
149 (often smaller, less silicified taxa) for still, clear waters, while others (often larger and heavily
150 silicified species) require turbulent waters to remain suspended within the photic zone (high
151 light zone allowing phytoplankton to photosynthesise). Other species can thrive in conditions
152 with reduced light and higher nutrient concentrations, generated as nutrients are resuspended
153 in the water column from deeper mixing due to increased turbulence, and in some cases, it is
154 documented that this can increase nutrient uptake (Kilham et al. 1986; Bradbury et al. 2002;
155 Rioual et al. 2007; Winder and Hunter 2008; Dell'aquila et al. 2017). This means periods of
156 change in wind and turbulence can be rapidly identified in the diatom assemblages. Our
157 diatom record is supported by additional proxies; in this case, sedimentary data (varve
158 counting, micromorphology and high resolution XRF analyses)(Martin-Puertas et al. 2012),
159 combined with pollen analyses at the same resolution as the diatom reconstruction, to assess
160 for landscape change and human impact, and a chironomid-inferred summer temperature
161 record (C-IT). Together these allow reconstruction of climate and environment around the

162 Homeric GSM (2400 – 3000 cal. BP). This multiproxy approach is essential to ensure changes
163 in the diatom reconstruction are not driven by changes on the landscape (e.g. landscape
164 clearance removing shelter from the edge of the lake leading to detrital input into the lake, as
165 this could also influence diatom productivity). We compare these to the wind sensitive MFM
166 record, to produce a regional picture of the atmospheric circulation, and consider this in the
167 light of published records of atmospheric change at this time, such as precipitation and aridity.
168 We also examine a wind reconstruction that utilises seasonal ice core records and an isotope
169 enabled model simulation during the LIA (Sjolte et al. 2018), which allows us to better
170 understand the atmospheric response to GSM during the last millennium and support the
171 climate response further back into the Holocene.

172 **Study Site:**

173 Diss Mere is a small eutrophic lake (~3.4 ha) located in the east of England (52° 22'N, 1° 6'E;
174 29 m a.s.l), on the edge of the North Sea (Fig. 1.a), a key region for wind energy production
175 (Geyer et al. 2015). The lake is one of the few varved (annually-laminated) records in the UK
176 covering the Holocene period, has a maximum water depth of ~6 m and no surface inflows or
177 outflows (Peglar et al. 1984). Historic weather data for Norfolk show mean annual
178 temperatures of 14.1°C max and 6.0°C min, mean annual precipitation of 652 mm (min rainfall
179 February, max rainfall October), with seasonal average rainfall between 34 and 72 mm. Winds
180 are predominantly from the south-east, with an average annual speed of 8.9 knots (10 m
181 heights) (UK Met Office).

182 The sedimentary record (DISS-16) is ca. 14.5 m long and 8473 ± 40 varves are preserved
183 between 8.88 – 13.15 m sediment depth. The varves consist of a calcite summer sub-layer
184 and an organic-diatom autumn to spring sub-layer (Fig. 1.b) (Martin-Puertas et al. 2021). The
185 floating varve chronology was tied to the IntCal20 timescale (Reimer et al. 2020), using a
186 Bayesian *P_Sequence* deposition model with a fixed K and automatic outlier detection (Bronk
187 Ramsey 2008, 2009). The model combined prior data from five radiocarbon dates and two
188 known tephra layers (Glen Garry and OMH-185) (Martin-Puertas et al. 2021; Walsh et al.

2021). The resulting age-depth model (DISSV-2020) places the varved sequence between ca. 2100 and 10,300 cal. BP with decadal scale age uncertainties (95% confidence). The DISSV-2020 chronology was published by (Martin-Puertas et al. 2021) and further details on the construction of the chronology and a full dataset is freely available on the Varved Sediments Database (VARDA) repository at <https://varve.gfz-potsdam.de/>.

Data and Methods

Sediments and X-ray Fluorescence (XRF) core scanning data

Four parallel sediment cores were obtained in September 2016 from the deepest part of Diss Mere, using a 90 mm diameter UWITEC piston corer (Martin-Puertas et al. 2021). The sediment profiles were cross correlated using a total of 67 macroscopically visible marker layers and the best-preserved sections were combined to construct a 14.5 m long continuous composite profile (DISS-16) (Martin-Puertas et al. 2021). Varve counting and microfacies analysis (varve composition and varve thickness measurements) were studied on overlapping thin sections of 10 cm length under the microscope (x80 magnification). The duration of the climatic anomaly was calculated using the varve count-based time scale and relative varve counting error between marker layers. The uncertainty was calculated as the standard deviation of four replicate varve-counts. When we compare the duration of climate anomalies between Diss Mere varves and other varved records, the errors are propagated using the law of combination of errors (for more information see Supplementary Information).

Micro-XRF core scanning data were acquired every 0.2 mm by irradiation of the split core surface with a Cr X-ray source (30 kV, 30 mA) for 10 s using an ITRAX XRF-core scanner. XRF measurements are presented as central log ratios (clr) in order to provide a more reliable prediction of element concentration in the sediments (Weltje and Tjallingii 2008). Additional micro-XRF scanning maps were measured on impregnated sediment blocks used for thin-section preparation (Supplementary Fig. S1). Elemental mapping analyses were performed in a vacuum chamber at 50 μm resolution with a M4 Tornado micro-XRF scanner. This micro-XRF scanner is equipped with a Rh X-ray source (50 kV, 0.60 mA) in combination with

216 polycapillary X-ray optics, to produce a high intensity irradiation spot of about 20 μm that
217 allows fast measurement times (30 ms).

218 Diatoms

219 81 contiguous samples at 0.5 cm intervals between 909.3-949.8 cm were prepared for diatom
220 compositional analyses following the digestion procedure (Battarbee et al. 2001). This
221 involved removal of organics and carbonates with H_2O_2 and HCl respectively, and during
222 rinses NH_3 , was used to prevent diatom clumping. Diluted samples were pipetted onto cover
223 slips, evaporated and then mounted in NaphraxTM mounting resin. Slides were counted using
224 a Leitz Laborlux D at x1000 magnification, until a minimum of 300 diatoms were identified.
225 Identifications were made using key diatom taxonomies (Krammer, K. and Lange-Bertalot
226 1986, 1988, 1991a, b; Lange-Bertalot 2001; Krammer 2002). Raw counts were transformed
227 to percentages to provide relative abundances.

228 Pollen

229 For pollen analysis, 72 samples were taken contiguously at 0.5 cm resolution between 913.8
230 cm and 950.3 cm. Preparation followed well-established procedures (Faegri and Iversen 1989;
231 Moore et al. 1991), with steps including the addition of *Lycopodium* spores before chemical
232 treatment to enable the calculation of pollen concentrations (Stockmarr 1971), heavy liquid
233 flotation using sodium polytungstate (SPT; at a specific gravity of 2.0 g cm^{-3}) and acetolysis.
234 Slides were mounted in glycerine jelly and pollen identification took place under 400x
235 magnification on an Olympus CX41 light microscope. A minimum counting sum of 500 Total
236 Land Pollen (TLP) was achieved for each slide with pollen nomenclature following (Stace
237 2010).

