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New models of North West European Holocene palaeogeography and inundation

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ABSTRACT

This paper presents new 500 year interval palaeogeographic models for Britain, Ireland and the North West French coast from 11000 cal. BP to present. These models are used to calculate the varying rates of inundation for different geographical zones over the study period. This allows for consideration of the differential impact that Holocene sea-level rise had across space and time, and on past societies. In turn, consideration of the limitations of the models helps to foreground profitable areas for future research.

1. Introduction

In this paper we present, and make available in an interactive format, new high-resolution (500 year interval), palaeogeographic models for Britain, Ireland and the broader area shown in Fig. 1 from 11,000 BP to present day. In addition, we use these data to address the longstanding call (Reid, 1913, 10; Clark, 1936; Coles, 1998, 45; Leary, 2009, 227; Van de Noort, 2011) for more detailed consideration of the extent, timing and significance of landscape transformation over the Holocene. In so doing we demonstrate the variable histories of change across the North West European continental shelf, and the impact that scale of analysis has upon interpretation.

The archaeological significance of the changing palaeogeography of Europe has long been established, since Reid's (1913) work on submerged forests. There, and in subsequent publications by a range of scholars (Clark, 1936; Coles, 1998, 1999; Gaffney et al., 2007), maps of the changing shape of land and sea boundaries have proven pivotal to discussion of prehistoric activity and social connectivity. These outputs have been used to demonstrate the size of past habitable landscapes now submerged offshore, and to allow perspective to be gained on the impact such changes may have had on past communities.

This paper utilises a recent Glacial Isostatic Adjustment (GIA) model (Bradley et al., 2011) and data from bathymetric surveys, to generate new high temporal and spatial resolution reconstructions. In turn, these outputs are queried to allow for quantification of variable rates and extents of inundation over the study area. This helps progress discussion as to both the changing shape of North West Europe over the Holocene, and the possible significance of those changes for people in the past.

2. The palaeogeography of North West Europe: a history of research

The presence, implications and archaeological potential of submerged landscapes in North West Europe have long been

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known. Reid's (1913) pioneering work on the submerged forests and offshore peats surrounding Britain not only led to one of the first palaeogeographic reconstructions of the North Sea basin as terrestrial space (1913, 40), but also gave a clear call for more detailed work on this topic in future. The recovery of a Mesolithic antler harpoon from the Leman and Ower banks in 1931 led Clark and Godwin (1956) to build on Reid's work, investigating the submerged deposits of the North Sea for themselves. For Clark (1936) this saw a transformation of the North Sea plain from a marine environment into an undervalued and under-investigated submerged terrestrial landscape.

However, as Coles (1998, 48) notes, following this early development of interest, the North Sea Plain receded from archaeological view. It became at best a hypothetical bridge between Britain and the continent. Thus, while Jacobi (1976) saw the North Sea as land in the Mesolithic, little weight was given to that space beyond being a corridor for past movement. In this context, Louwe Kooijmans' pioneering (1971) documentation of faunal material recovered from the Brown Bank failed to receive the attention it deserved in mainstream archaeological discourse. However, while archaeology may have shifted its focus away from this topic, great advances were made in the Earth Sciences. In particular Jelgersma's (1979) work in the North Sea helped to communicate the extent and rate of change via new relative sea-level curves. This work would prove fundamental to later developments, establishing a crucial baseline from which archaeologists could work.

It was not until the 1990s that publications by Wymer and Robins (1994) and Coles (1998, 1999, 2000) helped to re-establish the significance of understanding the changing shape of Northwest Europe within the context of British and Irish archaeology. Critically, Coles (1998, 45) made clear that our approach to this topic should move beyond seeing submerged spaces as bridges, but instead view them as once inhabited landscapes. Concomitant with this was an appreciation of the fact that palaeogeographic change did not occur in a social or physical vacuum. As such, Coles (1998, 77) pushed researchers to attempt to grapple with the specifics of the rate, nature and social impact of sea-level change.

The degree to which this space could be accurately described accelerated through the late twentieth and early twenty first century. Improvements in computer power and software aided the construction of graphical outputs combining different data sets. This saw the creation by Shennan et al. (2000) of some of the most heavily reproduced palaeogeographic maps for the UK. Here data from regional relative sea level (RSL) curves were integrated to generate time slice maps at 1000 year intervals. Subsequent work (Shennan and Horton, 2002; Brooks et al., 2011) served to further refine this understanding through integrating new relative sea-level data and outputs from Glacial Isostatic Adjustment models.

Over the same period, pioneering use of 3D seismic data for offshore landscape reconstruction by Gaffney et al. (2007), (Gaffney and Fitch, 2009) helped demonstrate and map the survival of submerged Holocene landscape features. In addition, increased marine development in the UK led to large-scale review of offshore data (Ward et al., 2006; Selby, 2009; Tappin et al., 2011), helping to bind together geophysical and geotechnical renderings of the offshore zone. Work across the European North Sea coastline (Peeters et al. 2009; Hijma et al. 2011) continued to demonstrate recovery of Palaeolithic and Mesolithic material from both the Brown and Dogger Banks, but with additional large amounts of in situ material recovered from buried strata closer to the Dutch coast (Weerts et al., 2012). In the UK, finds from the submerged Mesolithic site at Bouldnor Cliff (Momber et al., 2011) further demonstrated the potential for the recovery of material in situ. As such, Reid's (1913) hypothetical spaces were more readily modelled and had their potential proved through recovered finds and geotechnical data.

While the above work has helped to shape our understanding of the submerged record, continued advances in sea-level reconstruction techniques, and acquisition of new data, mean that palaeogeographic models need to be updated to provide the broader context for this material. In addition, while the issues we are interested in as archaeologists mesh with those of earth scientists, archaeologists often call for consideration of change at higher temporal and spatial resolutions. Thus, while Shennan et al. (2000) and Brooks et al.'s (2011) palaeogeographic models provide a good sense of change at one thousand and two thousand year intervals respectively, they are still at odds with archaeology's desire (Coles, 1998, 77) to understand rates of change at a more human scale. As such, this paper moves to a five hundred year temporal interval and a higher spatial resolution for outputs than have previously been made available. In addition, it uses the model outputs to quantify varying rates of change across different zones within the study area. As such, through the models created here we seek to establish how the shape of North West Europe changed over the Holocene, and how variability in the rate of change may have impacted on people in the past.

In recent years, much archaeological attention has been focused on events which appear dramatic when viewed at a macro temporal and spatial scale – such as the total loss of Doggerland (Coles, 1998, 1999, 2000; Weninger et al., 2008) or the separation of Britain from the continent (Tolan-Smith, 2008). In this paper, we also seek to investigate changes which may appear less dramatic, but were in fact no less important, across the study zone. In addition, just as Coles (1998, 77) argued that the North Sea plain needed to be seen as more than a corridor, so we argue for the need to better understand the changing qualities of maritime space. The opening up of channels, the formation of islands and changes in depths of water along maritime routeways, will have impacted on both movement over the water and the distribution of ecosystems within it. This is not a trivial concern for archaeologists interested in issues of connectivity and social change (Bell and Warren 2013; Sturt and Van De Noort, 2013; Van de Noort, 2011).

