Last Interglacial sea-level data points from Northwest Europe

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Abstract. Abundant numbers of sites and studies exist in NW Europe that document its geographically and geomorphologically diverse coastal record from the Last Interglacial (Eemian, Ipswichian, Marine Isotope Stage 5e). This paper summarises a database of 146 known Last Interglacial sea-level data points from in and around the North Sea (35 entries in The Netherlands, 10 Belgium, 23 in Germany, 17 in Denmark, 9 in Britain) and the English Channel (24 entries for British and 25 for the French side, 3 on the Channel Isles), believed to be a representative and fairly complete inventory and assessment from ~80 published sites. The geographic distribution (~1500 km SW-NE) across the near-field of the Scandinavian and British Ice Sheets, and the attention paid to relative and numeric age control, are assets of the NW European database. The research history of Last Interglacial coastal environments and sea level for this area is long, methodically diverse and spread through regional literature in several languages. Our review and database compilation effort drew from the original regional literature, and paid particular attention to distinguishing between sea-level index points (SLIPs) and marine and terrestrial limiting-points. We also incorporated an updated quantification of background rates of basin subsidence for the central and eastern North Sea region, utilising revised mapping of the base Quaternary, to correct for significant basin subsidence in this depocentre. As a result of subsidence lagoonal and estuarine Last Interglacial shorelines of Dutch and German Bight are preserved below the surface. In contrast, Last Interglacial shorelines along the English Channel are encountered above modern sea level.

This paper describes the dominant sea-level indicators from the region compliant to the WALIS database structure and referenced to original data sources. The sea-level proxies are, in majority, obtained from locations with well-developed lithostratigraphic, morphostratigraphic and biostratigraphical constraints. Most continental European sites have chronostratigraphic age control, notably through regional Pollen Association Zones with duration estimates. In all regions, many SLIPs and limiting points have further independent age-control from luminescence, uranium-series, amino acid racemisation and electron spin resonance dating techniques. Main foreseen usage of this database for the near field region of the European ice sheets is in glacial isostatic adjustment modelling and fingerprinting Last Interglacial ice sheet melt.

1. Introduction

Near-field records of Last Interglacial (LIG; ~129-116 ka; within Marine Isotope Stage (MIS) 5e) sea level are critical for establishing improved reconstructions of past ice sheets, constraining models of solid Earth processes and fingerprinting the source of ice sheet melt (Dutton et al., 2015; Long et al., 2015). However, the near-field LIG sea level has received comparatively little attention compared to the far-field, due to the challenges of dating estuarine sequences prior to radiocarbon chronologies and the complications of regional glacial isostatic adjustment (GIA). The main aim of this paper is to describe a standardized database of geological sea-level proxies, compiled using the tools available through the World Atlas of Last Interglacial Shorelines (WALIS) project for north west (NW) Europe, in particular around the North Sea and English Channel region. This is a location that is proximal an extensive MIS 6 Eurasian ice sheet (e.g. Svendsen et al. 2004; Ehlers and Gibbard, 2004; Lambeck et al., 2006; Lang et al., 2018) and has an extensive history of palaeoenvironmental research (e.g., Dixon, 1850; Harting, 1874; Van Leeuwen et al., 2000).

The dataset documented in this paper comes from several countries and physiographically diverse lengths of LIG coastline, including tectonic depocentre areas with significant background basin subsidence (North Sea basin). The research history in this region is long, going back to the 19th century when marine molluscan biostratigraphic evidence first identified the buried Last Interglacial equivalent of the North Sea (Harting, 1874; Lorié, 1906; Nordmann, 1928), and former shorelines along the south coast of England (Dixon, 1850; Reid, 1892, 1893, 1898). Many of the sites documented here were studied 50+ years ago, by experts in microfossil and sedimentological analysis rather than with a focus on establishing sea-level index points (SLIPs) under now well-developed frameworks (Shennan, 1982; van de Plassche, 1986; Hijma et al., 2015; Rovere et al., 2016), meaning that data considered essential for modern sea-level databases (e.g. elevation surveys) are missing in some instances. Age constraints are also a challenge. In NW Europe, age control on LIG estuarine deposits typical relies on relative dating based on micro- and macro-fossil biostratigraphy (notably pollen, Zagwijn, 1961, 1996), and amino-acid racemisation (AAR) dating of fossil material. Although the biostratigraphic schemes allow us to resolve relative ages within the interglacial (i.e., early, middle and late), tying them to an absolute chronology has to rely on chronostratigraphical correlations to other parts of Europe and the North Atlantic. More recently studied, or revisited, sites may have numeric OSL or U-series age constraints, which improves the dating independence.

The thickness and nature of the LIG coastal geomorphology and sedimentary sequences in NW Europe vary considerably. Differences in geological-geomorphological settings along and between the large stretches of coast have influenced the depth of preservation, surveying and mapping strategies and the taphonomy characteristics of typical sites. In the southern North Sea coastal region (e.g. The Netherlands, NW Germany and SW Denmark) and their offshore, key sites are many meters-thick infills of topographic depressions in deglaciated terrain, between the maximum ice-margins of the Saalian glaciation (MIS 6) and the Last Glacial (Fig. 1) (e.g. Zagwijn, 1983; Höfle et al., 1985; Streif, 2004; Beets et al., 2005; Konradi et al., 2005).

Along the English Channel many LIG sites comprise of flights of raised beaches, e.g. West Sussex coastal plain, southern England (Bates et al., 2010) and Cotentin, northwest France (Coutard et al., 2006). Both along the North Sea and the English Channel, the mouths of rivers record transgressed palaeovalleys and provide opportunities to constrain the regional LIG sea-level highstand (e.g. Antoine et al., 2007; Briant et al., 2012; Bogemans et al., 2016; Peeters et al., 2016). In the interest of brevity, a summary of the history of research in the study area is provided in the Appendix (A1).

This paper sets out to describe the SLIPs and supporting marine limiting and terrestrial limiting data points (Table 2) extracted from the regional literature, evaluated and stored in the WALIS database according to the prescribed interface and formats. This paper first covers the North Sea, then the English Channel region. This regional division is also somewhat reflected in the descriptions of SLIP types, Vertical Land Motion (VLM) and age assignments (various dating methods). At the end we provide some reflections on future research challenges in this region.

Table 1 Global and regional time division schemes with details of the Eemian/Last Interglacial period

Worldwide division schemes				***Regional division schemes***				
Generic	*Chrono-stratigraphic*	*Marine Isotope Stratigraphy*		*NW Europe*	*Subdivisions, timing of regional glaciation maxima, varve-count durations Eemian PAZs in NW Germany*		*British Isles*	
(Holocene)	Holocene	MIS 1		(Holocene)	…		(Holocene)	
Last Glacial	Late Pleistocene	*Termination I*	*14.7 ka*	Weichselian	Lateglacial		Devensian	Late
		MIS 2	LGM		*~29-27, ~24-21 ka*			Middle
		MIS 3			Pleniglacial			
		MIS 4			*~70 ka*			
		MIS 5c-a			Early Weichselian			Early
		MIS 5d	*~115 ka*		EW-I			
Last Interglacial (LIG)		**MIS 5e**		**Eemian *~125 ka***	**E6**	**~ 4000 yr**	**Ipswichian *~125 ka***	***late***
					E5	**~ 4000 yr**		***middle***
					E1-E4	**~ 3000 yr**		***early***
Penultimate Glacial	Middle Pleistocene	*Termination II*	*~132 ka*	Saalian	LS		Wolstonian	late
		MIS 6	PGM		*Warthe substage ~140 ka* *Drenthe substage ~160 ka*			
Older interglacials		…			…			

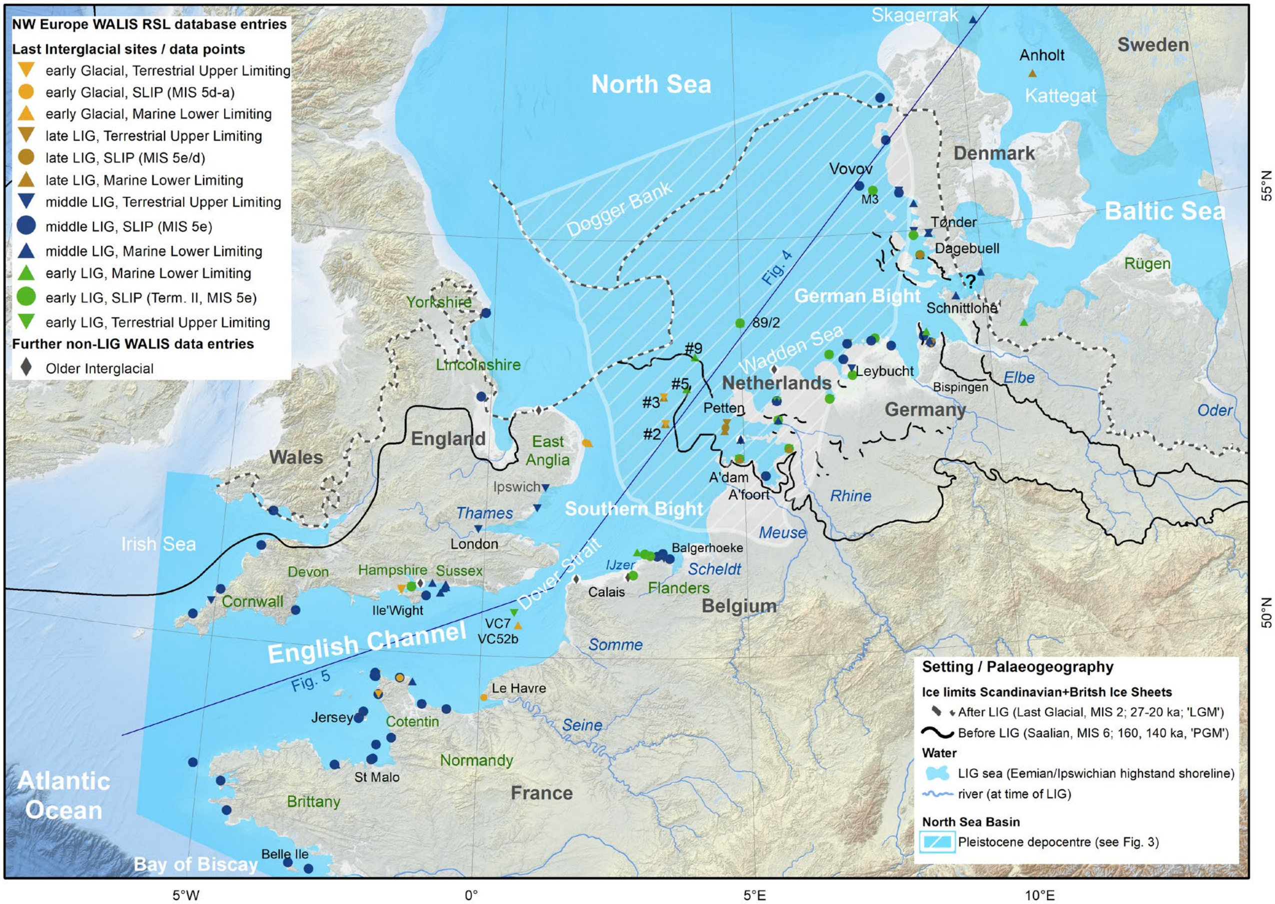

Figure 1. Overview of study area with data points (legend groups cf. Section 5) showing location of all datapoint entered into WALIS as part of this work. Penultimate (Saalian, MIS 6) and Last Glacial ice-limits compiled from regional studies (Ehlers et al., 2004; Busschers et al., 2008; Moreau et al., 2012; Lang et al., 2018; Gibbard et al., 2018; Cartelle et al., 2021) and adjoining superregional overviews (Ehlers and Gibbard, 2004; Batchelor et al., 2019). Pleistocene depocentre in North Sea further detailed in Section 3.3. Axis through North Sea and English Channel inform the presentation of data in Figs. 4 and 5. Selection of topographic names from text included, offshore sites with informal short IDs from source papers. Bathymetry and DEM backdrop: EMODnet Bathymetry Consortium (2020), their WMS-service which incorporates land data © OpenStreetMap contributors 2020, distributed under the Open Data Commons Open Database License (ODbL) v1.0.

Table 2: NW Europe WALIS data point totals, split by region.

Region	Main Age control	Last Interglacial			Older Interglacials		
		SLIPs	Mar. limit.	Ter. limit.	SLIPs	Mar. limit.	Ter. limit.
North Sea							
N Netherlands (NL)	Glaciogenic underlain*;	12	12	11	2	0	0
Central NL lagoon, Rhine estuary	PAZs; Lusi. biota.; OSL, AAR						
Belgium (B)	PAZs, OSL	8	1	1	1	0	0
Scheldt estuary							
NW France (F)	TL/OSL				1	0	0
Calais							
German Bight (GER)	Glaciogenic underlain*;	11	4	5			
Wadden Sea, Elbe estuary	PAZs						
SW Denmark (DK)	Glaciogenic underlain*;	6	2	3			
Tønder, Esbjerg	PAZs; FAZs; AAR; Lusi. biota.						
N Denmark (DK)	Glaciogenic under and overlain; FAZs;	0	6	0			
Skagen, Anholt	Lusi. Biota, AAR						
SW Baltic (GER)	Glaciogenic underlain* *and* overlain;	0	3	0			
Kiel	FAZs; PAZs; Lusi. biota.						
North England (UK)	Glaciogenic underlain* *and* overlain;	2	0	1			
East Anglia (UK)	Biostratigraphic (macro- and micro-fossil),	1	2	1	1	0	2
Norfolk, Suffolk	AAR						
Thames Estuary (UK)	Biostratigraphic (macro- and micro-fossil),	0	0	2			
London, Mersea	AAR						
English Channel							
Hampshire & West Sussex (UK)	OSL, AAR	3	6	5	0	5	4
Offshore (UK)	OSL	0	1	1			
Devon (UK)	Speleothem U-series	1	0	0			
Normandy (F): *Cotentin*	Morphostratigraphy, OSL, TL	10	1	3			
Channel Islands (UK): *Jersey*	Morphostratigraphy, U-series	3	0	0			
NE Brittany (F)	Morphostratigraphy, OSL	4	1	1			
Further West							
SW Wales (UK)	AAR	3	0	0			
W Cornwall (UK)	AAR	3	0	1			
W & S Brittany (F)	Morphostratigraphy	5	0	0			
TOTALS		72	39	35			

* One can commonly separate the Eemian from older interglacial deposits because they directly overly MIS 6 glaciogenic sediments.

2 Sea level indicators and chronostratigraphy

2.1 Regional context

Considerable spatial variation exists along the coastline of the present North Sea and English Channel (Fig. 1), as did during the LIG (regionally known as Eemian and Ipswichian, Table 1). Extensive lowland coastal plains with back-barrier tidal environments, marshes and lagoons dominate the Belgian-Dutch-German-Danish stretch of North Sea coast. These are interrupted by headlands of Saalian age ice-marginal morphology, as well as by estuaries and deltas of the main rivers: Scheldt, Meuse, Rhine, Ems, Weser, Elbe. The northern English and East Anglian coasts of the North Sea have cliffs comprising Middle Pleistocene till accumulations over Cretaceous chalk bedrock. In SE England, the Thames Estuary is flanked by a coastal plain with smaller estuaries and Paleogene outcrops to the north and smaller-estuary interrupted chalk cliffs to the south. The connection between the North Sea and English Channel is a transgressed gorge, eroded repeatedly since the Middle Pleistocene by lowstand periglacial and proglacial outwash rivers (Gibbard, 1995; Bridgland and D'Olier, 1995; Gupta et al., 2007; Toucanne et al., 2010; Mellett et al., 2013). The British and French coasts on either side of the English Channel alternate between estuaries (Somme, Seine, Sélune, Rance) and embayments rimmed with cliffs and gravelly/sand beaches, in a variety of substrates (Mesozoic, Palaeozoic, crystalline). Bedrock islands off the main coasts, such as the Isle of Wight and Channel Islands, were also islands in the LIG (section 4).

There are also notable differences between LIG coastal geomorphology and that of today. The broad position of estuaries and cliff-beach settings along the English Channel and SW North Sea can be regarded essentially the same between the LIG and Holocene (Fig. 1). In contrast, the configuration of lagoons, river mouths and morainic islands in the Netherlands' and the German Bight sectors of the North Sea, critically in the area between the Saalian maximum and Last Glacial limits, is relatively different (Fig. 1). In the eastern North Sea region the Eemian transgression flooded a paraglacial landscape left after the Saalian deglaciation, whereas the MIS 6 glaciation did not extend as far south over the UK (Ehlers and Gibbard, 2004). Furthermore, long-term basin subsidence of the area means that in locations onshore and offshore the Netherlands and NW Germany (depocentre indicated in Fig. 1), even the shallowest preserved LIG sea-level archives are encountered several meters below modern MSL, below their elevation of deposition. By comparison, western North Sea and English Channel LIG features along the coast of the UK and France are generally preserved at elevations higher than present sea level. The combination of of the 'fresh' MIS-6 glaciated landscape and regional basin subsidence (Cohen et al., 2014; Cohen, 2017) strongly affects the way deposits can be geologically and palaeogeographically mapped, reconstructed and studied (e.g., mainly from boreholes versus mainly from outcrops), as well as the areal extent over which deposits tend to have preserved (extensive basin-central patches, versus small pockets along the rims of a system) and what relative age controls and dating opportunities apply, resulting regional variability in applied dating techniques (Table 2).

2.2 Overview of Indicator Types

A wide range of sea-level indicators are present in NW European literature recording the LIG sea-level history in this region. Most of these studies constrained RSL elevations of SLIPs by combining sedimentary properties, fossil content and architectural evidence (Fig. 2). In the scope of the special issue and the WALIS database format we reviewed the literature and categorized the findings to WALIS-standardized sea-level indicator types (listed in Table 3a and further documented below), with particular attention to submerged valleys and further alluvial coastal plain settings from which series of SLIPs in lateral and vertical sequence can constrain sea level through multiple stages of the interglacial. In Table 3b we summarise the decision-making process of which geological observations become what SLIP types, and the priority that is given in cases where a site could be classified as multiple SLIP types.

We employ 10 SLIP types; five of which were already part of the WALIS database ('WALIS generic'), and five of which have been added by us during our literature review ('Paper Author added'). The SLIP types are split over three main settings (labelled A, B, C in Fig. 2 and Table 3b). Documentation of marine terraces and raised beaches (from setting A) is kept short as these SLIP types had been introduced and used in earlier WALIS publications (e.g. Rubio-Sandoval et al., 2021; Cerrone et al., 2021 in this special issue; as well as Rovere et al., 2016). SLIP types from estuarine river mouth, lagoonal and incised valley alluvial settings and the study-area specific glaciogenic isolation basins (i.e. settings B and C) are documented in sections 2.2.1-2.2.6. All these SLIP types are widely used in Holocene RSL databases; their introduction in LIG context and documentation here is mainly a formalization for WALIS purposes.

The decision-making workflow in Table 3b shows that in addition to the specifically added types (Salt Marsh, Basal Peats, Drowned Valley Floor, Estuarine Terrace, Isolation Basin (WALIS type IDs 17-20 and 37), we also occasionally use more generic, readily available 'lagoonal deposits' and 'shallow or intertidal fauna' classifications (WALIS type IDs 15 and 33), though as far less favoured options. Table 3b also outlines how to differentiate sites/sample as a marine or terrestrial limiting data point, rather than a SLIP. For example: so called 'regressive peat beds' from the late LIG that previous literature have used as sea-level constrains, we instead classified as late interglacial terrestrial limiting data points (Table 2).