238 Chironomidae

239 21 samples were taken between 909.8 and 950.3 cm, at a 2 cm resolution. Pilot samples had
240 low head capsule concentrations, so sample volumes were increased (2.2 g for pilot samples,
241 10 g for additional samples). Samples were heated to 80°C in 10% KOH for 3 minutes or until

242 fully disaggregated and sieved through 180 μm and 90 μm meshes. Both size fractions were
243 retained and agitated for 10-15 seconds in a sonic bath and re-sieved prior to picking and
244 examined at x20 and x30 magnification. Chironomid remains were picked and mounted in
245 hydromatrix on microscope slides, and identified to genus, sub-genus or species-type under
246 x100-400 magnifications (Weiderholm 1983; Brooks et al. 2007). Percentages were
247 calculated and diagrams plotted using Tilia and Tilia View (Grimm 1987). Mean July air
248 temperatures were derived using the modern Norwegian chironomid–temperature transfer
249 function (Brooks and Birks 2001) and percentage data are square root transformed prior to
250 analyses, to minimise variance. Reconstructed temperatures were calculated using a
251 weighted averaging partial least squares regression model (WA-PLS) and all analyses were
252 run in R v 3.6.0 (R Core Team 2020).

253 Solar forcing record

254 Here we use the recently updated IntCal20 ^{14}C calibration curve (Reimer et al. 2020) to
255 assess solar variability over the considered period. On timescales shorter than 500 years, the
256 cosmogenic radionuclide variability is likely dominated by the effects of solar shielding of
257 galactic cosmic rays, as illustrated by the agreement between higher ^{14}C production rate and
258 lower solar activity over the past 400 years (Lal and Peters 1967; Snowball and Muscheler
259 2007; Muscheler et al. 2016). The agreement between ^{14}C production rate and ^{10}Be measured
260 in Greenland ice cores supports the production-induced changes in these records, i.e.
261 rejecting the hypothesis that the ^{14}C variations are driven by carbon cycle changes (Vonmoos
262 et al. 2006). We calculated the ^{14}C production rate from the atmospheric ^{14}C fluctuations using
263 a box-diffusion carbon cycle model (Siegenthaler 1983) assuming a constant carbon cycle.
264 The uncertainty in the IntCal20 calibration curve was quantified using 100 posterior
265 realizations of possible atmospheric ^{14}C curves obtained via fitting Bayesian splines to the ^{14}C
266 data underlying IntCal20 (Reimer et al. 2020; Heaton et al. 2020). In Figure 3 we show the
267 average of 100 possible realisations of the production rate.

268 Climate reconstruction

269 In the wider discussion of our results, we use a published reconstruction of sea level pressure
270 (SLP) (Sjolte et al. 2018) covering CE 1241-1970, as well as the corresponding 850 mb wind
271 extracted using the same methods (Sjolte et al. 2018). The reconstructions are based on the
272 analogue method selecting best matching years from the output of the ECHAM-wiso/MPIOM
273 isotope enabled climate model (horizontal resolution, $3.75^\circ \times 3.75^\circ$) compared to seasonal
274 resolution Greenland ice core oxygen isotope records. Using an ensemble approach, the
275 mean of the 39 best matching years of the climate model fields (e.g., SLP), are used to make
276 the reconstruction. Full details of the methods used for the reconstruction are given in Sjolte
277 et al. (2018), and the reconstruction has been validated against reanalysis data (Sjolte et al.
278 2018, 2020). The analysis for the min-max anomalies in Figure 4 excludes years possibly
279 impacted by volcanic eruptions (Sjolte et al. 2018).

280 **The proxy-record of Diss Mere**

281 The time window in this study covers ca. 2400 to 3000 cal. BP (varve number 367 - 988),
282 which is 40 cm long (910 – 950 cm of depth) in the sedimentary record of Diss Mere (Fig. 1.c).
283 The Bayesian age-depth model provides an absolute age uncertainty of between ± 27 and 33
284 years along the studied interval and the relative varve counting error is ± 8 years
285 (Supplementary Table 1), providing exceptional absolute and relative precision for our
286 palaeoecological reconstruction (Martin-Puertas et al. 2021).

287 Varves are, generally, well preserved along the studied time window with Varve Quality Index
288 (VQI) of 3.48 (4 being outstanding varve preservation). Varve thickness variability is relatively
289 constant through most of the study interval with an average varve thickness of 0.6 mm (Fig.
290 2.a). The main components of the varved sediments, i.e. authigenic calcite, diatom blooms
291 and detrital background sedimentation, are represented by Calcium (Ca_{clr}), Silica (Si_{clr}) and
292 Titanium (Ti_{clr}), respectively (Fig. 2.b-d; Supplementary Information Fig. 1). Sediment
293 composition is quite stable along the entire episode with Ca being the most abundant element.
294 Ti values are low suggesting that the detrital input into the lake is a minor process influencing
295 lake deposition. Si values are associated with biogenic silica production, primarily from diatom

296 blooms occurring within the lake (Supplementary Information Fig. 1). Only a 60-year interval
297 (ca. 2810 – 2750 cal. BP) at 936.4-929 cm depth show anomalies in both varve preservation
298 and thickness from 2810 to 2750 cal. BP. For the first 40 years, from ca. 2810 to 2770 cal.
299 BP, the varve thickness increases (average 0.93 mm) and both the calcite and the detritus
300 sub-layer are thicker, but the laminations are discontinuous, which prevent an exhaustive
301 varve thickness measurement (Fig. 2.a). The VQI goes down to a minimum of 2 during this
302 interval. Varves are intercalated with 1-2 cm thick massive deposits mainly composed of Ca
303 and Si that could represent re-deposition of calcite mud, likely from the littoral zone
304 (Supplementary Fig. S1). From 2770 to 2750 cal. BP, the laminations are not well preserved
305 (VQI=1) and 20 varves were interpolated (Fig. 1.c; Fig. 2.a; Supplementary Table S1).
306 Following these 20 years, varves preserve well again (VQI=3-4) (Fig. 1.c; Fig. 2.a).

307 Diatoms as a proxy record of windiness at Diss Mere

308 Diatoms are abundant throughout the Diss Mere sequence, and during the studied time
309 window are dominated by planktonic *Pantocsekiella ocellata* (Pantocsek) K. T. Kiss and E.
310 Ács, *Lindavia comta* (Kützing) Nakov, Gullory, Julius, Theriot & Alverson, *Stephanodiscus*
311 *parvus* Stoermer and Håk and littoral *Nitzschia gracilis* Hantzsch. The record divides into three
312 main sections, with additional small fluctuations occurring throughout the assemblage. Diatom
313 preservation is good at Diss Mere, as measured by the F_{index} (Fig.2.E; Supplementary
314 Section 1.1), which has reasonably high values throughout (average 72% pristine), indicating
315 the majority of diatom frustules preserved are in excellent condition. Although dissolution is
316 generally limited, it is noted between 2748 - 2712 \pm 28 cal. BP that the F_{index} values are
317 lower, highlighting that during this period it is possible that some of the smaller and lightly
318 silicified species may have been preferentially removed from the record. This is supported by
319 lower levels of Si_{dfr} , which may be linked to this increased diatom dissolution. This increased
320 dissolution is likely due to lower silica saturation in the water column at this time (Cohen 2003;
321 Flower and Ryves 2009). It is only once silica levels are restored, that the diatom F_{Index}
322 values increase, due to increased silica availability.

