1 A two-millennium dinoflagellate cyst record from Gullmar Fjord, a Swedish Skagerrak

2 sill fjord

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10 ABSTRACT

11 Gullmar Fjord, a sill fjord on the Skagerrak coast of western Sweden, contains a valuable sedimentary archive for the last 2500 years. This archive encompasses a temporal 12 record from the Roman Warm Period, the Dark Ages, the Medieval Warm Period, the Little 13 14 Ice Age and into the modern warm period. A high resolution dinoflagellate cyst analysis has 15 been completed on this archive using material from two cores taken from the deepest part of 16 the fjord, Alsbäck Deep. The recovered dinoflagellate cysts have provided a quantitative 17 temporal record that has been used to construct a dinoflagellate cyst spectrum and has been 18 subjected to both Q-mode cluster analysis and CABFAC factor analysis with varimax 19 rotation. In addition the heterotrophic ratio and both the thermophilic and cryophilic ratios 20 have been calculated to assist with the interpretation of the results. Well preserved and diverse 21 dinoflagellate cyst assemblages have been recovered throughout the sedimentary sequence 22 and have been used to explore surface water conditions within the fjord over this time interval. Although a clear link is observed between the cyst assemblages and the climate 23 24 phases of the Subatlantic, established from previous stable isotope work, there was little

25 change in the cyst populations and indeed they reflect the known modern cyst floras. 26 However a major change was seen in the incoming of *Gymnodinium nolleri* during the Dark Age and its reduction to a relict species towards the end of the Little Ice Age. Comparisons to 27 28 other published work confirm the regional nature of this dinoflagellate cyst event but its ecological preferences remain enigmatic. A second major change was also recognised around 29 the late 1960s/early 1970s and was associated with differences in nutrient availability from 30 either a diminution in upwelling, as the NAO changed from a negative phase to a positive, or 31 32 from marine pollution or a combination of both. Otherwise the dinoflagellate cyst 33 assemblages can be grouped, using the factor analysis, into F1 Protoperidinium spp. indet. 34 (round, brown cysts); F2 Gymnodinium nolleri and F3 Lingulodinium polyedrum and Protoceratium reticulatum. The cluster analysis shows a similar subdivision into units closely 35 associated with the recognised climate phases of the Subatlantic. Possible climate 36 37 environments have been explored, but because of the relatively minor variations in the 38 assemblages and the lack of autecological information, only relatively small scale changes 39 were recognised except for the clear, but complex nature of the recent warm period. 40 41 Keywords: Holocene, Subatlantic, dinoflagellate cysts, palaeoclimates, Skagerrak, Sweden 42 1. Introduction 43 44 The Holocene, as presently defined, is the second epoch of the Quaternary 45 Period, notwithstanding the introduction of the Anthropocene (Jalasiewicz et al., 2010; 2011). It is the most recent interval of geological time and the present-day interglacial. The base of 46 the Holocene has proved difficult to define, in traditional depositional sequences, based upon 47 48 evidence for contrasting climatic conditions. Walker et al. (2009) proposed that the base be

49 defined on the basis of the NGRIP ice core reflecting the first signs of climate warming at the 50 end of the Younger Dryas/Greenland Stadial 1 cold phase. This boundary was placed at 11 51  $700 \pm 99$  yr b2K (before AD 2000).

Various attempts have been made to sub-divide the Holocene following the use 52 53 of the Blytt-Sernander pollen climatostratigraphy (Sernander, 1908). Although with its 54 limitations, such as the proven diachroneity of pollen zones (Smith and Pilcher, 1973), its conceptual framework was eventually redefined to provide a chronostratigraphical scheme 55 constrained by radiocarbon ages (Mangerud et al., 1974). The presence of climatic 56 57 fluctuations within the Holocene provides a link between changes occurring on a millennial timescale to those that are much shorter i.e. representing centennial or decadal variations. 58 Within the Subatlantic, the last 2500 yr BP, the recognition of several climatic phases such as 59 60 the Roman Warm Period (RWP), the Dark Ages (DA), the Medieval Warm Period (MWP) and the Little Ice Age (LIA) (Lamb, 1995) has proved to be important. These climatic phases 61 62 are key to the study of the various forcing factors affecting climate at a time when summer solar insolation was and is declining (Wanner et al., 2011), resulting largely from changes 63 within the precession of the equinoxes. Among other driving forces involved are changes in 64 65 solar activity (Mauguoy et al., 2002), volcanism (Sicre et al., 2011; Miller et al., 2012), the state of the North Atlantic Oscillation (Trouet et al., 2009, Olsen et al., 2012) and changes in 66 the Gulf Stream (Lund et al., 2006). In addition, changes in the Atlantic Meridional 67 68 Overturning Circulation (AMOC) are implicated with significant climate impacts throughout 69 the Holocene (Hoogakker et al., 2011). This climatic variability within the Subatlantic and its 70 phases is suggested to have rather weak amplitude, estimated at ca. 2°C for sea surface 71 temperatures (Bond et al., 1997).

72 In order to understand the present day climate, and the controls that force73 change, it is necessary to detail the recent past. The study of the Holocene is paramount in this

respect. This is especially true given the concerns about the present climate change, global
warming and the marked increase of atmospheric carbon dioxide since the start of global
industrialisation. Carbon dioxide levels in the atmosphere breached 400 ppm in 2013,
<u>http://www.esrl.noaa.gov/gmd/index.html</u>), in sharp contrast to the pre-industrial level of 280
ppm. There is increasing evidence that already there have been regime shift changes within
the North Atlantic circulation in the 1920s and 1930s (Drinkwater, 2006) and more recently in
the 1980s (Beaugrand et al., 2002) and further changes are feared (Reid and Valdés, 2011).

Gullmar Fjord on the west coast of Sweden provides an ultra-high resolution 81 82 archive of sediment encompassing the Subatlantic phase of the Holocene including the RWP, the MWP and the LIA together with a record of modern warming. It is one of the most 83 studied marine areas in the world with the first hydrographical measurements being taken as 84 85 early as 1869. It is also the site of one of the world's oldest marine research stations founded by the Royal Swedish Academy of Sciences in 1877. In particular Gullmar Fjord is a sill fjord 86 87 (Fig. 1A, B) and as such is a site of net sediment accumulation. Negligible tidal activity and high sedimentation rates of 0.7-1.4 cm a<sup>-1</sup> (Filipsson and Nordberg, 2004) result in Gullmar 88 89 Fjord becoming a high resolution environmental archive (Howe et al., 2010). In addition, the 90 hydrography of the fjord, the stratified water column (Fig. 1 C) and the long residence time of the deep water together with high oxygen consumption from the decay of organic material 91 92 results in severe hypoxia. In turn this affects the benthic communities and increases the 93 likelihood of nil or low activity within the bottom macrobenthos leading to a concomitant lack 94 of bioturbation. These fine-grained sediments deposited in low oxygen environments, often 95 undisturbed by bioturbation and deposited in high accumulation environments, are ideal for 96 the preservation of a high-resolution dinoflagellate cyst temporal record.

97 Finally Gullmar Fjord is ideally placed within the Skagerrak/Kattegat to reflect98 changes in the North Sea and further connections to the North Atlantic, and particularly to

99 monitor changes in the geographical ranges of temperate dinoflagellate cysts and the input of 100 cysts more usually found in the sub-arctic/arctic regions. Hence the provision of a high-101 resolution temporal record over the last two millennia, at a time when a number of climate 102 phases are known but not well understood, can only enhance the understanding of this time 103 interval. In this paper we provide new data on the recovered dinoflagellate cyst record in 104 order to detail changes within the surface waters of the fjord. This is part of a larger study that 105 encompasses sedimentology, bulk sediment geochemistry, stable isotope analysis (Filipsson 106 and Nordberg, 2010) together with benthic foraminiferal stratigraphy (Filipsson and 107 Nordberg, 2004; Polovodova et al., 2011; Polovodova Asteman et al., 2013) and 108 dinoflagellate cysts (Harland et al., 2006).

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#### 110 2. Materials and methods

111 This study is based on two sediment cores: GA113-2Aa and 9004, which were 112 both collected at 116 m water depth in the deepest basin of Gullmar Fjord, the so-called 113 Alsbäck Deep (58°17.570' N, 11°23.060' E) (Fig. 1). The core 9004 (731-cm long) was 114 sampled with a piston corer ( $\emptyset$ =7.6 cm) aboard of *R/V Svanic* in 1990. The core GA113-2Aa (60-cm long), in contrast, was recovered by using a Gemini corer ( $\emptyset$ =8 cm) during 1999 from 115 116 the *R/V Skagerak*. Together these cores represent a continuous sediment record, with no gap 117 in between (Polovodova Asteman et al., 2013), through the Subatlantic to recent times. 118 In the laboratory the cores were split in two halves. One half was used for bulk 119 sediment geochemistry (Corg and C/N ratio), stable carbon isotopes and foraminiferal analyses 120 (Filipsson and Nordberg, 2004; 2010; Polovodova et al., 2011; Polovodova Asteman et al., 2013). The other half was used for the analysis of its dinoflagellate cyst content - for the core 121

122 GA113-2Aa see full datasets published in Harland et al. (2006) and for the core 9004 the

results are presented herein. The full datasets are held on open file and can be accessed fromthe Department of Earth Sciences, University of Gothenburg, on request.

Eleven intact mollusc shells were recovered in life position from the core 9004 125 and were subject to <sup>14</sup>C AMS analysis (Fig. 2; see also Filipsson and Nordberg, 2010; 126 Polovodova et al., 2011; Polovodova Asteman et al., 2013). The dating of shells was 127 performed at the Ångström Laboratory (Uppsala University, Sweden) using the marine model 128 calibration curve (Reimer et al., 2004; Bronk Ramsey, 2005). A <sup>14</sup>C half-life of 5568 yr was 129 used and the margin of error is 1 $\sigma$ . Ages were normalized to  $\delta^{13}$ C of – 25‰ according to 130 Stuiver and Polach (1977), and a correction corresponding to  $\delta^{13}C = 0\%$  (not measured) 131 versus PDB has been applied. For the core 9004 record we used a reservoir age of 500 yr 132  $(\Delta R=100)$  (Nordberg and Possnert, unpubl. data; see also discussion in Polovodova et al., 133 134 2011). The AMS results showed that the core 9004 spans a temporal record from ca. 350 BC to 1900 AD and includes the Roman Warm Period (~300 BC - 400 AD), the Dark Ages Cold 135 136 Period (~400 – 600 AD), the Medieval Warm Period (~1000 – 1350 AD) and the Little Ice Age (~1350 – 1850 AD) (Lamb, 1995). The core GA113-2Aa was dated by using  $^{210}$ Pb and a 137 constant rate of supply (CRS) model (Appleby and Oldfield, 1978), which suggested that the 138 139 core material was deposited between ca. 1915 and 1999 (Fig. 2) and thereby encompasses the 140 most recent warming. The full <sup>210</sup>Pb dating details are published in Filipsson and Nordberg (2004).141

The measurements of bulk sediment geochemistry were performed on sediment material prior to dinoflagellate cyst analyses. The organic carbon samples from core GA113-2Aa were analysed at University of Gothenburg (Sweden) using a Carlo Erba NA 1500 CHN analyser. Samples from the core 9004 were run at Bremen University (Germany) using a Vario EL III CHN analyser and simultaneously were subject to the total nitrogen (TN) measurements (Filipsson and Nordberg, 2010). Thus the data on C/N ratio for the topmost 60

148 cm (100 yr) of the record (core GA113-2Aa) were missing (Polovodova Asteman et al., 2012: 149 Fig. 4). To fill in this gap a new Gemini core G113-119A was collected at the same location 150 during an expedition of *R/V Skagerak* in September 2011. The core was later subjected to 151 measurements of  $C_{org}$  and TN using Carlo Erba NA 1500 CHN, and together with data from 152 core 9004, provided a continuous record of C/N ratio (Fig. 4 herein).