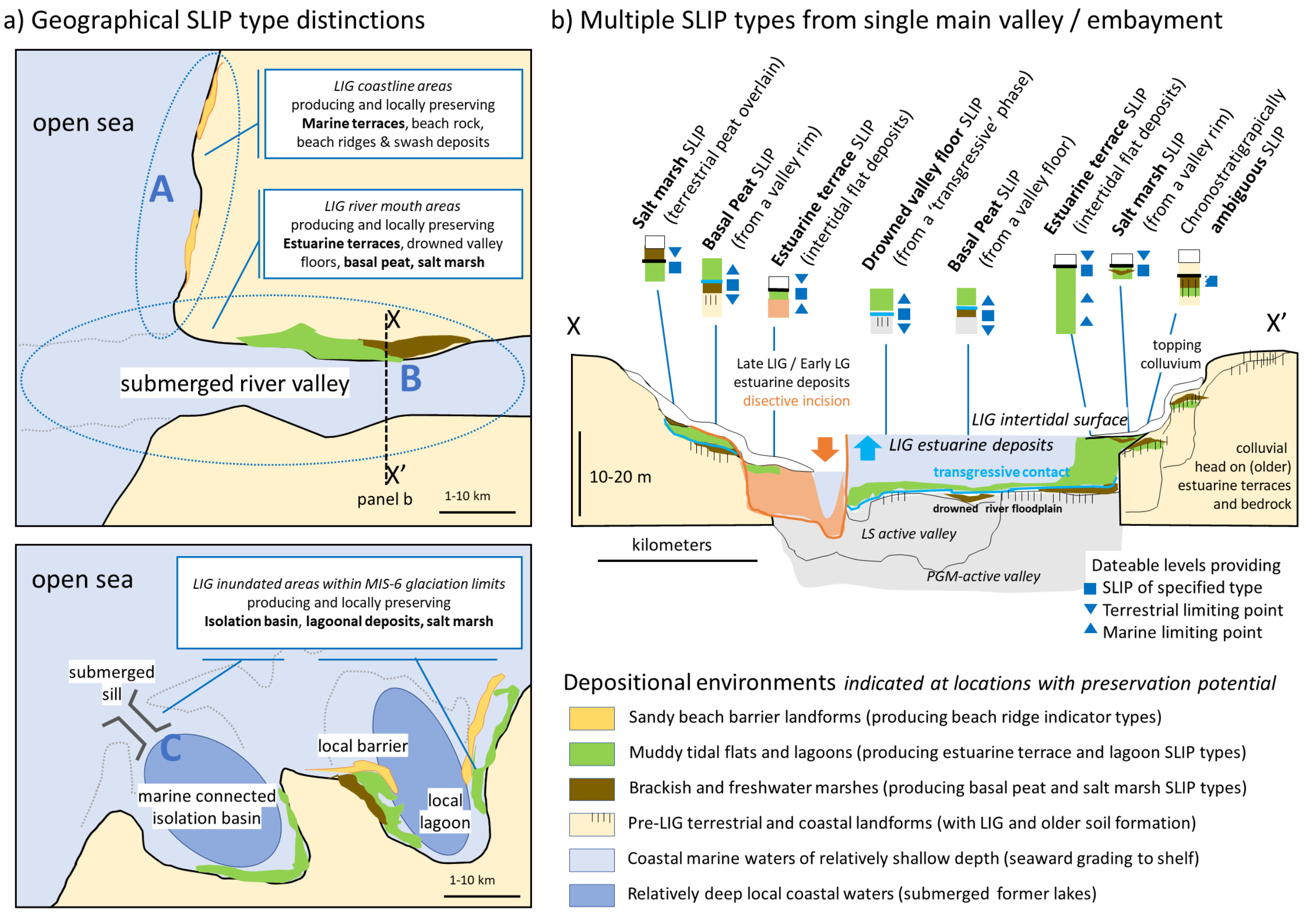

Figure 2. Schematic map (a) and section (b) illustrating the geographical and sedimentary distinctions between the various SLIP types used for NW Europe in the WALIS database. In panel (a) three main groups of SLIPs are distinguished: A – coastline areas facing open sea; B – estuaries filling drowned river valleys; and C – glacially-inherited marine-connected isolation basins and embayments. In panel (b) multiple SLIP types, as well as terrestrial and marine limiting data points are summarised from local outcrops and boreholes. This includes SLIPs which record RSL rise, SLIPs which record stable sea level, and SLIPs which record RSL fall causing dissection and incision (orange arrow) within the estuarine cross-section. The symbology introduced for SLIP, Terrestrial Limiting and Marine Limiting points matches those in Figure 1 and Figures 4 and 5. Drowning sequences (e.g., submerged valley floors or basal peats, spanning a local or regional transgressive contact, common from early to middle interglacial phases in NW Europe) also record a a terrestrial limiting data point below a SLIP. In contrast, estuarine terrace SLIPs typically have marine limiting indicators from facies underlying the SLIP and are common from middle-late and post-interglacial phases (Table 1).

Table 3a: Types of RSL indicators used in NW Europe database.

Name of RSL indicator	Indicator reference(s)	ID in WALIS	Region and # of occurrences
WALIS-generic, *not documented here – see WALIS supporting literature, including other ESSD special issue papers*			
Marine Terrace	Pirazzoli, 2005 Pedoja et al., 2011 Rovere et al., 2016	7	France (12 LIG, 3 older) United Kingdom (1)
Beach deposit or beach rock	Mauz et al., 2015 Rovere et al., 2016	11	France (6 LIG, 1 older) United Kingdom (4 LIG, 9 older)
Beach ridge; Beach swash deposit	Otvos, 2000 Rovere et al., 2016	12, 29	France (1) United Kingdom (2 LIG, 1 older)
Lagoonal deposit	Rovere et al., 2016 Zecchin et al., 2004	15	Netherlands (3 LIG, 1 older)
Paper Author added as part of this study, *documented by sections 2.2.1 to 2.2.5.*			
Drowned valley floor (transgressive contact)	Vis et al., 2015 Peeters et al., 2016, 2019	17	Netherlands (1) Denmark (1)
Basal Peat (non-mangrove)	Jelgersma, 1960 Van de Plassche, 1982 Zagwijn, 1983 Hijma and Cohen, 2019	18	Netherlands (3) Germany (3) Denmark (2)
Isolation Basin (marine connection)	Zagwijn, 1983 Van Leeuwen et al., 2000 Beets et al., 2006	19	Netherlands (3)
Estuarine Terrace (preserved tidal flat surface)	De Moor and De Breuck, 1973 Zagwijn, 1983 Peeters et al., 2016, 2019	20	Belgium (9 LIG, 1 older) Germany (5) Netherlands (2 LIG, 1 older)
Salt marsh (various subtypes)	Engelhart and Horton, 2012	37	United Kingdom (2)
WALIS-generic, *but region specific information provided in section 2.2.6*			
Shallow or intertidal marine fauna	Subregion specific Refs in section 2.2.6	33	Germany (3) Denmark (3) United Kingdom (3)

Table 3b: Practical scheme for SLIP type choice, as developed during data entry

Start	**Select whether you are assessing NW European data points from a setting best characterized as:**
	A - Raised beach and marine terraces coastline (typical along the English Channel coast);
	B - Estuarine river mouth, lagoonal, incised valley (typical along the North Sea coast);
	C - Some other siuation: region specific.
Setting A	**Is beach rock, beach ridge deposits and/or beach ridge swash deposits recognised?**
	If Yes → WALIS SLIP types 11, 12, 29 Dating control options: direct OSL, AAR; indirect: bracketing terrestrial deposits
	If No → WALIS SLIP type 7 *opt for the marine terrace generic entry*
	Morphostratigraphic feature. Indirect dating control from inset terrestrial deposits
Setting B	**Are Salt Marsh deposits described?** *Usually based on sedimentology and biota (microfossils and mollusca)*
	If Yes → WALIS SLIP type 37 Dating control options: pollen; indirect: OSL, AAR, pollen on bracketing deposits
	Is freshwater Basal Peat described? *This is terrestrial peat (macro- and micro-fossils) overlain by subaquous deposits*
	If Yes → WALIS SLIP type 18 Dating: pollen; indirect: OSL, AAR, U-series on bracketing deposits
	Is intertidal or supratidal facies described? *Usually based on sedimentology and biota (microfossils and mollusca)*
	If Yes → WALIS SLIP type 20 Lithostratigraphic feature. Dating: direct OSL, AAR; indirect bracketing deposits.
	Is subtidal lagoonal facies described? *Usually based on sedimentology and biota (microfossils and mollusca)*
	If Yes → WALIS SLIP type 15 Lithostratigraphic feature. Dating: direct OSL, AAR; indirect bracketing deposits.
	Are shallow marine fossils described in the deposits and not in reworked or otherwise displaced context?
	If Yes → consider WALIS SLIP type 33, specifying water depth based on biota
	Alternatively: treat as Marine Limiting data point, using conservative (shallowest) water depth (= No SLIP).
	Is the material a terrestrial peat overlying non-descript shallow marine deposits?
	If Yes → consider treating the site as a Terrestrial Limiting data point with the age of the peat (= No SLIP).
Setting C	**Is the site a transgressed glaciogenic lake (tongue basin, tunnel valley) and can be treated as an isolation basin?**
	If Yes, do the deposits otherwise classify as one of the options under B?
	If Yes again → Treat as Setting B Deposits and potential SLIP are from after the moment of marine connection
	If No → WALIS SLIP type 19 Dating control options: sequence deepest part basin, across connection moment
	Are shallow marine fossils described in the deposits and not in reworked or otherwise displaced context?
	If Yes → consider WALIS SLIP type 33 specifying water depth based on biota
	Alternatively: treat the site as Marine Limiting data point using the most conservative (shallowest) water depth (= No SLIP)
	Alternatively: browse WALIS' further catalogue of SLIP types developed for other regions, consider specifying a new type.

2.2.1 Indicator type: Drowned Valley Floor

This indicator type relates to a contact between terrestrial depositional facies (below) and subaqueous depositional facies (above) and provides constraints for marked sea-level rise created SLIPs (e.g. Fig. 2b). The terrestrial facies is typically a decimeter thick river organic mud with immature palaeosol, if not a flood-basin peat bed, with further fluvial facies below.

The subaquatic facies is typically a decimeter-meter-thick organic mud, rich in fine and coarse detrital organic matter, rich in silt admixture, bearing tidal indicators, bearing microfossil indicators of occasional brackish, estuarine inwash. It grades upward into established tidal, brackish to saline, full estuarine facies. See Hijma and Cohen (2011; 2019) for Holocene examples and Sier et al. (2015) and Peeters et al. (2016; 2019) for LIG examples.

The transgressive contact has a direct relationship to the point of estuarine inundation, and is therefore a SLIP. The secondary contact within the terrestrial facies can be used as a terrestrial limiting point. Herein the estuary in a freshly drowned lowland valley differs (e.g. Martinius and Van den Berg, 2011) from later stages of estuary development as observed in highstand-filled estuaries (inland propagation, amplification and dissipation does affect estuarine-type SLIPs). In wide valleys experiencing relatively rapid postglacial transgression, 'underfilled' estuaries result in which tidal amplification (owing to estuary funnelling) is not yet a major factor (tides may in fact be dampened inland in such estuaries). On the other hand, in inland parts of the estuary riverine discharge may impose a gradient and lift waterlevels to the same altitudes and above those of high tides in the estuary mouth (Van de Plassche, 1995; Vis et al., 2015). For these reasons, the 'Drowned Valley Floor' base-estuarine indicator type is kept separate from the 'Basal Peat' and 'Estuary terrace' indicator types.

In formula (HAT = Highest Astronomical Tide; MSL is mean sea-level, a.k.a. half tide):

WALIS Reference Water Level description:	(HAT to MSL) / 2
WALIS Indicative Range description:	HAT to MSL

2.2.2 Indicator type: Basal Peats

Basal Peats are terrestrial deposits encountered along the base of transgressive-to-highstand depositional systems and in submerged position on inner shelves (e.g. Jelgersma, 1979; Hanebuth et al., 2000). Using basal peats as RSL indicators became widely established in Holocene sea-level communities since the 1970s (Van de Plassche, 1986), both onshore and offshore. Jelgersma (1961) and Van de Plassche (1982, 1995) provide classic Holocene reference examples for The Netherlands. Likewise, it is useful as an RSL indicator in interglacial coastal settings (e.g. Zagwijn, 1983; Streif, 1990, 2004; Konradi et al., 2005), especially when combined with palynological investigations to provide time-control on the position within the interglacial (see section 2.3).

Basal peats are submerged terrestrial peats (swamp, fen, carr, marsh) overlain by subaqueous deposits (tidal, estuarine or lagoonal (organic) muds), allowing to position a regional transgressive surface at the drowning contact (e.g. Hijma and Cohen, 2011, 2019). Basal peats occur over multiple substrates and palaeosurfaces, such as those provided by valley floors and valley rims (e.g. Fig. 2b), but also over interfluve highs (regional relief) as well as on the flanks of small-scale isolated local relief within broader coastal-deltaic plains. The encountered peaty terrestrial facies is typically a few decimeters thick (in compacted state, cf. Greensmith and Tucker, 1986; Brain, 2015). Depending on lateral and vertical position (Fig. 2b) the basal peat may overly a surface with just an immature floodplain palaeosol (see Drowned Valley Floor description), or a surface with a more developed palaeosol (e.g. interfluve settings).

The very top of a Basal Peat bed indicates submergence of a swamp/marsh and this level may be taken as a SLIP. The very base of Basal Peat bed indicates a palaeo-groundwater level (GWL), and in a sea-level reconstruction context that level becomes a terrestrial limiting point. In argued cases a limiting point may be upgraded to a SLIP if it formed along the inland rim of a transgressive lagoonal or lagoonal-deltaic environment (e.g. Van de Plassche, 1986; Nelson, 2015). To do so, one should assess the palaeogeographical situation of the basal peat data point, or swarm of data points (Vis et al., 2015; Hijma and Cohen, 2019).

In formula:

WALIS Reference Water Level description:	GWL
WALIS Indicative Range description:	Swamp peat: (GWL to GWL-0.2m); Marsh peat (GWL-0.3 to GWL-0.8m).

2.2.3 Indicator type: Isolation Basin

Isolation basins are used extensively in Holocene sea-level studies in higher latitude coastal environments, making use of the prominent occurrence of lakes in freshly deglaciated environments, and the ecological sensitivity of such water bodies when connecting and disconnecting from the sea (e.g., Sundelin, 1917; Shennan et al., 2005; Long et al., 2011). In the North Sea area, substantial lakes formed when ice sheet cover from the penultimate glaciation disintegrated (during MIS 6). The period at which these lakes connected to the North Sea and transformed into highstand marine embayments has been a primary constraint on the relative timing of the Eemian Transgression (e.g. Zagwijn, 1983). The reconstructed elevation of lake sills (the lowest point of the basin rim; Fig. 2b) provides the elevation of a SLIP of this type, whereas the contact between lacustrine environment (lower) and brackish-marine environment (upper) established in central part of a basin is where age control is obtained. Ideally the sill of an isolation basin is formed of unmodified bedrock (Long et al., 2011). In the North Sea case, it is formed by glacial diamicton and/or glaciotectonised ridges (Zagwijn, 1983; De Gans et al., 2000), which means additional uncertainty as to their elevation must be considered. Our WALIS database entries have registered the lake centre core location as coordinates, and note fields mention separately where the paired sill level is positioned. Reference Water Level description and Indicative Range link to the sill location. Water depth of the lake is irrelevant for the application.

In formula:

WALIS Reference Water Level description:	(HAT to MSL)/2
WALIS Indicative Range description:	(HAT to MSL) + uncertainty sill level position

2.2.4 Indicator type: Estuarine Terrace

This indicator type is introduced as a variant of the Marine Terrace and Raised beach entries (Table 3) as used elsewhere in the WALIS database. This served to allow to assign different indicative meaning to elevations sampled from estuarine terraces where the 'flat' surfaces are usually formed in facies bearing intertidal sedimentological indications (alluvial terraces), than to marine terraces that are flattened due to abrasion processes (straths). A basic difference with the Marine Terraces is the orientation: 'across' respectively 'along' that of the coastline (Fig. 2, Table 3b: Setting A vs. Setting B). A further difference is the opportunity to tie in estuarine terraces with fluvial and terrestrial units, and this way (Zagwijn, 1983; Peeters et al., 2016) recognize disective incision associated to sea-level fall this way (Fig. 2b). Paraphrasing the Marine Terrace description (Pirazzoli et al., 2005), it considers "any relatively flat surface of estuarine origin". In the estuarine case, the flatness of the abandoned surface is not so much due to wave action and storm swash, but more due to intertidal/supratidal flooding just prior to terrace abandonment. See Table 3b for the distinction with 'lagoonal deposits' and 'shallow and intertidal fauna'. In landward direction, estuarine terraces grade to riverine terraces/former floodplains that provide terrestrial limiting points rather than SLIPs. Examples include Balgerhoeke (Heyse, 1979; IDs 339, 340; Scheldt: middle LIG, inland 'high stand') and site Petten (Zagwijn, 1983; ID 146; Rhine: late LIG, sea-ward 'regressive').

In formula:

WALIS Reference Water Level description: (HAT + MSL) / 2

WALIS Indicative Range description: (HAT to MSL)

2.2.5 Indicator Types: Salt marsh (various subtypes)

Salt marshes have been used extensively in Holocene sea-level research, as their elevation and position are directly controlled by the tidal elevation and therefore can be directly related to a reference water level (Engelhart and Horton, 2012; Shennan et al., 2018; Barlow et al., 2013). The indicator type differs from 'basal peat' and 'estuarine tidal flat' types because the study of microfossils allowed to identify it as a coastal salt marsh specifically. The identification of palaeo salt marsh is usually through the identification of salt marsh specific taxa such as the pollen of *Plantago maritima* and *Triglochin* (Gehrels, 1994); the presence of salt marsh foraminifera such as *Jadammina macrescens, Miliammina fusca* and *Trochammina inflata* (Gehrels, 2000; Edwards and Horton, 2000); and brackish water diatoms and ostracods (Penney, 1987; Zong and Horton, 1998; Barlow et al., 2013). Such microfossils cover a limited elevation range from HAT to MSL and hence make palaeo salt marshes an excellent SLIP. Where sedimentation could keep up with the rate of RSL change, salt marsh may be preserved at the transgressive or regressive boundaries often between freshwater peats and estuarine silts and clays. Microfossil sampling resolution is often coarse in LIG estuarine sediments (>5-10 cm intervals) and coastal salt marsh deposits may be missed between samples. Therefore, there are only two explicit occurrences in the LIG salt marsh SLIPs within the NW European database. A number of sites classified as 'Basal Peat' SLIPs may well be overlain by fine grained marine sediments that could be salt marsh. Also several 'estuarine terrace tidal flats' sites are reported to have been overlain by salt marsh muds and peats (e.g. Balgerhoeke, Belgium, IDs 339 and 340; Land Hadeln, Germany. IDs 882 and 883). Revisiting such sites may present opportunities to narrow down the indicative range of some of these SLIPs.