323 The earliest section (~3000 cal. BP) of the Diss Mere diatom assemblage is relatively stable,
324 with *P. ocellata* dominating (~50-90%), alongside lower (generally <30%), fluctuating *L. comta*
325 and *N. gracilis*. *P. ocellata*'s dominance is linked to its opportunistic tendencies, small size and
326 slow sinking rates, allowing it to thrive in wide-ranging conditions (Rioual et al. 2007; Malik
327 and Saros 2016) (Supplementary Table S2). It's occurrence alongside *N. gracilis*, indicates
328 high light intensity, which these species favour (Fritz 1989; Malik and Saros 2016), and
329 consequently, that the period of mixing is limited (as this would reduce water clarity and light
330 availability through sediment resuspension), but sufficient to allow low quantities of *L. comta*
331 to be sustained in the plankton. A brief occurrence of *S. parvus* at $\sim 2926 \pm 28$ cal. BP may
332 indicate a short-lived period with increased mixing/turbulence, required by *Stephanodiscus* to
333 sustain its position in the photic zone (Kilham 1990) (Supplementary Tables S2 and S3).

334 A second shift from *P. ocellata* to *S. parvus* between $\sim 2767 - 2755 \pm 28$ cal. BP also indicates
335 increased turbulence (triggering declining light availability due to reduced water clarity, needed
336 for photosynthesis (Kilham et al. 1986; Kilham 1990; Bradbury et al. 2002; Rioual et al. 2007))
337 and littoral input, potentially from wind-induced wave activity at the shoreline, which may have
338 driven the increased quantity of *N. gracilis* at this point (Fritz 1989). Deeper and prolonged
339 annual mixing episode(s) could also explain the changes in the varve preservation during this
340 period, where varves are interpolated, as varve preservation requires anoxic/suboxic bottom
341 water (Zolitschka et al. 2015).

342 The following shift to *L. comta* at $\sim 2749 \pm 28$ cal. BP is considered to indicate changing
343 proportions of nutrients in the water column, potentially driven by a reduction in mixing depth
344 and therefore reduced internal mixing of nutrients, including phosphorous, which
345 *Stephanodiscus* requires in high quantities (Kilham et al. 1986; Kilham 1990; Rioual et al.
346 2007) (Fig. 2.f; Supplementary Fig. S1; Supplementary Table S2), although it still suggests
347 continuing turbulence, which is required to keep it suspended in the photic zone (Winder and
348 Hunter 2008). Low levels of *P. ocellata* are likely sustained during a shortened period of
349 summer stratification (Rioual et al. 2007). Reduced mixing depth or duration may also explain

350 the renewed varve preservation after ~2750 cal. BP. Alongside this, *N. gracilis* almost
351 disappears from the record at $\sim 2754 \pm 28$ cal. BP, indicating that light intensity is reduced
352 (Fritz 1989), supporting the interpretation of increased turbulence (Supplementary Table S2).
353 From 2621 ± 29 cal. BP *L. comta* completely disappears from the record, while *P. ocellata*
354 returns to dominance, indicating reduced turbulence and wind induced mixing (Fig. 2.f;
355 Supplementary Tables 2 and 3).

356 In summary, we suggest the occurrence of *L. comta* and *S. parvus* indicate increased
357 turbulence in the lake and consider this a proxy for increased windiness in the area around
358 the site (Moreno-Ostos et al. 2009)(Fig. 3a).

359 Multi-proxy cross-validation of the climate signal

360 In addition to the diatom record, we have included a ~5-year-resolution pollen record and a
361 ~30 - 50-year-resolution chironomid inferred temperature reconstructions (CI-T), in order to
362 reconstruct the landscape around the lake and to determine the extent to which land-use
363 change could have impacted our proxy responses during this time interval. Arboreal taxa, such
364 as *Quercus*, *Corylus* and *Alnus*, are well represented in the Diss Mere pollen profile, and
365 abundances of these woody taxa remain relatively stable throughout (Fig. 1.h; Supplementary
366 Fig. S1). Low levels of herbaceous taxa are present in the pollen record, and include taxa
367 associated with human activity. Overall, we interpret the landscape at Diss Mere to comprise
368 a vegetation mosaic of predominantly mixed-deciduous woodland with patches of open land.
369 There is no evidence for widespread clearance of woodland cover during the interval
370 presented (2988 – 2478 cal. BP), but the herbaceous taxa composition reflects the likely
371 presence of some arable and pastoral activity in the vicinity of the lake. The Diss Mere pollen
372 profile fits a pattern of low-impact, mixed pastoral arable landscape seen during the Late-
373 Bronze Age in the UK (Brück 2019).

374 Given the high temporal resolution of the record, we see evidence of short-lived fluctuations in
375 the relative abundance of woodland vs. open taxa between 2810 - 2770 cal. BP, indicating

376 possible changes in the nature and intensity of the human activity. However, in this instance, if
377 human activity did increase during this interval, it did not result in widespread woodland
378 clearance around Diss Mere. We infer this from using the absolute pollen data (Fig. 1.h) that
379 show the total amount of pollen from woodland taxa remained mostly stable, with mainly an
380 increase in pollen from herbaceous taxa. A lack of evidence for large-scale woodland
381 clearance suggests that small changes in vegetation would not have had a substantial impact
382 on the lake system and ecology and functioning during this time interval, for example through
383 erosion and associated detrital input from widespread land clearance. Therefore, we see no
384 evidence for significant human impact on the lake during the study period, which support wind-
385 forced turbulent conditions.

386 The CI-T data for the Diss Mere record highlight that during the early phase of our study
387 interval (ca. 3000 - 2680 cal. BP), spring summer conditions remained warm, at least within
388 the uncertainties of the technique, although it is possible that if the increased windiness
389 highlighted from the diatoms is occurring during the autumn months, it may not be recorded
390 by this predominantly summer proxy. However, from ~2680 cal. BP in the CI-T record it
391 appears that even summer temperatures are reduced, with additional samples being required
392 to confirm this in future (Fig. 2.g).

393 **Atmospheric response to Late-Holocene long-term solar forcing in the European-** 394 **Atlantic region.**

395 Our Diss Mere diatom record shows a windiness anomaly from 2767 ± 28 cal. BP covering
396 147 ± 8 years, exactly coinciding with the GSM (Stuiver and Kra 1986) (Fig. 3). Due to the
397 annual resolution of the GSM as measured in IntCal20 (Reimer et al. 2020), the maximum
398 uncertainty of our correlation between the duration of our anomaly and the GSM is + 8.06
399 years. The record appears to show a winter response (i.e. autumn to spring) to solar forcing,
400 when diatoms undergo their largest blooms during the mixing limnological season. However,
401 the low solar activity might also have triggered summer cooling during the second half of the
402 solar minimum as shown by the C-IT record (Fig. 2.g).