3. Theory and method

As Lambeck et al. (2010, 65) have clearly stated, resolving differences in relative sea-level through time is a complicated matter, requiring consideration of:

> "(1) changes in ocean volume, (2) radial displacement of the land surface by changing load, (3) changes in the gravitational potential as a result of the deformation of the planet and redistribution of mass across its surface, (4) changes in the shape of ocean basins and, (5) the redistribution of water within these basins"

Researchers have collected empirical evidence for the impact of these changes for over a hundred years (Reid's (1913) submerged forests stand as one coarse grained proxy indicator). More recently rigorous standards have been set (Shennan, 1982, 54) with regard to what can be counted as a robust sea level index point (SLIP). Collection, auditing and analysis of SLIP data has enabled the creation of high resolution regional relative sea-level curves (Shennan et al., 2006; Brooks and Edwards, 2006; Smith et al., 2011, 2012) for Britain and Ireland. As Brooks et al. (2011, 13) note, the only problem with these records is that they are often confined to the present coastal margins. Due to this distribution there is remarkably little direct evidence from submerged areas of the continental shelf through which to construct RSL curves (see Ward et al., 2006). The result of this is that for offshore landscapes we hold little robust evidence for the rate at which submergence occurred.

Glacial Isostatic Adjustment (GIA) models help to move beyond this problem through simulating the five points listed above, permitting the generation of time and area specific models of past sea-level. The outputs of these simulations can then be calibrated against the empirical records and refined. GIA models have long been used to generate palaeogeographic reconstructions at the shelf scale (Lambeck, 1996; Shennan et al., 2000; Peltier et al., 2002; Brooks et al., 2011). However, the process is iterative, with new data constantly being acquired and new calculations for earth mantel viscosity being developed to refine outputs. When matched with a topographic surface, these data allow for new simulations of changing palaeogeography.

The first step in the method adopted here was the creation of a combined topographic and bathymetric digital elevation model of present conditions for the area shown in Fig. 1 within ArcGIS 10.1. This incorporated data from the sources given in Table 1.

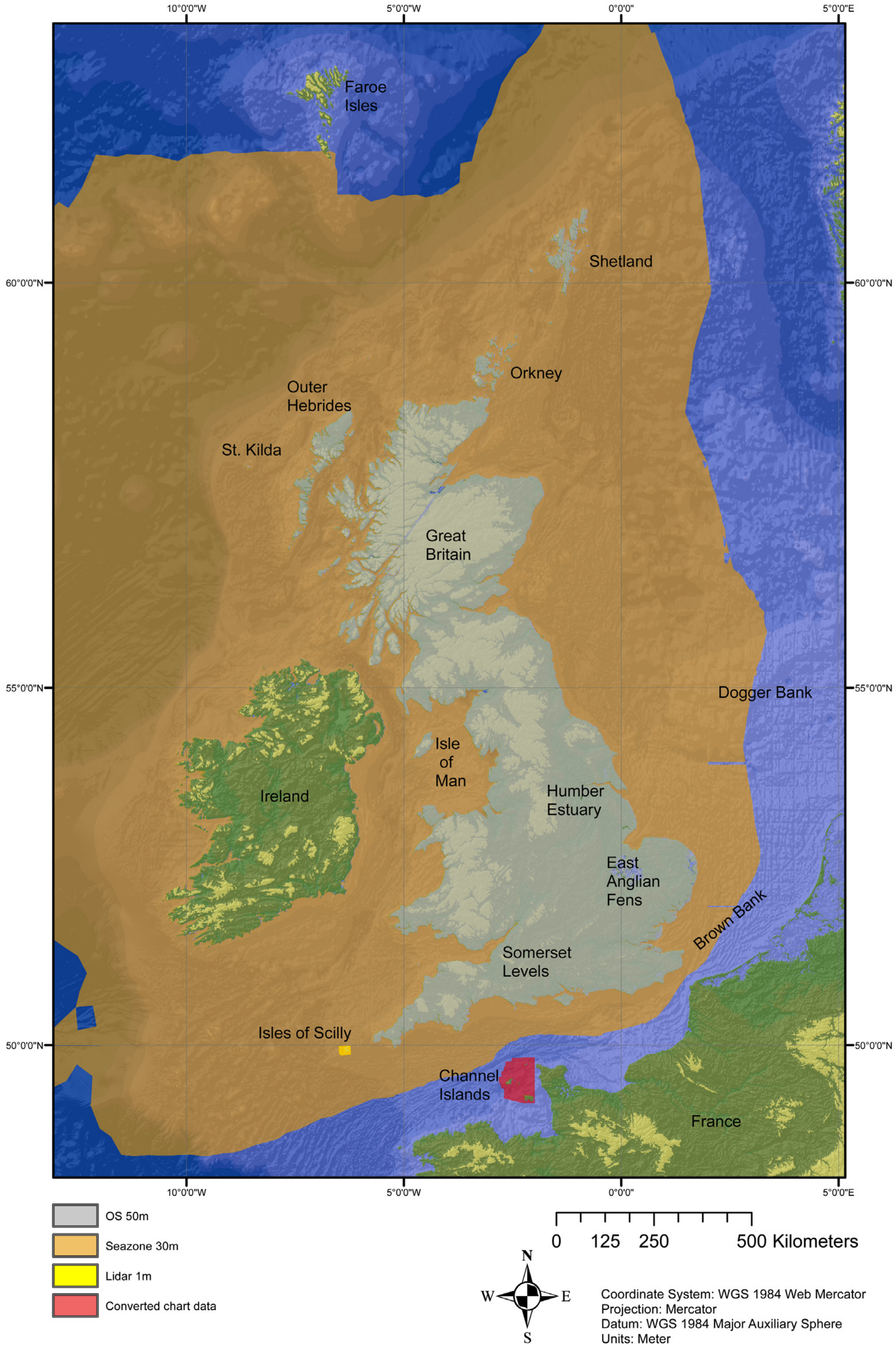

Fig. 1. Map showing the area modelled within this paper, extents and resolution of different contribution datasets and key places mentioned. Map produced in part from Ordnance Survey Digimap, SeaZone solutions and GEBCO 08 (www.gebco.net) data. ©Crown Copyright/database right 2012. An Ordnance Survey/EDINA supplied service. ©Crown Copyright/SeaZone Solutions. All Rights Reserved. Licence No. 052006.001 31st July 2011. Not to be Used for Navigation. Additional data courtesy of the Channel Coastal Observatory.

Table 1
Topographic and bathymetric data sources used.