In formula:

WALIS Reference Water Level description: (HAT to MSL)/2
WALIS Indicative Range description: (HAT to MSL)

2.2.6 Indicator Type: Shallow or intertidal marine fauna

This generic SLIP indicator type entry in WALIS considers palaeobiological identified marine fauna that can be associated with very shallow water and/or intertidal environments, especially where fossilized '*in viva*'. It was used when sedimentary, morphological identifiers are not available, and where sites did not convincingly fall in one of the categories listed above. In the North Sea, macroscopically, usually these are the shells of intertidal mollusca. In Danish contexts foraminifera and diatom assemblages have been used as water depth and current regime biotic indicators in Eemian shallow marine beds (e.g. Konradi, 1976; Konradi et al., 2005; Van Leeuwen et al., 2000; Beets et al., 2006). Most commonly, though, it is the macroscopically spotted shells of molluscan fauna that are used. *Cerastoderma edule* (also known as *Cardium*) and *Scrobicularia plana* are very common intertidal species in the North Sea, in Holocene and LIG deposits alike. *Macoma Baltica* and *Spisula truncata* are also frequently encountered (and used for AAR characterisation; Miller and Mangerud 1986, Meijer and Cleveringa, 2009, Demarchi et al., 2011). In deeper waters of the offshore North Sea, Skagerrak and SW Baltic, the common species are *Arctica islandica* (also known as *Cyprina*) and *Turritella communis*. In the English Channel, foraminifera *Elphidium* sp. and *Ammonia* sp. are common intertidal indicators (e.g., Bates et al., 2010). Some of these species ('Lusitanian components') in the LIG extended their common presence into North Sea and SW Baltic too (e.g. Madsen et al., 1908; Miller and Mangerud, 1986; Funder et al., 2002; Meng et al., 2021), whereas in the Holocene they did not (or to a far more limited extent). Examples are *Venerupis senescens* (*Tapes aurea (var. eemensis), Paphia aurea, Amygdala*), *Bittium sp., Cardium exiguum*. Nolf (1973), Miller and Mangerud (1986: their part II), Meijer and Preece (1995), Wesselingh et al. (2010), and Meijer et al. (2021) are illustrative biota-oriented papers on this. This means that literature-reported molluscan faunas hold both 'vertical' indicative meaning, as well as 'age' chronostratigraphic meaning.

For this type, RWL and IR are based on the upper and lower limits of living modern analogue faunas. In formula:

WALIS Reference Water Level description: (Upper_limit to Lower_limit) / 2
WALIS Indicative Range description: (Upper_limit to Lower_limit)

2.3 Eemian chronostratigraphy

Where U-series or OSL dates were reported, this age information was inserted into WALIS' database structure. The great majority of sites in continental NW Europe, however, have chronostratigraphic relative age constraints for which a separate registration scheme exists. We filled this with entries for the Eemian pollen zones (PAZs, numbered E1-E6) of Zagwijn (1996) as established for The Netherlands. The info of this part of the WALIS contents is copied in Table 4. In note fields for each entry, we included the correlation to regarded equivalent zones in various NW German and Danish biostratigraphic schemes for the LIG (references in Table 4 footnote). In dedicated numeric fields, we registered duration constraints provided by varve counts from the Bispingen site in NW Germany (Müller, 1974), as well as correlated minimum and maximum absolute ages (Table 4: left side). The communicated numeric ages aim to encompass all presently considered options for the age span represented by the floating PAZ scheme (see Long et al., 2015), which include early onset and late onset options (Table 4: right side). Details on the age information (maximum and minimum spans; early or late onset options) are provided in the Appendix (A2), as well as in the note field for the main entry in the WALIS database itself.

Since the Tzedakis et al. (2018) publication on Italian speleothem U-series chronology and the Iberian margin marine isotopic record, the early-onset correlation option for PAZ E1-E6 stretches from c. 129 to 116 ka (PAZ E5 commencing around 124 ka), and a late option is to have it cover c. 126 to 112 ka (with PAZ E5 ending by 117-6 ka, and durations closer to Müller 1974's original estimates). The respective WALIS minimum and maximum age entries for each PAZ cover both options. We note that the application of Eemian PAZ schemes to divide within the interglacial is relatively straightforward in the LIG coastal zone because of the 'glaciogenic deposits underlain' circumstances at most Netherlands, German and Danish sites (Table 2). We stress that the PAZ correlation-attributed numeric ages (i.e. the.onset scenarios in Table 4) should only be applied to localities in the North Sea side of our research area. Bispingen (location of Müller 1974's varve-counts) is at the furthest 100 km from the German Bight and within 500 km of our Belgian sites (Fig. 1). If entries for RSL indicators with palynology-derived chronostratigraphic age control are needed for sites further east (e.g. Russian 'Mikulinian' zonation) or to the southwest in the English Channel, we advise adding separate entries in WALIS, allowing to adapt advised oldest and youngest age bounds, and explore possible W-E diachronicities.

The situation for UK sites is different, as palynological indications and setting are often ambiguous in revealing whether an interglacial deposit correlates to the LIG or an older counterpart. Due to significant advances in AAR methods (Penkman et al., 2013), combined with river terrace stratigraphy (Bridgland, 1994), vertebrate and mollusca biostratigraphy (Schreve, 2001; e.g., Preece, 2001) and independent geochronology, many British sites previously thought to relate to the LIG based on Ipswichian pollen stratigraphy (e.g., Hollin, 1977) are now argued to actually date from preceding interglacials (Penkman et al., 2008, 2011, 2013). Therefore, many correlated 'Ipswichian' sites from the UK were not included in the database. Those sites with AAR-based LIG age associations were included in the WALIS provided database substructure for this dating type.

Table 4: Chronostratigraphical entries for North Sea, Skagerrak-Kattegat and SW Baltic Sea

Age constraining information, encoded in WALIS' chronostratigraphic unit duration and age fields					Scenario-based age attributions, fitting the Lower and Upper constraints	
Chronostratigraphic divisions tied to North Sea LIG sea-level data points	Duration constraint (yrs)**	Duration uncertainty (yrs)***	'upper' (=oldest) numeric age (ka)	'lower' (=youngest) numeric age (ka)	example early onset scenario (ka)	example late onset scenario (ka)
*Zagwijn 1961, 1983, 1996 **						
EW-I	*10,000*	800	115	102	115 to 105	113 to 102
E6/EW break	*(600)*	200	115	112.5	~115	~112.5
E6 (E6a, E6b)	4000	250	120	112.5	120 to 115	116.5 to 112.5
E5/6 break	*(600)*	200	120	116	~120	~116
E5	4000	250	124	117	124 to 120	122.5 to 117
E4 (E4a, E4b)	1800	110	127	122.5	127 to 124	124.5 to 122.5
E3 (E3a, E3b)	675	45	128.5	124.5	128 to 127	125 to 124.5
E2 (E2a, E2b)	425	30	129	125	128.5 to 128	125.5 to 125
E1	100	10	129	125.5	~129	~125.5
Entire Eemian (E1-E6)	11000	500	129	112.5	129 to 115	126 to 112.5
Seidenkrantz 1993						
Kattegat Stadial	*1200*	200	131	126	131 to 129.5	127.5 to 126
Kristensen et al., 2000						
Cyprina clay (undivided)	6750	500	128	116	128 to 121	124.5 to 116
Cyprina clay, upper saline (E4b, E5, E6a)*	4700	400	126	116	126 to 121	122.5 to 116
Cyprina clay, lower saline (E3b, E4a, E4b)*	1950	200	128	122.5	128 to 122	124.5 to 122.5
Cyprina clay, lowest brackish (E2b, E3a)*	350	100	128.5	124.5	128.5 to 128	125 to 124.5

* WALIS entries use Zagwijn (1961, 1983, 1996) scheme. Descriptions for entries include correlations to schemes of: Jessen and Milthers (1928, op. cit. Funder et al., 2002:Table 2); Selle (1962 op. cit. Konradi et al., 2005:section 8); Behre (1962); Müller (1974) and Menke and Tynni (1984). Correlation for Cyprina Clay complies to that in Kristensen et al. (2002) and Meng et al. (2021).

** In regular font, for E1 to E6: based on Müller (1974), Zagwijn (1996), NW-German low land varved lake site 'Bispingen'. In *italics*: For E5/6 break and E6/EW break: arbitrarily defined to 300 years on either side of break. For EW-I: compliant varve counts in Eifel mar lakes (Sirocko et al., 2005) and their dust-flux correlation with Greenland ice-cores NGRIP and NEEM (ibid., NEEM community members, 2013; Sier et al., 2015). For Kattegat Stadial: assessment of Seidenkrantz (1993). These estimated durations are regarded minimum durations in the early onset scenario.

*** Author expert judgement: acknowledges varve miscount possibilities as well as PAZ correlation diachronicity issues over ca. 400 km distance between 'coastal Netherlands' (Zagwijn, 1961; Amersfoort) and 'NW German terrestrial' sites (Müller, 1974; Bispingen) and/or Eifel mar lakes (Sirocko et al., 2005) and/or NE Denmark (Kattegat Stadial, Seidenkrantz, 1993) and/or the SW Baltic (Cyprina clay, Kristensen et al. (2002).

3 Elevation measurements and corrections

3.1 Elevation measurements and datums

For any palaeoenvironmental record to provide a useful indictor of past sea level, the elevation of the deposit or landform must be recorded (Shennan et al., 2015). Following WALIS database structures for this, the measured elevations for the studied sites have been reported in various forms, detailed in Table 5. Our approach has been to express elevations for data points as much as possible to 19/20th century reference mean sea level (details given in Table 6), applying conversions from local datums when needed (for further dicussion see Woodroffe and Barlow, 2015).

Table 5: Techniques to establish present elevation

Measurement technique	Description
Differential GPS (DGPS)	Positions acquired in the field by 'rover' GPS stations, corrected either in real time or during post-processing with respect to the known position of a 'base' GPS station (or a geostationary satellite system). DGPS accuracy depends on distance from base station, and number of static positions acquired per location.
Metered tape or rod	The end of a tape or rod is placed at a known elevation point, and the elevation of the unknown point is calculated using the metered scale and, if necessary, clinometers to calculate angles.
Total station or Auto/hand level	The accuracy of the elevation measurement is also inversely proportional to the distance between the instrument and the point being measured. Furthermore, it takes over the accuracy of the benchmark used when setting up the Total Station or Hand levelling survey.
Multibeam bathymetry data + core depth	Bathymetry derived from multibeam surveys in offshore areas, below which the depth along cores is expressed. Errors differ with coring system (gravity, vibro-coring, rotary drilling...) and should be assessed case by case.
Technique not reported: value read from publication.	The elevation measurement technique is unknown, where the technique is left unmentioned it most probably was hand level or metered tape.
Technique not reported: value read from cross-section in publication	The elevation was extracted from a published sketch/topographic section.

Table 6: Sea level datums made use of in this study.

Datum name	Datum description
Mean Sea Level / General definition	General definition of MSL, with no indications to which datum the measurement referred to. A datum uncertainty can be established on a case-by-case basis.
DNN (Danish ordnance datum, prior to DVR90)	DNN (Dansk Normaal Nul) is the O.D. in Denmark used during the 20^{th} cy. It is about equal to second-half 20^{th}-cy MSL (mean half-tide) as observed in 10 tide gauges along the Danish coast. DVR90, which ties to NAP, replaced DNN in the early 2000s. 0.02 m DNN is 0 m DVR90 in N Denmark; -0.14 m DNN is 0 m DVR90 in SW Denmark.
NAP, NHN, NN (Netherlands ordnance datum, Amsterdam, also 0 level for the German ordnance datum)	NAP (Normaal Amsterdams Peil) is the O.D. in the Netherlands, and NHN (Normalhöhennull) the German O.D. that shares the datum. The zero level is about equal to second-half 20th cy MSL (mean half-tide) as observed in tide gauges along the Dutch coast. NHN replaced precursor NN (Normalnull) in the early 2000s, that also tied to NAP.
TAW+2.33 (Belgian ordnance datum, Oostende, offset to get from LAT to MSL)	TAW is a datum based on Lowest Astronomical Tide (LAT) at Oostende (Belgium). 0 m TAW (Belgium) is -2.33 m NAP/NHN (Netherlands, Germany), and hence +2.33 m is the datum offset. For reference: 0 m TAW (Belgium) is -1.83 m NGF (France).
OD (British Ordnance Datum Newlyn)	In the U.K., OD is defined as the mean sea level at Newlyn (Cornwall, UK) between 1915 and 1921. For reference, modern MSL is 0.14 m above ODN at Portsmouth and Sheerness, and 0.23 m below ODN at Immingham.
NGF-IGN69 (French Ordnance Datum, Marseille)	NGF (Nivellement General de la France) is the ordnance datum for continental France. The zero level equates to Mediterranean mean sea level (mean half-tide) in Marseille as gauged between 1885 and 1897. For reference, $20/21^{th}$-cy MSL is 0.505 m above NGF at Brest, 0.585 at Cherbourg, 0.491 at St Malo, 0.585 at Le Havre and 0.571 at Calais, and 0.50 m NGF at Oostende (Belgium, see TAW).

3.2 Compaction corrections

Most SLIPs and limiting data points are from sites and indicator types that do not require compaction correction e.g., marine terraces, beach deposits, drowned valley floor and isolation basin sills (Table 3). Basal peat, lagoonal and estuarine tidal flat type indicators do require estimates of compaction as the sediments hosting the indicators are more compressible and these are often sampled from buried positions with considerable overburden. The decompaction approach is a pragmatic one. Detailed compaction correction in general is not feasible, but corrections based on analogies and experiences in Holocene settings are, and our approach using decompaction factors was based on that. For the Holocene, geomechanic empirical-calibrated modelling suggests to similar decompaction factors for basal organic beds and clayey tidal lagoonal sequences (e.g. Greenfield and Tucker, 1986; Brain, 2015; Keogh et al., 2021) as deployed below. The corrections have been primarily applied to records from Netherlands, NW Germany and SW Denmark, and then mainly to basal peat SLIPs and associated marine limiting indicators (Fig. 2b). All site-specific compaction corrections are documented in the 'Notes on elevation and indicative range' field for each entry.

For basal peats we assume a full analogue with Holocene deposits from the area. Where Holocene peats are overlain by 10-15 m of coastal overburden, transgressed peats are compressed to 50-33% of their original thickness, with the greatest majority of this compression happening in the first millennia after burial (Hijma et al., 2009; Hijma and Cohen, 2011), when the first 5 meters of overburden accumulated (Van Asselen et al., 2011; Keogh and Törnqvist, 2019; Keogh et al., 2021). Decompaction of decimeter-thick basal peat beds is achieved by multiplying thickness by a factor of 2 to 3 (Berendsen et al., 2007; Hijma and Cohen, 2019). For Eemian basal peats, the overburden is similarly thick, but existent for longer time and relatively sandy (descriptions stored in note fields summarize overburden composition for those database entries where compaction assessments were incorporated). We hence considered a decompaction factor of 2.5 to 3.5 for dominantly organic beds, and 2 to 3 for clay-peat alternating intervals.

For SLIPs from lagoonal deposits and estuarine tidal flat surfaces (Fig. 2; Table 3a), decompaction of clayey tidal deposits immediately underlying these levels is considered. As in the application to the top of basal peats, also for the tops of estuarine packages we mainly assess 'post-depositional' compaction. The compressing of any underlying basal peats would have occurred rapidly, i.e. during the functioning of the estuary and eventually resulting in the filled estuary with the tidal flat surface (Brain, 2015), and hence be represented by the thickness of the deposits. Subtidal clayey facies is regarded more prone to remaining compaction (decompaction factor 1.5 to 2.5) than intertidal and supratidal facies (decompaction factor 1 to 1.5) because the latter had been subjected to wet-dry cycles at time of deposition (Paul et al., 2005). The thickness and composition of overburden affect opting for the lower or higher side of the decompaction factor.

A few sites in the database are from particularly thick organo-clastic Eemian sequences e.g., deglaciation-inherited deep channels onshore in the German Bight (e.g. Dagebuell, Schnittlohe) and from glacial-tongue basins in the Netherlands (e.g. Amsterdam, Amersfoort; Fig. 1). We avoided including heavily-compaction influenced sea-level markers and regression terrestrial limiting points from such localities - instead opting for sites along the rims of the basins (see Kasse et al., 2022 for the Amersfoort example). From the deep and thick German Bight sequences, SLIPs and limiting points are only recorded in the database from the deepest levels in the sequences, for which compaction corrections are relatively minor. The environments became subaqueous following the transgression and it is the proxy water depth inaccuracy, rather than decompaction, that affects indicator elevation position and associated uncertainty. In the Amsterdam tongue basin, an isolation basin style sill of glaciogenic deposits controls the elevation of sea level, and therefore compaction could be ignored.

3.3 Vertical Land Motion (VLM) correction

Rates of vertical land motion (VLM) due to basin subsidence and sediment loading in the North Sea Basin are in the order of 0.1-0.2 m/kyr (Kooi et al., 1998), resulting in up to 10 meters of apparent RSL fall simply due to VLM at locations around the LIG highstand shoreline, and up to 20 meters further offshore at locations closer to depocentres (Fig. 3). Such spatial variation in tectonic subsidence thus significantly affects how vertical positions of inland and offshore sourced RSL data points through the interglacial can be compared. Earlier studies that compiled LIG sea-level data from the North Sea region, as part of larger-scale analysis (notably: Lambeck et al., 2006 and Kopp et al., 2009), implemented VLM corrections (mainly to the data points from Zagwijn, 1983; Fig. A1a) to account for this. Accordingly we develop updated VLM corrections based on geological information independent of the LIG data points. To do this consistently for all onshore and offshore sites from The Netherlands, NW Germany and SW Denmark we incorporate up-to-date mapping of the base Quaternary (= base Pleistocene) sediments in these areas, and expand and update the subsidence quantification analysis from Kooi et al. (1998). Applying VLM corrections allows us to remove uniform background non-GIA land-level change, which in turn allows the regional spatial and temporal pattern of GIA RSL due to the proximity of the Eurasian ice sheets to be explored.

The VLM rates for the southern North Sea in Fig. 3 echo those obtained for Dutch sectors in Kooi et al. (1998: their Figure 4, all three components totaled), who performed a tectono-sedimentary back-stripping analysis on thickness of Quaternary and Neogene sequence of the basin and presented mean rates estimated over the last 2.6 Ma. The starting point for that was the mapping of Quaternary thickness in the North Sea Basin ('accommodation'), based on collated offshore seismo-stratigraphic and onshore lithostratigraphic mappings and relying on identification of Early Pleistocene marine strata therein (tens to hundreds of meters below the seabed and Middle Pleistocene glaciogenic unconformities; Ottesen et al., 2014). For reanalysis and assessment of the 1998 outcomes (1990s state of mapping coarsly offshore), we re-generated such source materials from current onshore-offshore geological survey digital mapping resources (2020 state of mapping, especially refined offshore and better aligned across national borders). For the onshore and nearshore the Netherlands, the VLM results broadly reproduced the accommodation patterns and mean subsidence rates over the last 2.6 Ma. For areas further offshore, the mapping of the base Quaternary had been considerably revised (e.g. Lamb et al., 2018) compared to 1990s. This has shifted depocentre contours, which locally nudged VLM values from -0.03 to +0.03 m/kyr relative to the 1998 results. VLM rates for the German Bight lay outside the area covered in the 1998 analysis but are now otherwise produced in the same way. Fig. 3 thus is an expansion of earlier basin subsidence component quantifying work.

The contour lines in Fig. 3 served as VLM-subsidence isolines where values for newer data points had to be assessed. VLM used in WALIS for this region ranges from 0.02 m/kyr at marginal locations, to 0.24 m/kyr at sites over Quaternary depocentres. VLM rate uncertainty is ±0.01 for sites along the basin margin (subsidence of -0.02 to -0.03 m/kyr) and increases to ±0.04 in far offshore depocentres. The propagated effects of combined age uncertainty, palaeoRSL uncertainty and VLM uncertainty to projecting North Sea data points in age-depth plots is considerable, shifting from decimeters to meters as reporting palaeoRSL elevation with and without VLM correction in the next sections will show. Our vertical corrections and associated uncertainties for the Zagwijn-1983 subset were verified to reproduce such calculations reported in Lambeck et al. (2006). We also verified our rate uncertainties against those used in Kopp et al. (2009). The WALIS registered uncertainty for North Sea offshore site '#2' is similar (-0.03 vs -0.0255 m/kyr), but for inshore sites of the Zagwijn-1983 series our uncertainties are roughly twice those used in Kopp et al. (2009).