403 A climate change around the Homeric GSM has been widely reported around the world. In the
404 North Atlantic-European region, there are some records that can be compared to our study to
405 provide support for a regional climatic impact. Irish bog records have been used for a number
406 of years to reconstruct bog wetness, and, by extension, precipitation. Multiple bog records for
407 Ireland were synchronised using tephra horizons and this synchronisation showed a drying
408 trend followed by a 'wet shift' between ~2800 and 2600 BP (Armit et al. 2014), with the wet
409 shift occurring at the end of this period of atmospheric change. Furthermore, while
410 chronological uncertainties, especially around the use of 'wiggle matching' for radiocarbon age
411 modelling (Blockley et al. 2007), preclude detailed comparison with our results, a wet shift has
412 also been reported during this period for the Netherlands (van Geel et al. 1996). Additionally,
413 further to the south and east of our study, increased aridity has been reported for the Dead
414 Sea between ~3000 and 2400 BP, based on varve counts and radiocarbon dating
415 (Neugebauer et al. 2015). All these proxy records in this period suggest broader evidence for
416 region wide changes in atmospheric dynamics.

417 The only other record with an annually-resolved wind reconstruction during the Homeric GSM
418 linked to a robust chronology that is comparable to the Diss Mere record is MFM (Martin-
419 Puertas et al. 2012). We compare these two records alongside cosmogenic isotope-based
420 solar activity data (atmospheric ^{14}C production rates, ^{14}C) (Reimer et al. 2020) during the
421 Homeric GSM (Fig. 3), to test potential solar-forced impacts on the wind patterns at the North
422 Sea edge and western Europe. Both varved records report diatom proxies for wind strength
423 (diatom composition, this study, and varve thickness linked to intensified diatom blooms in
424 MFM (Martin-Puertas et al. 2012)). The onset of the windy conditions at Diss Mere occur very
425 rapidly, in less than 5 varve years (based on the observed varve counts per/cm). It is important
426 to note that the relative counting uncertainty in varve years, especially over short-lived events
427 is always much smaller than the absolute uncertainty of placing those events into absolute
428 calendar time. In this case the calendar age of the onset of windy conditions in Diss is $2767 \pm$
429 29 cal. BP, based on the Bayesian combination of varve counting, radiocarbon dating and

430 tephrochronology that underpins the absolute chronology of the site (Martin-Puertas et al.
431 2021). This is synchronous with the onset of increased windiness in MFM which has an
432 absolute age, based on varve counting and radiocarbon dating, of 2759 ± 39 cal. BP (Martin-
433 Puertas et al. 2012). The combined absolute calendar uncertainty of the onset of the regional
434 wind response is ± 48 years, which is also synchronous with the GSM at ~ 2750 cal. BP,
435 reconstructed by the increase in ^{14}C production rates discussed above (Reimer et al. 2020).
436 There are, however, important differences in the duration of the signals in the two varve
437 records, with the wind anomaly lasting ~ 58 varve years longer in MFM (199 ± 9 varve years
438 (Martin-Puertas et al. 2012)) than in Diss Mere (147 ± 8 varve years), and a combined varve
439 year uncertainty of this comparison of $+ 12$ varve years (Fig. 3; see supplementary for
440 propagation of errors), suggesting different atmospheric responses across the GSM at these
441 two locations. At Diss Mere, the end of the windy interval at 2638 ± 28 cal. BP, where diatom
442 species switch back to dominance of *P. ocellata* from *L. compta*, which continues until the end
443 of the studied interval (~ 2400 cal. BP). This switch in diatom dominance coincides with the
444 end of the Homeric GSM at 2635 cal. BP (Reimer et al. 2020), while thicker varves continue
445 in MFM until 2560 ± 48 cal. BP covering the secondary solar minimum at $\sim 2614 - 2594$ cal.
446 BP (Fig. 3). According to the ^{14}C concentration changes observed in the IntCal20 curve
447 (Reimer et al. 2020) (Fig. 3.d), this second solar minimum has a lower amplitude than the
448 Homeric GSM, and may have had a less of an impact on atmospheric processes. Our initial
449 interpretation of the comparison between the two records is that the Diss Mere record is more
450 sensitive to the amplitude of solar forcing than MFM.

451 The relative proximity of MFM and Diss Mere (~ 1000 km distance) means it is logical to expect
452 for the two sites to show similar changes. While this is clearly the case for the onset of the
453 changes within the two records, the sustained turbulence signal at MFM compared to Diss
454 Mere require further consideration. While the difference in duration between the two records
455 could be down to chance and be driven by independent local factors, the co-occurrence of the
456 shifts in the two diatom records lends support to a larger scale driver. We see coincidence as

457 an explanation for the similarity of the two records as being unlikely for several reasons. Firstly,
458 in MFM there is a direct record of the solar minimum in the sediment ^{10}Be profile that is
459 absolutely in phase with the change in the diatom record. This places the onset of turbulent
460 conditions synchronously with the solar forcing. Secondly, the fact that there is an identical
461 switch, at the same time in Diss Mere, means this change is also synchronous with the
462 annually resolved ^{14}C record of the solar minimum in IntCal20 (Reimer et al. 2020). To us, for
463 all of this to line up randomly seems to be pushing chance too far as a likely explanation.
464 Furthermore, while the diatom records do not allow quantitative reconstruction of wind speed,
465 they do allow a qualitative estimation of windy conditions, independent between the sites,
466 which suggests a strong relationship with external climate forcing. Future studies are now
467 required on the few annually resolved records in the wider European region are needed to
468 explore the relationship we propose between the amplitude of solar forcing and the dynamics
469 of the atmospheric response across the region. Such records are very rare, however, other
470 GSM's have available reconstructions of the influence of solar activity on atmospheric
471 dynamics that are relevant to testing our interpretation.

472 **Reconstruction of the wind response to long-term solar forcing in the last millennium**

473 To examine whether the proxy-based linkage between windiness and GSM occurred during
474 other GSMs in the Holocene and to provide additional context for interpreting the underlying
475 feedback mechanisms, we use an atmospheric circulation reconstruction for winter (DJF)
476 responses to solar forcing in the North Atlantic region, between 1241-1970 CE (Sjolte et al.
477 2018), with special emphasis on the wind patterns (Fig. 4; Fig. 5). We have chosen this time
478 window because it covers the most recent period with GSMs, the LIA. Our reconstruction is
479 the longest available from a very limited number of seasonally resolved atmospheric
480 circulation reconstructions available for comparison (e.g. Luterbacher et al. 2002; Valler et al.
481 2021), with no such study existing for the Homeric GSM. While this is a different GSM, we
482 argue that a large signal in solar forcing is required to see an impact in atmospheric circulation

483 and, thus, this is the most meaningful comparison possible to consider alongside our proxy
484 data.