Source	Description	*x,y* resolution	Coordinate system	Vertical datum
Ordnance Survey (UK)	Topography for the United Kingdom	50 m	Ordnance Survey of Great Britain 1936	Newlyn
SeaZone Ltd.	Bathymetry for UK national waters	30 m	WGS 1984	Chart Datum (Lowest Astronomical tide)
SeaZone	Bathymetry for the Channel Islands	Vector data converted to 30 m raster	WGS 1984	Chart Datum (Lowest Astronomical tide)
Channel Coastal Observatory	Lidar for Isles of Scilly	1 m	Ordnance Survey of Great Britain 1936	Newlyn
Digimap Guernsey	Topography for the Channel Islands	10 m	Guernsey Grid	St. Peter Port (Guernsey)
GEBCO 08 version 20100927, http://www.gebco.net	Topographic and Bathymetric data for the wider study area	30 arc-seconds (c. 900 m)	WGS 1984	Mean Sea Level (MSL)

The extent of each dataset used can be seen in Fig. 1. Each dataset was projected into the WGS84 coordinate system, and corrected to the same vertical datum (mean sea-level) to allow merging into a single surface. In the case of the SeaZone data, this required adjustment from Chart Datum (roughly equivalent to lowest astronomical tide) to mean sea-level. This was achieved through adjusting bathymetric values in relation to an inverse distance weighted surface created from the Ordnance Survey's Vertical Offshore Reference Framework (VORF) dataset. VORF was developed by a combined team from the Ordnance Survey, United Kingdom Hydrographic Office and the British Geological Survey specifically to help resolve vertical datum issues such as those present within this project (Iliffe et al., 2006).

With data corrected to the same vertical datum, the different sources could be combined into a single digital elevation model for the present day. The variable inputs were re-sampled to 30 m *x,y* resolution, to match the SeaZone bathymetry. Where this meant down-sampling the mean value of the highest resolution data was retained. Where it saw an up-sampling of data no attempt was made to refine data through interpolation, the cells were resampled with the existing value retained.

With the topographic surface created, one of the major challenges facing palaeogeographic reconstruction becomes apparent. Accounting for the totality of sedimentation or erosion through time across the study area is near impossible. Here, in order to demonstrate the potential impact of this factor on reconstructions a small area of aggraded landscape was remodelled. An isopach was generated from borehole data (as described by Sturt (2006)) to give the depth of Holocene sediment for the East Anglian Fenland. This depth of material was then removed from the digital elevation model to recreate the pre-inundation early Holocene landsurface of the basin. The impact of this exercise was the reduction in height of local topography by a maximum of 24 m along the current coastline (where surviving deposits are deepest), thinning out to the north, south and western margins. The end result is the transformation from a low lying plain to a more pronounced river basin with greater accommodation space available for inundation or sedimentation (as shown in Fig. 5a–c below). This sample area stands as an exemplar within the model to help demonstrate the impacts of geomorphological processes (Holocene aggradation in this instance) on model outputs.

Data points for the area shown in Fig. 1 were extracted from Bradley et al.'s (2011) GIA at 500 year intervals, on a 5 km grid. These points describe difference between present day elevation at a given location, and the elevation of the earth's surface in relation to mean sea-level for the given time slice. As Brooks et al. (2011, 8) note, this GIA model and associated eustatic sea-level curve (shown in Fig. 2) has been tightly tested against empirical observations and shows good conformity; an observation confirmed by Smith et al.'s (2011) recent review of Holocene sea-level change in Northern Britain and Ireland. The data points from the GIA were then interpolated via an inverse distance weighting (IDW) algorithm in

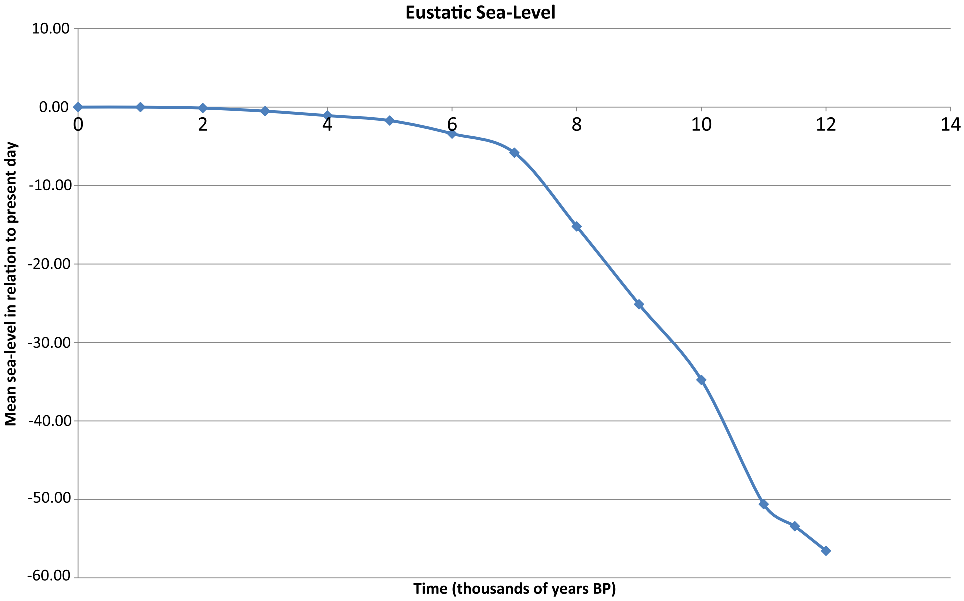

Fig. 2. Eustatic sea-level curve utilised within the model. For additional details on its fit with SLIPs and regional records please see Bradley et al. (2011).