We do not provide VLM rates for the stable and modestly uplifting areas around the margin of the North Sea Basin and along the English Channel. Independent estimation of the rates of VLM are not available, as studies that provided uplift rates did so based upon the same marine terrace elevations that we consider our SLIPs. Very modest long-term subsidence rates may apply to NE Belgium, Denmark and N Germany during the Pleistocene, or alternatively they can be viewed as fairly stable (Kiden et al., 2002). Whether the Dover-Calais area is neotectonically active, and owing to what cause, is debated (e.g. Van Vliet-Lanöe et al., 2000; Westaway et al., 2002; García-Moreno et al., 2015). The region is also known to have lost considerable volume of bedrock in Middle Pleistocene times (proglacial erosion of Dover Strait; Gibbard, 1995; Gupta et al., 2007, 2017) with some isostatic uplift in response. Regardless, the apparent uplift due to both GIA and non-GIA VLM based upon the flight of raised beaches is modest (+0.02 to +0.04 m/kyr; Pedoja et al., 2018). Similar applies to sites along the English and French sides of the English Channel. The flight of raised beaches in West Sussex (Bates et al., 2010; Briant et al., 2019) occurs in an area where net uplift is thought to be significant, with apparent rates between 0.06 and 0.12 m/kyr, explaining the mean vertical separation of highstand beaches of the last few cycles (e.g. Westaway et al., 2006), although these rate calculations are sensitive to terrace age attributions (see appendix). Moreover, the values for sections of French and English coastlines are total rates, that do not independently allow for separation into the VLM sought for non-GIA and likely GIA (including hydroisostasy) components. Overall, the anticipated non-GIA VLM vertical corrections for uplifting sites along the Channel coast would be significantly smaller than the ones specified for the North Sea depocentre (perhaps with West Sussex data points as a local exception). Developing such corrections remains an ongoing challenge for this area.

Where we report VLM-corrected elevations for North Sea SLIPs and limiting data points in the next section, we calculated these with the 'late onset' numeric ages as listed in Table 4. The vertical positions will further rise if the age model is shifted to the older onset scenario. In the transect plot of Fig. 4, such age-attribution sensitivities will affect early and late LIG data points collected offshore more than the mid interglacial data points that predominantly come from inland positions (section 4.1 and 4.2).

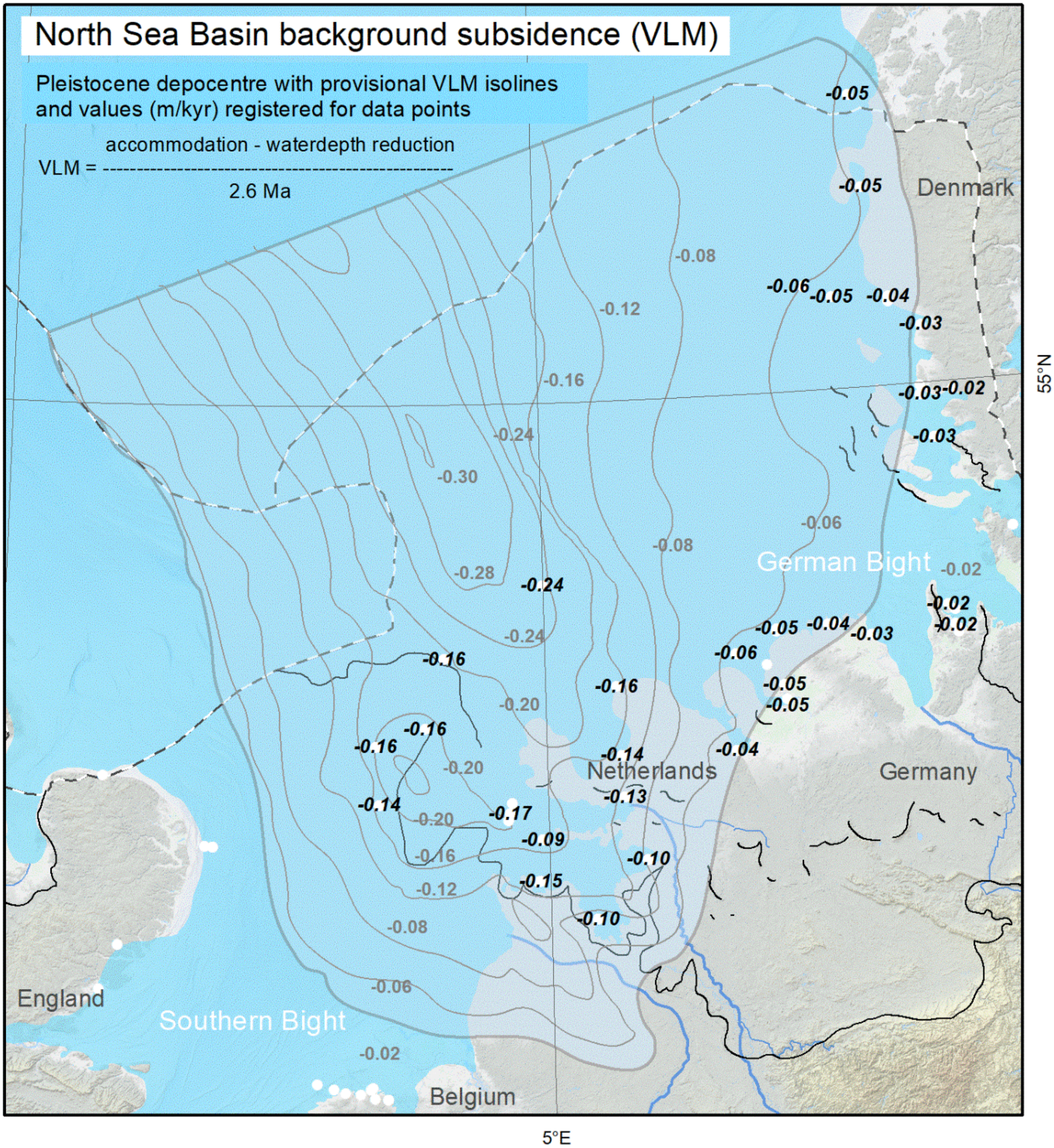

Figure 3: VLM rates (m/kyr) for North Sea Basin LIG data points. Area of subsidence and VLM contours, based on depth base-Pleistocene in marine formations (onshore and offshore data NL, GER and DK geological surveys), negotiated for water depth reduction during the Early Pleistocene (isoline increment: 0.04 m/kyr, i.e. equivalent to 5 m RSL correction accumulated over 120 kyr). Values in black *italics*: WALIS VLM entries for LIG data points, reproducing Kooi et al. (1998) for the Netherlands. Offshore, subsidence patterns deviate subtly from the 1998 publication and for the Germand Bight coverage was extended, based on improved mapping of base Pleistocene. Backdrop as in Figure 1, containing land data © OpenStreetMap contributors 2020, distributed under the Open Data Commons Open Database License (ODbL) v1.0.

4 Overview of data points

This section summarises the database contents for NW Europe, as based upon the data input considerations outlined above. The overview is grouped by region, and where age constraints allowed are broadly characterised as early, middle and late LIG. Figures 4 and 5 present the data points along broad SW-NE transects in the North Sea and the English Channel (see Fig. 1), i.e. at increasing distance from main MIS-6 ice cover over NW Europe.

4.1 North Sea: Netherlands and Belgium

In the Netherlands and Belgium availability of national online geological datasets (e.g. Van der Meulen et al., 2013) means that all sites and boreholes in this region were looked up in web-portals to verify coordinates, surface elevations, layer depths etc. For The Netherlands' we used www.dinoloket.nl/en/subsurface-data, for Belgium (Flanders) www.dov.vlaanderen.be and we have included the original IDs from these portals. Coordinates of legacy sites based on outcrops were also checked using digital topographic and aerial photography resources.

Deposits along the rim of the Dutch Eemian coastal plain are typically lagoon- and estuary-fringe sites in the central Netherlands (Fig. 1; see also Fig. A1), most famously Amersfoort (Zagwijn, 1983; Cleveringa et al., 2000; Kasse et al., 2022; WALIS IDs 133, 137, 138), but also at Oosterwolde (Peeters et al., 2016; IDs 134-136), Rutten (Sier et al., 2015, Peeters et al., 2016; IDs 109, 111, 114, 115), Scharnegoutum (Zagwijn, 1983; IDs 124-127) and Annen (Bosch, 1990, IDs 4260, 4261). Each of these provided multiple SLIPS and limiting points, from PAZ E4 onwards (PAZ E4-E6; site Oosterwolde OSL-dated). The most inland, shallowest preserved coastal beds are encountered at -8 to -10 m MSL, notably at Amersfoort, Annen (both PAZ E5) and Scharnegoutum (PAZ E5/6 break). With VLM-corrections applied, these relatively highest SLIPs plot at +3.5 m, +1.2 m and +6.2 m MSL respectively. From earlier in the interglacial (PAZ E4), additional SLIPs have palaeoRSL depths between -21 and -13 m MSL, and with VLM-correction these plot between -8.3 and -1.4 m (PAZ E4a) and -7.1 and +1.2 m (PAZ E4b). Overall, SLIP uncertainties range ±0.35-1.3 m when decompaction is included, and to ±3.6-4.5 m when VLM is included (Fig. 4).

Seaward from the inner rim of the Eemian coastal plain,marine deposits are encountered down to -40 m MSL, and at -35 to -65 m MSL offshore. This area provides SLIPs which record evidence of transgression during PAZ E3 such as near Amsterdam (Zagwijn, 1983; Cleveringa et al., 2000; De Gans et al., 2000; Van Leeuwen et al., 2000; Beets and Beets, 2003; IDs 118-120) and offshore boreholes 'BH89/2' (Sha et al., 1991; Beets et al., 2005), as well as during PAZs E6 and EW, such as at Petten (Zagwijn, 1983: IDs 146-148). Terrestrial limiting points help further constrain maximum elevations for early interglacial sea-level rise (PAZ E1-E2), while marine limiting points (for PAZ E4 to E5) constrain minimum heights for the middle interglacial.

Figure 4: SW-NE organised plot of Last Interglacial WALIS data entries for the North Sea, split to type and relative position. Transect location in Fig. 1. Colour coding separates data points of middle LIG relative age from those attributed to earlier and later phases within the LIG (see also Table 1). Bottom panels shows sites and age-depth plot (without VLM corrections) as a screenshot of WALIS' interactive viewer (Garzon and Rovere, 2021): https://warmcoasts.eu/world-atlas.html, which includes © OpenStreetMap contributors 2020 data as basemap (distributed under ODbL 1.0). Only LIG data points are plotted.

The PAZ E3a SLIP from the Amsterdam glacial basin (ID 118) is characterised as an 'isolation basin' type, recording the moment of marine connection. The sill-height of this isolation basin occurs at -39.0 ± 2.0 m MSL (tidal amplitude and sill elevation uncertainties considered), which with VLM accounted for rises to -19.4 ± 4.8 m MSL. Offshore site BH89/2 is also a glacial basin (Beets et al., 2005), where transgression of an isolation basin is recorded (ID 122; PAZ E3a) at -53.8 ± 9.0 m MSL. The large uncertainty is due to the poorly defined sill location for this basin. This site has the greatest estimated basin subsidence (Fig. 3); applying a VLM correction of -0.24 ± 0.05 m/kyr means the elevation is adjusted to -24.1 ± 10.9 m MSL (Fig. 4). At Petten (ID 148; PAZ E6b) we combined coeval terrestrial and marine limiting evidence in a transect of cores (Zagwijn, 1983), to define a SLIP at +0.9 ± 4.7 m (VLM corrected). North Sea boreholes '#2', '#3', '#5' and '#9' (Zagwijn, 1983) provide terrestrial and marine limiting data points only (IDs 309, 311, 317, 319 320, 380), as do onshore boreholes such as Noorderhoeve (ID 898; Meijer, 2002; Peeters et al., 2016).

The majority of Belgian RSL data points are from estuarine tidal deposits preserved W-E along the rim of the LIG Scheldt estuary (Fig. 1; see also Fig. A1). They occur at shallower subsurface positions than in the Netherlands, with three inland SLIPs coming from pit exposures: Meetkerke (De Moor and De Breuck, 1973; Nolf, 1973; ID 3259; see Fig. A1), Pit Dhondt and Pit Coppens (Heyse 1979; IDs 341, 345), and three more from boreholes at Waterpolder and Balgerhoeke (Heyse, 1979; IDs 338-340). The latter is the most eastward and shallowest site, preserving supratidal mud (ID 339, PAZ E5) and salt-marsh peat (ID 340, PAZ E5) though the absence of microfossil analysis to confirm this means this datapoint is characterised as of 'estuarine terrace' type. The other SLIPs are from intertidal levels. For PAZ E5, the NW Belgian RSL positions occur between -3.1 and -2.9 m MSL (Pit Coppens, Waterpolder, Balgerhoeke), with a lower data point of -5.4 m MSL (Pit Dhondt) during PAZ E5 potentially recording the onset of falling RSL. These values include large modern-day outer estuary tidal amplitudes for the Scheldt, with mesotidal palaeoRSL uncertainties ranging ±0.8-1.6 m. Reducing tidal range uncertainties and considering modest subsidence (e.g. 0.02 ± 0.02 m/kyr) will raise the elevation of the Belgian points and warrants further investigation.

Westwards, further Belgian sites reveal truncated sequences lacking supratidal contacts, generating transgressive SLIPs from PAZ E4, ranging between -14.1 ± 1.6 m MSL (Vlissegem: De Clercq et al., 2018; ID 353) and -4.1 ± 0.8 m MSL (Meetkerke), whereas terrestrial site Vossenhol (Heyse, 1979; ID 337) constrains RSL to below -4.3 ± 0.2 m MSL during the same period. Offshore, borehole GR1 (De Clercq et al., 2018) reveals active tidal scour during PAZ E4, suggesting a marine lower limit at -38.3 m MSL. Lastly, in southwest Belgium, boreholes at Woumen and Kellen in the Ijzer palaeovalley (Bogemans et al., 2016) provide maximum SLIP altitudes of -5.7 m MSL (ID 346; including some decompaction and assuming 2 to 3.5 m tidal amplitude), and at -3.1 m MSL for an older interglacial (ID 347; MIS 7).

4.2 North Sea: Germany and Denmark

In NW Germany and SW Denmark, the LIG highstand shoreline ran roughly parallel to that of the modern Wadden Sea (Fig. 1), locally preserving tidal flat and supratidal marsh deposits below -7.5 m MSL. Where the shoreline turns north in the German Bight, it shows more LIG estuarine indentations than it does in present times. These inshore settings, like in The Netherlands and Belgium, produced a series of tidal flat surfaces topped by terrestrial limiting points, suggesting falling RSL. These are the German sites Leybucht and Land Hadeln (Höfle et al., 1985; Streif, 1990; 2004: IDs 880-884, 4271-4273), Danish classic site Tønder (Madsen et al., 1909; Nordmann, 1928; Friborg, 1996; IDs 865, 866) and further sites Ribe, Esbjerg, Ringkobing and Harbooere (Konradi et al., 2005; IDs 869-873). In NW Germany, highest sea level positions appear to have recorded for the entire length of PAZ E5. Where Danish-German sites have palynological chronostratigraphical control, the database entries encoded the established regional correlation schemes (e.g. Kristensen et al., 2000; Funder et al., 2002) towards the Zagwijn scheme (Table 4: upper rows). Where the relative dating was instead correlated to phases in the deposition established for the 'Cyprina Clay' (relatively deep water in the SW Baltic), this was encoded as such and subsequently in turn correlated to the Zagwijn PAZ scheme (Table 4, lower rows; following Funder et al., 2002).

PalaeoRSL from the shallowest SLIPs between Ems and Weser estuaries (Fig. 1) plot at -10 m MSL (Leybucht, Land Hadeln), which is ~5 m deeper than the data points north of the Elbe estuary in Danish-German borderlands (Tønder, Ribe; marine limiting data only). Northwards into Denmark, SLIP elevations fall to between -15 to -10 m MSL (Esbjerg, Ringkobing, Harbooere). A particularity is borehole site Vovov Bakkeoer (Konradi et al., 2005; ID 874) in the West-Danish offshore area, that revealed a patch of Saalian till/outwash deposits with Eemian marine cover, bearing foraminiferal evidence for later-shallower local submergence, than that of the deeper waters surrounding it (e.g. Horn Reef M3; ID 864). Hence, despite being positioned offshore, this 'drowned island' location produces a middle interglacial SLIP (E4b-E6a) at -14.3 ± 1.3 m MSL. Terrestrial LIG exposures are obtained from around modern MSL (-4 to +2 m) from shallow boreholes (Esbjerg, ID 871) and a classic exposures in low cliffs along the Danish Waddensea (Emmerlev Klev; Nordmann, 1928; ID 867). They place a terrestrial limit at -3.6 m MSL and at modern sea level (0 m MSL), to which inland shallow lacustrine beds at Tønder add a third such point at +2 m (Friborg, 1996; ID 866). Deploying VLM corrections to the German and Danish sites (with generally lower subsidence rates than applied to data points in the Netherlands, Fig. 3), adjusts the maximum RSL elevations to between -5.2 and +2 m MSL (and -7.1 m for Vovov Bakkeoer), while projecting the terrestrial limits to +1.2 to +4.4 m MSL. The vertical uncertainty of these SLIPs ranges between ±0.5 and ±1.0 m and expands to typically ±2.5 m when VLM is included. Importantly a good part of the middle interglacial SLIPs after VLM correction in this region have a position just below present MSL, suggesting significant near-field GIA fingerprint effects to be in play in this area (as in the Holocene, e.g. Vink et al., 2007).

A cluster of early and late Eemian, rather than middle interglacial data points comes from relatively deep and/or offshore boreholes in the Ems estuary and West-German Wadden Isles Borkum, Norderney and Spiekeroog (Höfle et al., 1985; Streif, 1990, 1991, 2004; Schaumann et al., 2021; IDs 885-888, 4269-4270, 4274-4275). These include a transgression SLIP (Borkum; ID 886, PAZ E3b) at -36 m MSL and a coeval terrestrial limiting at -16.5 m MSL (Ems Estuary, ID 885, PAZ E3), as well as terrestrial limiting points at -8.5 m MSL (Norderney, ID 887, PAZ E6) and -16.5 m MSL (Spierkeroog, ID 888, PAZ E6b.EW-Ia), coincident with the end of the interglacial. With differential VLM correction, the points plot at -28.6 and -9.1 m MSL (PAZ E3), respectively -8.5 and -16.5 m MSL (PAZ E6/EW). Uncertainties are ±0.5-1.0 m without and ±2.5 m with VLM correction.

A further major cluster of such early and late Eemian sites comes from the German-Danish borderlands from deeper buried estuarine and marine deposits filling outwash valleys inherited from the MIS-6 deglaciation. The lower parts of these valley fills (typically below -17 m MSL) survived erosion by glacio-fluvial outwash systems of Last Glacial age. The sites recorded regional-transgressive sequences, which yield early Eemian SLIPs and marine limiting points. Higher up the sequences also recorded local regression and those levels have provided late Eemian data points. The cluster comprises sites Schnittlohe (Kosack and Lange, 1985; Lambeck et al., 2006; ID 889), Dagebuell (Winn and Erlenkeuser, 1995; Winn et al., 2000; IDs 875-877), Højer (Madsen et al., 1909; Nordmann, 1925; Konradi et al., 2005; ID 868) and Horns Reef M3 (Konradi et al., 2005: ID 864) in the German Bight, and sites Krummland (Winn and Erlenkeuser, 1995; Winn et al., 2000; ID 878, 879) and Tuschenbeck (Winn and Erlenkeuser, 1998; ID 890) along the Baltic Sea German coastline (Fig. 1). These type of sites is especially important along the SW Baltic, as there it represents rare preservation of inland-most coastal and estuarine beds, as the Last Glacial ice advance overran areas that otherwise eroded superficial littoral LIG deposits (making the area unsuitable to provide LIG SLIPs). In the SW Baltic, the sequences typically hold lacustrine deposits in the lowest part, which due to imprecise water depth control do not offer valuable terrestrial limiting points. However, the timing of marine inundation is well established, occurring in PAZ E3a in Baltic facing sites Tuschenbeck and Krummland, and later at the inland site of Schnittlohe (PAZ E4). North Sea facing sites Horns Reef M3 (basal peat), Dagebuell (beach facies at base) and Højer (shallow channel fill peat) all come from the valley floor, rather than lake settings, which provides a better opportunity to define RSLs.