485 It has been argued that 11-yr sunspot minima are correlated with negative index of the NAO,
486 increased Atlantic/European blocking frequency (Gray et al. 2016) and weakness of the
487 subpolar gyre (SPG) (Moffa-Sánchez et al. 2014), in response to the top-down mechanisms
488 (Woollings et al. 2010). Atmospheric response to long-term solar forcing, however, resembles
489 the EA (Sjolte et al. 2018) leading to a northwest-southeast gradient and intensified
490 northerlies. At present, the EA is the secondary mode of climate variability in the North Atlantic
491 with impact on western Europe but rarely on France and the UK (Barnston and Livezey 1987).
492 During GSM, however, the long-term shift in atmospheric response is potentially due to an
493 accumulative effect of atmosphere-ocean feedbacks over time in relation to a weaker SPG
494 reducing the heat transport to the north-western North Atlantic and reinforcing, thus, mid-
495 Atlantic blocking shifting atmospheric circulation from a westerlies-dominated circulation
496 (NAO) to northeasterlies-dominated circulation (EA) (Sjolte et al. 2018). Our reconstruction
497 results show anomalous northerlies (EA-like circulation) over the North Sea forced by GSM
498 (Fig. 4.b), which agrees with a pronounced meridional circulation and reduced westerlies
499 during the Late Maunder Minimum reported from ships' logbook daily wind records in the
500 English Channel (Mellado-Cano et al. 2018).

501 As enhanced lake overturning could be sensitive to strong wind episodes rather than average
502 wind strength, we have also analysed the correlation between the standard deviation (STD)
503 of the 850 mb wind (i.e. wind strength) and solar forcing. These analyses were run for both
504 the entire period of the reconstruction (1241-1970 CE) and a time window that includes the
505 Spörer, Maunder and Dalton GSM during the LIA (1400-1970 CE) only, in order to assess
506 potential spatial extension (i.e. westward displacement) of the meridional wind anomalies (i.e.,
507 EA-like circulation) linked to a shifting amplitude of the solar forcing (Fig. 5). The results
508 suggest intensified winds at both MFM and Diss Mere occur during GSM, however, the signal
509 appears to be expressed more consistently in western Europe than along the North Sea coast

510 (Fig. 5.a). A negative correlation at both sites is stable for the 1400-1970 CE time-window, but
511 correlation is weaker between 1241-1400, a period of higher solar activity (Fig. 5.b), which
512 indicates the wind strength signal is most closely associated with low solar activity
513 (Supplementary Section 2). What is particularly interesting, is that for the full period of the
514 reconstruction (1241-1970), which is a period with both solar minima, but also enhanced
515 sunspot activity, the atmospheric response over Europe (including Diss Mere and MFM) is not
516 significant (Fig. 4.a). Importantly, however, when we run for the model for time period covering
517 the Spoorer and Maunder minimums (Fig. 5.a), when low solar activity is dominant, the
518 atmospheric response to SLP is significant. Additionally, in terms of spatial distribution, the
519 mapping of the reconstructed atmospheric response to solar forcing (Fig. 5.b) locates Diss
520 Mere at the boundary between positive (west) and negative (east) wind-solar correlation
521 zones, which would mark the western limit of the regions impacted by the EA-like circulation
522 (Fig. 5.a).

523 **Atmospheric dynamics and the spatial differences in wind response**

524 Solar-forced spatial migrations of sea level pressure centres affecting the regional impact of
525 the EA (Moffa-Sánchez et al. 2014; Hernández et al. 2020, 2021) could explain the absence
526 of a wind response during the secondary solar minimum ~2614-2594 cal. BP in Diss Mere,
527 while there is still a signal in MFM (Fig. 3). As suggested in Figure 5a, Diss Mere in the East
528 of England is in a zone with lower correlation with long-term solar forcing than the region
529 around MFM. Thus, while the EA was the principal mode of climate variability during the
530 Homeric GSM as seen in both sites, the shorter solar minimum between ~2614-2594 cal. BP
531 might not be of sufficient amplitude of solar forcing to keep an impact of the EA over the UK.
532 Thus, the turbulence in the lake was not sufficient to maintain the dominance of *L. comta* and
533 instead there is a return to *P. ocellata* which does not have the high nutrient requirements,
534 and its smaller size allows it to thrive in less turbulent waters due to slow sinking rates
535 (Cherepanova et al. 2010; Duleba et al. 2015; Malik and Saros 2016). However, caution is
536 required, as Diss Mere and MFM are only separated by ~1000km and the SLP reconstruction

537 has a resolution of 400km (Sjolte et al. 2018), so the difference between the two sites cannot
538 be reproduced with absolute precision, however, and further testing of our evidence for the
539 nature of wind regime change and GSM requires reconstructions with higher spatial resolution.

540 **Conclusion**

541 We have generated new wind sensitive proxy data from the high resolution annually laminated
542 lake record at Diss Mere, Norfolk and compared this to annual wind sensitive proxies from
543 MFM. Our data suggests that spatially transgressive changes may have occurred in the
544 atmospheric response to GSMS, depending on the amplitude of the solar signal. Our study
545 highlights the importance of understanding potential changes and regional variations in
546 windiness (Lean et al. 1997; Maycock et al. 2015), for critical areas like the North Sea (Geyer
547 et al. 2015). Further investigation is now required on the amplitude of the response of
548 atmospheric circulation to long-term solar forcing and varying boundary conditions (i.e. orbital
549 parameters, greenhouse gases concentration and feedback mechanisms). In particular,
550 deepening our understanding of how solar-modulated modes of climate variability can trigger
551 regional differences, which could have important influences on the spatial distribution of wind
552 anomalies and impacts of extreme weather events, in the North Atlantic-European region
553 (Zubiate et al. 2017).

554 **Declarations**

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560 **Availability of data and material:** Datasets available from Varved Sediments Database
561 (VARDA) repository at <https://varve.gfz-potsdam.de/>.

562 **Code availability:** Not Applicable

563 **Authors' contributions:**

564 P. Harding and C. Martin-Puertas designed the study and led the writing of the manuscript. P.
565 Harding was responsible for the diatom analyses. C. Martin-Puertas led the coring campaign
566 and was responsible for sediment core data analyses and interpretation of the geochemical
567 data. J. Sjolte was responsible for climate simulations. A. A. Walsh was responsible for the
568 pollen analyses. R. Tjallingii ran the geochemical analyses and contributed to the
569 interpretation of the data. CL and PL provided the C-IT data. P. Harding, C. Martin-Puertas,
570 A. A. Walsh, M. Perez, R. Tjallingii, C. Langdon, P. Langdon, S. Blockley, A. Brauer and A. M.
571 Milner jointly interpreted the proxy data and J. Sjolte, P. Harding, C. Martin-Puertas, S.
572 Blockley and R. Muscheler jointly interpreted the climatic implications of the study. All the
573 authors contributed to the discussion and the writing of the final manuscript.