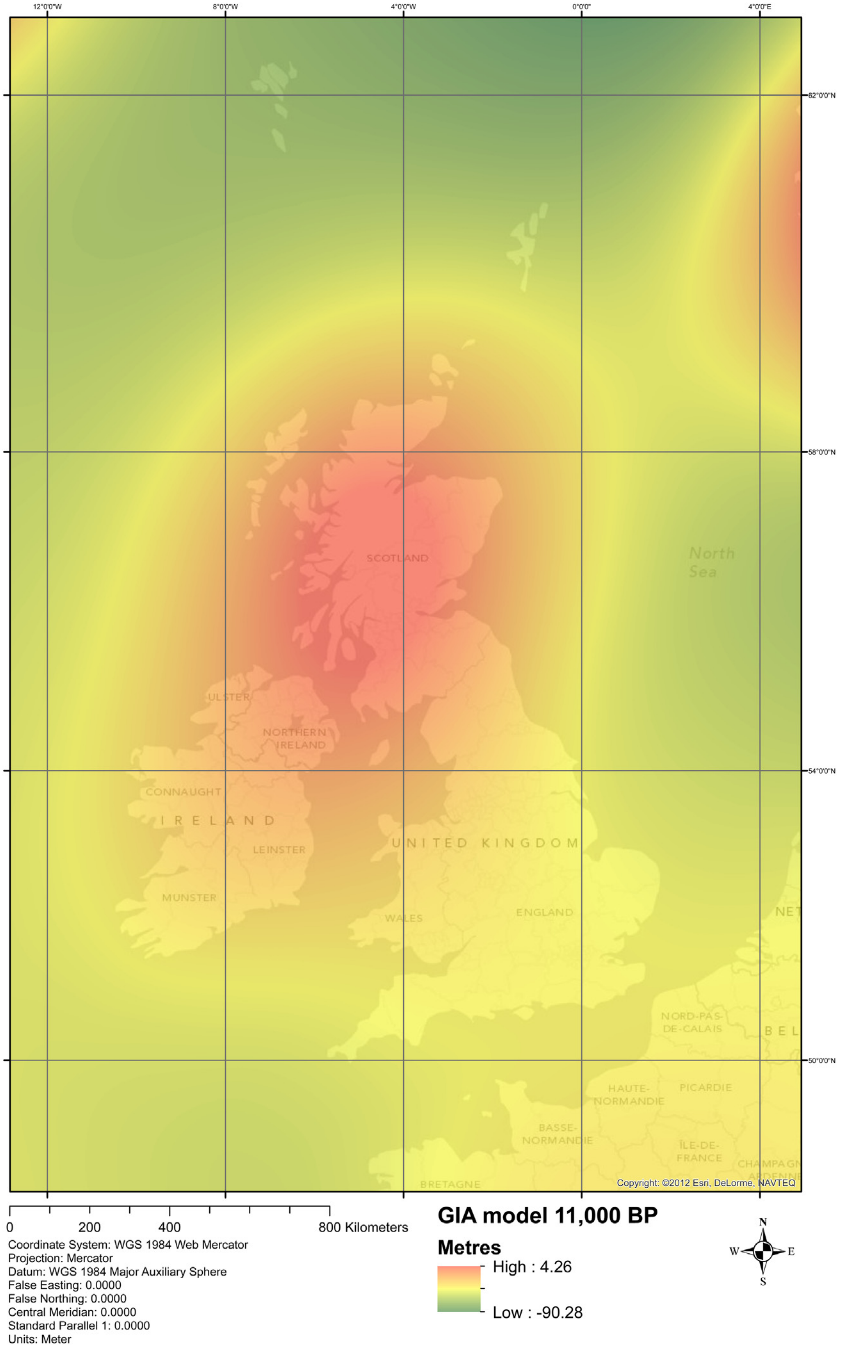

Fig. 3. GIA IDW model output. The value in metres shows the amount of uplift/subsidence that has occurred between 11,000 BP to present day period in relation to MSL.

ARCGIS 10.1 to generate a raster grid at 30 m resolution (shown in Fig. 3). An IDW interpolation method was chosen due to the even nature of the exported grid points from the GIA, and the need to ensure that the highs and lows of the input points were maintained as maxima and minima values for the final surface. The resulting raster grids could then be 'subtracted' from the modern digital elevation data to give a model of the computed topography for any given 500 year time-slice.

In order to move beyond rendering of palaeogeography alone, the resulting time specific elevation models were reclassified within ArcGIS 10.1 to allow quantification of the area inundated between each 500 year time-step (shown in Fig. 4). This was achieved by giving data in each time slice new values; 2 for anything below 0 MSL (marine conditions) and 1 for anything above 0. The reclassified layers were then added together via a raster maths function. A resulting value of 4 indicated the area was marine in the last and current time step, a value of 3 indicated inundation had occurred over the 500 year period for that cell, and 2 a continuation of dry land conditions.

In addition, to help move beyond generic accounts of total area lost for the whole continental shelf, the study area was divided into four sub-areas (Fig. 5); North Sea, English Channel, Western Seaways, and Western Ireland/Atlantic. Data could then be generated with regard to inundation rates for each zone. Rather than being arbitrary, the four sub-areas selected relate to major basins and potential prehistoric interaction zones (Needham, 2009; Westerdahl, 1995). As such, they allow for consideration of change at scales commensurate with trends seen in material

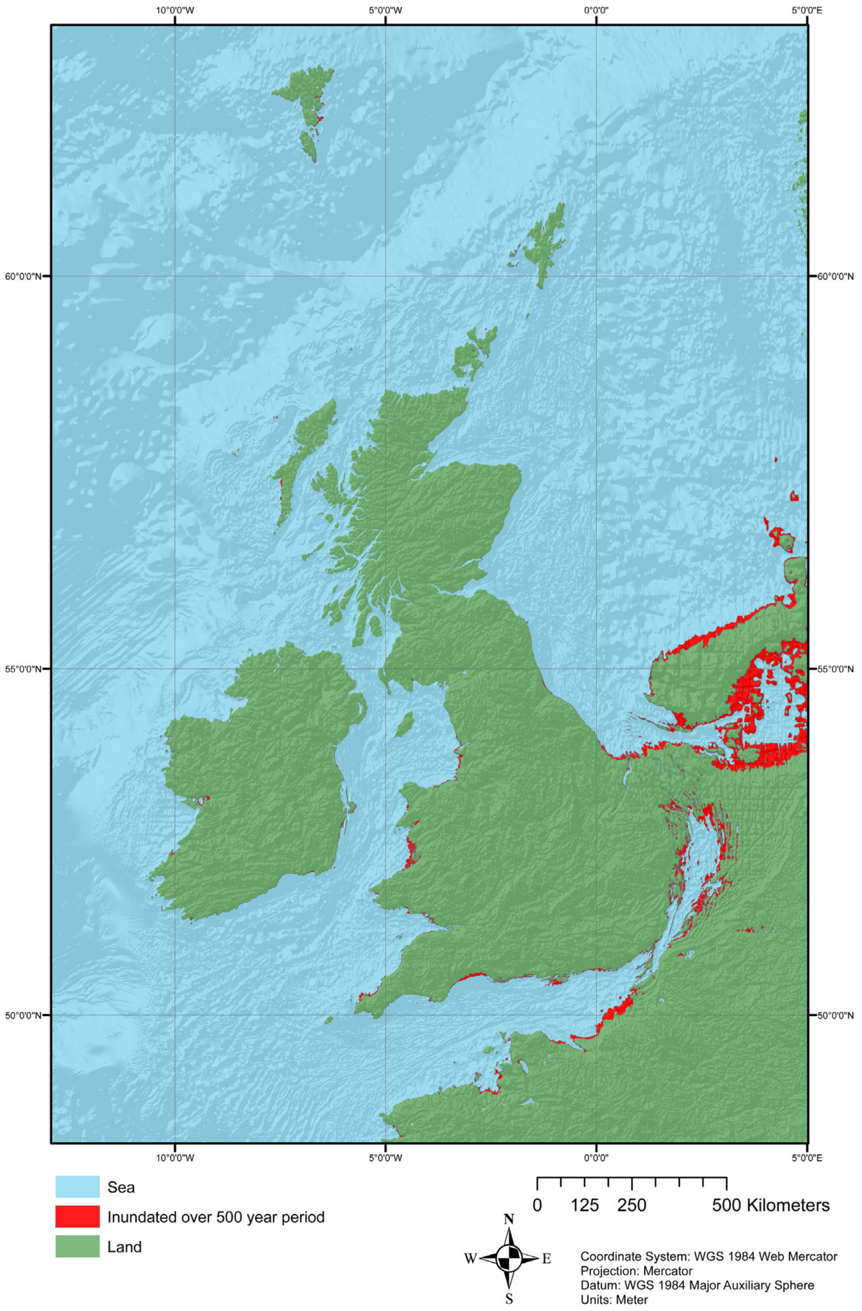

Fig. 4. Map showing the area inundated between 10,000 and 9500 BP. Map produced in part from Ordnance Survey Digimap, SeaZone solutions and GEBCO 08 (www.gebco.net) data. ©Crown Copyright/database right 2012. An Ordnance Survey/EDINA supplied service. ©Crown Copyright/SeaZone Solutions. All Rights Reserved. Licence No. 052006.001 31st July 2011. Not to be Used for Navigation. Additional data courtesy of the Channel Coastal Observatory.

culture studies, with regard to connectivity and communication from the Mesolithic onwards.