Early interglacial SLIPs from local transgressive contexts are present at -40.0 m MSL (ID 864, PAZ E2a), at -24 m MSL (ID 875; PAZ E3a-E4b) and at -23 m MSL (ID 868, PAZ E4) and plot at -33.8 ± 0.6 m, -20.3 ± 1.7 m and -19.3 ± 2.0 m MSL respectively with differential VLM correction (Fig. 4). In the sequences at Dagebuell, Schnittlohe, Krummland and Tuschenbeck this is followed by marine limiting data from PAZ 4b-E6a, the highest at -12.5 m (Krummland; ID 879), as well as -6.8 m (Dagebuell, ID 876) and -4 m (Schnittlohe, ID 889). The top of the Eemian marine sequence at Dagebuell is intertidal, and records a regressive SLIP at -9.7 m MSL (ID 878; PAZ E6; -3.2 ± 1.9 m MSL with VLM correction), which is rare from N Germany (Fig. 4). Abundant palynological, foraminiferal, molluscan and high-density subsurface mapping provides control on the setting, palaeoenvironment and relative ages of the above set of sites. At Dagebuell additional U-series (base), oxygen isotopic investigations (middle), and an ESR date (top) confirm a MIS-5e age (Winn et al., 2000).

Lastly, two deep-water marine limiting sites are available from the NE of Denmark, Skaerumhede I (Houmark-Nielsen, 1987; Larsen et al., 2009; ID 856) and Flakket, Anholt (Seidenkranz, 1993; IDs 857-861). The former is a deep research borehole recovering some 80 meters of deep-water facies (Lower Skaerumhede Clay Fm.) deposited in the LIG equivalent of the Skagerrak channel (Fig. 1), with foraminifera and mollusca biostratigraphy (Knudsen and Lykke-Andersen 1982; Knudsen et al., 2009) which tie the water depths to 100-200 m in the facies encountered at -135 m MSL. This translates to a single marine limiting point (ID 856) at -17.5 ± 17.5 m MSL (Fig. 4). Marine palynological and biostratigraphically data from Flakket also (Seidenkrantz, 1993), suggested deepending water depth from 35 ± 5 to 100 ± 10 m between the onset of the Eemian (ID 857; Kattegat Stadial; ID 858; PAZ E2a-E3a) and though the middle and later stages of the interglacial (ID 859; PAZ E3a-E4b; ID 860; PAZ E4b-E6a). This deepening correlates with the Cyprina Clay phases in the SW Baltic (Table 4) and with the boreo-Lusitanian (see section 2.2.6) molluscan and foraminifera in the Skaerumhede borehole. With species water depth tolerances accounted for, the marine limiting depths rise from -40 to -36.5 m MSL in the early Eemian, then to +1 ± 15 m MSL during PAZ E3a-E3b, and a maximum of +22 ± 5.4 m MSL (PAZ E4b-E6a). The top of the Flakket sequence shows a decreasing water depth, but the site remains marine during PAZ E6 defining a marine limiting point (ID 861) of +13.0 ± 5.4 m MSL. The apparent super-elevation of the LIG RSL data from these northwesternmost sites (Fig. 4) reflects the strong gradient in GIA from this repeatedly ice-covered part of the study area, to the increasingly GIA-peripheral North Sea and Channel regions to the southwest (similar as known from Holocene sea-level studies for NE Denmark, Clemmensen et al., 2018).

4.3 North Sea: Thames Estuary, East Anglia, North England

Sea level data points from the western North Sea coast primarily comprise of estuarine deposits from in or just above tidal frame. In the Thames, Preece (1999) describes a terrestrial limiting point (ID 3713) based upon the presence of freshwater mollusca throughout a sequence of organic silts from -2.4 to + 3 m OD, that overly a basal gravel (similar to the stratigraphy found at other locations in Trafalgar Square). The presence of the brackish water ostracod *Cyprideis torosa* and a few tests of the foraminifera *Elphidium articulatua,* which were likely carried upstream by tidal action, suggests this site was deposited just beyond the limit of HAT. Similarly macro- (hippopotamus, hyaena and elephant) and micro-fossils (freshwater ostracods and mollusca) found in a channel sequence at East Mersea in Essex constrains a terrestrial limiting point (ID 3715) within the modern foreshore at ~3.2 m OD (Bridgland et al., 1995a; Briant et al., 2012). A further terrestrial limiting point (ID 4064) is present at Bobbitshole, Suffolk, which is the type-site for the Ipswichian interglacial, with the youngest LIG freshwater deposits as indicated by pollen and mollusca at approximately +1 m OD (West and Godwin, 1957; Sparks, 1957). The age of each of these terrestrial-limiting sites is constrained by AAR dating of *Bithynia tentaculata* opercula, with ascription of a MIS 5e interglacial supported by the biostratigraphy (Penkman et al., 2013).

The same AAR dating method (Penkman et al., 2013) is applied to the sequence from Tattershall Castle, Lincolnshire, where a salt marsh pollen sequence of detrital mud and organic silts contains grains of *Chenopodiaceae*, *Plantago maritima* and *Artemisia*, alongside the brackish water ostracods and mollusca *Pseudamnicola confuse* and *Hydrobia ventrosa* (Holyoak and Preece, 1985). This allows us to ascribe this site to the salt marsh indicator type and a SLIP of -0.75 ± 0.71 m OD (ID 3736). Further north, on the modern East Yorkshire coast is the only non-estuarine MIS 5e deposit from this region; a chalk boulder beach (Lamplugh, 1887; Catt and Penny, 1966), overlain by windblown sands from which OSL samples were collected and dated to 120.9 ± 11.8 yr (Bateman and Catt, 1996). Due to the presence of landslide material covering the LIG boulder beach (visited by NLMB in 2020) there is some uncertainty as to the exact elevation of the beach (ID 1380; 2.3 ± 2.8 m OD), which had to be estimated from the field diagrams (Bateman and Catt, 1996; Catt and Penny, 1966). Offshore of Norfolk two vibrocores record a transgressive sedimentary succession of sands and silts sat over a unit of glaciofluvial gravel and gravely sand (Paddenberg et al., 2008, Russell and Tizzard, 2011). Silty deposits at ca. -29.54 m OD date to MIS 5 and display a micro-fossil assemblage dominated by the ostracod *Cyprideis torosa* and foraminifera *Ammonia becarii*, *Haynesia germanica* and *Elphidium oceanis* indicative of intertidal environments (IDs 3432, 3433, 3434).

4.4 English Channel: Southern England

Sea-level data from Southern and Southwest Britain include a mix of marine and terrestrial limiting data, as well as precise SLIPs. Several important sites along the Hampshire (Briant et al., 2006; 2019) and West Sussex (Bates et al., 2010) coastlines have been dated using OSL, providing an absolute chronology for the terraced sequences of raised littoral deposits along this stretch of the southern British coastline. In West Sussex, the Aldingbourne Raised Beach sequence of marine sands and gravels found at elevations between +17.5 m and 27.4 m OD (at Norton Farm and Pear Trea Knap; IDs 3716-3722) dates to MIS 7 based on replicate OSL sampling at multiple sites (Bates et al., 2010). The lower positioned Pagham Raised Beach sequence of marine sands and gravels, has been dated at multiple sites to MIS 5, and in places to MIS 5e (Bates et al., 2010). Its SLIP elevations are around +5 m OD (sites Selsey West Street, Pagham Water Treatment Plant, Chalcroft Nurseries, Warblington and Woodhorn Farm; IDs 3723-3733).

Fluvial deposits found at intermediate elevations between the Aldingbourne and Pagham Raised Beaches (Solent Breezes, IDs 3734, 3735) and dated to MIS 6, provide important terrestrial limiting data points (Bates et al., 2010). In Hampshire, several sequences have been dated that contain interglacial estuarine organic deposits located between lower and upper marine sand and gravel units (Allen et al., 1996; Briant et al., 2006; 2019). At Lepe, lower gravel units are OSL dated to MIS 6, provide terrestrial limiting points (ID 3755, 3757, 3758). The upper gravel units date to MIS 4 (IDs 3753, 3754, 3756), placing the interbedded estuarine deposits in MIS 5 (SLIP IDs 3759, 3760), albeit that a paired date for the estuarine deposits is unavailable (Briant et al., 2006; 2019). OSL dates from overlying gravels in comparable sequences at Pennington Quarry (IDs 3761-3764) place buried estuarine deposits at -4.6 m OD in late MIS 5 (Allen et al., 1996; Briant et al., 2006), and provide terrestrial limiting points. Buried interglacial estuarine deposits associated with the Solent River estuary system are further found on the Isle of Wight in association with the Bembridge Raised Beach (ID 4004; +4 m OD), which is dated with thermoluminescence to MIS 5e (Preece et al., 1990).

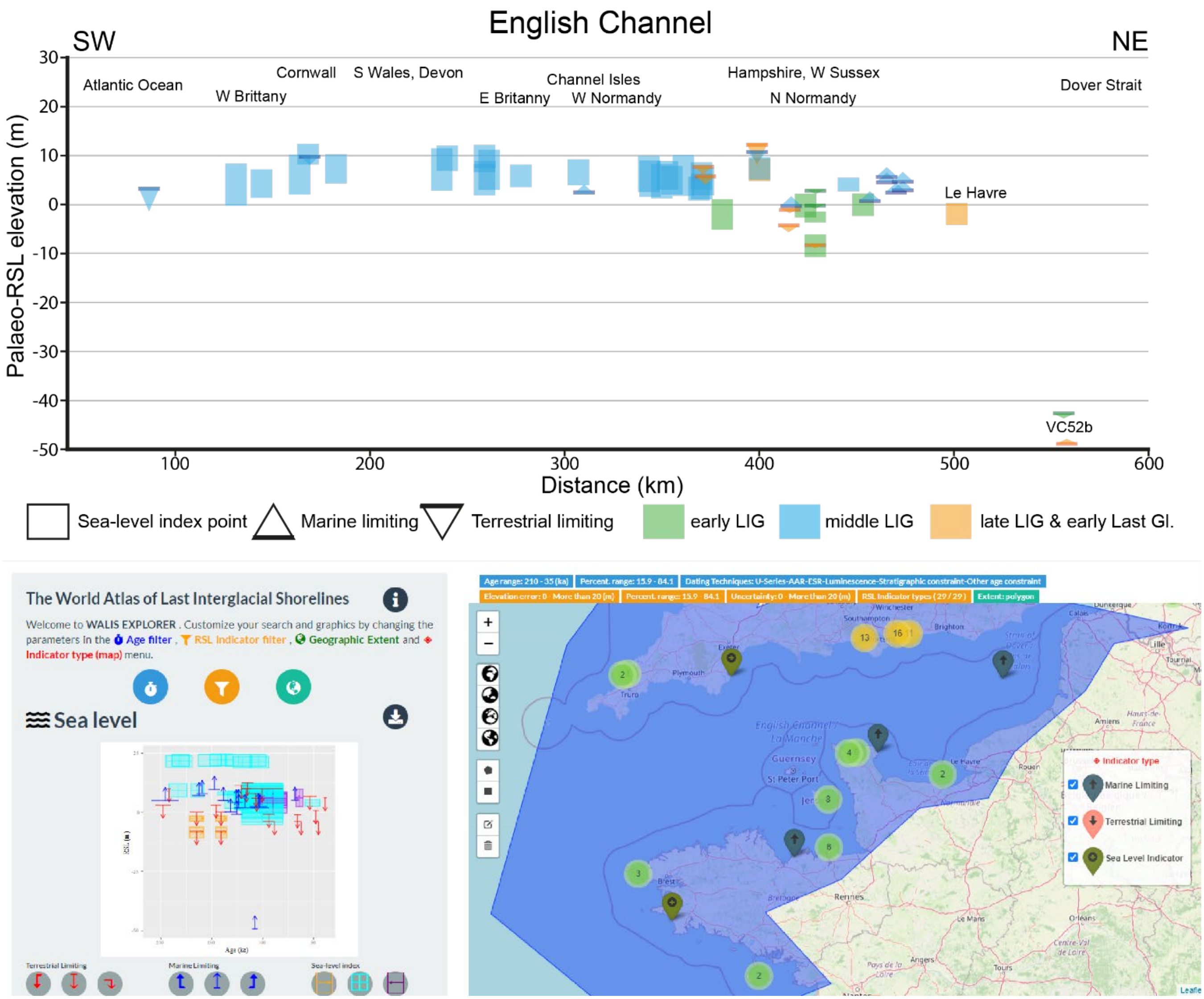

Figure 5: SW-NE organised plot of Last Interglacial WALIS data entries for the English Channel, split to type and relative position. Transect location in Fig. 1. Colour coding separates data points of middle LIG relative age from those attributed to earlier and later phases within the LIG (see also Table 1). Bottom panel shows sites and age-depth plot as a screenshot of WALIS' interactive viewer (Garzon and Rovere, 2021): https://warmcoasts.eu/world-atlas.html, which includes © OpenStreetMap contributors 2020 data as basemap (distributed under OdbL 1.0). Only LIG data points plotted.

Raised interglacial beaches in both Devon and Cornwall (Scourse, 1996; Campbell et al., 1998) are commonly associated within sequences of pebble conglomerate beach facies sitting on top of raised wave-cut platforms, and overlain by backshore sand facies that grade into aeolian dune sands. Four sites are included, of which only one (Fistral Beach, Newquay; ID 729) has a geochronology supported by thermoluminescence dating, independent from AAR (Southgate, 1985). That site dates overlying dune deposits (+9 m OD), providing a terrestrial limiting data point. The further three sites (Trebetherick, St Ives Bay, Saunton; IDs 528, 730, 735) each have AAR and stratigraphic information that indicate MIS 5 provenance (Andrews et al., 1979; Bowen et al., 1985; Davies, 1983, 1984; James, 1968, 1975, 1995, 2008; Gilbert, 1996; Scourse, 1996; Campbell et al., 1998), yet with low confidence in age quality. These plot as SLIPs at +4.2 to +7.2 m OD (Fig. 5).

The remaining MIS 5-associated data points included for Southern and Southwest Britain derive from raised littoral sediments found within cave systems in South Devon (Proctor and Smart 1991; ID 4008), South Wales (Sutcliffe and Currant 1984; Stringer et al., 1986; Sutcliffe et al.1987; IDs 4005-4007), and on Jersey (Keen et al., 1981; ID 4003). Each site contains speleothem deposits in association with the raised littoral sediments providing robust chronologies based on U-series dating. The Minchin Hole Cave (IDs 4005, 4006) site in South Wales is further supported with luminescence dates (Southgate 1985). Lastly, offshore in the English Channel, vibrocores dated by luminescence record a fluvial palaeosol (ID 3679) of late MIS-6 age at -42.9 m OD and laminated sand (ID 3678) rich in shell fragments and shallow marine foraminifera (*Elphidium* sp. and *Ammonia* sp.) of MIS-5 age at -48.8 m OD (Mellett et al., 2012; 2013).

4.5 English Channel: Northwest France

The most common sea level indicators in the French side of the English Channel are marine terraces and raised beaches. These features have been described from west Brittany to east Normandy as part of a staircase of coastal platforms with each step attributed to different interglacials (Coutard et al., 2005, 2006; Pedoja et al., 2011; 2014; 2018). The lower level is generally ascribed to the LIG and its age has been constrained by dating the deposits sat on top of the platforms (mainly heads, loess and beach sediments) or by the identification of Palaeolithic artefacts (Mousterian industry, Cliquet et al., 2003; 2009; Cliquet 2013; Regnauld et al., 2003; Lautridou and Cliquet, 2006). Absolute ages are available at a limited number of locations and the rest of the sites are regionally correlated based on the developed stratigraphic frameworks (van Vliet-Lanoë et al., 2000; Bates et al., 2003; Regnauld et al., 2003; Monnier et al., 2011; Pedoja et al., 2018).

Marine terraces are generally found between 0 and +8 m NGF in mainland France (e.g., Trez Rouz, ID 3677; Cap La Hague, ID 3674; Asnelles, ID 3672) and in different islands distributed along Brittany's west coast (e.g., Belle Ile, ID 3667; Ouessant, ID 3658; Chausey, ID 3668). In Brittany, dune sands from deposits overlying an abrasion platform at Du Guesclin (ID 3659) were dated by Regnauld et al. (2003) providing a minimum age of 90 ka, and artefacts attributed to early Palaeolithic age were found overlying an equivalent platform at Le Verger (Regnauld et al., 2003; ID 3660). Absolute ages pointing to MIS 5 were also obtained from raised beach deposits at +8 m NGF at Piégu (ID 3657) by ESR on quartz grains (Bahain et al., 2012). Normandy shows the highest density of LIG sites, particularly around the Cotentin peninsula, including a suite of sea level index points, and marine and terrestrial limiting data. Sandy beach deposits that are found between 4 and 7.9 m NGF (IDs 3550, 3551, 3646, 3651, 3671) have been dated by OSL and TL to MIS 5, probably MIS 5e (Folz, 2000; van Vliet-Lanoë et al., 2006; Coutard et al., 2006; Cliquet et al., 2009), while aeolian sands (mainly dunes, IDs 3536, 3549, 3648) and marine deposits (ID 3552) provide ages for marine and terrestrial limiting points. Further east, in Le Havre, beach sediments found at -1 m NGF (ID 3676) has been interpreted as MIS-5e regressive deposits based on its stratigraphic position (Breton et al., 1991; Lautridou et al., 2003), but absolute ages are not available.

5 Closing Remarks: Challenges and Recommendations

This database presents 146 LIG data points from NW Europe, standardised to the format and structure of WALIS and taking into consideration VLM, compaction and elevational uncertainities where possible to provide a comprehensive overview of LIG sea level in the region. The history of research in the region presents a wealth of data and opportunities, but also presents some interesting challenges that users of this database should take into consideration and provide stimulus for future research.

5.1 Chronostratigraphical challenges

Near-field sites often include temperate and high-latitude estuarine sequences (e.g. salt marsh) which due to their close relationship with tidal levels have the potential to provide accurate and precise vertical constraints on RSL (Shennan et al., 2015). The main challenge with such data points is not vertical, but temporal imprecision and dating-control independency (amongst others because the timeframe is outside the reach of radiocarbon dating). Such is a challenge of any LIG sea-level database. Even in low-latitude regions where absolute U-series dating can be applied to palaeo-corals, debate on the age constrains remains (e.g., Chutcharavan and Dutton, 2021). In our study area, the MIS-6 glaciation limit divides the study area and the dataset quite evenly (N=74 within the glaciation limit, N=73 outside). For locations within the Saalian ice limit, the lower stratigraphic units left by the ice provides a strong maximum chronological constraint. Therefore the main chronological challenge in this area is determining the absolute ages for the successive Eemian pollen zones (Table 4; Appendix A2). This is especially relevant if rates of sea-level rise and fall during parts of the interglacial are to be resolved and analysed, and if one tries to investigate to what extent LIG developments (climatological, sea-level history, coastal depositional) are analogous to Holocene situations and anticipated futures. This high resolution chronostratigraphical issue remains intertwined with other challenges, discussed in sections below.