153 Dinoflagellate cysts were recovered from both cores GA113-2Ab and 9004. In 154 the first case samples were taken at 1 cm intervals and subjected to normal palynological 155 processing (see Wood et al., 1996). The sediment consists of homogenous organic-rich clay, 156 which on processing yields large amounts of amorphous organic material (AOM). The 157 samples were not subjected to oxidising reagents so as to prevent the selective loss of 158 protoperidiniacean cysts (Dale, 1976; Zonneveld et al., 2008) but were subjected to prolonged 159 washing and filtering, together with the use of ultrasound (up to 2 min) to free the 160 dinoflagellate cysts from the AOM. The resulting palynological residues were stained with 161 Safranin, dispersed onto cover slips using Elvacite and bonded to microscope slides using 162 Petrapoxy 154 resin with a refractive index of 1.54. Core 9004 was sampled at 10 cm 163 intervals but otherwise was treated the same as GA113-2Ab except for washing through a 10 164 μm nylon sieve and a 212 μm brass sieve to provide a suitable size fraction for study. 165 Ultrasound was also employed together with heavy liquid separation, where minerals 166 remained, using zinc chloride solution with a SG 1.95, to provide suitable slides for study. It 167 is unlikely that the small differences in processing techniques will have adversely affected the results of this study. 168

Both cores were treated quantitatively so as to calculate the numbers of dinoflagellate cyst species per gram of sediment. The original dry weight of sample was noted and aliquot subsamples were taken for mounting and counting (Harland, 1989). Samples were counted from a single slide representing either 1 g of sediment or a fraction thereof using an x

40 objective of a Zeiss Axiolab microscope. The numbers of cysts per gram of sediment were 173 used to construct a dinoflagellate cyst spectrum and were also subjected to statistical analyses 174 175 by the software PAST, University of Oslo (Hammer et al., 2001). The Q-mode cluster 176 analysis is used in biostratigraphy for clustering of samples in contrast to the R-mode 177 analysis, which is used for clustering of measured variables e.g. associations of various 178 species (Parker and Arnold, 1999). In our study the Q-mode cluster analysis was based on an unweighted pair group average (UPGMA) algorithm and a Bray-Curtis similarity index. The 179 180 UPGMA method creates clusters, which are joined based on the average distance between all 181 members in the two groups (Hammer et al., 2001). The Bray-Curtis index is a common 182 similarity index used for abundance data (Bray and Curtis, 1957). The UPGMA method was 183 chosen because its dendrograms are known to show the highest cophenetic correlation (Sokal, 184 1986). Cophenetic correlation approaching 1.0 is a necessary criterion for optimality of the 185 chosen clustering method (Davis, 1986). In our study the UPGMA algorithm and Bray-Curtis 186 similarity together yielded a correlation of 0.81. The Bray-Curtis index was also chosen 187 because it reproduced dendrograms of Harland et al (2006) for the core GA113-2Aa and 188 Harland and Nordberg (unpubl. data) for 9004, which were created by using a different 189 statistical package (TILIAGRAPH). In order to confirm the presence of observed cluster units 190 we use a parallel multivariate technique i.e. factor analysis as recommended by Parker and 191 Arnold (1999). A simple CABFAC (Calgary and Brown Factor Analysis: Klovan and Imbrie, 1971) Q-mode factor analysis with varimax rotation was performed on data of the most 192 193 abundant dinoflagellate cysts. The varimax rotation is commonly used to maximize the 194 variance in factor loadings i.e. to increase the explanatory value of factors (Parker and 195 Arnold, 1999).

196 The raw counts, percentages, calculated cysts per gram of sediment and197 statistical data are held on open file at the Department of Earth Sciences, University of

198 Gothenburg, Sweden.

199 As well as the counts, and to enhance the interpretative potential, two simple 200 ratios were calculated from the data. The first of these, the heterotrophic ratio, was originally 201 described as the gonyaulacean ratio (Harland, 1973) and later somewhat re-formulated via the 202 peridiniacean/gonyaulacacean cyst ratio (Lewis et al., 1990) into the heterotrophic ratio (de 203 Vernal and Marret, 2007). It has often been used as a measure of dinoflagellate productivity despite the fact that the dinoflagellate cyst record provides only a small window on the 204 205 dinoflagellate motile cell populations; the relationships between productivity and the 206 heterotrophic ratio is not known in detail and certainly not in any quantitative sense. Only 207 some 13-16% of dinoflagellate species are known to produce fossilisable cysts (Head, 1996). 208 In this instance the ratio is constructed simply by dividing the number of heterotrophic species 209 by the autotrophs. Basically the ratio recognises the major ecological difference between 210 those species that have a photosynthetic nutritional strategy and those that feed upon various 211 prey species within the plankton. It is a relatively simplistic approach and does not recognise 212 the often complex food webs within the phytoplankton and the various heterotrophic and 213 mixotrophic strategies utilised by differing dinoflagellate species (see Harland, 1988). 214 Heterotrophic dinoflagellate species are often known to favour diatom species as prey (Jacobson and Anderson, 1986) so their numbers are thought to mirror diatom productivity, if 215 216 with a slight temporal lag. As a simple ratio there is often difficulty with its interpretation in 217 that increases in the ratio may equally result from increased numbers of heterotrophic species 218 or a decline in the autotrophs and vice versa, therefore it is usually best to detail the absolute 219 numbers of both, as herein, to show clearly how the two groups are reacting to changing 220 environments over time. Whilst not necessarily a quantitatively accurate measure of 221 productivity it is, however, useful as a guide to changes occurring within the dinoflagellate

cyst assemblages that possibly reflect fluctuations in the dinoflagellate populations, thebroader phytoplankton and perhaps nutrient availability.

224 In addition to the main, largely ubiquitous, components of the dinoflagellate cyst assemblages i.e. the round, brown cysts of Protoperidinium spp., Gymnodinium nolleri, 225 Lingulodinium polyedrum and Protoceratium reticulatum, there are a number of other species 226 227 that do not play such a large part in the assemblage either in number or proportion. Sometimes these species are more specialised in their ecological preferences and as such have 228 229 the potential of providing rather more information for the interpretation of environmental 230 change through the temporal record. It is these species that have been selected as either thermophilic or cryophilic to provide a simple thermophilic and/or cryophilic ratio; a second 231 232 ratio to enhance the interpretative potential of the dinoflagellate cyst record. The ratio is 233 constructed by dividing the numbers of thermophilic species by the cryophilic to give a thermophilic ratio and vice versa to provide a cryophilic ratio. In terms of the cyst 234 235 assemblages from GA113-2Ab and core 9004 the following have been identified as possibly 236 useful. They are grouped into two categories i.e. the more thermophilic species, preferring 237 warmer water environments and the more cryophilic species, preferring colder regimes 238 following the information largely provided in Zonneveld et al. (2013). However, despite the accumulated data this is not a precise science and so these listings are somewhat subjective in 239 240 the context of the particular recovered species from the Gullmar Fjord cores taken in a temperate biogeographical setting. They are offered as a possible additional approach to the 241 242 interpretation of the record. Not including the more ubiquitous species, the thermophilic 243 species consist of the following with an indication of their summary temperature, preferences 244 after Zonneveld et al. (2013):

245

246 Lejeunecysta marieae (Harland 1991) Lentin et Williams 1993 – not known

247	Lejeunecysta oliva (Reid 1977) Turon et Londeix 1988 – temperate to subtropical
248	Lingulodinium polyedrum (Stein 1883) Dodge 1989 – temperate to tropical
249	Operculodinium israelianum (Rossignol 1962) Wall 1967 – subtropical to tropical
250	Polykrikos kofoidii (Chatton 1914) Matsuoka et al. 2009 – subpolar to subtropical
251	Protoperidinium conicum (Gran 1900) Balech 1974 – polar to tropical
252	Protoperidinium divaricatum (Meunier 1919) Parke et Dodge 1976 – temperate to tropical
253	Protoperidinium leonis (Pavillard 1916) Balech 1974 - temperate to tropical
254	Protoperidinium oblongum (Aurivillius 1898) Balech 1974 – temperate to tropical
255	Protoperidinium pentagonum (Gran 1902) Balech 1974 – subpolar to tropical
256	Protoperidinium stellatum (Wall 1968) Head 1999 – temperate to tropical
257	Protoperidinium subinerme (Paulsen) Loeblich III 1969 - temperate to tropical
258	Spiniferites bentorii (Rossignol 1964) Wall et Dale 1970 – temperate to tropical
259	Spiniferites delicatus Reid 1974 – subtropical to tropical
260	Spiniferites membranaceus (Rossignol 1964) Sarjeant 1970 – temperate to tropical
261	Spiniferites mirabilis (Rossignol 1964) Sarjeant 1970 - temperate to tropical
262	Spiniferites cf. pachydermus (Rossignol 1964) Reid 1974 – temperate to tropical
263	Spiniferites ramosus (Ehrenberg 1838) Mantell 1854 – subpolar to tropical
264	
265	And the cryophilic species with their temperature preferences, mostly after
266	Zonneveld et al. (2013):
267	
268	Bitectatodinium tepikiense Wilson 1974 – subpolar to temperate
269	Islandinium cf. cezare (de Vernal et al. ex de Vernal in Rochon et al. 1999) Head et al. 2001 –
270	subpolar to polar

271 Islandinium minutum (Harland et Reid 1980) Head et al. 2001 – temperate to polar

272 *Pentapharsodinium dalei* Indelicato et Loeblich III 1986 –temperate to polar

273 *Protoperidinium conicoides* (Paulsen 1905) Balech 1974 – temperate to polar (Dale 1983)

274 Spiniferites elongatus/frigidus Reid 1974 – polar to subtropical

275

276 It is immediately apparent that many more species are identified as being rather 277 more thermophilic, whereas those identified as cryophilic are much fewer in number. This is not unexpected given the position of Gullmar Fjord in relation to the Skagerrak and North Sea 278 279 and the nature of the temperate modern flora (Persson et al., 2000). Also many of the species 280 are known to be distributed across several biogeographical zones and are not always clear indicators of temperature. Although temperature is clearly the most important determinant of 281 282 dinoflagellate cyst distributions (Zonneveld et al. 2013), at the autecological level many other 283 factors play a part and locally may have a controlling role.

284

# 285 **3. Results**

#### **286** 3.1. Lithology

The sediments recovered in the core GA113-2Aa were olive-green-grey and 287 288 contained mainly organic-rich silt and clay (Filipsson and Nordberg, 2004), hence yielded the 289 high amounts of AOM in the palynological preparations. The core 9004 also consisted mainly 290 of homogeneous green-grey gyttja clay, again with substantial amounts of AOM, with 291 scattered small gastropods and intact mollusc shells in life position (Nuculana spp, Yoldiella 292 sp, Nucula spp, Abra spp, and Thyasira spp). There were, however, some changes in lithology especially at 364-367 cm where there was a more greyish sediment layer, which had at the 293 294 base a thin (1-2 mm) horizon of silt and sand containing high amounts (>50%) of the shallow-295 water foraminiferal taxa (*Elphidium* spp.: Polovodova et al., 2011). Below this there was a

distinct brownish horizon at 367-369 cm with plant fragments, and after 369 cm and further
down core the sediment turned back to a green-grey again. Both, the plant fragments, which
resembled peat remains, and the shallow water foraminiferal fauna, exotic to the deep fjord
basin, suggested that this horizon might represent a turbidite. Therefore the depth interval
364–369 cm was removed from the age model (Polovodova et al., 2011) but can be seen in its
original position in Fig. 2.