To help bring discussion down to a human level, each interaction zone was further sub-divided, with separate inundation rate data generated for island groups present. This provided three scales of analysis, shelf scale, interaction zone, and island level. The area inundated per 500 year time step for each region was calculated in square kilometres. This allowed for quantification of total change over the 11,000 years, and relative change within each 500 year window.

Before moving onto detailed discussion of the results it is worth commenting on the reliability of the models produced. The images in Fig. 6 are flawed, but remain archaeologically valuable. The flaws stem from the fact that sedimentation and erosion over the Holocene will have changed the morphology of the seabed and land surfaces. As such, some of the topographic highs and lows rendered in these images relate to on-going geomorphological processes, rather than the specifics of past topography. The impacts of this should not be underestimated, as demonstrated by the East Anglian Fenland example. Here, if compared to the Humber or Somerset levels regions (which underwent similar stories of Holocene infilling) we see a dramatically different picture of palaeogeographic change over the simulated period. For the Humber and Somerset levels the modern coastline is replicated into the past, for the East Anglian Fens we see an expansion of the North Sea well inland from the early Holocene onwards. However, while this

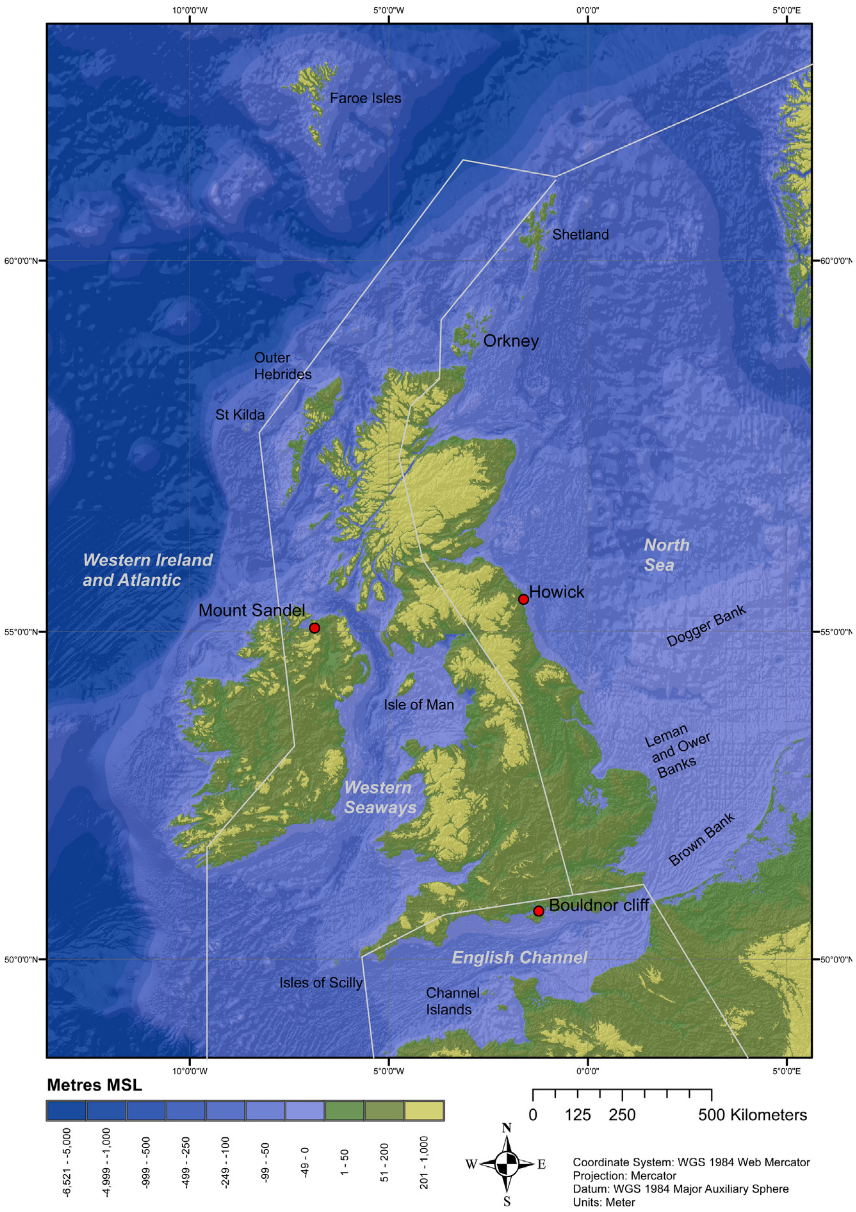

Fig. 5. Map showing the four interaction zones for which inundation rates were calculated. Sites and islands mentioned in the text are also labelled. Map produced in part from Ordnance Survey Digimap, SeaZone solutions and GEBCO 08 (www.gebco.net) data. ©Crown Copyright/database right 2012. An Ordnance Survey/EDINA supplied service. ©Crown Copyright/SeaZone Solutions. All Rights Reserved. Licence No. 052006.001 31st July 2011. Not to be Used for Navigation. Additional data courtesy of the Channel Coastal Observatory.

is a more accurate representation of marine transgression for the earlier Holocene of the Fenland (as the model is not 'blocked' by later deposits), the model overestimates the marine transgression from the Bronze Age onwards when deposition of sediment (partly due to anthropogenic activity (Lewin et al., 2005; Sturt, 2006)) saw progradation within the basin which has not been accounted for.

Furthermore, the images presented here do not account for possible changes in tidal range. Work by Uehara et al. (2006) has illustrated the potential magnitude of impact this may have had, particularly during the late Pleistocene near the edge of the continental shelf. However, recent work by Cazenave (2012) indicates that beyond the southern North Sea basin, where the radical reconfiguration of land/sea boundaries sees more marked changes in tidal ranges, for the majority of the area considered here over the last 8000 years there has been little change in tidal range. Finally, the resolution of the model at the outer margins, where GEBCO data was relied on, means that the ability to pick out surviving bathymetric relief is diminished.

The consequence of these known flaws is that the palaeogeographic models are broadly representative of past change, but will constantly need to be refined through empirical observation by both archaeologists and earth scientists. In addition, more work needs to be done on attempting to account for sedimentation and erosion over the study period. That being said, the data presented here offer an important way forward with regard to quantifying degrees of change, and attuning our minds to its variable nature.