Outside of the ice margin, the limited lithostratigraphic controls means that assigning a pollen biozone to one specific interglacial is difficult. Although recent advances in AAR dating has led to some progress to resolve this problem, it has still resulted in several ambiguous sites not being included in our compilation (section 4.3). The chronological particularities and uncertainties of the North Sea region affect the basin subsidence corrections and graphical comparison of WALIS data against earlier work and syntheses. Users of this database must be mindful of these regionally-specific chronological challenges, which are dicussed further in the Appendix A2. There also remains considerable opportunities to revisit many interglacial sites and to apply now established sea-level research protocols (Shennan et al., 2015) and spatially intensive geochronology sampling strategies that, if combined with statistical (e.g. Bayesian) frameworks, could greatly advance knowledge and data precision across this region.

5.2 Vertical Land Motion over- and underestimation

In the North Sea area we provide estimates of the rates of VLM based upon independent geological mapping (section 3.3), presented as an average rate calculated over the last 2.6 Ma (mapping of base Quaternary). There is strong indication (analysis in Barthes et al., 1999; Kuhlman et al., 2006ab; Arfai et al., 2018) that the 2.6-0 Myr averaged subsidence rate that Kooi et al. (1998) reported is the combined result of a phase of very strong sediment-loading subsidence induced between 2.6 and 1.8 Ma (rates considerably higher than average), followed by much reduced subsidence after 1.8 Ma (rates below average, estimated at 80%). Additional changes in the rate of basin subsidence before and after 1 Ma may also be speculated on, but for that timeframe are hard to spatially quantify and calculate independently of presumed GIA vertical motions. For the 2.0-1.5 Ma timeframe, it may be possible in the future to map 'base Olduvai' consistently across the depocentre, and use that to quantify VLM rates for the youngest 1.8 Ma. Awaiting such analysis, one could decide to regard presently included VLM rates (Fig.. 3) as maximum subsidence rates, and opt to lower them by 80% as an advised minimum rate. Doing so would result in a lowering of the reported VLM-corrected palaeo sea-level elevation (Fig. 4, section 4.1), by some 5 meters in offshore depocentre locations and by some 2 meters for coastal sites.

For the English Channel coasts and the English side of the North Sea, the database provides no VLM rates and our review presents these as generally smaller than +0.04 m/kyr, with the local West Sussex exception of possibly up to +0.12 m/kyr. These are clear maximum values and it is important to compare these to regional GIA modelling outputs to assess the amount of vertical motion that glacio- and hydroisostatical processes could explain. So far, the studies addressing long-term land level and those addressing GIA during interglacials have mostly been separate work, and resolving this was beyond the scope of a database filling project. A future dedicated study should seek to separate out non-GIA and GIA VLM in the region and then enter values for the former to the WALIS entries for along the English Channel.

5.3 Comparison to older interglacials

The current version of the NW Europe database contains a modest number of older sea level data points (Fig. 1 and Table 2): 5 SLIP sites along the North Sea (Morton, Norfolk UK; Sangatte, NW France; Kellen, Belgium; Noorderhoeve and Ameland in The Netherlands; IDs 4063, 3665, 347, 895, 429), and along the Channel the OSL-dated Aldingbourne raised beach (West Sussex, UK – see 4.4). All of these are attributed to MIS 7 (Gale et al., 1988; Hoare et al., 2009; Balescu et al., 1991; Bogemans et al., 2016; Meijer et al., 2021) and likely represent RSL highstand positions. The indicators occur in raised position along English Channel, East Anglia and also in the Dover Strait (Sangatte), and subsided position in The Netherlands (VLM rates, section 3.3). The Belgian site is from the Ijzer-valley and in facies and setting similar to the LIG counterpart Woumen (Bogemans et al., 2016; ID 346). The Morton site is a beach deposit with no clear nearby counterpart in East Anglia. Sangatte is also without preserved LIG counterpart, attributed to Holocene highstand erosion (section 5.5). The Dutch sites (Meijer, 2002; Meijer et al. 2021; IDs 429, 895), are from estuaries overridden by the MIS-6 glaciation. In terms of depositional environments, they are similar to LIG and Holocene settings, but in terms of geographic position and orientation they are dissimilar. Geological Survey investigations in the Northern Netherlands (Bosch, 1990; and later and ongoing work) reveals a complex of glaciogenic (older than MIS 6), estuarine and fluvial deposits, including regionally traceable peat and shallow intertidal levels, similar in degree of preservation as such from the LIG. This will certainly provide opportunity to add older-interglacial RSL data points from this region in the near future contributing to insights in both RSL rise and maximum positions during the Middle Pleistocene. The series of MIS-7 and older attributed sites along the Thames Estuary (see Appendix A2) has not been entered due to limited chronological constraints. Our compilation efforts focused on the LIG, however we do recommend that WALIS is expanded with entries for older interglacials.

5.4 Comparison to Holocene sea level indicators

There is a long history of research into Holocene RSL sea-level indicators from this region, in particular in the UK and Netherlands (Shennan, 1989; Flemming, 1982; van de Plassche, 1982), the databases of which provide the foundation for the design of modern RSL databases (Hijma et al., 2015). For recent datasets, we refer to Vink et al. (2007) and to HOLSEA regional publications (Shennan et al., 2018; Hijma and Cohen, 2019; Rosentau et al., 2021; Bungenstock et al., 2021). This wealth of information has provided important insights into our data review for the LIG, in particular when defining the indicative meaning (Shennan, 1986; van de Plassche, 1986) where we have documented the SLIP types in use for LIG sea-level reconstruction in estuaries, barrier-lagoon and glacially inherited embayment systems, particlulary along the North Sea.

It is a different matter, however, to interpret the LIG relative sea-level signals in age-depth plots directly to Holocene counterparts. Such requires differential correction of VLM (sections 3.3 and 5.4), which in turn is dependent on age-attribution (section 2.3, 5.1 and Appendix A2), and the degree of analogy drawn between Holocene and LIG. The spatio-temporal pattern of deglaciation of the NW European ice sheets over Termination II vs. Termination I is a key driver of differences in RSL between the Holocene and LIG (e.g. Lambeck et al., 2006; Long et al. 2015), and may even help constrain the chronologies (Appendix A2). Our data entry in WALIS and this paper prepare for and recommend (section 5.5), but do not execute LIG to Holocene intercomparisons.

5.5 Near Field importance in resolving global Last Interglacial sea levels

The main foreseen use of this database from the near-field region of the European ice sheets is in GIA modelling and analysis of ice melt fingerprints. The pattern and magnitude of RSL change at near-field sites, proximal to existing or former ice sheets, are strongly dependent on the magnitude and timing of the change in ice load and the relaxation characteristics of the underlying mantle (Farrell and Clark, 1976; Yokoyama and Purcell, 2021). Therefore, near-field sea level observations have the power resolve ice sheet histories and changes in the solid Earth that far-field data do not; as has been extensively demonstrated with near and intermediate field Holocene RSL data (e.g., Lambeck, 1995; Peltier, 2002; Bradley et al., 2011; Engelhart et al., 2011; Long et al., 2011) and has also been explored before with LIG data (Lambeck et al., 2006). The relative density of data in NW Europe, over a transect away from the Saalian ice sheet margin (Figs 4 and 5), means RSL data from this region has the potential to reconstruct the magnitude and deglaciation of the MIS-6 Eurasian ice sheet, which is currently poorly constrained and important for both near and far-field LIG sea level (Rohling et al., 2017; Dendy et al., 2017). Near-field sites can also take advantage of the sea-level fingerprint of ice sheet mass balance changes to constrain the source of ice sheet melt (Tamisiea et al., 2001; Mitrovica et al., 2009). Ongoing debate suggests asynchronicity between the timing of the contribution of the Greenland and Antarctic ice mass loss to LIG barystatic sea level (Rohling et al., 2019; Turney et al., 2020); a hypothesis which near-field RSL data can test (Kopp et al., 2009; Hay et al., 2014; Long et al., 2015).

One of the challenges of near-field RSL data is that regional GIA is a dominant component of the overall sea-level signal. This does in turn present advantages, as alongside long term VLM, GIA can provide the accommodation space for the accumulation and preservation of (near-)continuous late Quaternary sedimentary packages (e.g. Eaton et al., 2020). Interglacial RSL highstands will occur earlier in the far field than the near field due to solid Earth processes, with the initial transgressive phase being relatively slow and prolonged and therefore having the potential to capture fluctuations in RSL (Cohen et al., 2012; Long et al., 2015). At the end of an interglacial, RSL fall in the near-field is relatively marked, as changes in ocean volume due to growth of ice sheets of the commencing glacial phase, outpaces regional GIA. Improving the quality of LIG SLIPs needs to be an area of intensive research, as near-field RSL constraints from pervious warm periods are essential to identify the sources and forcing mechanisms responsible for sea-level change (Dutton et al., 2015).

5.6 Future data collection directions

The records in the NW Europe database typically cover the middle part of the Eemian, general recording the latter phases of RSL rise and a regional highstands as such evidence is preserved onshore and in shallow marine boreholes. By comparison records from the early interglacial and evidence of falling sea level to MIS 4 are much more limited and widely spatially distributed, compounding uncertainties in VLM corrections (section 5.2). In light of this, targeted collection of a series of transgressive SLIPS from along submerged Saalian palaeorelief off the Dutch coast (see geomorphological context in Cartelle et al., 2021) has been carried out (ERC RISeR project; Barlow cs.), and are anticipated to append the current dataset.

Current offshore boreholes which record late LIG sea level likely include RSL changes from the MIS 5c and MIS 5a substages (Table 1), and potentially even from MIS 3. There are limited data points from these periods, and requires a targeted data collection effort to resolve the signal. The offshore record potential for the Late Pleistocene is not restricted to terrestrial limiting data from fluvial settings alone, but also includes marshy deltaic and shallow marine strata. There appears significant potential in the Southern Bight, where new generations of seismic surveying instruments and analysis capacity are used for targeted vibro-coring of submerged landscape features (e.g. Missiaen et al., 2020), including at places with sea-level indicative potential. In this region, *falling stage* sea-level research interest on the North Sea shelf links up with that for Neanderthal and Mesolithic archaeology (e.g. Hijma et al., 2012), and with intensifying human activity in the nearshore for windfarm construction and dredging for coastal nourishment and seaward harbour extensions (e.g. Cartelle et al., 2021), adding to the potential wider research. The potential for late MIS 5 RSL data points is not restricted to just offshore, but extends to the North Sea coastal zone and the western rim of Holland, where basal parts of younger than LIG estuarine and fluvial-tidal channels appear preserved below younger Rhine and Rhine-Meuse deposits (Törnqvist et al., 2000; Wallinga et al., 2004; Busschers et al., 2005; 2007; Hijma et al., 2012; Peeters et al., 2016), with OSL-dating a readily deployable dating technique in such settings (e.g. Mellett et al., 2012; 2013; De Clercq et al., 2018).

On land, new data collection need not be constrained to finding new sites. Many sites from the older literature are still possible to revisit, and collect new data to upgrade the quality of the chronologies and elevation constraints. Such work has been carried out with focus on older late Quaternary interglacials in southern and eastern England (iGlass project NE/I008675/1; Long et al., 2015; Barlow et al., 2017), re-coring and resampling at Amersfoort (e.g. Kasse et al., 2022), and work at Tønder (Friborg, 1996), Dagebuell (Winn et al., 2000) and Norderney (Schaumann et al., 2021). Choices of which legacy sites to revisit should be guided by outstanding research questions e.g. constraining important spatial gaps for GIA modelling, instead of returning to classic sites that have been well-studied.

6 Data availability

The NW Europe database (Cohen et al., 2021; V2: 2022: https://doi.org/10.5281/zenodo.6478094), as a scientific product, is open access. The data points used in this study were compiled and contributed to WALIS by the authors and in various ways the entries cross-refer to (i) governmental databases (with public portals, but their contents not open data / open access in the academic output sense) and (ii) to tabulated and graphed data contained in recent and legacy literature (in great majority web disclosed, not in all cases open access, DOI referenced where appropriate). The files at this link were re-exported from the WALIS database interface on 19 April 2022. A description of each field in the database is contained at https://doi.org/10.5281/zenodo.3961544 (Rovere et al., 2020), readily accessible and searchable at https://walis-help.readthedocs.io/en/latest/. More information on the World Atlas of Last Interglacial Shorelines can be found at https://warmcoasts.eu/world-atlas.html. Users of the database are encouraged to cite the original sources alongside with our database and this article.

Author contributions

KMC, RB, VC and NLMB each reviewed regional bodies of literature, compiled the data, assigned indicative meanings, and documented WALIS database entries that underpin this paper: with the Netherlands, Belgium, the German Bight, Denmark and the Danish-German SE of the Baltic sea compiled by KMC; the British North Sea coast compiled by NLMB; Sussex coastal plain, southeast England and France, and offshore records in the British North Sea complied by VC; and southern and southwest Britain compiled by RB. KMC and VC prepared figures and tables. FSB and KMC assessed North Sea basin subsidence VLM. All authors edited the manuscript (in the template of the WALIS database special issue), designed figure and table legends, and addressed referee comments. KMC, FSB and NLMB executed the revision.

Competing interests

The authors declare that they have no conflict of interest.

Special issue statement

This article is part of the special issue “WALIS – the World Atlas of Last Interglacial Shorelines”. It is not associated with a conference.

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(University of Leeds) and Chronis Tzedakis (University College London) for discussion around UK interglacial pollen. Preprint reviews and comments by Torbjörn Törnqvist and an anonymous reviewer greatly helped in preparation of the final paper. The data used in this study were compiled in WALIS, a sea-level database interface developed by the ERC Starting Grant WARMCOASTS (ERC-StG-802414), in collaboration with the PALSEA (PAGES–INQUA) working group. The database structure was designed by Alessio Rovere, Deirdre Ryan, Thomas Lorscheid, Andrea Dutton, Peter Chutcharavan, Dominik Brill, Nathan Jankowski, Daniela Mueller, Melanie Bartz, Kim Cohen and Evan Gowan.

Appendix

Users of the database may wish to familiarise themselves with the background to the research landscape, and therefore this appendix provides further details as to the history of research in Northwest (NW) Europe into LIG and related coastal deposits. Furthermore and related, users may wish to inform themselves on the chronological challenges of assigning numeric ages to data points within the region, and background between the early and late onset age options in Table 4 of the main text. Hereto the appendix supplies some documentation and discussion.

A1. Overview of NW European research history on LIG coastal landscapes

There is a long history of palaeoenvironmental and sedimentological research in NW Europe, dating back to the 19th century. However, much of this work predates modern standards for sea-level databases and therefore is of variable quality and application for the WALIS database.

North Sea: Netherlands onshore and offshore

A key paper on LIG sea-level data points in the southern North Sea and onshore Netherlands is Zagwijn (1983), which importantly also informs relative age control within the interglacial by regional pollen assemblages (‘pollen association zones’, PAZs) of know durations (PAZs E1-E6; Table 1 in main text and discussed below), which is applied extensively in NW European settings. The non-GIA corrected sea-level record encompasses a period of rising RSL (>20 m within 1000 years early in the Eemian), a slowdown and highstand (over ca. 6000 years, in the middle of the Eemian) and a sea level drop during the late Eemian (ca. 4000 years), Early Weichselian and later. These data points have been included in many later global compilations (e.g. Kopp et al., 2009), but because the absolute age of the Eemian pollen zone chronology remains debated (see Appendix A2), different authors have used and placed the start of the RSL curve at different points, from ~130 ka to ~120 ka (discussed further in Long et al., 2015).

In the late 1980s, offshore investigations by geological surveys from all North Sea countries revealed the location of the initial Eemian RSL rise offshore the northern Netherlands (Sha et al., 1991; Beets et al., 2008; site BH89/2). New data points also became available from the onshore NE Netherlands, from geological survey mapping campaigns (e.g. Bosch, 1990). In the

1990s, the infill and setting of the Amsterdam and Amersfoort basins were subject of detailed multi-proxy studies, aiming to resolve history of the Saalian deglaciation and the Eemian interglacial optimum (Van Leeuwen et al., 2000; Cleveringa et al., 2000), though focus was on chronostratigraphy, palaeoclimatology and general depositional history, more than improving reconstruction of past sea level. A cross-section from the centre of Amsterdam Basin to the southeastern rim (De Gans et al., 2000) confirmed the presence of intertidal deposits from the Eemian highstand, echoing Zagwijn (1983) observations. At this time, amino acid racemisation (AAR) dating of marine mollusca shells (Miller and Mangerud, 1986), confirmed the Eemian age of the offshore and onshore mollusca bearing beds recorded in Zagwijn (1983).

Since the late 1990s, investigations concentrated on the sedimentary development and chronostratigraphy of the river Rhine. Initially, this focused on areas south of the Saalian maximum ice limit (Törnqvist et al., 2000; Wallinga et al., 2004; Busschers et al., 2005, 2007; Hijma et al., 2012), where falling RSL erosion and reworking dominated and hence no Eemian sea-level constraints are preserved (Fig. 1 and Table 2 in the main text). Coastal deposits onlap Saalian glaciogenic landforms and river valleys, or the floors and rims of valleys that dissected such landforms. OSL dates from within the Late Saalian and Eemian units confirm their deposition occurred between 140-110 ka (Busschers et al., 2007; Peeters et al., 2016). The river Rhine significantly shifted course during the Late Pleistocene, from its northerly route occupied during the Saalian deglaciation and throughout the Eemian, to the southerly course that it shares with the rivers Meuse and Scheldt. This shift explains the absence of preserved Eemian coastal sites in the subsurface of today's Rhine-Meuse delta immediately south of the Saalian glacial limit. In the last 10 years, the northerly Rhine course and Eemian estuary have received significant research attention (Sier et al., 2015, Peeters et al., 2016; 2019), yielding new sites at Rutten and Oosterwolde with sea-level indicators from relative inland lagoon-rims (Peeters et al., 2016).

North Sea: Belgium, Southern Bight

LIG coastal intertidal deposits in Belgium are encountered at shallow depths along the inland rim of the modern coastal plain, typically separated from Holocene equivalents by periglacial deposits of Last Glacial age. From the NW of Belgium, the monograph of Heyse (1979) provides a series of pit exposures, describing the sedimentology and palynology (using the PAZ E1-E6 scheme, as in The Netherlands). Further LIG deposits from estuarine environments are associated with valley fills underlying the Flanders coastal plain; the main one cut by the river Scheldt in the Middle Pleistocene (Flemmish Valley; Gibbard, 1988; De Moor and Pissart, 1992), and in the SW, a second valley of the same broad age cut by the river IJzer (Bogemans et al., 2016). De Moor and De Breuck (1973) and Nolf (1973) describe the tidal sedimentology and marine mollusca of pit site Meetkerke (Fig. A1d), west of Brugge. Mathys (2009) and De Clercq et al. (2018) mapped the onshore-offshore continuation of these valley systems, the former with morphostratigraphic attention (intersection of Last Glacial dissected phenomena of the Dover Strait; Bridgland and D'Olier, 1995; Gupta et al., 2007), the latter with particular attention to palaeogeography during phases of RSL rise and fall during the LIG (Fig. A1e).

Compared to the relatively straight present-day coastline, the Eemian coastline is considered a more irregular, with Paleogene clay hilly outcrops forming capes and islands. The cluster of sites documented by Heyse (1979), occupies a position just north of a clay outcrop. River valleys functioned in the valleys before and after the LIG. As in many lower reach valley settings, the falling and lowstand RSL induced considerable erosion of the Belgian LIG valley fills. Onshore, highstand deposits are only preserved locally along valley rims. Near the modern coastline, early transgressive units are preserved locally below erosive contacts. During the most recent RSL fall (Table 1 in the main text), the Scheldt river established northwestward to northward valleys into the SW Netherlands (Vandenberghe, 1985), further explaining the degree of preservation of LIG deposits in the NW of Belgium and spatial distribution of WALIS entries.