302 3.2. Organic carbon and C/N ratio

303 The organic carbon curve of the cores GA113-2Aa and 9004 showed an 304 increasing trend towards the core top with a long-term average of 1.79% (Filipsson and 305 Nordberg, 2010) (Fig.4). The C/N ratio measured in G113-119A and 9004 generally 306 fluctuated between 5 and 10, indicating the organic matter of primarily marine origin 307 (Redfield et al., 1963) (Fig.4). In relation to its long-term average of 8.3, the C/N curve 308 showed several intervals with relatively lower values at 670-810 cm (~350 BC- 400 AD), 309 290-490 cm (~880-1400 AD) and 110-190 cm (~1650-1850 AD). These intervals were 310 separated by periods characterised by higher C/N ratio at 490-660 cm (~400-880 AD), 190-311 290 cm (~1400-1650 AD) and 0-90 cm (present to ~1850 AD).

**312** 3.3. Dinoflagellate cyst analyses

The 60 samples from the core GA113-2Aa (Harland et al., 2006) and 71 samples from the core 9004 have been subject to analysis and yielded well preserved and diverse assemblages of dinoflagellate cysts together with other palynomorphs such as spores, pollen and the inner organic linings of benthic foraminiferal tests. The full floral list of species is given in a separate section herein. A taxonomical study was not undertaken since most of the recovered species are well known and relatively easy to identify.

319	The full dinoflagellate cyst spectrum is shown at the Fig. 3 and the major
320	changes in the record previously mentioned by Harland et al. (2006) and Harland and
321	Nordberg (2011) are indicated by dashed lines. The numbers of cysts per gram of sediment
322	were subject to a Q-mode cluster and simple CABFAC factor analyses, which detail the more
323	significant shifts in the dinoflagellate data.
324	3.3.1 Statistical analyses
325	3.3.1.1 Cluster analysis
326	Based on dinocyst species occurrence, the UPGMA algorithm and Bray-Curtis similarity
327	index clustered samples into six dinoflagellate cyst units (Fig. 4; also see in description
328	below). The units were distinguished subjectively by using stratigraphic and palaeoecological
329	controls, e.g. by comparing the position of defined clusters to major floral and environmental
330	changes in the record.
331	
332	Unit A: This unit represents a core interval of 662-790 cm (~350 BC - 250 AD) and
333	falls entirely within the Roman Warm Period, based on the age model
334	published in Filipsson and Nordberg (2010) and revised in Polovodova
335	Asteman et al. (2013). It is largely characterised by Protoceratium reticulatum,
336	Lingulodinium polyedrum, Lejeunecysta oliva and Protoperidinium spp. indet.
337	[i.e. round, brown cysts]. The unit is easily distinguished by the absence of the
338	microreticulate cysts of Gymnodinium nolleri (see Harland and Nordberg,
339	2011). The average total number of cysts per gram of sediment varies between
340	9900 and 18800. The increase of thermophilic dinoflagellate species at 700-
341	722 cm suggests the occurrence of somewhat warmer conditions in the surface
342	waters (Fig.3). This unit is also characterised by a higher heterotrophic or H/A

343	ratio derived from high heterotroph numbers and low autotroph numbers
344	during the Roman Warm Period possibly due to higher productivity and/or
345	increased seasonality (Fig.3) but certainly due to a change in the surface water
346	environment.

347 Unit B: The unit falls within a core interval of 503-662 cm (~250 - 800 AD). The age model suggests that this unit falls within the Dark Ages, which separated the 348 349 Roman and Medieval warm periods. It is characterised by the incoming of the microreticulate cysts, which represents a significant change in dinoflagellate 350 351 cyst assemblages (Fig.4). Also the unit contains P. reticulatum, Spiniferites spp. indet. including S. elongatus, Pentapharsodinium dalei, Islandinium 352 353 minutum and Protoperidinium conicum. The number of cysts shows a range of 354 9100 - 22500. The unit can be divided in two parts based on variations of 355 thermophilic and cryophilic ratio: 1) the interval 550-662 cm, which is 356 characterised by relatively high numbers of cryophilic cysts and 2) the interval 357 503-550 cm where thermophilic ratio shows higher values (Fig.3). The H/A ratio has low values within Unit B (Fig. 3). 358

359 Unit C: The unit comprises a core interval 302-493 cm (~800 - 1400 AD) and 360 corresponds to the Medieval Warm Period and the early part of the Little Ice 361 Age. Generally it is recognised by lower numbers of cysts including L. polyedrum, P. reticulatum, Spiniferites spp. indet., and the microreticulate 362 363 cysts of Gymnodinium nolleri. The total number of cysts varies between 5400 364 and 19200. This unit is characterised by a distinctly higher thermophilic ratio at 443-493 cm corresponding to the onset of the Medieval Warm Period (Fig.3). 365 366 The H/A ratio remains low throughout the extent of this unit (Fig.3).

367	Unit D:	This unit at 91-291 cm core depth (~1400 - 1850 AD) encompasses the major
368		part of the Little Ice Age. It is characterised by increased numbers of L.
369		polyedrum, P. reticulatum, Protoperidinium spp. indet. [i.e. round, brown
370		cysts] and Gymnodinium nolleri. The total number of cysts varies between
371		8696 and 27200. This unit again shows an increase of the thermophilic ratio in
372		its initial part at 241-261 cm, followed by somewhat higher numbers of
373		cryophilic dinoflagellate cysts at ca. 181 and 231 cm (Fig.3). The H/A ratio
374		shows low values until ca. 120 cm core depth, after which it increases
375		following low numbers of autotrophs and high numbers of heterotrophs
376		(Fig.3).
377	Unit E:	This unit largely corresponds to the Unit II of Harland et al. (2006) placed at
378		22-60 cm interval of the core GA113-2Aa and deposited between 1915 and
379		1969. According to Harland et al. (2006), this part of the record is
380		characterised by a range of 2464-8176 dinoflagellate cysts per gram of
381		sediment. Species composition of this unit shows high numbers of
382		Bitectatodinium tepikiense, L. polyedrum, Spiniferites elongatus, S. mirabilis
383		and Protoperidinium spp. Among other characteristics of this unit, there is a
384		marked peak of the thermophilic dinoflagellate cyst ratio, whereas the H/A
385		ratio remains low (Fig.3).
386	Unit F:	This unit is equivalent to the Unit I of Harland et al. (2006); it falls within the
387		uppermost part of the record (1-21 cm) and is deposited between 1969 and
388		1999. Its diversity is relatively high and is represented by 29 species. The
389		number of cysts per gram within this unit ranges from 1005 to 7328. In
390		particular the unit is characterised by high numbers of Protoceratium
391		reticulatum, S. bentorii, P. dalei, Protoperidinium avellana, Protoperidinium

392 conicoides, Protoperidinium conicum, Protoperidinium pentagonum,
393 Islandinium cf. cesare and Polykrikos kofoidii. The thermophilic ratio
394 decreases with a concurrent increase of cryophilic cysts within the unit. The
395 H/A ratio clearly show high values in the youngest part of the record.

396

The most significant change in our 8 m long record from the Gullmar Fjord is
associated with the microreticulate cysts of *Gymnodinium nolleri*. These cysts are particularly
frequent between ca. 90 and 660 cm. It has been previously noted by Harland and Nordberg
(2011) that these microreticulate cysts make a first appearance during the Dark Ages (ca. 400
AD) and virtually disappear at the termination of the Little Ice Age (after 1850 AD), although
small numbers of cysts persist to the present day.

#### 403 *3.3.1.2 Factor analysis*

404 The factor analysis resulted in three factors, which together explained 98% of 405 variance (Table 1). Additional text required here from Irina. Four dinoflagellate species 406 demonstrated absolute values of factor scores >1 (Fig 4), which usually implies a high species 407 contribution to the factor (Klovan and Imbrie, 1971). The analysis divided the record into 408 three dinoflagellate cyst assemblages represented by factors 1-3 (Fig 4). The first assemblage 409 corresponded to Factor 1 (76% of variance) and was characterised by high numbers of 410 Protoperidinium spp. indet. [i.e. round, brown cysts] and Lingulodinium polyedrum, as well 411 as by an absence of the microreticulate cysts of *Gymnodinium nolleri*. This assemblage was 412 equivalent to Units A and F, as well as the later part of the unit D (Fig. 4) defined by cluster 413 analysis. The second assemblage corresponded to Factor 2 (16% of variance) and was 414 characterised by high abundances of the microreticulate cysts of *Gymnodinium nolleri* and by lower numbers of Protoperidinium spp. indet. [i.e. round, brown cysts]. This assemblage 415

416	linked together units B, C and D, which were clearly distinguished by the cluster analysis
417	(Fig.4). Finally, the last assemblage corresponded to Factor 3 (6% of variance) and was
418	characterised by dinoflagellate species L. polyedrum and Protoceratium reticulatum. This
419	assemblage was equivalent to unit E as defined by the cluster analysis.

# 420 <u>3.3.2 Heterotrophic ratio</u>

421 Notwithstanding the caveats discussed earlier in the description of the 422 heterotrophic ratio the Gullmar Fjord dataset shows a fivefold division of the record (Fig.3). It is high in the older part at 660-800 cm, then at 70-200 cm and in the most recent part of the 423 424 record, which results from higher heterotroph numbers in relation to the autotrophs. These 425 higher ratio values correspond to the Roman Warm Period, the second part of the Little Ice 426 Age and the modern warming. The low ratio values are found between 200 and 660 cm, as 427 well as at ca. 30-70 cm. This corresponds to the time interval including Dark Ages, the 428 Medieval Warm Period and the first phase of the Little Ice Age, which are all generally characterised by little change in the ratio and only a small variation in numbers of 429 430 heterotrophic and autotrophic dinoflagellates.

#### 431 <u>3.3.3 Thermophilic and cryophilic ratios</u>

The majority of the identified species were thermophilic in character, whereas 432 433 cryophilic taxa were fewer in number. This is not surprising given the position of Gullmar 434 Fjord in relation to the Skagerrak (see earlier comments). The dinoflagellate cyst assemblages 435 recovered from the cores GA113-2Aa and 9004 are typical for this part of the Swedish west 436 coast and generally reflect the temperate latitude and compare well to other cyst assemblages 437 commonly found throughout the Skagerrak and Kattegat (Persson et al., 2000; Grøsfjeld and 438 Harland, 2001; Fjellså and Nordberg, 1996) the North Sea around the UK (Reid, 1972; 439 Harland, 1977) and into the north-eastern part of the North Atlantic (Harland, 1994; Harland

and Howe, 1995; Van Nieuwenhove et al., 2013). The recovered species are mostly neritic 440 441 with very few taxa reflecting a more oceanic habitat (see full species listing).

442 The thermophilic ratio shows an almost fourfold occurrence of warmer climate 443 periods. An increase in thermophilic cysts around 700 cm; at ca. 430-540 cm; at ca. 250-270 cm and from 60 cm onwards corresponding well with the Roman Warm Period, the Medieval 444 445 Warm Period, the first phase of the Little Ice Age, as previously suggested as being characterised by a more temperate climate (Polovodova Asteman et al., 2013), and finally the 446 447 most recent warming.

448 The cryophilic ratio, in contrast, is higher between 573-612 cm; 403-443 cm; at 449 241 cm and finally at 192 cm. These depths within the cores fall within the Dark Ages, the 450 Medieval Warm Period and the Little Ice Age respectively. Although there are some discrepancies in that certain cryophilic species occur within warm climatic phases, the general 451 452 pattern is mainly consistent with the known climate phases and given that the general 453 character of the dinoflagellate cyst assemblages does not change significantly overall.