4. Results

Fig. 6 shows the changing palaeogeography of the study area from 11,000 BP to the present day at five hundred year intervals.

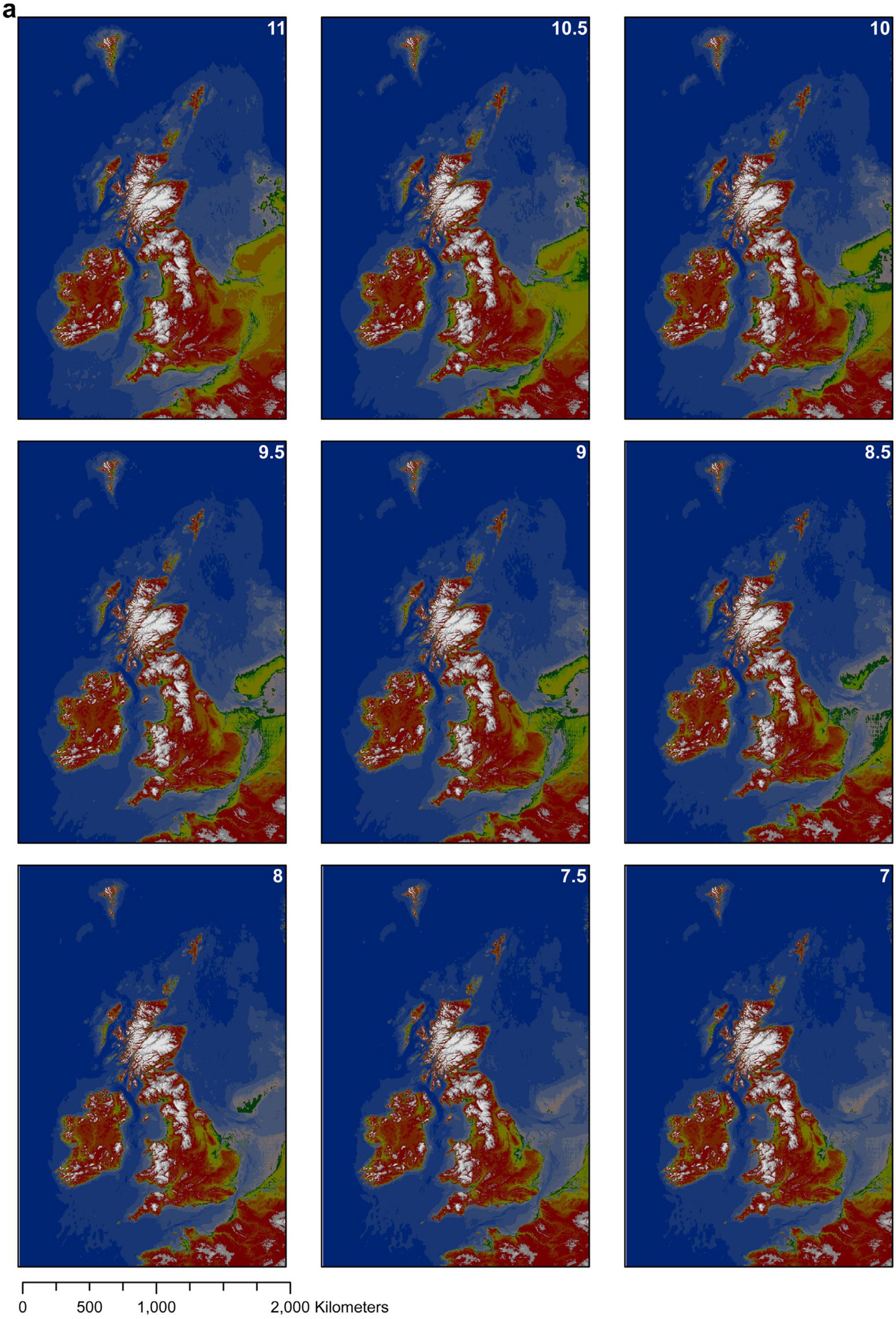

Fig. 6. (Parts a, b and c) Palaeogeographic models from 11,000 BP to present (kml versions available online). Map produced in part from Ordnance Survey Digimap, SeaZone solutions and GEBCO 08 (www.gebco.net) data. ©Crown Copyright/database right 2012. An Ordnance Survey/EDINA supplied service. ©Crown Copyright/SeaZone Solutions. All Rights Reserved. Licence No. 052006.001 31st July 2011. Not to be Used for Navigation. Additional data courtesy of the Channel Coastal Observatory.