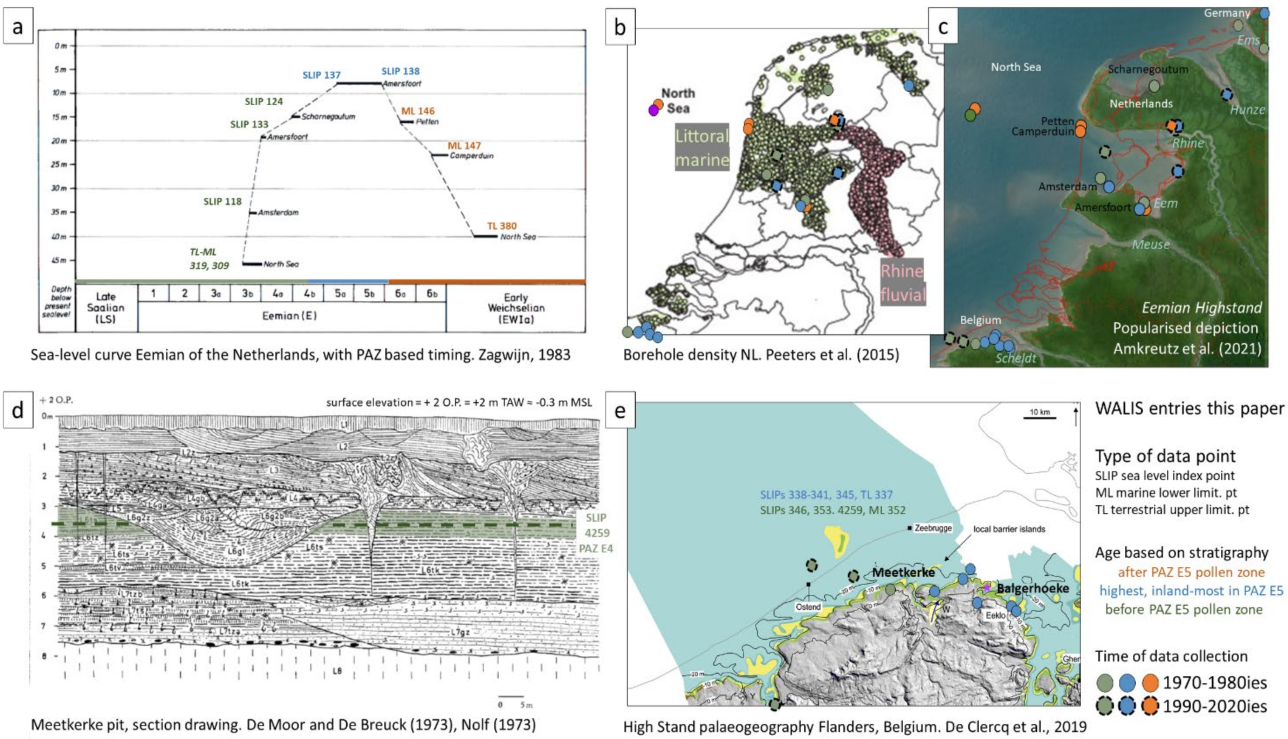

Figure A1. Selected figures illustrating research history and database contents for The Netherlands (panels a-c) and Belgium (panels d-e), with annotations (database IDs, grouping early, middle and late LIG points). a) sea level curve of Zagwijn (1983). b) Borehole density for the Netherlands (Peeters et al., 2015) overlain with legacy and more recent RSL data points. c) Popularised depiction of Eemian highstand (Doggerland exhibition, Rijksmuseum voor Oudheden, Leiden; Amkreutz et al., 2021). d) Exposure drawing of pit Meetkerke, Belgium (De Moor and De Breuck, 1973), elevation of SLIP highlighted. e) Palaeogeographical map for Eemian highstand in Flanders, for a series in De Clercq et al. (2018). Panels reproduced with permission (a-e: Stichting NJG; Elsevier; RMO/Odé; present holder unknown, archived by Vliz.be; Wiley).

North Sea: German Bight, NW Germany, SW Denmark

LIG coastal deposition in and along the German Bight accumulated and preserved in very similar setting to those in central and Northern Netherlands. The research history starts with boreholes at Tønder (Madsen et al., 1908) and Højer (Nordman, 1928) in the Vidå valley. The area lay outside Scandinavian ice sheet coverage of the Last Glacial, though outwash produced along that margin buried and eroded the Eemian coastal record. Eemian sediments overlay and infill landforms generated during the Saalian glaciation, deglaciation, readvance (Drenthe-2 and Warthe morainic lines) and (glacio-)fluvial dissection (conduits of Vidå, Eider, Elbe, Weser and Ems). Miller and Mangerud (1986) resampled sites from along the Danish Eemian North Sea. Höfle et al. (1985) and later Streif (2004) summarised evidence around the German Bight, linking up to Dutch, Belgian and English North Sea coastal sectors, and providing comparison with older interglacials and the Holocene. Konradi et al. (2005), in their paper entitled *Marine Eemian in the Danish eastern North Sea*, provide palaeogeographical details for an inventory of sea-level indicator sites. They aptly characterise the Danish Eemian shoreline as 'more irregular than present'. Some of the sea-level data points are reported from environments resembling those of the modern Wadden Sea, whereas others come from what would better be called 'fjords' and 'straits' cut in the Quaternary glacial and riverlain substrate of the freshly exposed glacial landscape at the onset of Eemian transgression. A palaeogeographical particularity is a W-E marine highstand passage between German Bight and SW Baltic Sea across the German-Danish border (Schleswig-Holstein), unlike the peninsular present situation (Winn and Erlenkeuser, 1995; Konradi et al., 2005). Such a connection is suspected from geological mapping of the German Bight Eemian highstand (e.g. at Schnittlohe, ID 889, N Germany; Menke 1985; Knudsen 1985) and from biotic changes in the SW Baltic regionally extensive Cyprina Clay marine beds (Funder et al., 2002), although the supposed connection would have been shallow and is not fully traced and hence not evident (Miller and Mangerud, 1986; Kosack and Lange, 1985; Schulz et al., 2001 - op cit. Konradi et al., 2005).

RSL rise inundated extensive areas of the German Bight Saalian glacial derived push-moraine and till-plateau islands (dubbed 'Bakkeør'), which were subsequently hidden by LGM and deglacial sediments, and subsidence. Between the Bakkeør-island series and the Danish mainland a retreat-stage meltwater plain is present which was inundated by RSL rise (research background in Konradi et al., 2005:24). Southwest of the Bakkeø-islands/Warthe limit lay the Elbe valley, an ice-marginal river during the Warthe ice-limit and the LGM, which formed an Eemian estuary preserving LIG sea-level indicators recorded by Menke and Tynni (1984); Menke (1985) and Streif (1990; 1991). West of the Elbe valley/estuary, a secondary morainic limit exists (Fig. 1; e.g. Ehlers et al., 2004), and the associated lows host Eemian and Early Weichselian terrestrial deposits (Selle and Schneekloth 1965; Behre et al., 2005; key sites Oerel and Glinde). The northernmost, deepest sites also preserve evidence of marine incursions (Streif 1990, 2004). Further West, the till plateau of Ost-Friesland and minor valleys set into it host Eemian coastal deposits (Dechend and Sindwoski, 1956; Schaumann et al., 2021), similar to sites further west along the Wadden Sea in the Netherlands.

Age-control of the NW German and SW Danish sites (Table 2) is largely based upon pollen investigations on terrestrial beds immediately below and above tidal coastal deposits and contained in the brackish and saline deposits, resolving broad-scale vegetation succession (i.e. in Danish and German origin PAZ schemes, tightly correlated to the Zagwijn E1-E6 scheme; e.g. Funder et al., 2002). Like in the Dutch sector, the basal Saalian deglacial geomorphological means identifying LIG from older interglacial deposits is relatively simple. Importantly, no inland fluvial-estuarine sites are known for the German Bight: falling RSL and lowstand erosional activity during the last glacial cycle (Table 1) appears to have mostly removed expected Eemian morphostratigraphic records from along the valleys of Elbe, Weser and Ems. This is in contrast to the Rhine, Scheldt and Thames estuaries in the Dutch, Belgian and English LIG North Sea coastal segments, respectively.

Skagerrak and SW Baltic: N Denmark, NE Germany

In NE Denmark, deep boreholes on the Jutland peninsula and islands facing the Skagerrak-Kattegat embayment reveal thick marine sequences from deep marine environments overlying Saalian-aged till and below Last Glacial erosive contacts (Jessen et al., 1910; Bahnson et al., 1974; Knudsen and Lykke-Andersen 1982; Knudsen et al., 2009). In NW Denmark coastal marine Eemian deposits occur at shallower depths, not dissimilar to these in areas unaffected by glaciation in SW Denmark. Their positions within the Last Glacial limit and the level of disclosure that borehole-based subsurface mapping can give means that some displacement cannot be excluded. Sites in this part of Denmark provide information on palaeocoastline positions (Fig. 1 in main text), but less so for reconstructing sea-level elevations (Konradi et al., 2005).

In SE Denmark, modern day cliff sections in glacial deposits on the isles facing the Baltic, such as Ristige Klint and Aero (Madsen et al., 1908), provide outcrops of shallow marine, coastal and near-coastal terrestrial beds, which have been extensively studied in a palaeoenvironmental content (overview in Kristensen et al., 2000, Funder et al., 2002), and OSL-dated (Murray and Funder, 2003; Buylaert et al., 2011). In the SW Baltic Sea, mollusca and foraminifera associations at the base of the Cyprina Clay, and geological mapping of N-S running straits separating the Danish Isles connecting the Baltic to the Kattegat (similar to the geography today), reveal marine connections along these N-S routes (Kubisch and Schönfeld, 1985; Kristensen et al., 2000; Funder et al., 2002). As the interglacial unfolded, the salinity and temperature signals in the biota markedly changed (Kristensen et al., 2000) and, importantly for sea-level reconstruction, a connection across Schleswig-Holstein may have established (Funder et al., 2002).

Vertical constraints sea level along the SW Baltic is not well presevered, as would-be littoral sequences experienced subsequent subglacial erosion by the Scandinavian ice-sheet expanding across it during the Last Glacial, plus deglacial fluvial erosion and reworking (Rühberg, 1995; Meng et al., 2021). In the deeper water palaeogeographic setting on the Danish side, the Baltic is marine into the Early Weichselian, owing to its deep N-S connections to Kattegat and Skagerrak. The secondary connection W-E across Schleswig (Fig. 1) is considered to have fallen dry early on in PAZ E6, as site Schnittlohe then shows a return to lacustrine conditions (section 2.3). Peatlands and lacustrine littoral environments replaced brackish marine environments at the end of the interglacial (PAZ E5/6 transition) also in Baltic Sea palaeo-bays in NE Germany (Meng et al., 2021), but the evidence for this is from displaced and reworked contexts and no sites have provided opportunity of water level reconstructions.

North Sea: Thames Estuary, East Anglia, North England

The stratigraphy of the Thames region of eastern England has been extensively studied and documented from the 19th century as the development of London and the surrounding area exposed multiple phases of cold-riverine and warm organic interglacial sediments, many with marine and freshwater micro and macro-fossils. The discovery of Eemian *Hippopotamus* remains during excavations of Trafalgar Square in the 1950's (Franks, 1960) garners continued wider attention; but numerous less publicised investigations have identified previous interglacial brackish, coastal and shallow marine sediments (e.g., Abbott, 1892; Hinton and Kennard, 1901; Sparks and West, 1963; Gibbard, 1985; Preece, 1999). Similarly in East Anglia, local site investigations document the presence of brackish or marine mollusca at several sites corresponding to the 'Ipswichian' (Eemian) interglacial based upon pollen stratigraphy, for example at March (Whitaker et al., 1893) and Wretton (Sparks and West, 1970). Further north, evidence of LIG sea level is sparser with much of it removed by the subsequent Last Glacial (Devensian) ice advance along the coast of North East England and Yorkshire (Catt, 2007; Sutherland et al., 2020), and is largely restricted to the Sewerby raised beach, East Yorkshire (Lamplugh, 1887; Catt and Penny, 1966; Bateman and Catt, 1996), which is now buried under a landslide.

A major challenge is that interglacial sites from England, unlike in the Dutch-German-Danish contexts where Saalian glaciogenic landforms and substrates make it possible to separate LIG from older interglacial sites, often appear in ambiguous stratigraphic positions. Where palynological and mollusca identified to be from warm periods and near-coastal environments, the sites lack independent dating, and pollen sub-stages of the 'Ipswichian' and the preceding 'Hoxnian' interglacials have very similar vegetation profiles (Thomas, 2001; Turner and West, 1968). Attempts to correlate seven, then termed, 'Ipswichian' estuarine sequences from the Thames, alongside those from East Anglia, based upon pollen sub-stages and their relative elevations, resulted in a paper by Hollin (1977) identifying the potential for a double LIG sea-level highstand. Though in keeping with more recent hypotheses (e.g., O'Leary et al., 2013), significant advances in AAR methods (Penkman et al., 2013), combined with Thames terrace stratigraphy (Bridgland, 1994), vertebrate and mollusca biostratigraphy (Schreve, 2001; e.g., Preece, 2001) and independent geochronology (e.g., OSL) has since shown that many British 'Ipswichian' sites actually date from the preceding three marine isotope stages (Penkman et al., 2008, 2011, 2013). Trafalgar Square is the only site in Hollin's (1977) analysis which is still regarded of LIG age.

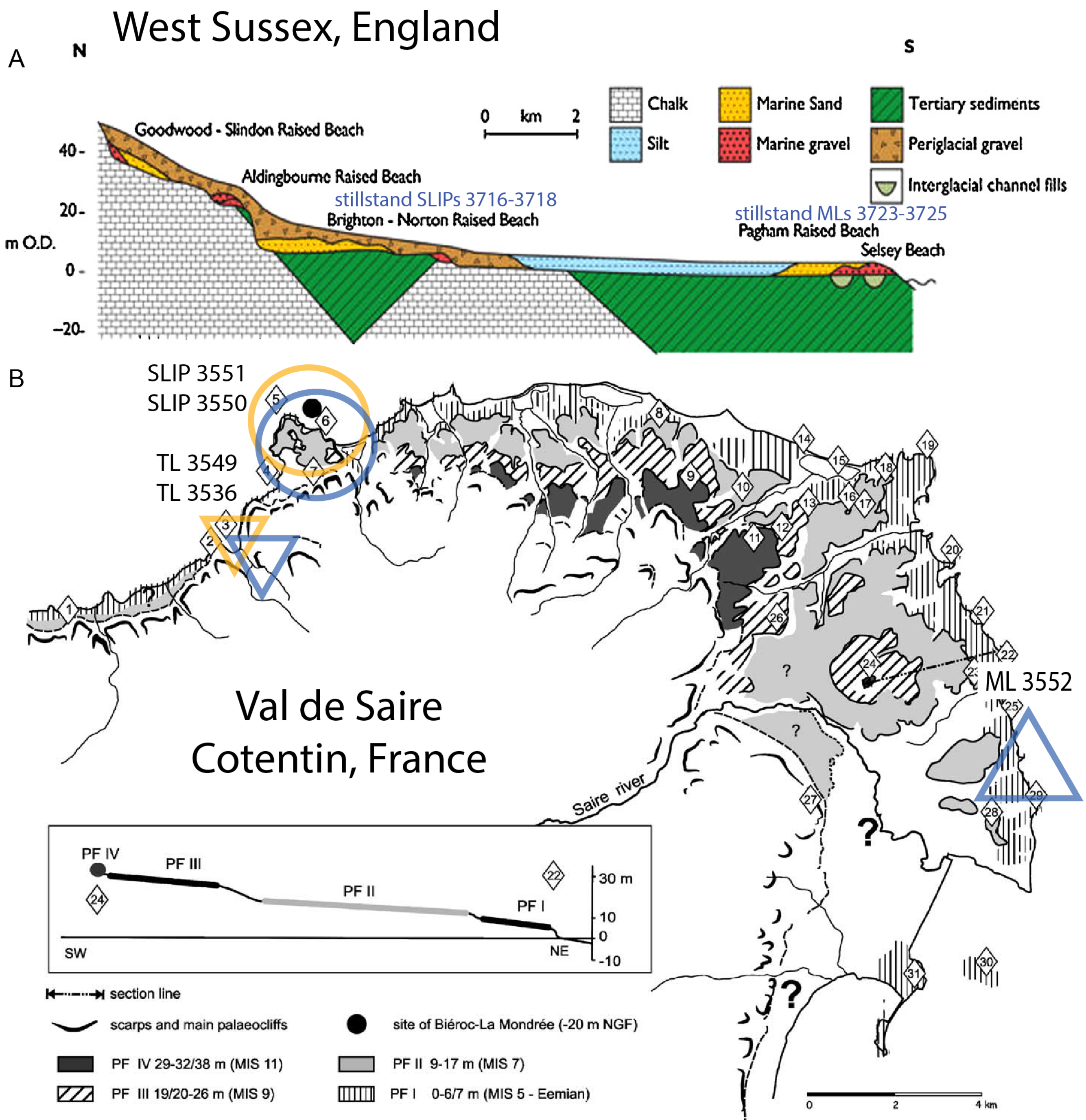

Figure A2 - Selected figures illustrating research history and database contents for South England (panel A) and Northwest France (panel B), with annotations (database IDs, grouping in transgression, stillstand, highstand). A) Schematic section of raised beach series (Bates et al., 2010), with SLIP producing and ML producing sites annotated. B) Wave-cut platforms (PFs) as mapped for NE Cotentin (Coutard et al., 2006), annotated with LIG SLIPs, MLs and TL locations, associated to the PF I level. Panels reproduced with permission (A, B: Elsevier).

English Channel: Southern England

LIG deposits are found along the length of the southern coastline of Britain, typically as part of expansive sequences of raised littoral terraces from the Pleistocene. Occurrences of Pleistocene deposits that formed during interglacials are well documented across all southern coastal counties (Prestwich, 1892) in early literature; from Kent in the south east (Mackie, 1851), through Sussex (Godwin-Austen, 1857; Prestwich, 1859; Reid, 1892), Hampshire (Reid, 1893) and Dorset (Weston, 1852; Prestwich, 1875), to Devon and Cornwall (De La Beche, 1839; Ussher, 1879) in the southwest. Pleistocene littoral deposits occur around Lands End (the southwesternmost point of mainland Britain) and can be found on the northern coastlines of Cornwall and Devon, the east coast of Somerset (Woodward, 1876) and from there across the southern coastline of South Wales (Murchison 1868; Prestwich, 1892). Unsurprisingly, the early literature associated with these widespread deposits extends to include raised littoral deposits on the main island groups in the English Channel: the Isle of Wight (Godwin-Austen, 1855; Prestwich, 1859), the Isles of Scilly (Barrow, 1906), and the Channel Islands (Zeuner, 1946).

Early literature typically relied on the identification of mammalian and molluscan faunas, as well as pollen assemblages and successions, to attribute deposits to successive interglacials. The elevations and relative positions of littoral terraces (typically, raised beach deposits) are also used. The relative elevations of deposits also became a useful tool for tracking contemporaneous raised littoral terraces across wider geographical areas (Palmer and Cooke, 1923; Arkell, 1943; Mitchell, 1960; Orme, 1960; West and Sparks, 1960; Hodgson, 1964). A commonality that emerged was that the Ipswichian (Eemian/MIS 5e) interglacial was likely associated with the lowest terrace of deposits, often reported as a '15 foot raised beach' (*c.* 4.5 m O.D.) (Fig. A2a). However, association with the preceding interglacial (MIS 7) was hard to rule out, especially given the presence of multiple, distinguishable low-level raised beach deposits at several locations (Davies and Keen, 1985; Mottershead et al., 1987; Bates et al., 1997). Dating attempts often remained inconclusive and debated (Mitchell, 1972; Bowen, 1973). Unfortunately, despite the development and application of novel quantitative dating approaches during and since the 1980s, many low-level raised littoral deposits in southern and southwest Britain still lack confident and precise age determinations (see Appendix A2).