454

#### 4. Discussion 455

456

#### 4.1 The Roman Warm Period (prior to ~400 AD):

457 The Roman Warm Period, also called the Roman Climate Optimum, is often 458 associated with a climate episode during the expansion of the Roman Empire (Wang et al., 459 2012). This period was characterised by an increasingly warm and dry summers both for the 460 British Isles and central Europe (Lamb, 1995). A maximum of glacier retreat in the European 461 Alps (Jörin et al., 2006) and a warm ocean surface north off Iceland, based on reconstructions 462 by oxygen isotopes (Eiríksson et al, 2006), also support a hypothesis of climate amelioration 463 during that time.

In our record, the abundant thermophilic species and, in particular, 464 465 Lingulodinium polyedrum within cluster Unit A, and the dinoflagellate cyst assemblages 466 represented by Factor 1, imply that the RWP was characterised by increased sea surface 467 temperatures (SSTs) in the Gullmar Fjord. Lingulodinium polyedrum tends to be seen as a summer blooming species, indicating stable water conditions at a time of depleted nutrients 468 (Harland et al., 2004) and occurring in modern oceans at SSTs > 10.1°C (Zonneveld et al., 469 470 2013). High relative abundances have been observed in upwelling cells or below river 471 discharge plumes and in highly stratified waters. It often occurs in regions with a strong 472 seasonal effect where eutrophic conditions prevail at times of upwelling or upwelling relaxation. (Zonneveld et al., 2013). Oxygen isotopic ratios measured from shells of the 473 474 limpet Patella vulgata from Hebrides Islands off NW Scotland suggested that summer 475 temperatures may have reached 13.3°C during the Roman Warm Period (Wang et al., 2012). 476 Considering the North Atlantic region in general, SSTs >15°C were obtained for the Rockall 477 Trough, NE Atlantic, based on planktonic foraminiferal Mg/Ca ratios by Richter et al. (2009). 478 In Gullmar Fjord the higher abundances of *L. polyedrum* during the RWP can be favourably 479 compared with similar high numbers of L. polyedrum through the modern warm period and 480 clearly associated with higher SSTs (~15- 18°C) (see Fig. 5. Harland et al. (2006)) from the GA113-2Aa dataset and the Bornö instrumental water temperature record). 481

At the same time high abundances of *Protoceratium reticulatum* prior to 400 AD may be associated with an influx of north temperate, nutrient enriched North Atlantic Current into Gullmar Fjord via the North Sea and the Skagerrak. According to a 5200-yr reconstruction of the North Atlantic Oscillation (NAO) by Olsen et al., (2012), the NAO was in a positive phase during the Roman Warm Period and may have been connected to a stronger North Atlantic Current due to positive temperature and precipitation anomalies (Trouet et al., 2012).

Another characteristic feature of the RWP may be an association with higher 489 490 primary productivity, as indicated by the increased abundances of the benthic foraminifer N. 491 *iridea*, which feeds upon fresh phytodetritus and was reported from the core 9004 by 492 Polovodova Asteman et al., (2012). Although the increased abundances of heterotrophic 493 dinoflagellates, as a well as lower C/N ratio seem to support this hypothesis, one should keep 494 in mind the caveat that only 13-16 % of dinoflagellates produce fossilisable cysts (Head, 1996). Therefore the dinoflagellate cyst record can only offer a small window on the total 495 496 primary productivity within the fjord. However taken together, the increased heterotrophic 497 ratio, the lower C/N ratio together with high numbers of Protoperidinium spp. indet. all point towards the increasing availability of nutrients in the water column at this time. The seasonal 498 499 effect at this latitude is not inconsistent with an influx of high nutrients in the spring and early 500 summer and the establishment of a stable water column in the autumn (Harland et al., 2004) 501 with an accompanying seasonal depletion of nutrients in a complex dynamic environment 502 much like the present day. This seasonality (see Wang et al., 2012) cannot be underestimated 503 in the interpretation of these temperate near shore sediment archives.

504 The boundary between dinoflagellate cyst units A/B and factors F1/F2, see above, is of great importance to the planktonic dinoflagellates, as indicated by statistical 505 506 analyses, and reflected both within the ubiquitous species and those that make up a more 507 minor part of the assemblages. This same temporal boundary is also reported in the benthic 508 foraminiferal record from the core 9004 (Polovodova Asteman et al., 2012) and taken together is indicative of an important change in the palaeoceanography of the region 509 510 impinging on these coastal sediments preserved in Gullmar Fjord. This boundary coincides 511 with the onset of a general climate deterioration associated with the initiation of the Dark 512 Ages Cold Period.

513

#### 514 <u>4.2 The Dark Ages Cold Period (ca. 400-800 AD):</u>

515 The Dark Ages is often associated with a "cold spell" separating the Roman and 516 Medieval Warm Periods and it happens to overlap with a time of mass migration of peoples 517 (so-called "Völkerwanderung") in the central Europe (Lamb, 1995; Hines et al., 1999; Büntgen et al., 2011) and hence The Dark Ages Cold Period. Millet et al. (2009) studied 518 519 laminated sediments from the Lake Anterne in the northern French Alps and, using insect 520 remains, obtained estimates of July air temperatures < 10°C for 400-680 AD, a time which 521 corresponds with the major part of the Dark Ages. A number of bogs in northern Europe have 522 also demonstrated a significant shift to a wetter and colder climate at ca. 550 AD (Barber et al., 2004). Another indication of cooler climate during the Dark Ages was evidenced by the 523 widespread abandonment of land and cultivation in the Jaeren coastal region of SW Norway 524 525 (Salvesen, 1979).

526 In Gullmar Fjord, during this period the environmental conditions may indeed 527 have become slightly cooler based upon the increased presence of *Spiniferites elongatus*, Pentapharsodinium dalei, Islandinium minutum and Islandinium cf. cezare grouped above 528 into the set of cryophilic dinoflagellate cysts. Of these three species Islandinium minutum is 529 530 probably the best known as a species associated with polar environments. Zonneveld et al. 531 (2013) provided a total SST w-s of -2.1-29.3° C; however its highest abundances occur in the 532 polar regions where it is a component of modern assemblages from inshore and offshore 533 Svalbard (Grøsfjeld et al. 2009; Howe et al. 2010). Often associated with Islandinium minutum is the related form, Islandinium cf. cezare, which is thought to have a more restricted 534 polar distribution; higher numbers are found in regions where the surface waters are  $< 0^{\circ}$  C in 535 536 winter (Zonneveld et al. 2013). Also recognised within this group is *Pentapharsodinium dalei* a species known to be abundant where temperatures in the surface waters are  $< 0^{\circ}$  C; in 537 538 Nordic region it is observed where sea-ice is a feature (Howe et al., 2010) and it has been

observed in Svalbard fjords (Grøsfjeld et al., 2009). Also P. dalei blooms during the spring 539 540 and competes with diatoms for nutrients in an unstable water column (Harland et al., 2004). 541 High abundances of *Pentapharsodinium dalei* thus imply that seasonality within the record is 542 also important during the Dark Ages Cold Period. It should be noted, however, that P. dalei 543 has also been recorded from the milder climates of the Recent Warm Period in Gullmar Fjord 544 (Harland et al., 2006) suggesting that a simple abiotic temperature control is too simplistic 545 and that both nutrient availability and seasonality play an important role. Finally Spiniferites 546 elongatus has long been recognised as a temperate to subpolar dinoflagellate cyst (Harland 547 and Sharp, 1986) and interestingly it has been observed in both coastal sites and also in an 548 oceanic setting (Zonneveld et al., 2013). The lower cyst numbers of L. polyedrum during this 549 time also support the hypothesis of cooler surface water conditions.

550 This time interval is also characterised by a major change in the dinoflagellate cyst assemblages, observed for the core 9004, associated with the species Gymnodinium 551 552 nolleri. This conspicuous microreticulate cyst makes its first appearance in the record after ca. 553 400 AD (660 cm) and is likely associated with a general cooling of the sea surface (Harland 554 and Nordberg, 2011). The introduction of these microreticulate cysts to the 9004 record at ca. 555 400 AD coincides with an increase of the benthic foraminiferal species Adercotryma glomerata, which is commonly associated with cold-water (<4°C) environments (see 556 557 discussion in Polovodova Asteman et al., 2013). This reinforces the evidence and our 558 interpretation about colder climatic conditions during the Dark Ages. It had been previously 559 noted by Harland and Nordberg (2011), that in some Holocene sediment records (e.g. Thorsen 560 et al., 1995; Fjellså and Nordberg, 1996; Thorsen and Dale, 1998; Fig. 1 herein) 561 microreticulate cysts of G. nolleri were mistaken for Gymnodinium catenatum, a species, 562 which produces cysts of a very similar morphology but notably larger in size. Gymnodinium catenatum occurs with the SST<sub>w-s</sub> of 3.4°C – 29.0°C, respectively (Zonneveld et al., 2013) 563

and in these Holocene sediment records it is, therefore, often associated with a warmer 564 565 climate intervals, as e.g. Medieval Warm Period (Thorsen et al., 1995; Fjellså and Nordberg, 566 1996; Thorsen and Dale, 1998). Considering that the cyst size is important, together with the 567 number of paravesicular rows within the paracingulum, the previous interpretations were based upon a probable misidentification of G. catenatum; caution is, therefore, advised when 568 569 using these earlier environmental interpretations within the Skagerrak-Kattegat region.

570

571

#### 4.3 The Medieval Warm Period (900-1350 AD):

572 A number of tree-ring based reconstructions from the northern and west-central 573 Scandinavia indicate the presence of a climate warming during the Middle Ages, which is 574 often centered on 1000 AD (e.g. Grudd, 2008; Gunnarson et al., 2011). The Medieval Warm 575 Period coincides with a Great Solar Maximum at 1100-1250 AD (Zicheng and Ito, 2000) and its temperature optimum evolved at  $\sim 1000 - 1300$  AD when there was a sharp maximum of 576 577 warmth in most of Europe (Lamb, 1995). A number of proxies from the NE Atlantic and 578 Nordic Seas indicate that the warming of the MWP, as reflected by higher SSTs, was most 579 pronounced before 1200 AD (Cunningham et al., 2013).

580 It is surprising that in Gullmar Fjord record, the interval corresponding to the MWP shows little variation in both the total number of dinoflagellate cysts and H/A ratio to 581 582 support increasing SSTs during that period (Fig. 3). This is reinforced by an additional 583 dinoflagellate cyst analysis performed on the MWP interval at a greater resolution (Harland & 584 Nordberg, unpublished data). However, from the temporal distribution of the thermophilic 585 cysts in the sediment archive, it is obvious that there is a three-fold increase of the 586 thermophilic ratio at around 1000 AD (450 cm), which might imply a shift towards more temperate climate conditions and surface water temperatures. Also, given the hypothesis of 587 588 that G. nolleri is an indicator of colder climates and reduced surface water temperatures is

correct (Harland and Nordberg, 2011), the obvious decline in numbers of *G. nolleri* at 440500 cm, simultaneous with an increase of thermophilic cysts (Fig. 3), may well indicate the
onset of the Medieval Warm Period. This change is also supported by the results of factor
analysis, which shows a short intrusion of Factor 1 corresponding to the *Protoperidinium* spp.
indet. assemblage at ~440-500 cm (Fig. 4).