574 **Ethics approval:** Not Applicable

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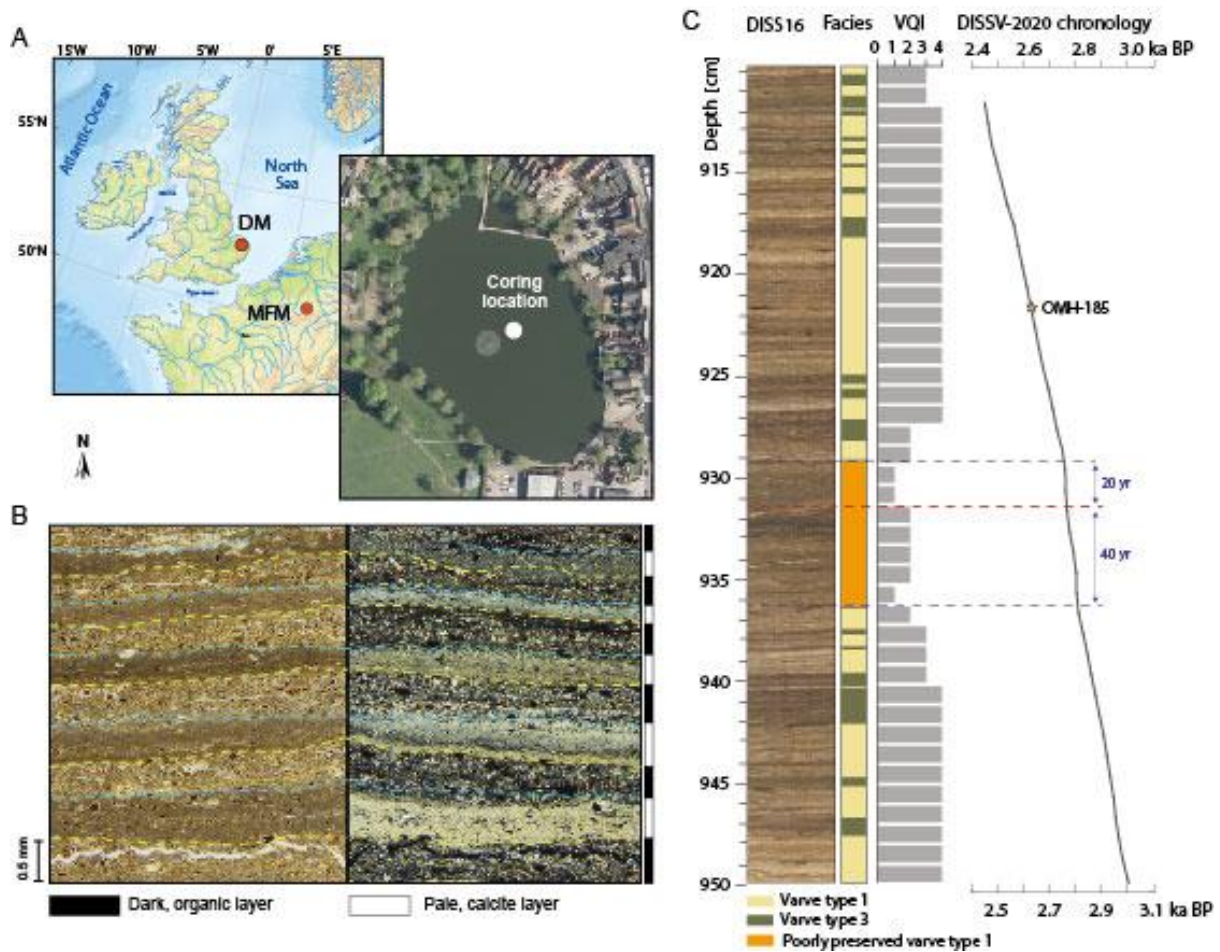
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Figures and Tables

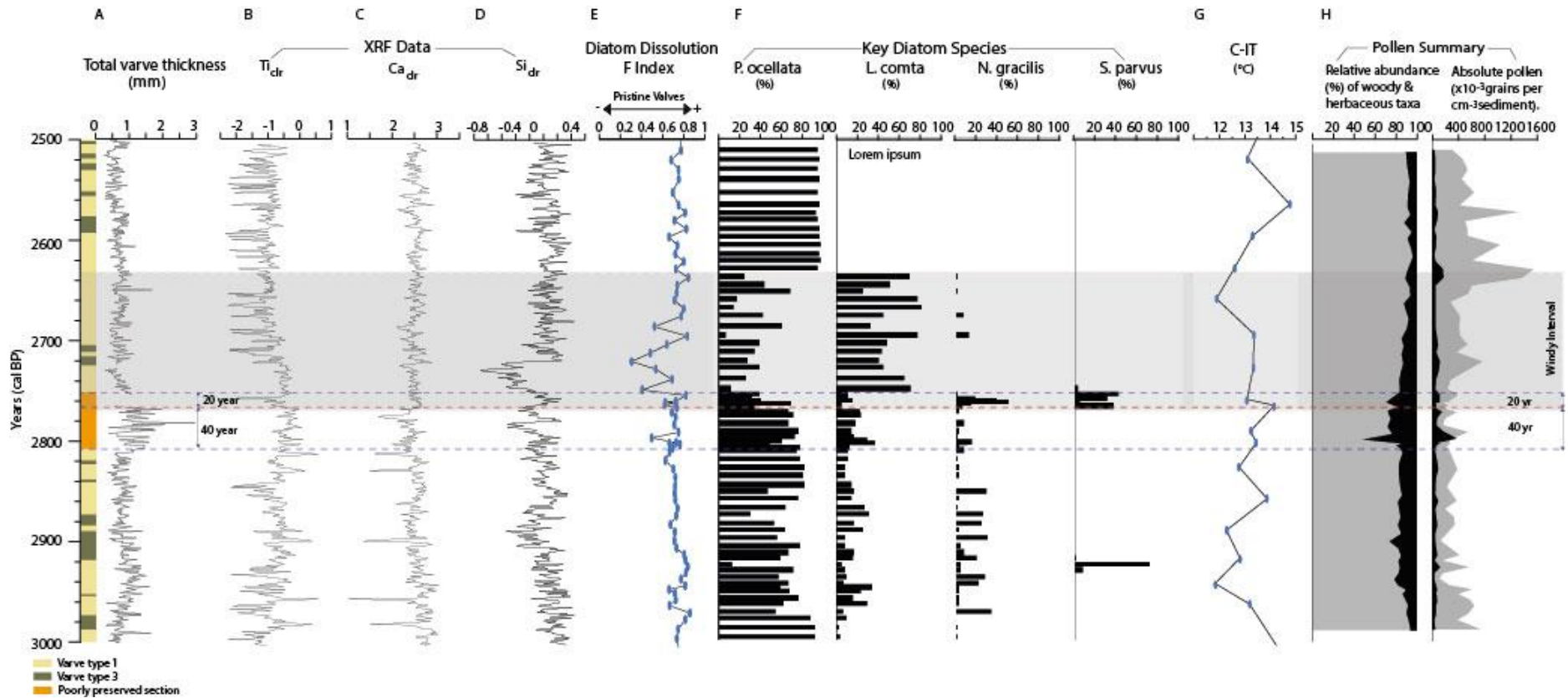
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830 **Fig. 1** Site Map and Diss Mere Proxy Records (A) European regional map showing Diss
 831 Mere, UK and Meerfelder Maar, Germany (MFM), alongside aerial photography of Diss
 832 Mere (B) Structure of varves in the Diss Mere record in plane light (left) and in polarized light
 833 (right): dark organic varves (primarily planktonic diatoms, organic, mostly aquatic, matter and
 834 a low amount of detrital sediments) and calcite varves made of a pale spring/summer sub-
 835 layer (primarily planktonic diatoms and authigenic calcite), (C) Diss 16 core stratigraphy and
 836 facies alongside Varve Quality Index (VQI) and the DISSV-2020 chronology for the studied
 837 interval (Martin-Puertas et al. 2021).