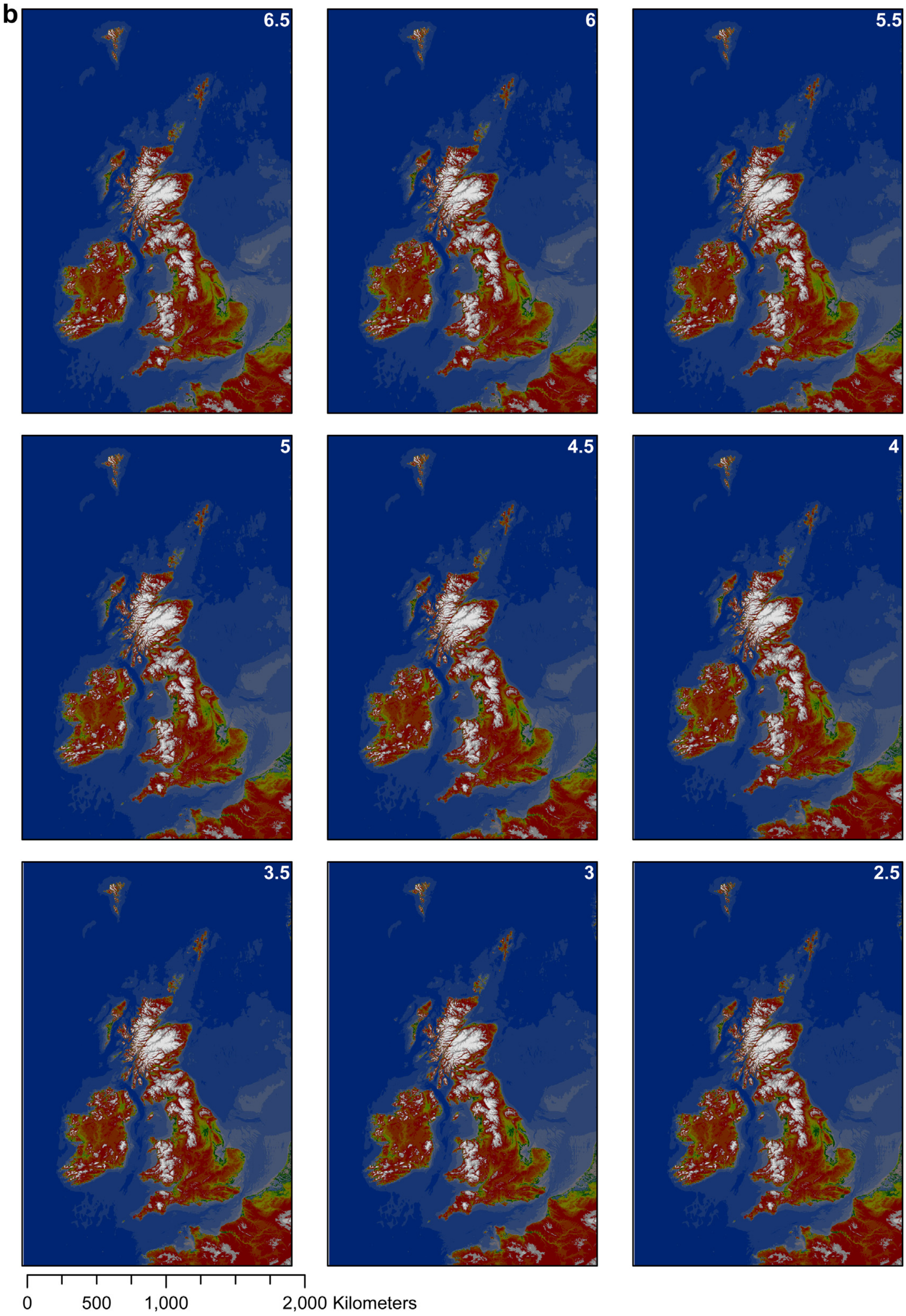

Fig. 6. (*continued*).

The same data are available to download as interactive KML files from the journal website and from the UK's Archaeology Data Service (http://dx.doi.org/doi:10.5284/1016098) allowing a higher resolution and interactive view. At the large scale shown in Fig. 5 it is possible to pick out the broader story of change, from connection to the continent through to the separation of Britain and the loss of what Coles (1998) termed Doggerland (the land associated with the topographic high of the Dogger Bank).

Fig. 7 shows the area inundated in square kilometres per 500 year window for each of the four interaction zones. The North Sea zone

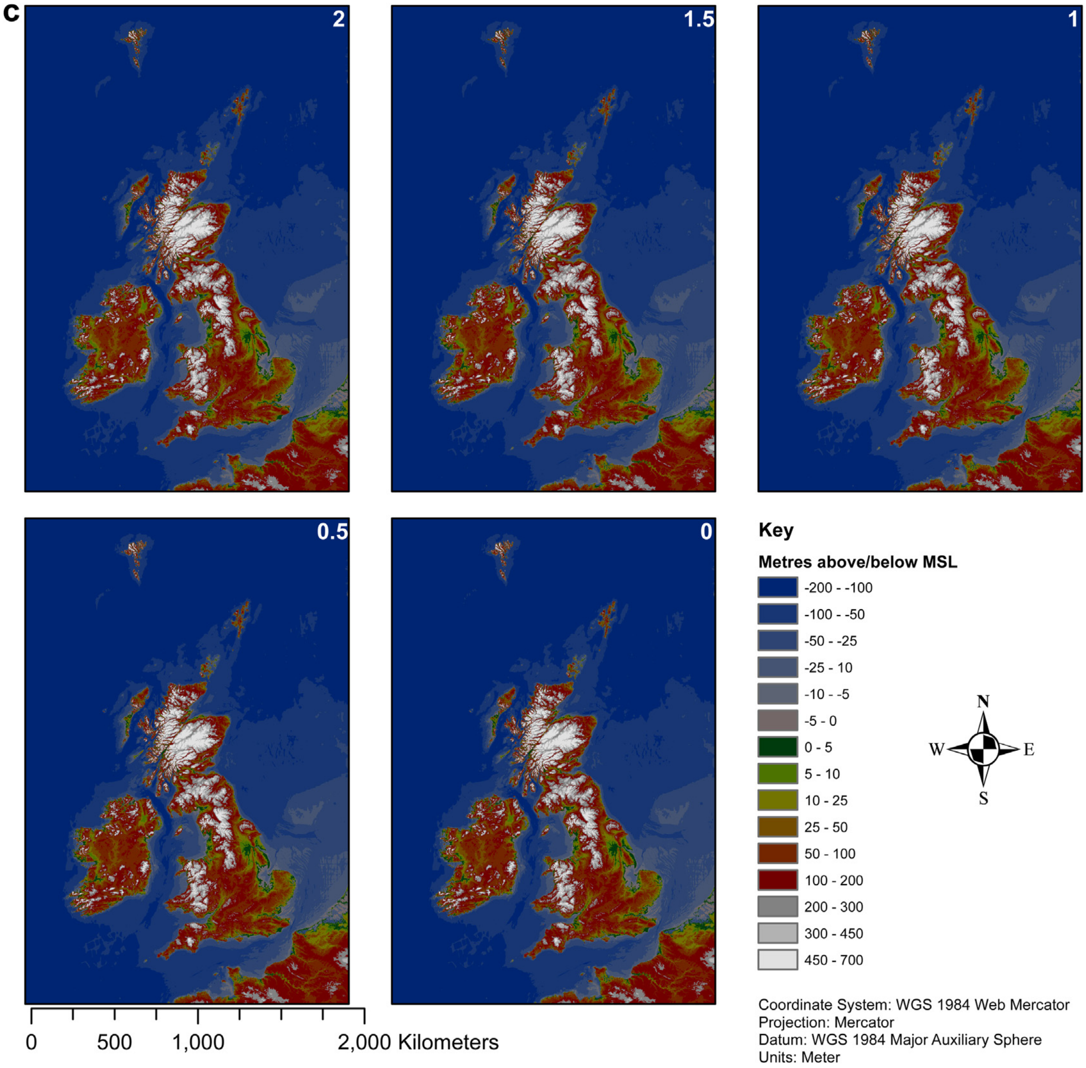

Fig. 6. (*continued*).

with its shallow topography and bathymetry sees the submergence of an area twice that of all the other three regions added together (127,422 vs. 59,149 km^2). This demonstrates the now well noted (Coles, 1998, 1999, 2000; Leary, 2009) large-scale nature of change that occurred over the Holocene for this region. However, the total area inundated, and the substantial changes of the Dogger bank region, are only part of a broader story and have the potential to shift focus away from considering the variable impact of change along different coastlines. Fig. 8 shows a chart for each of the interaction zones, normalised against total area inundated over the 11,000 year period. In addition, the impact on smaller island regions within each zone is drawn out for comparison within the same figure.

Within Fig. 8 it begins to become possible to pick out how local topography impacts on regional patterns. Within the English Channel, the Channel Islands as a whole plot a different story to the wider basin, but then when considered in greater detail the island of Guernsey experiences a further difference with regard to inundation history. Similarly the Isles of Scilly undergo a more complex story of change, with both significant alterations in palaeogeography at c. 9000–8000 BP and then again at around 2000 BP. Orkney also demonstrates a regional variant on a wider trend, with more pronounced loss between 8000 and 7000 BP.