594

## 595 <u>4.4 The Little Ice Age (1350-1850 AD):</u>

The Little Ice Age is commonly associated with a widespread expansion of glaciers in the Arctic and Alpine regions in response to climatic changes at ~1350-1850 AD (Lamb, 1995; Miller et al., 2012). The period 1675–1710 AD has been identified as the coldest phase (climax) of the LIA (Lamb, 1983), which also coincides with the Maunder Minimum in solar activity (1645-1715 AD: Mauquoy et al., 2002). However, the timing of the climax often differs between various reconstructions (e.g. Moberg et al., 2005; Ljungqvist, 2010; Cunningham et al., 2013) because of differences in their methodology.

603 Based on the foraminiferal data, Polovodova Asteman et al. (2013) suggested 604 that the first phase of the LIA (1350 - 1650 AD or ca. 180-290 cm) could be characterised by somewhat higher productivity as compared to its second phase (1650 -1850 AD or 90-290 605 606 cm). This coincides with a marked increase in the microreticulate cysts of Gymnodinium 607 nolleri in the dinoflagellate cyst assemblages, which Harland and Nordberg (2011) placed at 608 the onset of the Little Ice Age. It is also noteworthy that the numbers of Islandinium cf. 609 *cezare* also begin to increase at about the same level and continue to be present throughout the 610 Little Ice Age before falling away at the onset of the Modern Warm Period; it does however continue in small numbers until 1999 (Harland et al., 2006). There is a peak of Gymnodinium 611 612 nolleri at ca. 160 cm, which may well coincide with the climax of the Little Ice Age but in 613 reality these calculated abundances are based upon small raw counts that the saw tooth

dinoflagellate cyst spectrum portrays more as 'noise' and not as any significant change in the
environment within the surface waters of Gullmar Fjord. High resolution sampling tends to
produce data often confused by spurious detail much of which is 'noise' and difficult if not
impossible to interpret with precision (see later).

- 618
- 619 <u>4.5 The Modern Warm Period (the 20<sup>th</sup> century)</u>

620 The anthropogenic emissions of greenhouse gases from the burning of fossil fuel have contributed to the development of the modern/recent global warming. During the 621 second and third decades of the 20<sup>th</sup> century the modern climate warming became noticeable 622 623 around the world (Lamb, 1995; Thompson et al., 2010). The global air temperatures of the 624 1980s exceeded those of the 1930s, which are generally considered to be the warmest decade in recent times (e.g. Berhard, 1993; Smith et al., 2008; Hansen et al., 2010). According to 625 626 recent estimates (e.g. Gouretski et al., 2012) the upper 400 m of the oceans became 0.3-0.7°C 627 warmer since 1910 and there were two distinct periods of a stronger temperature increase: 1900 - 1940/45 and 1970 - 2003. 628

629 In the most recent part of the Gullmar Fjord record, which has been detailed by Harland et al. (2006), there is a profound increase in abundance of thermophilic dinoflagellate 630 631 cysts, which appears to be in line with the reported modern warning (see above). Based on a 632 dinoflagellate cyst spectrum and hydrographic observations, Harland et al. (2006) reported a 633 shift in Gullmar Fjord cyst record, which occurred in about the late 1960s/early 1970s and 634 mirrored a change in North Atlantic Oscillation from a negative phase to its predominantly 635 positive phase. This change is seen herein as illustrated by the change from an assemblage characterised by high numbers of *Bitectatodinium tepikiense*, *Lingulodinium polyedrum*, 636 637 Spiniferites elongatus and Spiniferites mirabilis, which gives way to an assemblage characterised by Protoceratium reticulatum, Spiniferites bentorii, Pentapharsodinium dalei 638

639 and several species of Protoperidinium. According to Björk and Nordberg (2003), this NAO 640 shift was responsible for a decreased upwelling frequency in the fjord between the 1950s and 641 1990. This upwelling, resulting from the predominantly northerly winds at a time of negative NAO, controlled the availability of nutrients coming to the surface fjord waters via advection 642 643 and Ekman pumping from the more offshore area. The NAO mostly influences the climate 644 during the winter with minor correlations between climate and NAO during the summer. Nonetheless the extra nutrients provided by increased upwelling during the negative phase of 645 646 the NAO will provide a most useful inoculum. As the NAO changed into its positive phase 647 the upwelling decreased and consequently had a major effect on both the ambient dinoflagellates population and cyst production (Harland et al., 2006). However this 648 649 interpretation has been the subject of some controversy (Dale, 2009; Harland et al., 2010; 650 Harland et al., in press). According to Dale (2009), both increased abundance of heterotrophs 651 and high L. polyedrum suggest an eutrophication signal during the late 1960s/early 1970s in 652 the Gullmar Fjord, albeit of different character, rather than a climate-induced hydrographic 653 variability. This, however, remains questionable since a very similar dinoflagellate cyst signal 654 is now known to be characteristic of the Roman Warm Period (Fig. 3) during times when 655 human activity was far from its peak. Although the interpretation of this most recent part of 656 the record may differ somewhat we can agree 'the importance of regional decadal-level 657 climate forcing of coastal eutrophication through NAO, ENSO etc.' (Dale 2009, p.112) and 658 the added complexity of identifying differing nutrient signals and their effects on the 659 dinoflagellate populations. Further discussion is welcomed as 'Cyst signals in sediments have 660 helped us identify these important questions' (Dale 2009, p.112).

The boundary at 1960s/70s separating two dinocyst assemblages, typical of
 Gullmar Fjord during 20<sup>th</sup> century (Harland et al., 2006), has also been distinguished in the
 current study by statistical analyses, which were run on the long-time series including both

GA113-2Aa and 9004 records. This boundary separates clusters E and F, as well as factors F1 664 665 and F3 (Fig. 4), which represent the different dinoflagellate cyst assemblages. Also from 666 Figure 3 it is obvious that there is clear difference in the abundances of total dinocysts 667 between cores GA113-2Aa and 9004; this may have resulted from slightly difference 668 processing techniques, see earlier. However findings from shallow bays along the Bohuslän 669 coast suggest that sediments deposited some hundreds of years ago contain more organic 670 material than today suggesting an environment more nutrient rich (Cossellu and Nordberg, 671 2010).

672

673 Recent work on the ecology of dinoflagellates (Smayda and Reynolds, 2003) 674 has discussed their collective strategies for survival in a largely neritic environment with high physical disturbance, light stress and nutrient limitations; the latter seemingly of key 675 676 importance in the fjords along the west coast of Sweden. Various adaptive strategies have 677 been recognised with many of the cyst forming dinoflagellates being known as **R**-strategists (ruderal or disturbance tolerant species) in order to overcome turbulent surface water 678 environments. Patterns of change within dinoflagellate cyst assemblages over this 2500 year 679 680 record cannot be regarded as a simple reaction to changes within the environment of one or 681 two abiotic parameters. Nutrient availability may be a result of pollution within the fjord 682 leading to eutrophication or may result from upwelling from depth in the more offshore areas 683 of the Skagerrak. Even within the R-strategist dinoflagellates there will be differences in their 684 reaction to this nutrient influx complicated by seasonality, temperature, salinity amongst the abiotic factors and undoubtedly a myriad of biotic factors that remain an enigma. It is clearly 685 686 complex and caution is advised in order to avoid the over interpretation of this and other 687 dinoflagellate cyst records. The dinoflagellate cyst record remains a small window onto the

total phytoplankton regime occupying the surface water environments within the GullmarFjord through the Subatlantic.

690

# 691 5. Comparisons

692 In many respects this study is unique providing a high resolution dinoflagellate 693 cyst record through the last 2500 years. However three earlier accounts of research published for the immediate area are relevant. The first (Thorsen et al., 1995) details the dinoflagellate 694 695 cyst analysis from Core 8903 in the Kattegat (Fig. 1A) proving a record over the last 3500 696 years BP. A series of four dinoflagellate cyst Zones were described largely recognised on the 697 abundance of Gymnodinium catenatum (now identified as Gymnodinium nolleri in Harland 698 and Nordberg, 2011). Our record closely mirrors their results to the extent that our Units B-D, 699 Factor 2 are clearly correlatable to their Zone 2 and our Units E and F, Factors 1 and 3 to their 700 Zone 1. Although differences are apparent in the climate interpretation the two taken indicate 701 a common dinoflagellate cyst archive for the last 2500 years in the Skagerrak and Kattegat. 702 The high abundances of the microreticulate cysts have no modern counterpart (Thorsen et al., 703 1995) and therefore remain somewhat difficult to interpret.

The second (Fjellså and Nordberg, 1996) concerns Core 8902, also in the Kattegat (Fig. 1A), which dates back until to at least 6390 years BP, and reveals within the Subatlantic part of the sequence the same record of microreticulate cysts as seen previously by Thorsen et al. (1995) and as discussed herein. In this case their Assemblage Zones 2 and 1 are equivalent to our Units E and F. Both these records reinforce the presence of microreticulate cysts in the Kattegat and are directly correlatable to the record described here from the Skagerrak.

The third study (Thorsen and Dale, 1998) detailed the effect of small scale 711 712 climate changes on one of the components of the recovered dinoflagellate cyst assemblages, 713 namely Gymnodinium catenatum. Cores 9307, 9308 and 9310 from the southern Norwegian 714 coast along the northern edge of the Skagerrak (Fig. 1A) were analysed and the regional 715 signal of the microreticulate cysts through the past 2000 years was recognised. They linked 716 the increased numbers of the microreticulate cysts with the warmer climatic phases of the 717 Subatlantic but did recognise a peak in numbers also within the Little Ice Age. The smaller 718 size range of their microreticulate cysts was recognised and some uncertainty was expressed 719 in the identification of these cysts with G. catenatum. The authors suggested that the species 720 had responded to small climatic changes such as maximum summer SST (Thorsen et al., 721 1995). Interestingly Thorsen and Dale (1998) regarded the occurrence of the microreticulate 722 cysts as additional to other elements of the dinoflagellate cyst assemblages and that the effect 723 of climate change over the last 2000 years has been relatively small.

724 The misidentification of Gymnodinium catenatum and its link to warmer surface waters probably led to some misinterpretation of the environment. This study provides a more 725 726 detailed high resolution account with better controlled chronology. Hence our records of the 727 microreticulate cysts do not increase in abundance through warm phases of the Subatlantic 728 but are more closely related to the cooler phases. Nonetheless these high abundances of 729 microreticulate cysts did occur before any substantial anthropogenic impact in the region. 730 Removal of these microreticulate cysts from the dinoflagellate cyst assemblages leaves the 731 remaining cyst species showing little change throughout the Subatlantic as previously noted 732 above by Thorsen and Dale (1998).

733

#### 734 6. Conclusions

735 This study has presented a detailed high resolution dinoflagellate cyst record 736 through the Subatlantic phase of the Holocene i.e. the last 2500 years. It is a part of a multi-737 proxy approach to provide a comprehensive account of climate change through the latest 738 Holocene encompassing both natural changes, as a result of various forcing factors, and of 739 anthropogenic affects as the area became under the influence of peoples as they developed an 740 agrarian economy and later became industrialised. This mixture of natural change and the increased influence of peoples has the potential to provide something of a baseline for future 741 742 climate change as atmospheric carbon dioxide levels continue to increase. Some of the other 743 results have already been published and a full synthesis of our results is in progress.

744 As previously noted, a temperature change of some 2° C or less may not presage 745 much change within the phytoplankton along the west coast of Sweden and indeed for many 746 species little change is obvious (Thorsen and Dale, 1998). However two important 747 assemblage changes are noteworthy; the first is the incoming of the microreticulate 748 dinoflagellate cyst Gymnodinium nolleri at the beginning of the Dark Ages Cold Period and 749 its almost disappearance at the start of the Recent Warming. Once thought to be a toxic warm 750 water species, as Gymnodinium catenatum, it is here noted to be rather seemingly more 751 associated with cooler waters and non-toxic. Comparison with other records reveals these 752 cysts are characteristic of this time interval throughout the Skagerrak and Kattegat region 753 even if their ecological preferences are still somewhat enigmatic. The second is the major 754 change seen in the cyst assemblages around the late 60s/early 70s, within the Recent 755 Warming period and associated with nutrient availability whether from offshore upwelling in 756 the Skagerrak under the influence of the NAO or pollution within the fjord.