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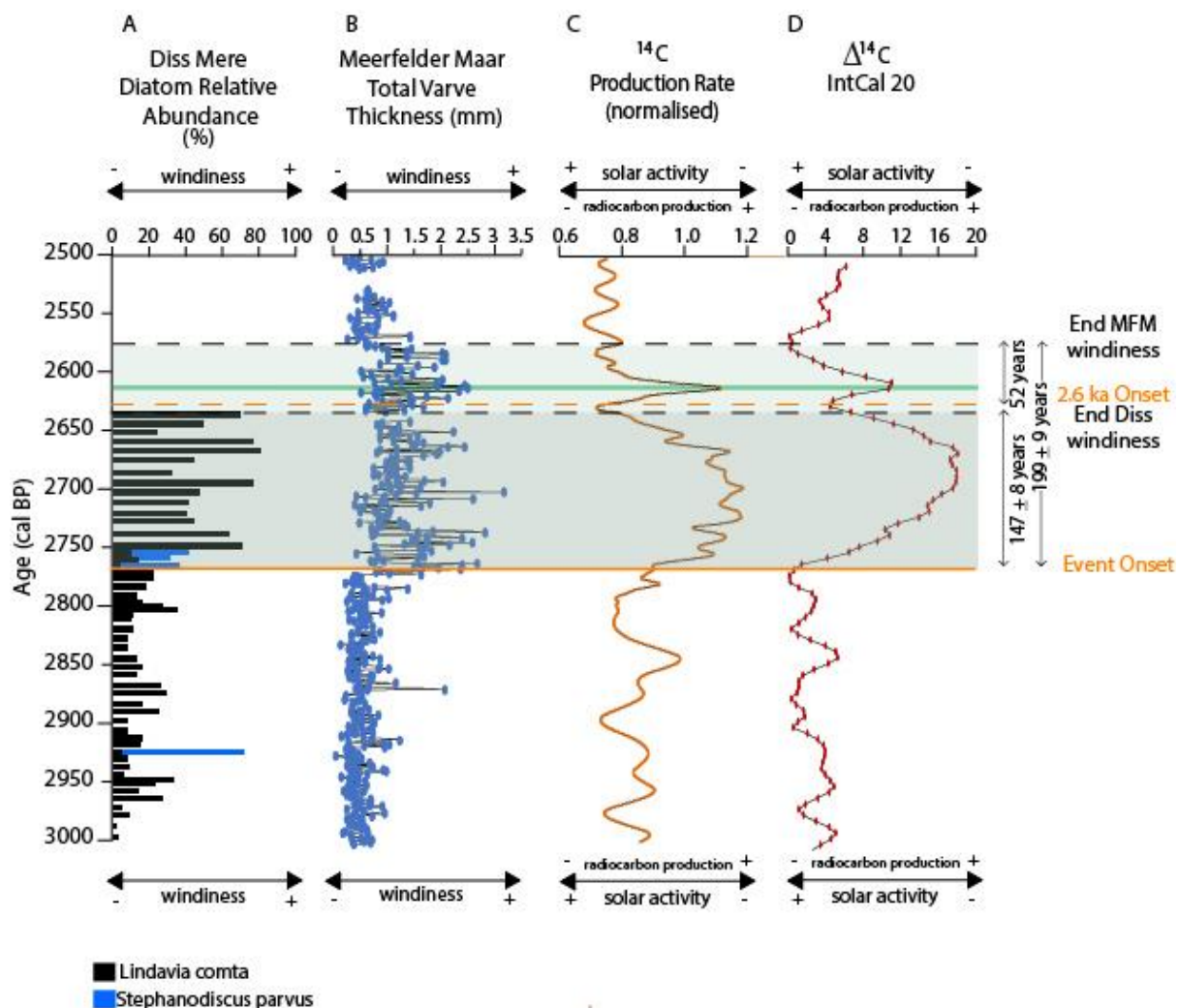


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842 **Fig. 2 Diss Mere sediment and proxy records for the study interval, 910-950 cm of sediment depth.** From left to right: (A) Diss Mere
 843 Microfacies - varve type 1 corresponds to a calcite (spring-summer) / diatomaceous detritus (autumn-winter) couplet and varve type 3
 844 corresponds to a diatom bloom (spring-summer) / diatomaceous detritus (autumn-winter)(Martin-Puertas et al. 2021) alongside total varve
 845 thickness (mm); (B-D) XRF Data (B) Ti central logged ratio; (C) Calcium central logged ratio and (D) Silica central logged ratio; (E) Diatom
 846 dissolution F Index summary; (F) key diatom species (%), *Pantocsekiella ocellata*, *Lindavia comta*, *Nitzschia gracilis* and *Stephanodiscus*
 847 *parvus*, (G) C-IT reconstruction ($^{\circ}\text{C}$, uncertainty of $\pm 1^{\circ}\text{C}$, note lower resolution of samples for the C-IT reconstruction), (H) Pollen summary
 848 showing relative proportions (%) and absolute concentrations of woody (grey) vs herbaceous (black) taxa. Dashed blue lines highlight section

849 of poor varve preservation with red dashed line highlighting the start of a section where varves are interpolated. Grey banding highlights period
850 of increased windiness documented in the diatom record.

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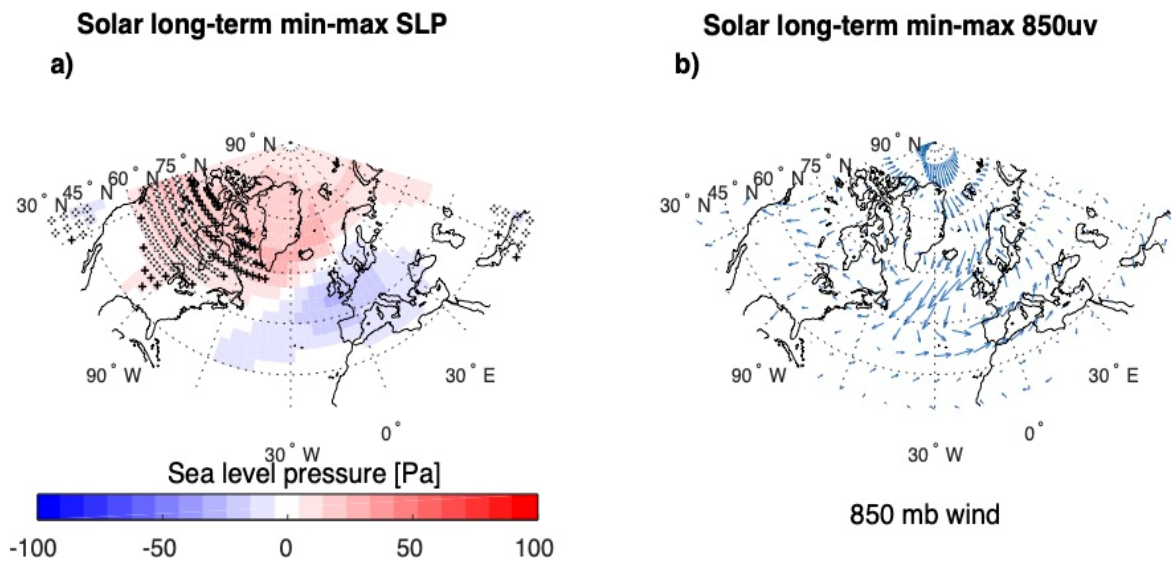