English Channel: Northwest France

The northwest coast of France, from Britany to the Straits of Dover, is characterised by the occurrence of a staircase of polygenic coastal platforms that were correlated with Pleistocene interglacial periods. These platforms are intermittently covered by a variety of coastal (mainly raised beaches) and periglacial deposits (heads and loess) that have been studied for more than a century (Barrois, 1877, 1882; Bigot, 1885, 1930; Pellerin and Dupeuble, 1979; Lautridou et al., 1999; Regnauld et al., 2003; Coutard et al., 2005, 2006; Cliquet et al., 2009; Pedoja et al., 2018). The absence of well-preserved fossiliferous remains in most of these sites gave rise to an extensive discussion about their chronostratigraphy, and the age was generally established based on the altitude of the beach deposits relative to other sites. In the Armorican Massif, two levels of marine deposits, between 0-5 and 15-20 m above sea level were attributed to the LIG (Elhaï, 1963), while Morzadec-Kerfourn and

Monnier (1982) attributed the three lower levels, found between 0-15 m in Britany, to three distinct marine transgressions, probably MIS 9 to MIS 5.

The discovery and excavation of Palaeolithic sites along the coast and the progressive application of thermoluminescence (TL), optically stimulated luminescence (OSL) and electro spin resonance (ESR) geochronology (e.g., Balescu et al., 1991; Balescu and Lamothe, 1992; Loyer et al., 1995; Folz, 2000; Coutard et al, 2006; Cliquet et al., 2003, 2009; Monier et al., 2011) boosted the understanding of the coastal sequences and helped to better constraint the distribution of the LIG deposits. Loyer et al., (1995) suggested that up to four different interglacials were preserved in the same coastal platform in Saint-Brieuc Bay (Britany) based on palaeoenvironmental data and TL dating of loess deposits, later further supported by ESR dating of Palaeolithic sites (Bahain et al., 2012). TL dating of burnt flints in Port-Racine (Normandy) attributes beach deposits at 3 m to the LIG (Cliquet, 1992, Lautridou et al., 1999). Coutard et al. (2006) OSL dated several marine, beach and dune deposits in Val de Saire (Normandy; Fig. A2b) pointing to the MIS 5e to 5d. Despite the fragmentary nature of the deposits and the relatively small number of absolute age determinations, there were also some attempts to reconstruct the LIG coastline in Normandy (Regnauld et al., 2003) and to establish regional stratigraphic correlations across the English Channel (van Vliet-Lanoë et al., 2000; Bates et al., 2003). Deposits corresponding to the LIG appear better preserved in Britany and western Normandy (Fig. A2b) where the local geomorphology protected these sediments from later erosion; however, further east Pleistocene beach deposits were eroded in younger interglacials and the Holocene (van Vliet-Lanoë et al., 2000; Bates et al., 2003; Regnauld et al., 2003). As an exception, at Sangatte in NW France a cliff foot beach (De Heinzelin, 1966) that predates the LIG (Balescu and Haesaerts, 1984; Haesaerts and Dupuis, 1986; Balescu et al., 1991) is preserved under colluvium, re-exposed by Holocene erosion.

A2. Database regional chronostratigraphical challenges

One of the challenges of any LIG sea-level database is the chronostratigraphic constraints, as developing chronologies for Pleistocene timeframes is outside the reach of radiocarbon dating. In the structure of the WALIS database we have included entries for the Eemian pollen zones (PAZs) under 'chronostratigraphy' (Table 4 in main text), and have used this to encode the relative dating of LIG deposits in Netherlands', Belgian, German and Danish sites. This Appendix section provides some background on how the particular table stores the correlative numeric age constraints for these entries, on where the upper and lower ages communicated in Table 4 come from, and on time control on LIG data points for the English and French part of the study area.

How WALIS stores correlated numeric ages with chronostratigraphical entries

To make WALIS database usage not too dependent on positions regarding timing and duration of the NW European Eemian (see main text; see next section), the design of this section of the database (Rovere et al., 2020: 'Table Strat') allows for and requires the filling of 4 duration and timing database fields. Table 4 (main text) lists these four. Two of these deal with the locally established, varve-counting and palynological-correlation based durations of the respective chronozones (Müller, 1974; Zagwijn, 1996), and their uncertainty. These durations are regarded minimum durations in some numeric age attribution schemes (see main text and below), and have been used as more strict constraints in others. The two other fields then store an upper and lower limiting numeric age, of which the values have to be based on correlations to numerically dated sequences elsewhere, such as in SW Europe (Tzedakis et al. 2018: U-series speleothem based). The 'upper' age bounds the oldest moment the chronozone in question may have begun (called the upper age limit in WALIS, although vertical-geologically it is a 'lower' bound), the 'lower' age bounds the latest moment possibly represented by the chronozone in question. The upper and lower bounds mean that the floating chronozones should be assigned numeric ages within these bounds. It does not mean that the floating units stretch the full span of time between the upper (oldest possible onset age) and lower bound (youngest possible ending age).

Entries were made for 23 LIG chronostratigraphic divisions, 18 of them dealing with terrestrial palynological subdivisions (PAZs); 5 dealing with SW Baltic and Kattegat-Skagerrak marine environmental phases that in turn were correlated and connected to the PAZs (see Table 4 footnote). The entries also made use of a meta-field in the WALIS table structure, that stores parent-child relationships between chronozones. The entries refer to the six main pollen zones of Zagwijn (1961, 1983, 1996) floating scheme, and the descriptions include the further correlated schemes of Behre (1962), Selle (1962), Müller (1974) and Menke and Tynne (1984) for NW Germany; Jessen and Millers (1928) in Denmark and NW Germany; and the outcomes of discussions thereof in Benda and Schneekloth (1965), Grüger (1989), Zagwijn (1969) and Funder et al. (2002).

Comprehensive explanatory text, referencing positions taken in literature, fills the note field for the parent entries and provides a rationale for the lower and upper numeric ages provided. To avoid redundancy that note field for child entries just contains a cross-reference to the main note in the parent field.

The WALIS database itself and the Zenodo dataset extraction associated to this paper, only store age bounds and provide information regarding durations for chronostratigraphic entries, and thus not directly the older and younger onset ages considered in Table 4 (and its background section below). A database user may want to calculate an age-midpoints between both bounds, combine it with the minimum duration information, and formulate some rules that make sure that PAZ order and relative durations remain honoured while shifting or stretching the PAZ-series (e.g. as in Kopp et al., 2009: supplementary information) to reproduce the earlier and later onset options in Table 4 (main text), or a more optimized solution of own making. The latter could involve Bayesian age-modelling approaches (e.g. Bronk-Ramsey, 2008) to explore what amount and direction of shift best minimizes differences with sites that have numeric age control (e.g. against rare U-series ages, or against OSL ages and sequences thereof). This road of optimization has pitfalls, however, because the numeric dating techniques may themselves be subtly biased (inaccurate) to the older or younger site (U-series assumptions) or imprecise (OSL limitations). As demonstrated in the Holocene (e.g. Hijma and Cohen, 2019), ideally a regional Bayesian calibration approach combines optimizations in both the vertical (RSL, i.e. the other sections of this paper) and temporal (age) planes. The WALIS dataset of the paper may be a starting point for such work for the LIG (Düsterhus et al., 2016), incorporating LIG data from NW Europe. An alternative to Bayesian optimization against local independent numeric ages, is to integrate the floating-age shifting assessment with the regional sea-level predictions of GIA models. Lambeck et al. (2006) provides an early example where GIA modelling was iteratively used to assess an optimal shifting of the timing of the North Sea regional highstand, with an outcome within the lower and upper age bounds in Table 4. The caveat here is that the age solution is dependent on the ice history and rheologies implemented in such GIA modelling (with every simulation, there is a new optimum). The WALIS database chronostratigraphic entries at least provide absolute numeric bounds that any numerically optimized shifting of the floating PAZ-correlated scheme should stay within.

Background to the lower and upper ages specified in Table 4 for the North Sea region

The North Sea PAZ entries (section 3.3, Table 4 in the main text), bracket Zagwijn 1996's full set of PAZs (E1-E6) to between 129 ka (acclaimed earliest possible start of PAZ E1) and 112.5 ka (latest possible ending of PAZ E6). This totals 16,500 years, which broadly equals estimates of the length of the LIG globally (Lisiecki and Raymo, 2005: 130-115 ka for MIS 5e), but is longer than the varve-counted 11,000 years traditionally associated to the scheme since Müller (1974). This means that a user requiring absolute time control must decide where on the absolute time scale the Eemian starts (PAZ E1) and ends (PAZ E6).

In the literature, different positions and some debate exists regarding the absolute timing (i.e. numeric ages) of onset of what is palaeo-environmentally regarded the LIG in NW Europe. The debate and options regard a degree of anticipated diachronicity within and between the regional pollen schemes of the various countries, their correlation with Southern Europe counterparts, and (non)analogy with the Lateglacial-Holocene (e.g., Van Leeuwen et al., 2000; Cleveringa et al., 2000; Turner, 2002; Kukla et al., 2002; Beets and Beets, 2003; Beets et al., 2006; Lambeck et al., 2006; Sier et al., 2015; Long et al., 2015). The spread in quoted ages in that literature has been considered in filling the upper and lower bounding age for the PAZ E1-E6 entries (Table 4 in main text), but with some filtering and actualization to current (i.e. 2021) insight.

The youngest E1-E6 time span we considered is 125.5 to 112.5 ka. In that late onset option, the PAZ E5/6 break is put at ~116 ka (Table 1 in main text), which would mean that the regionally observed climatic cooling correlates (Sirocko et al., 2005) with global signals seen in Greenland ice-cores, deep-sea oxygen isotopes and coral-data derived LIG climate and sea-level history compilations (e.g. NEEM community members, 2013). Starting the NW European Eemian onset late implies the Blake palaeomagnetic event to have occurred early in the interglacial (Sier et al., 2015). Opting for even later onsets (Sier et al., 2015 coined an onset as late as 121 ka) is controversial, as that implies that North Sea temperate conditions started >5,000 years later than the onset of the interglacial conditions in Southwestern Europe at ~129 ka (Italian speleothems and Portuguese shelf: Tzedakis et al., 2018). With an onset at 125.5 ka the onset lag time between Southwestern and Northwestern unit is ca. 3500 years. Such a lag time implies that early in MIS 5e, greater temperature gradients existed N-S across Europe than did in the Holocene. Such scenario's can be considered (Kukla et al., 2002) because the timing of deglaciation of Scandinavia is not independently dated either and can be suspected to have been slower over Termination II than over Termination I as the MIS 6 ice mass was bigger than in MIS 2. Assuming that Scandinavian deglaciation was slower and the onset of the temperate conditions in NW Europe hence later, has repercussions for GIA and RSL both regionally and globally (Long et al., 2015). Adopting the younger onset options hence can be advisable when one wishes to assess scenarios where the Eemian course of Scandinavian deglaciation differed greatly from that in the Holocene.

Placing the start of the NW European Eemian between 129 ka (the upper bound) and 125.5 ka (the lower bound) provides in between options. The lag time between interglacial environmental conditions establishing in Southwestern and Northwestern Europe then is less than ~3 kyr. Such scenarios, e.g. entertaining an onset of 127 ka (~2 kyr), would be more analogous with the Holocene, both in terms of vegetation development, as regarding the duration of the Scandinavian deglaciation (and the timing of regional GIA response to unloading that drives a good part of the local sea-level signal in the region; Lambeck et al. 2006; Kopp et al., 2009; Long et al., 2015). Investigating this further is an important foreseen application of the WALIS data and may also contribute to resolve the course of events of LIG regional environmental and climatic change from southern to northern Europe.

An even earlier onset of the Eemian and hence the onset of sea-level rise in the North Sea, has been proposed by some authors, notably Funder et al. (2002) at 132.5 ka, and Beets et al. (2006) at 131 ka. We reject these options because they were falsified by the Portuguese shelf studies that put the onset at ~129 ka (Tzedakis et al., 2018), but not as far as 131 or 132.5 ka. In the case of Funder et al. (2002), the 132.5 ka age wa based on a preliminary U-series chronology for midpoint Termination II at ~135 ka (which Tzedakis et al., 2018 have U-series dated at c. 132 ka, i.e. a 3 kyr shift), which their interglacial onset lags 2.5 kyr. Starting from the presently considered midpoint of Termination II, the onset would be at ~129 ka, coinciding with Tzedakis et al. (2018) and our 'oldest option'. The Lambeck et al. (2006) GIA modeling study focused on the MIS-6 to MIS-4 time period in Europe. It used an ice history with the Warthe substage maximum set at 143-140 ka, and midpoint Termination II and onset Eemian age as in Funder et al. (2002). It reproduced the RSL curve of Zagwijn (1983) and from the cessecation of global RSL rise (i.e. the midpoint of Termination II onwards), deduces that 1.5-2.0 kyr of extra shifting the PAZs to the younger side is appropriate (i.e 4.0-4.5 kyr onset lag). The Lambeck et al. (2006) results are in line with a 128-127.5 ka Eemian onset, if they are updated with the 3 kyr shift of the midpoint of Termination II.

Lastly, an age of ~126 ka has long been considered for the onset of interglacial conditions is SW Europe (Iberian Shelf: Sanchez-Goñi et al., 1999; Shackleton, 2002; 2003) and used in some of the NW Europe onset age discussion too (without and with additional lag times), before it was falsified and revised to ~129 ka (Tzedakis et al., 2018). This revision affected onset-age positions taken in Sier et al. (2015) and the swath of options considered in Long et al. (2015). It has triggered us to consider 125.5 ka (4,500 years lag time to the onset in SW Europe) as the youngest onset option provided in Table 4.

What surfaces from the above summary is that the different advocated ages for onset of the Eemian pollen zones all include dependencies to one or more ages from isotopic records, which in turn have been subject to revision and choice (e.g. Tzedakis, 2003). This is the nature of correlative means of establishing numeric ages, and the effect of slowly increasing overall resolution and discovery of new records and techniques (also, for example, improvement in U-series dating). The sources of tie-point ages are (i) marine stacked records (e.g. the Termination II midpoint of Table 1; cf. Lisiecki and Raymo, 2005, derived from Shackleton 2002, 2003); (ii) events in the Greenland ice-cores (e.g. Sirocko et al., 2005, for the ending of the interglacial); and (iii) ages established with U-series dating from higher resolution speleothems and transferred to single marine isotopic records, most recently Tzedakis et al. (2018). The latter paper not only revised the interglacial onset age for Southern Europe (to ~129 ka), but also that of the midpoint Termination II as recorded in the same speleothem record and its correlation to the Iberian margin marine signals. The latter age was put at ~132 ka, pushed back 2 kyr compared to the Lisiecki and Raymo (2005) age of ~130 ka. The WALIS database may consider to update this numeric age in its dedicated part for MIS ages ('form_MIS_ages'; Rovere et al., 2020), to have the North Sea numeric age constraint entries fully compatible with the overall WALIS setup.

Time control and data filtering in England and France

In the British Isles, biostratigraphy has also been typically used to characterise the sites into the pollen sub-stages of the 'Ipswichian' and the preceding 'Hoxnian' interglacials (West, 1977), but without lithostratigraphic constraints as in continental Europe, or the presence of a full Ipswichian pollen profile at a single site. It has since been shown that these 'pollen interglacials' have very similar vegetation profiles and in fact represent more than one interglacial (Thomas, 2001; Turner and West, 1968), with many early 'Ipswichian' sites conflated with those from MIS 7 (Lewis et al., 2011; Bridgland, 1994), and the 'Hoxnian' pollen spectra shown to be very similar in both MIS 9 and 11 (Roe et al., 2009; Thomas, 2001). Furthermore, due to the lack of a continuous pollen profile (Lewis et al., 2011; Thomas, 2001), and the difference in the marine climate of the UK versus the relatively continental northwest European plain, it is not possible to simply correlate the 'Ipswichian' pollen zones with the Eemian zones from NW Europe (Turner, 2000).

Though dating approaches have significantly improved since many of UK 'Ipswichian' sites were first studied, not all sites are available to be revisited with modern methods; and therefore, several sites which some may consider to be evidence for LIG sea level have been discounted from our database. These include e.g Somersham, Cambridgeshire (West et al., 1999), Kirmington, Lincolnshire (Straw, 2018), Burtle Beds, Somerset (Kidson and Heyworth, 1976), plus 6 of the 7 Thames sites in Hollin's (1977) analysis. Furthermore, questions around microfossil and sediment reworking/preservation e.g. Tattershall Thorp, Lincolnshire (Holyoak and Preece, 1985) and Somersham (West et al., 1999), and debate around the presence/absence of fauna and flora during specific interglacials (e.g., Meijer and Preece, 2000) means sites that cannot conclusively be ascribed to a single interglacial period, or indicative meaning (i.e. ambiguous sites cf. Fig. 2b), are not included in the database.

To address some of the issues in biostratigraphic chronology across Britain, relative dating of interglacial coastal sites using amino-acid racemisation (AAR) began in 1979 (Andrews et al., 1979; Miller et al., 1979) and continued apace throughout the 1980s (Keen et al., 1981; Campbell et al., 1982; Davies 1983; Andrews et al., 1984; Bowen et al., 1985; Davies and Keen 1985). Such investigation was also performed on material from multiple marine interglacial sites collected from across Europe (Miller and Mangerud, 1986). A landmark review of these early works is given in Penkman et al. (2010). Early AAR results often indicated potential associations with two or more interglacial periods within individual sites, or even multiple ages within single interglacials. Major challenges were the evolving preparation procedures and inconsistent choices of species for sampling, which both hindered comparability of AAR values across different studies. Around the same time, results from the application of novel dating techniques to raised interglacial deposits in the region were being used to inform the AAR debate. U-series dates from the raised beaches at Belle Hogue Cave on Jersey (Keen et al., 1981) and at Minchin Hole (Sutcliffe and Currant 1984) and Bacon Hole (Stringer et al., 1986) in South Wales were often cited to correlate AAR-dated deposits to MIS 5e (Davies 1983; Bowen et al., 1985; Davies and Keen 1985; Bridgland et al., 1995b), although single U-series dates were insufficient for describing the full complexity of single sites given the multiple (age) groupings that were often present within

AAR analyses. Early thermoluminescence techniques were also being used at this time (Southgate, 1985) but were still unable to distinguish interglacial associations as results from fine grained and large grained sand fractions provided dates of MIS 5e or MIS 7, respectively.

Improved certainty in the AAR debate was reached by 2013 when an aminostratigraphy for the British Quaternary was developed using the opercula or the gastropod species *Bithynia tentaculata* (Penkman et al., 2013). Unfortunately, none of the existing AAR results from interglacial coastal sites in southern and southwest Britain were based on this species, and material from only limited sites in eastern England is available, and therefore definitive age determinations for many of these sites remain elusive, resulting in some sites being excluded from the database. Parallel to the AAR investigation efforts, development and application of luminescence and U-series dating techniques has gone some way to confirming interglacial associations at several sites (Preece et al., 1990; Proctor and Smart, 1991; Bates et al 2010; Briant et al., 2019), though there are numerous sites in both the UK and France that lack independent dating control (e.g., Tastet, 1999, Haslett and Curr, 2001).

With a few exceptions, most of the sites in northern France have been attributed to MIS 5 based on ages that were obtained from deposits overlying or underlaying the LIG features, and in most cases these results are not enough to discard older or younger than MIS 5e age attributions.

There remains considerable opportunity to revisit many (known and as yet undescribed) interglacial raised beach sites across southern and southwest Britain and France and to apply now established sea-level research protocols (Shennan et al., 2015) and spatially intensive geochronology sampling strategies that could combine with statistical (e.g. Bayesian) frameworks to greatly advance knowledge and data precision across this region.

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