757 Indeed many of the fluctuation within the dinoflagellate cyst assemblages are
758 quite subtle to observe especially within the saw tooth cyst spectrum. Undoubtedly the record
759 will contain a certain amount of 'noise' obscuring the data and interpretation. However with

the use of Q-mode cluster analysis and CABFAC factor analysis a comprehensive
interpretation of the record has been possible. The two statistical techniques reveal a
subdivision of the sediment archive into a series of informal dinoflagellate cyst units that
correlate well with the climate phases of the Subatlantic as recognised from previous stable
isotope work (Filipsson and Nordberg 2010).

765 However, and despite much research effort by many researchers including Zonneveld et al (2013), the detailed synecology and autecology of dinoflagellates and their 766 767 cysts is still very rudimentary so that environmental interpretations remain rather simplistic. 768 The sediment archive of fjords (Howe et al., 2010) provide a high resolution record of 769 planktonic change through the latest Holocene and perhaps more importantly has the potential 770 to provide a laboratory in which to test the ecology of these important members of the 771 phytoplankton. It is only with this knowledge that possible future scenarios along the Swedish 772 west coast can be understood at a time when carbon dioxide levels continue to increase as 773 climate changes.

774

## 775 7. Floral reference list

776 The list includes all the dinoflagellate cysts recovered from the cores GA113-2Aa (Harland et al., 2006) and 9004 in Gullmar Fjord, Sweden. Taxonomic references can be 777 778 found in Fensome and Williams (2004) and illustrations of many of the species can be found 779 in Rochon et al. (1999) and Harland et al. (2004b) from comparable material recovered in the 780 North Atlantic and along the west coast of Sweden. It is beyond the scope of this contribution 781 to provide a fully comprehensive taxonomy but all the material is available at the University 782 of Gothenburg. Although the biological names for dinoflagellate cysts are preferred some palaeontological names have been used where they provide increased nomenclatural 783 precision. 784

785	
786	Division DINOFLAGELLATA (Bütschli 1885) Fensome et al. 1993
787	Class DINOPHYCEAE Pascher 1914
788	
789	Order GYMNODINIALES Apstein 1909
790	Family GYMNODINIACEAE (Bergh 1881) Lankester 1885
791	Gymnodinium nolleri Ellegaard et Moestrup 1999
792	
793	Family POLYKRIKACEAE Kofoid et Swezy 1921
794	Polykrikos kofoidii Chatton 1914
795	
796	Order GONYAULACALES Taylor 1980
797	Family GONYAULACACEAE Lindemann 1928
798	Ataxiodinium choane Reid 1974
799	Bitectatodinium tepikiense Wilson 1973
800	Impagidinium sphaericum (Wall 1967) Lentin et Williams 1981
801	Lingulodinium polyedrum (Stein 1883) Dodge 1989
802	Nematosphaeropsis labyrinthus (Ostenfeld 1903)
803	Protoceratium reticulatum (Claparéde et Lachmann 1859) Bütschli 1885
804	Spiniferites bentorii (Rossignol 1964) Wall et Dale 1970
805	Spiniferites delicatus Reid 1974

806	Spiniferites elongatus Reid 1974
807	Spiniferites lazus Reid 1974
808	Spiniferites mirabilis (Rossignol 1964) Sarjeant 1970
809	Spiniferites ramosus (Ehrenberg 1838) Mantell 1854
810	Spiniferites spp. indet.
811	Family GONIODOMACEAE Lindemann 1928
812	Alexandrium tamarense (Lebour 1925) Balech 1985
813	
814	Order PERIDINIALES Haeckel 1894
815	Family PERIDINIACEAE Ehrenberg 1831
816	Pentapharsodinium dalei Indelicato et Loeblich III 1986
817	Family PROTOPERIDINIACEAE Bujak et Davies 1998
818	Islandinium cf. cezare (de Vernal et al. 1989 ex de Vernal in Rochon et al., 1999) Head et al.,
819	2001
820	Islandinium minutum (Harland et Reid 1980) Head et al., 2001
821	Lejeunecysta marieae (Harland 1991) Lentin et Williams 1993
822	Lejeunecysta oliva (Reid 1977) Turon et Londeix 1988
823	Protoperidinium avellana (Meunier 1919) Balech 1974
824	Protoperidinium claudicans (Paulsen 1907) Balech 1974
825	Protoperidinium compressum (Abé 1927) Balech 1974
826	Protoperidinium conicoides (Paulsen 1905) Balech 1974

- 827 Protoperidinium conicum (Gran 1900) Balech 1974
- 828 Protoperidinium divaricatum (Meunier 1919) Parke et Dodge 1976
- 829 Protoperidinium leonis (Pavillard 1916) Balech 1974
- 830 *Protoperidinium oblongum* (Aurivillius 1898) Balech 1974
- 831 Protoperidinium pentagonum (Gran 1902) Balech 1974
- 832 *Protoperidinium punctulatum* (Paulsen 1907) Balech 1974
- 833 Protoperidinium stellatum (Wall 1968) Head 1999
- 834 Protoperidinium subinerme (Paulsen 1904) Loeblich 1969
- 835 *Protoperidinium* spp. indet.
- 836

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851

# 852 **References:**

- Appleby, P.G., Oldfield, F., 1978. The calculation of lead 210 dates assuming a constant rate
   of supply of unsupported <sup>210</sup>Pb to the sediment. Catena 5, 1–8.
- 855 Barber, K.E., Chambers, F.M., Maddy, D., 2004. Late Holocene climatic history of northern
- 856 Germany and Denmark: peat macrofossil investigations at Dosenmoor, Schleswig-Holstein
- and, Svanemose, Jutland. Boreas 33, 132-144.
- Beaugrand, G., Reid, P.C., Ibañez, F., Lindley, A.J., Edwards, M., 2002. Reorganisation of
- North Atlantic marine copepod biodiversity and climate. Science Reports 296, 1692-1694.
- Berhard, H.W., 1993. Global warming unchecked: signs to watch for. Indiana Univ. Press,
  186 p.
- Björk G, Nordberg K., 2003. Upwelling along the Swedish west coast during the 20th
- century. Continental Shelf Research 23, 1143–59.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., de Menocal, P., Priore, P., Cullen,
- 865 H., Hajdas, I., Bonani, G., 1997. A pervasive millennial scale cycle in North Atlantic
- Holocene and glacial climates, Science 278, 1257–1266.
- 867 Bronk Ramsey, C., 2005. Improving the resolution of radiocarbon dating by statistical
- analysis. In: Levy, T.E., Higham, T.F.G. (Eds.), The Bible and Radiocarbon Dating:
- Archaeology, Text and Science. Equinox, London, pp. 57–64.
- 870 Bray, J.R., and Curtis, J.T., 1957. An ordination of the upland forest communities of Southern
- 871 Wisconsin. Ecological Monographs 27, 325-349.

- 872 Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O.,
- 873 Herzig, F., Heussner, K.U., Wanner, H., Luterbacher, J., Esper, J., 2011. 2500 Years of
- European Climate Variability and Human Susceptibility. Science 331, 578-582.
- 875 Clemmensen, L., Murray, A., Heinemeier, J., De Jong, R., 2009. The evolution of Holocene
- 876 coastal dune fields, Jutland, Denmark: A record of climate change over the past 5000 years.
- 877 Geomorphology 105, 303–313.
- 878 Crutzen, P.J., 2002. Geology of mankind. Nature 415, 23.
- 879 Cunningham, L.K., Austin, W.E.N., Knudsen, K.L., Eiríksson, J., Scourse, J.D., Wanamaker,
- A.D. Jr., Butler, P.G., Cage, A., Richter, T., Husum, K., Hald, M., Andersson, C., Zorita, E.,
- Linderholm, H.W., Gunnarson, B., Sicre, M.-A., Sejrup, H.P., Jiang, H., Wilson, R.J.S., 2013.
- 882 Reconstructions of surface ocean conditions from the northeast Atlantic and Nordic Seas
- during the last millennium. The Holocene 23, 921-935. doi: 10.1177/0959683613479677.
- 884 Cossellu, M. & Nordberg, K., 2010a. Recent environmental changes and filamentous algal
- mats in shallow bays on the Swedish West Coast a result of climate change? *J. Sea Res. 63*,
  202-212.
- B87 Dale, B., 1976. Cyst formation, sedimentation, and preservation: factors affecting
- 888 dinoflagellate assemblages in recent sediments from Trondheimsfjord, Norway. Review of
- 889 Palaeobotany and Palynology 22, 39-60.
- B90 Dale, B., 1983. Dinoflagellate resting cysts: "benthic plankton". In: Fryxell, G.A. (Ed.),
- 891 Survival strategies of the algae, Cambridge Unuversity Press, Cambridge, 69-136.
- Bale, B., 2009. Eutrophication signals in the sedimentary record of dinoflagellate cysts in
  coastal waters. Journal of Sea Research 61, 103-113.
- B94 Davis, J.C., 1986. Statistics and Data Analysis in Geology, John Wiley and Sons, New York.

- B95 Drinkwater, K.F., 2006. The regime shift of the 1920s and 1930s in the North Atlantic.
- 896 Progress in Oceanography 68, 134-151.
- deVernal, A., Marret, F., 2007. Organic-walled dinoflagellates: tracers of sea-surface
- 898 conditions. In : Hillaire-Marcel, C., de Vernal, A. (Eds.), Proxies in Late Cenozoic
- 899 Paleoceanography, Elsevier, Netherlands, 371-408.
- 900 Eiríksson, J., Bartels-Jonsdottir, H.B., Cage, A.G., Gudmundsdottir, E.R., Klitgaard-
- 901 Kristensen, D., Marret, F., Rodrigues, T., Abrantes, F., Austin, W.E.N., Jiang, H., Knudsen,
- 902 K. L., and Sejrup, H. P., 2006. Variability of the North Atlantic Current during the last 2000
- 903 years based on shelf bottom water and sea surface temperatures along an open ocean/shallow
- marine transect in western Europe. The Holocene 16, 1017-1029.
- 905 Fensome, R. A., Williams, G. L., 2004. The Lentin and Williams index of fossil
- 906 dinoflagellates 2004 edition. American Association of Stratigraphic Palynologists,
- 907 Contribution Series 4, 1-909.
- 908 Filipsson, H.L., Nordberg, K., 2004. Climate variations, an overlooked factor influencing the
- 909 recent marine environment. An example from Gullmar Fjord, Sweden, illustrated by benthic
- 910 foraminifera and hydrographic data. Estuaries 27, 867-881.
- 911 Filipsson, H.L., Nordberg, K., 2010. Variations in organic carbon flux and stagnation periods
- 912 during the last 2400 years in a Skagerrak fjord basin, inferred from benthic foraminiferal
- 913 δ13C. In: Howe, J.A., Austin, W.E.N., Forwick, M., Powell, R.D., Paetzel, M. (Eds.). Fjords:
- 914 Depositional Systems and Archives, Geological Society Special Publication 344, 261–270.
- 915 Fjellså, A., Nordberg, K., 1996. Toxic dinoflagellate "blooms" in the Kattegat, North Sea,
- 916 during the Holocene. Palaeogeogr., Palaeoclim., Palaeoecol. 124, 87-105.