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854 **Fig. 3** Diss Mere and Meerfelder Maar Comparison. (a) Key wind influenced proxies at Diss
 855 Mere, *Lindavia compta*, *Stephanodiscus parvus* (relative abundances: %), (b) alongside the
 856 Meerfelder Maar varve thickness record (mm) (Martin-Puertas et al. 2012), (c) ^{14}C
 857 production rate (normalised (Muscheler et al. 2005) calculated from IntCal20 (Reimer et al.
 858 2020)) and (d) 5-year resolution $\Delta^{14}\text{C}$ IntCal20 data (Reimer et al. 2020) for the 2500-3000
 859 cal. BP time-period, which includes the effects of the carbon cycle leading to smoothening
 860 and delay of the peaks compared to ^{14}C production rate. Solid orange line marks the onset
 861 of the Homeric solar minimum, while the dashed orange line highlights the transition to the
 862 secondary lower amplitude solar minimum (Steinhilber et al. 2012). Coarse black dashed
 863 lines mark the end of intensified wind conditions at Diss Mere and Meerfelder Maar. Green
 864 line marks the position of the solar proton event at ~2610 cal. BP (O'Hare et al. 2019), which
 865 increases the annual normalised ^{14}C production rate (on top of the effect of the longer-term
 866 solar minimum). Durations on the intensified winds are shown. All datasets are presented on
 867 their independent chronologies.

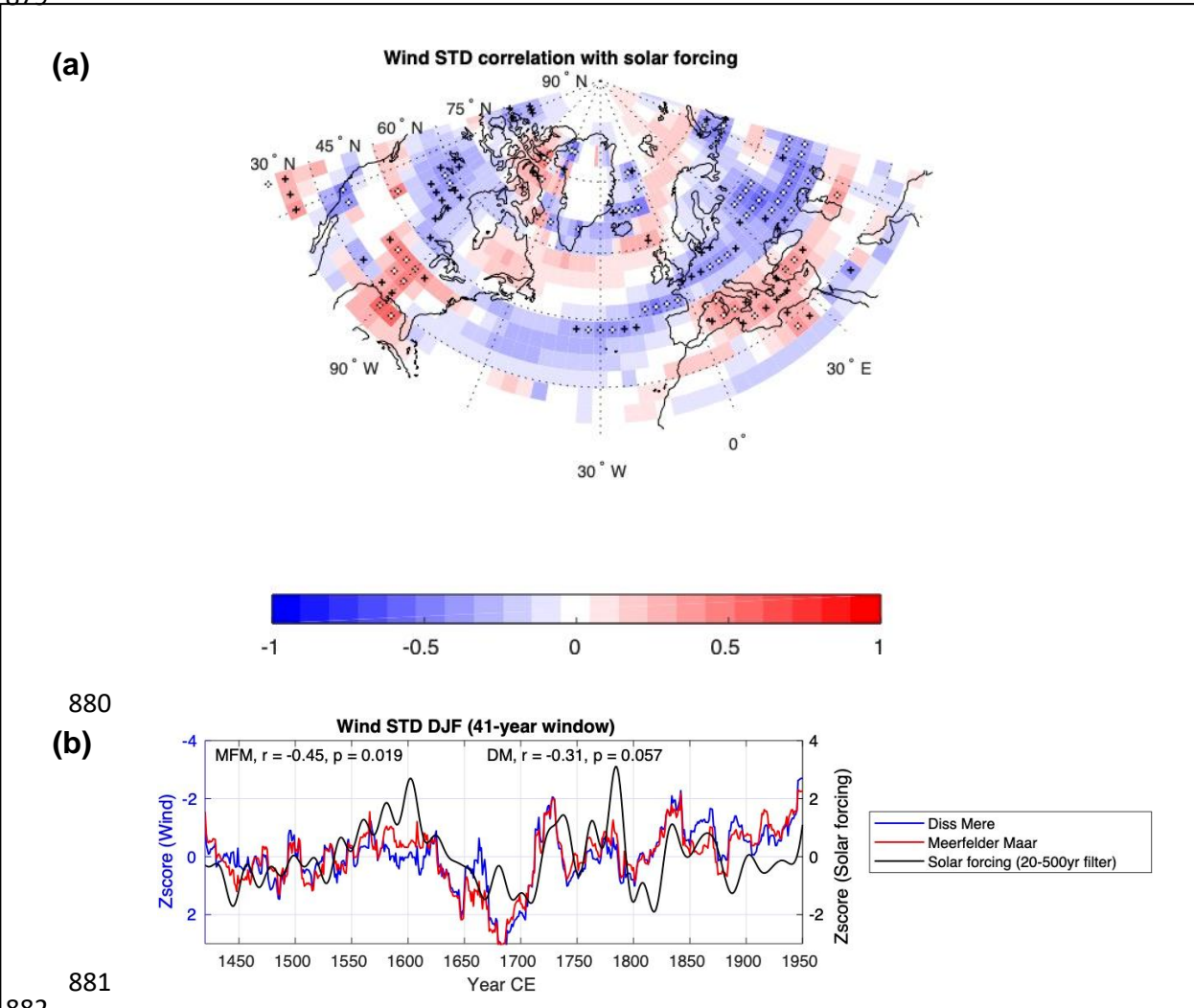
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870 **Fig. 4** Reconstructed atmospheric Sea Level Pressure (SLP) and the correlation to solar
 871 forcing (uv), derived from Sjolte al. (2018): (a) December, January, February (DJF) SLP
 872 anomalies (Pa) in response to long-term solar forcing (ultraviolet (uv)) (Brehm et al. 2021)
 873 (band-pass filtered for 60-500 year cycles). (b) corresponding figure to (a), but for the 850
 874 mb wind. The white stippling (a) indicates significant anomalies $p < 0.05$, and black stippling
 875 indicates significant anomalies $p < 0.1$ (two-tailed Student's t test), and blue arrows (b)
 876 indicate predominant wind direction. The spatial resolution of the model is $3.75 \times 3.75^\circ$.
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885 **Fig 5** Wind STD Climate Reconstruction for 1400 – 1970 CE derived from Sjolte al. (2018):
886 (a) Correlation between the moving 41-year standard deviation (STD) of the 850 mb wind
887 and solar forcing (Brehm et al. 2021) (band-pass filtered for 60-500-year cycles) 1400 –
888 1970 CE. The white stippling indicates significant correlation $p < 0.05$, and black stippling
889 indicates significant anomalies $p < 0.1$. (b) Time series of the moving 41-year STD of the
890 850 mb wind at Meerfelder Maar (MFM) and Diss Mere compared to solar forcing (Brehm et
891 al. 2021). The significance is estimated taking autocorrelation into account (Ebisuzaki 1997)
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