- Gouretski, V., Kennedy, J., Boyer, T., Köhl, A., 2012. Consistent near-surface ocean warming
  since 1900 in two largerly independent observing networks. Geophys. Res. Lett. 39, L19609,
  doi:10.1029/2012GL052975
- 920 Grøsfjeld, K., Harland, R., 2001. Distribution of modern dinoflagellate cysts from inshore
- areas along the coast of southern Norway. Journal of Quaternary Science 16, 651-659.
- 922 Grøsfjeld, K., Harland, R., Howe, J. A., 2009. Dinoflagellate cyst assemblages inshore and
- 923 offshore Svalbard reflecting their modern hydrography and climate. Norwegian Journal of924 Geology 89, 121-134.
- 925 Grudd, H., 2008. Torneträsk tree-ring width and density AD 500-2004: a test of climatic
- sensitivity and a new 1500-year reconstructions of north Fennoscandian summers. Clim.
- 927 Dynam. 31, 843-857.
- 928 Gunnarson, B.E., Linderholm, H.W., and Moberg, A., 2011. Improving a tree-ring
- 929 reconstruction from west-central Scandinavia 900 years of warm-season temperatures,
- 930 Clim. Dynam. 36, 97-108.
- Hammer, Ø., Harper, D.A.T., and Ryan, P.D., 2001. PAST: Paleontological Statistics
- 932 Software Package for Education and Data Analysis. Palaeontologica Electronica 4, 1–9.
- Hansen, J., Ruedy, R., Sato, M., Lo, K., 2010. Global surface temperature change. Rev.
- 934 Geophys., 48, RG4004, doi:10.1029/2010RG000345
- Harland, R., 1973. Dinoflagellate cysts and acritarchs from the Bearpaw Formation (Upper
- Campanian) of southern Alberta, Canada. Palaeontology 16, 665-706.
- 937 Harland, R., 1977. Recent and late Quaternary (Flandrian and Devensian) dinoflagellate cysts
- 938 from marine continental shelf sediments around the British Isles. Palaeontographica, Abt. B
- **939** 164, 87-126.

- Harland, R., 1988. Dinoflagellates, their cysts and Quaternary stratigraphy, New Phytol. 108,111-120.
- Harland, R., 1989. A dinoflagellate cyst record for the last 0.7 Ma from the Rockall Plateau,
- 943 northeast Atlantic Ocean. Journal of the Geological Society (London) 146, 951-954.
- Harland, R., 1994. Dinoflagellate cysts from the Glacial/Postglacial transition in the northeast
- 945 Atlantic Ocean. Palaeontology 37, 263-283.
- 946 Harland, R., Howe, J.A., 1995. Dinoflagellate cysts and Holocene oceanography of the
- 947 northeastern Atlantic Ocean. The Holocene 5, 220-228.
- 948 Harland, R., Nordberg, K., 2011. The identification, occurrence and importance of
- 949 microreticulate dinoflagellate cysts in the latest Holocene sediments of the Skagerrak and
- 950 Kattegat, west coast of Sweden. Review of Palaeobotany and Palynology 164, 84-92.
- 951 Harland, R., Nordberg, K., Filipsson, H.L., 2004. The seasonal occurrence of dinoflagellate
- 952 cysts in surface sediments from Koljö Fjord, west coast of Sweden a note. Review of
- 953 Palaeobotany and Palynology 128, 107-117.
- Harland, R., Nordberg, K., Filipsson, H., 2006. Dinoflagellate cysts and hydrographical
- 955 change in Gullmar Fjord, west coast of Sweden. Sci. Tot. Env. 355, 204-231.
- 956 Harland, R., Nordberg, K., Filipsson, H.L., 2010. A major change in the dinoflagellate cyst
- 957 flora of Gullmar Fjord, Sweden, at around 1969/1970 and its possible explanation. In: Howe,
- 958 J.A., Austin, W.E.N., Forwick, M., Powell, R.D., Paetzel, M. (Eds.), Fjords: Depositional
- 959 Systems and Archives, Geological Society Special Publication 344, 75-82.
- 960 Harland, R., Nordberg, K., Robijn, A., in press. Latest Holocene dinoflagellate cyst records
- 961 from the west coast of Sweden and their impact on the interpretation of environmental
- 962 change. In: Lewis, J., Marret, F., Bradley, L., (Eds.). Biological and Geological Perspectives
- 963 of Dinoflagellates. The Micropalaeontology Society, Special Publication 5, 37-48.

- Harland, R., Sharp, J., 1986. Elongate Spiniferites cysts from North Atlantic bottom
  sediments. Palynology10, 25-34.
- 966 Hass, H.C., 1996. Northern Europe climate variations during late Holocene: evidence from
- 967 marine Skagerrak. Palaeogeogr. Palaeocl. 123, 121–145.
- 968 Head, M.J., 1996. Modern dinoflagellate cysts and their biological affinities. In: Jansonius, J.,
- 969 McGregor, D.C. (Eds.). Palynology: principles and applications. American Association of
- 970 Stratigraphic Palynologists Foundation, Salt Lake City 3, 1197-1248.
- 971 Hines, J., Høilund Nielsen, K., Siegmund, F., 1999. The pace of change: studies in early-
- 972 medieval chronology (Cardiff Studies in Archaeology), Oxbow Books, 208 pp.
- 973 Hoogakker, B.A.A., Chapman, M.R., McCave, N., Hillaire-Marcel, C., Ellison, C.R.W., Hall,
- 974 I.R., Telford, R.J., 2011. Dynamics of North Atlantic deep water masses during the Holocene.
- 975 Paleoceanography 26, PA4214, doi:10.1029/2011PA002155.
- 976 Howe, J.A., Austin, W.E.N., Forwick, W., Paetzel, M., Harland, R., Cage, A.G., 2010. Fjord
- 977 systems and archives: a review. In: Howe, J.A., Austin, W.E.N., Forwick, M., Paetzel, M.
- 978 (Eds.). Fjords: Depositional Systems and Archives. Geological Society Special Publication
- 979 344, 5-15.
- 980 Howe, J.A., Harland, R., Cottier, F.R., Brand, T., Willis, K.J., Berge, J.R., Grøsfjeld, K.,
- 981 Eriksson, A., 2010. Dinoflagellate cysts as proxies for palaeoceanographic conditions in
- 982 Arctic Fjords. In: Howe, J.A., Austin, W.E.N., Forwick, M., Paetzel, M. (Eds.). Fjords:
- 983 Depositional Systems and Archives. Geological Society Special Publication 344, 61-74.
- 984 Jacobson, D.M., Anderson, D.M., 1986. Thecate heterotrophic dinoflagellates: feeding
- 985 behaviour and mechanisms, J. Phycol. 22, 249-258.
- Jörin, U.E., Stocker, T.F., and Schlüchter, C., 2006. Multicentury glacier fluctuations in the

- 987 Swiss Alps during the Holocene. The Holocene 16, 697–704.
- 988 Klovan, J.E., and Imbrie, J., 1971. An algorithm and FORTRAN-IV program for large scale
- 989 Q-mode factor analysis and calculation of factor scores. Mathematical Geology 3, 61-77.
- Lamb, H.H., 1983. Some studies of the Little Ice Age of recent centuries and its great storms.
- 991 In: Mörner, N.A. and Karlén, W. (Eds.). Climatic changes on a yearly to millennial basis:
- 992 Geological, historical and instrumental records. D. Reidel Publishing Company, Dordrecht.
- 293 Lamb, H.H., 1995. Climate History and the Modern World. Routledge, London and New294 York.
- Lewis, J., Dodge, J.D., Powell, A.J., 1990. Quaternary dinoflagellate cysts from the upwelling
- system offshore Peru, Hole 686B, ODP Leg 112. In: Suess, E., von Huene, R., et al. (Eds.).
- 997 Proceedings of the Ocean Drilling Program, Scientific Results 112, 323-328.
- Ljungqvist, F.C., 2010. A new reconstruction of temperature variability in the extra-tropical
  Northern Hemisphere during the last two millennia. *Geogr. Ann.* 92 A, 339–351.
- 1000 Lund, D.C., Lynch-Stieglitz, J., Curry, W.B., 2006. Gulf Stream density structure and
- transport during the past millennium. Nature 444, 601-604.
- 1002 Mangerud, J., Anderson, S.T., Berglund, B.E., Donner, J.J., 1974. Quaternary stratigraphy of
- 1003 Norden, a proposal for terminology and classification. Boreas 3, 109-128.
- 1004 Mauquoy, D., van Geel, B., Blaauw, M., van der Plicht, J., 2002. Evidence from northwest
- 1005 European bogs shows "Little Ice Age" climatic changes driven by variations in solar activity.
- 1006 The Holocene 12, 1-6.
- 1007 Miller, G.H., Geirsdottir, A., Zhong, Y.F., Larsen, D.J., Otto-Bliesner, B.L., Holland, M.M.,
- 1008 Bailey, D.A., Refsnider, K.A., Lehman, S.J., Southon, J.R., Anderson, C., Bjornsson, H., and
- 1009 Thordarson, T., 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained

- 1010 by sea-ice/ocean feedbacks, Geophys. Res. Lett. 39, L02708, doi:10.1029/2011GL050168.
- 1011 Millet, L., Arnaud, F., Heiri, O., Magny, M., Verneaux, V., Desmet, M., 2009. Late-Holocene
- 1012 summer temperature reconstruction from chironomid assemblages of Lake Anterne, northern
- 1013 French Alps. The Holocene 19, 317-328.
- 1014 Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlén, W., 2005. Highly
- 1015 variable Northern Hemisphere temperatures reconstructed from low- and high-resolution
- 1016 proxy data. Nature 433, 613–617.
- 1017 Olsen, J., Anderson, N.J., Knudsen, M.F., 2012. Variability of the North Atlantic Oscillation
- 1018 over the past 5,200 years. Nature Geoscience 5, 808-812.
- 1019 Parker, W.C., Arnold, A.J., 1999. Quantitative methods of data analysis in foraminiferal
- 1020 ecology. In: Sen Gupta, B.K. (Ed.). Modern Foraminifera, Kluwer Academic Publishers, 71-1021 89.
- Persson, A., Godhe, A., Karlson, B., 2000. Dinoflagellate cysts in Recent sediments from thewest coast of Sweden. Botanica Marina 43, 69-79.
- 1024 Polovodova, I., Nordberg, K., Filipsson, H.L., 2011. The benthic foraminiferal record of the
- 1025 Medieval Warm Period and the recent warming in the Gullmar Fjord, Swedish west coast.
- 1026 Mar. Micropal. 81, 95-106.
- 1027 Polovodova Asteman, I., Nordberg, K., Filipsson, H.L., 2012. The Little Ice Age: evidence
- 1028 from a sediment record in Gullmar Fjord, Swedish west coast. Biogeosci. Discuss. 9, 14053-
- 1029 14089.
- 1030 Polovodova Asteman, I., Nordberg, K., Filipsson, H.L., 2013. The Little Ice Age: evidence
- 1031 from a sediment record in Gullmar Fjord, Swedish west coast. Biogeosci. 10, 1275-1290.

- 1032 Redfield, A.C., Ketchum, B.H., Richards, F.A., 1963. The influence of organisms on the
- 1033 composition of seawater. In: Hill, M.N. (Ed.). The Sea, Wiley, New York, 26-77.
- 1034 Reid, P. C., 1972. Dinoflagellate cyst distribution around the British Isles. Journal of the
- 1035 Marine Biological Association U.K. 52, 939-944
- 1036 Reid, P.C., Valdés, L., 2011. ICES status report on climate change in the North Atlantic.
- 1037 ICES Cooperative Research Report 310, 262 pp.
- 1038 Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell,
- 1039 P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G.,
- 1040 Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac,
- 1041 G., Manning, S., Ramsey, C. Bronk, Reimer, R.W., Remmele, S., Southon, J.R., Stuiver,
- 1042 M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04
- 1043 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1029–1058.
- 1044 Richter, T.O., Peeters, F.J.S., Van Weering, T.C.E., 2009. Late Holocene (0-2.4 ka BP)
- 1045 surface water temperature and salinity variability, Feni Drift, NE Atlantic Ocean. Quaternary
- 1046 Science Reviews 28, 1941-1955.
- 1047 Rochon, A., de Vernal, A., Turon, J.-L., Matthiessen, J., Head, M.J., 1999. Distribution of
- 1048 recent dinoflagellate cysts in surface sediments from the North Atlantic Ocean and adjacent
- 1049 seas in relation to sea-surface parameters. American Association of Stratigraphic
- 1050 Palynologists, Contribution Series 35, 1-146.
- 1051 Salvesen, H., 1979. Jord I Jemtland, Östersund, AB Wisenska bokhandelens förlag, 187 pp.
- 1052 Sernander, R., 1908. On the evidence of Postglacial changes of climate furnished by the peat-
- 1053 mosses of Northern Europe. Geologiska Föreningen I Stockholm Förhandlingar 30, 465-473.

- 1054 Sicre, M.A., Hall, I.R., Mignot, J., Khodri, M., Ezat, U., Truong, M.X., Eiriksson, J.,
- 1055 Knudsen, K.L., 2011. Sea surface temperature variability in the subpolar Atlantic over the last
- two millennia. Paleoceanography 26, PA4218, doi:10.1029/2011PA002169.
- 1057 Smayda, T.J., Reynolds, C.S., 2003. Strategies of marine dinoflagellate survival and some
- 1058 rules of assembly. Journal of Sea Research 49, 95-106.
- Smith, A.G., Pilcher, J.R., 1973. Radiocarbon dates and vegetation history of the British Isles.
  New Phytologist 72, 903-914.
- 1061 Smith, T.M., Reynolds, R.W., Peterson, T.S., Lawrimore, J., 2008. Improvements to NOAA's
- 1062 historical merged land-ocean surface temperature analysis (1880-2006). Journal of Climate
- 1063 21, doi: 10.1175/2007JCLI2100.1
- Sokal, R.R., 1986. Phenetic taxonomy: Theory and methods. Annual Review of Ecology andSystematics 17, 423-442.
- Stuiver, M., Pollach, H.A., 1977. Discussions of reporting 14C data. Radiocarbon 19, 355–
  363.
- 1068 Thorsen, T.A., Dale, B., Nordberg, K., 1995. "Blooms" of the toxic dinoflagellate
- 1069 *Gymnodinium catenatum* as evidence of climatic fluctuations in the late Holocene of
- 1070 southwestern Scandinavia. The Holocene 5, 435-446.
- 1071 Thorsen, T.A., Dale, B., 1998. Climatically influenced distribution of *Gymnodinium*
- 1072 *catenatum* during the past 2000 years in coastal sediments of southern Norway.
- 1073 Palaeogeography Palaeoclimatology Palaeoecology 143, 159-177.
- 1074 Thompson, D.W.J., Wallace, J.M., Kennedy, J.J., Jones, P.D., 2010. An abrupt drop in
- 1075 Northern Hemisphere sea surface temperature around 1970. Nature 467, 444-447.
- 1076 Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C., 2009.

- 1077 Persistent positive North Atlantic Oscillation Mode dominated the Medieval Climate1078 Anomaly. Science 324, 78-80.
- 1079 Trouet, V., Scourse, J.D., Raible, C.C., 2012. North Atlantic storminess and Atlantic
- 1080 meridional overturning circulation during the last millennium: Reconciling contradictory
- 1081 proxy records of NAO variability. Glob. Planet. Change 84-85, 48-55.
- 1082 Van Nieuwenhove, N., Bauch, H.A., Andruleit, H., 2013. Multiproxy fossil comparison
- 1083 reveals contrasting ocean conditions in the western Iceland Sea for the last two interglacials.
- 1084 Palaeogeography, Palaeoclimatology, Palaeoecology 370, 247-259.
- 1085 Walker, M., Johnsen, S., Rasmussen, S.O., et al., 2009. Formal definition and dating of the
- 1086 GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland
- 1087 NGRIP ice core and selected auxiliary records. J. Quatern. Sci. 24, 3-17.
- 1088 Wang, T., Surge, D., Mithen, S., 2012. Seasonal temperature variability of the Neoglacial
- 1089 (3300-2500 BP) and Roman Warm Period (2500-1600 BP) reconstructed from oxygen
- 1090 isotope ratios of limpet shells (Patella vulgata), Northwest Scotland. Palaeogeography
- 1091 Palaeoclimatology Palaeoecology 317-318, 104-113.
- 1092 Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P., Jetel, M., 2011. Structure and origin of
- 1093 Holocene cold events. Quat. Sci. Rev. 30, 3109-3123.
- 1094 Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Palynological techniques processing and
- 1095 microscopy. In Jansonius, J., McGregor, D.C. (Eds). Palynology: principles and applications.
- 1096 American Association of Stratigraphic Palynologists Foundation, Salt Lake City 1, 29-50.
- 1097 Zalasiewicz, J., Williams, M., Haywood, A., Ellis, M., 2011. The Anthropocene: a new epoch
- 1098 of geological time? Phil. Trans. R. Soc. 369(1938), 835-841.
- 1099 Zalasiewicz, J., Williams, M., Steffen, W., Crutzen, P., 2010. The new world of the
- 1100 Anthropocene. Environ. Sci. Technol. 44, 2228-2231.

- 1101 Zicheng, Y., Ito, E., 2000. Historical solar variability and midcontinent drought. PAGES
  1102 Newsletter 8, 6–7.
- 1103 Zonneveld, K.A.F., Marret, F., Versteegh, G.J.M., Bogus, K., Bonnet, S., Bouimetarhan, I.,
- 1104 Crouch, E., de Vernal, A., Elshanawany, R., Edwards, L., Esper, O., Forke, S., Grøsfjeld, K.,
- 1105 Henry, M., Holzwarth, U., Kielt, J.-F., Kim, So-Young, Ladouceur, S., Ledu, D., Chen,
- 1106 Liang, Limoges, A., Londeix, L., Lu, S.-H., Mahmoud, M.S., Marino, G., Matsuoka, K.,
- 1107 Matthiessen, J., Mildenhal, D.C., Mudie, P., Neil, H.N., Pospelova, V., Qi, Y., Radi, T.,
- 1108 Richerol, T., Rochon, A., Sangiorgi, F., Solignac, S., Turon, J.-L., Verleye, T., Wang, Y.,
- 1109 Wang, Z., Young, M., 2013. Atlas of modern dinoflagellate cyst distribution based on 2405
- 1110 data points. Review of Palaeobotany and Palynology 191, 1–197.
- 1111 Zonneveld, K. A. F., Versteegh, G., Kodrans-Nsiah, M., 2008. Preservation and organic
- 1112 chemistry of Late Cenozoic organic-walled dinoflagellate cysts: A review. Marine
- 1113 Micropaleontology 68, 179-197.
- 1114
- 1115 Statistical software PAST is available at: <u>http://folk.uio.no/ohammer/past/</u>

1116

# 1118 Tables

1119 Table 1: Varimax scores for dinoflagellate cysts factors 1-3. The bold numbers indicate

1120 dinoflagellate species with high (>1) absolute value of factor scores. The eigenvalues and

1121 percentages of explained variance for each factor are also given below.

Dinoflagellate species:	Factor 1	Factor 2	Factor 3
Bitectatodinium tepikiense	-0.017	0.009	0.175
Lingulodinium polyedrum	-1.256	0.108	3.750
Protoceratium reticulatum	0.651	-0.381	1.938
Spiniferites bentorii	0.069	0.028	0.100
Spiniferites elongatus	-0.014	-0.019	0.102
Spiniferites mirabilis	-0.011	0.001	0.046
Spiniferites spp. indet.	0.120	-0.230	0.632
Pentapharsodinium dalei	0.107	-0.042	-0.009
Islandinium cf. cezare	0.217	-0.059	-0.004
Islandinium minutum	0.028	-0.062	-0.023
Lejeunecysta marieae	0.015	-0.004	-0.008
Lejeunecysta oliva	0.065	-0.045	-0.007
Protoperidinium conicoides	0.089	-0.002	-0.033
Protoperidinium conicum	0.203	0.036	0.256
Protoperidinium oblongum	0.066	0.004	0.029
Protoperidinium pentagonum	0.008	-0.011	-0.002
Protoperidinium stellatum	0.032	-0.032	-0.022
Protoperidinium spp. indet. [RB]*	3.942	-1.113	0.752
Gymnodinium nolleri	-1.149	-4.188	-0.310

Eigenvalues	100.02	21.11	7.24
Variance (%)	76.35	16.12	5.53

1122 \* [RB] stands for [round, brown]

#### 1124 Figure captures:

1125 Figure 1: Location of the Gullmar Fjord within the Skagerrak (A) and at the Swedish west

1126 coast (B) and stratification of the fjord's water masses with salinity ranges (s) and residence

times (t) following Arneborg, (2004) (C). Star indicates a sampling site for cores GA113-2Aa

and 9004; dashed line in the outer part of the Gullmar Fjord shows location of a sill at 42 m

1129 water depth; whereas abbreviations AW, SJC, NJC, NCC and BC stand for Atlantic Water,

South Jutland Current, North Jutland Current, Norwegian Coastal Current and Baltic Current,correspondingly.

1132 Figure 2: Chronology based on CRS model and <sup>210</sup>Pb (core GA113-2Aa; Filipsson and

1133 Nordberg, 2004a) and <sup>14</sup>C AMS datings of eleven mollusc shells in life position (core 9004;

1134 Filipsson and Nordberg, 2010). In the revised version of <sup>14</sup>C age model (Polovodova et al.,

1135 2011) a 500-yr reservoir correction has been applied, whereas a layer with a saw tooth pattern

at 357–371 cm indicates the primary position of a turbidite, which has been removed from the

age curve. Separated by dashed lines are curve intervals, characterised by changes in a

sedimentation rate. This version of the core 9004 age model is used after Polovodova

1139 Asteman et al. (2013), who updated the chronology by removing a ca. 40-cm gap between the

1140 cores GA113-2Aa and 9004.

1141 Figure 3: Dinoflagellate cyst spectrum for the last 2000 years. Abbreviations RWP, DA,

1142 MWP, LIA and RW represent the Roman Warm Period, the Dark Ages, the Medieval Warm

1143 Period, the Little Ice Age and the most recent warming, respectively. Calendar years AD/BC

to the right result from the chronology of cores GA113-2Aa and 9004.

1145 Figure 4: Results of the CABFAC factor analysis and cluster analysis. Abbreviations F1-F3

stand for dinoflagellate cyst assemblages represented by factors 1, 2 and 3; letters A, B, C, D,

1147 E and F indicate dinoflagellate cyst units resulting from cluster analysis (see text); the C/N

1148 ratio together with the C<sub>org</sub> curve were first published in Filipsson and Nordberg (2010);

- 1149 RWP, DA, MWP, LIA and RW represent the Roman Warm Period, the Dark Ages, the
- 1150 Medieval Warm Period, the Little Ice Age and the most recent warming, respectively;
- 1151 Calendar years resulting from the chronology of cores GA113-2Aa and 9004.

Fig. 1



■ Thorsen & Dale, 1998





Figure 4



**F1**: Protoperidinium spp. indet. [RB]

**F2**: Gymnodinium nolleri

**F3**: *L*. *polyedrum* + *P*. *reticulatum*