For areas that were distinct as island groups by 11000 BP it is possible to further quantify the variable nature of change, with calculation of the percentage of total land area lost per 500 year window (Fig. 9). Here the regional nature of change becomes more strongly apparent. Again, the Isles of Scilly emerge as undergoing large scale change at multiple points in time, with over 10% of total land area lost each 500 year period between 8500 and 7000 BP, 3500–2000 and at 1500–1000 BP.

5. Discussion

5.1. 11,000–8000 BP

As Figs. 6–8 make clear, there is a considerable transformation of the geography of North West Europe over this period. The Dover Straits are breached and Britain separates from the continent at some point between 8000 and 7500 BP. As Brooks et al. (2011, 11) note, this date is confirmed by coastal peats from along the south coast of England (Gupta et al., 2004; Massey et al., 2008) and France (Frouin et al., 2007). Within the English Channel, the Channel Islands of Guernsey and Herm form a single island, while Jersey and potentially Alderney remain joined to the French coast. Along the western seaways Scilly stands as a single island, as too does Orkney to the North. The Outer Hebrides are considerably larger than they are now, with a low lying coastal plain extending out to the West of the Uists. The sea itself is radically transformed over this period,

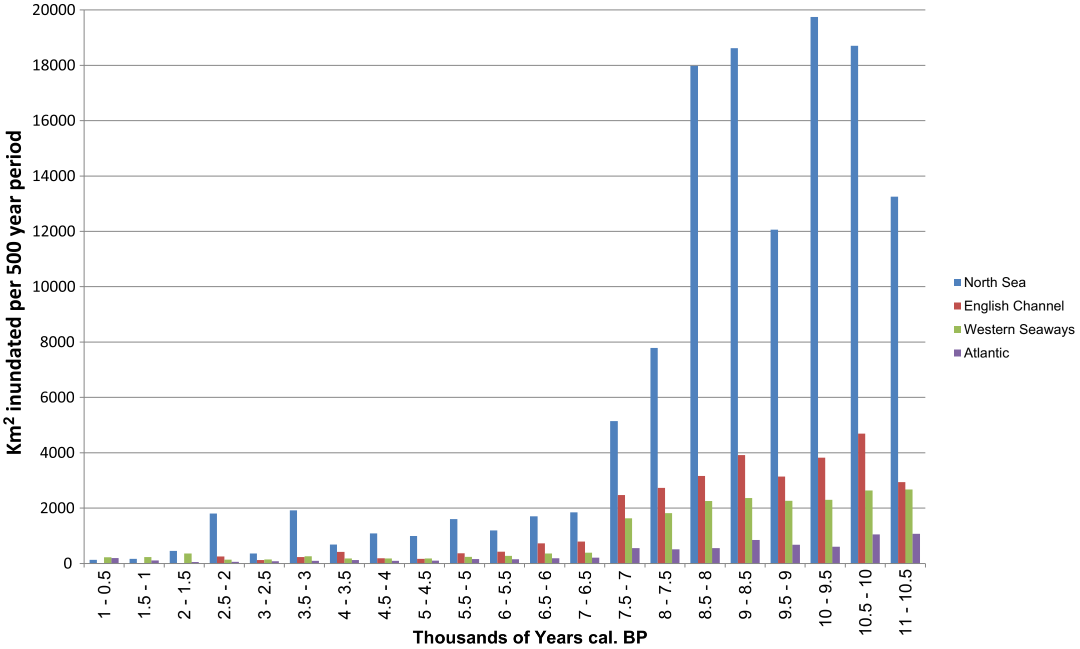

Fig. 7. Graph showing the area in square kilometres inundated over each 500 year period.

principally through the breaching of the Dover straits. A high flow of water over a relatively shallow seabed would have created difficult seafaring conditions, but potentially provided good fishing through the movement of nutrients from deeper to shallow waters.

The models and charts presented here to an extent smooth out some of the changes that will have occurred. Hijma and Cohen (2010) have documented how the sudden release of fresh water as part of the 8.2 kya event saw a rapid vertical jump in sea-level along parts of the Dutch coast. Similarly, Weninger et al. (2008) have argued that the Storegga slide tsunami at c. 8100 ± 1000 BP flooded Doggerland in a catastrophic finale to an otherwise slower process. However, while both of these instances will have had measurable impacts at different points in the study area, as Kiden et al. (2002) note, the realities of sea-level change can differ on small (sub 50 km) levels. Thus, while it is possible that both of these events played a part in the final submergence of Doggerland, we can expect that some areas will have seen dramatic impacts, while others responded more slowly due to localised geomorphology or shoreline ecology.

Coles (1998, 1999, 2000) and Leary (2009, 2011) both contend that the inundation of Doggerland and the surrounding North Sea Plain will have had a significant impact on Mesolithic populations, potentially forcing a population movement. The point is well made, but also applies beyond the topographic high of the Dogger bank. For those living along the coastal margins of the North Sea plain, in the Channel Island of Guernsey and the Isle of Man, it would appear from the rates described in Fig. 8 that the degree of change may have been perceptible at the level of multi-generational cultural memory (Assmann, 2011) and perhaps even at a generational level, with nearly twenty percent of total land area lost over different five hundred year periods.

Tolan-Smith (2008, 134) cites this rapid rate of change and the separation of Britain from the continent as “a major factor influencing the demographic development of Britain during the Early Mesolithic”. However, we need to think carefully about the concept of separation in this context. The creation of two separate landmasses via the breaching of the Dover strait may look dramatic in Fig. 6, but does that map onto what we know of Mesolithic lifeways in this period? Would a difficult stretch of water create an insurmountable barrier?

Tolan-Smith (2008, 151) notes that at this point there is clear evidence for Mesolithic seafaring, with Ireland being occupied along with the Isle of Man, Rhum, the Hebridean Archipelago and Howick on the East coast of England. Thus, as Warren (2005) and Garrow and Sturt (2011) have argued, there is ample evidence for a strong seafaring tradition in the Mesolithic. The colonisation of Ireland and the islands along the western shores of Scotland required navigation of difficult marine environments. As such, the separation of Britain from the continent is unlikely to have prevented communication, but rather reconfigured it. Thus, as much as we may want to view the visible point of separation as a fulcrum on which social relations pivoted, the truth may lie some way further off.

5.2. 8000–6000 BP

Within five hundred years of the opening of the Dover Straits, the final vestiges of Doggerland are submerged. Between 7000 and 6500 BP Jersey becomes separated from mainland Europe, with possible large inter-tidal islands remaining. At the same time, Scilly begins to fragment, splitting into three main islands while Orkney moves closer to its current configuration, with smaller islands (such as Papa Westray) breaking away from larger landmasses. On mainland Britain, today’s East Anglian Fenland has become a true extension of the newly formed North Sea, stretching far inland of the present coastline. Similarly, the Somerset and Humber Levels would have been undergoing marine transgression. As such, our understanding of terrestrial space also needs to be carefully considered; with reworking of estuarine areas and the expansion of former wetlands into open areas of sea, all serving to shape modes of transport and connectivity across the study area.

5.3. 6000–4000 BP

The Isles of Scilly have now formed into four distinct islands and Jersey is well separated from the mainland. The extended coastal

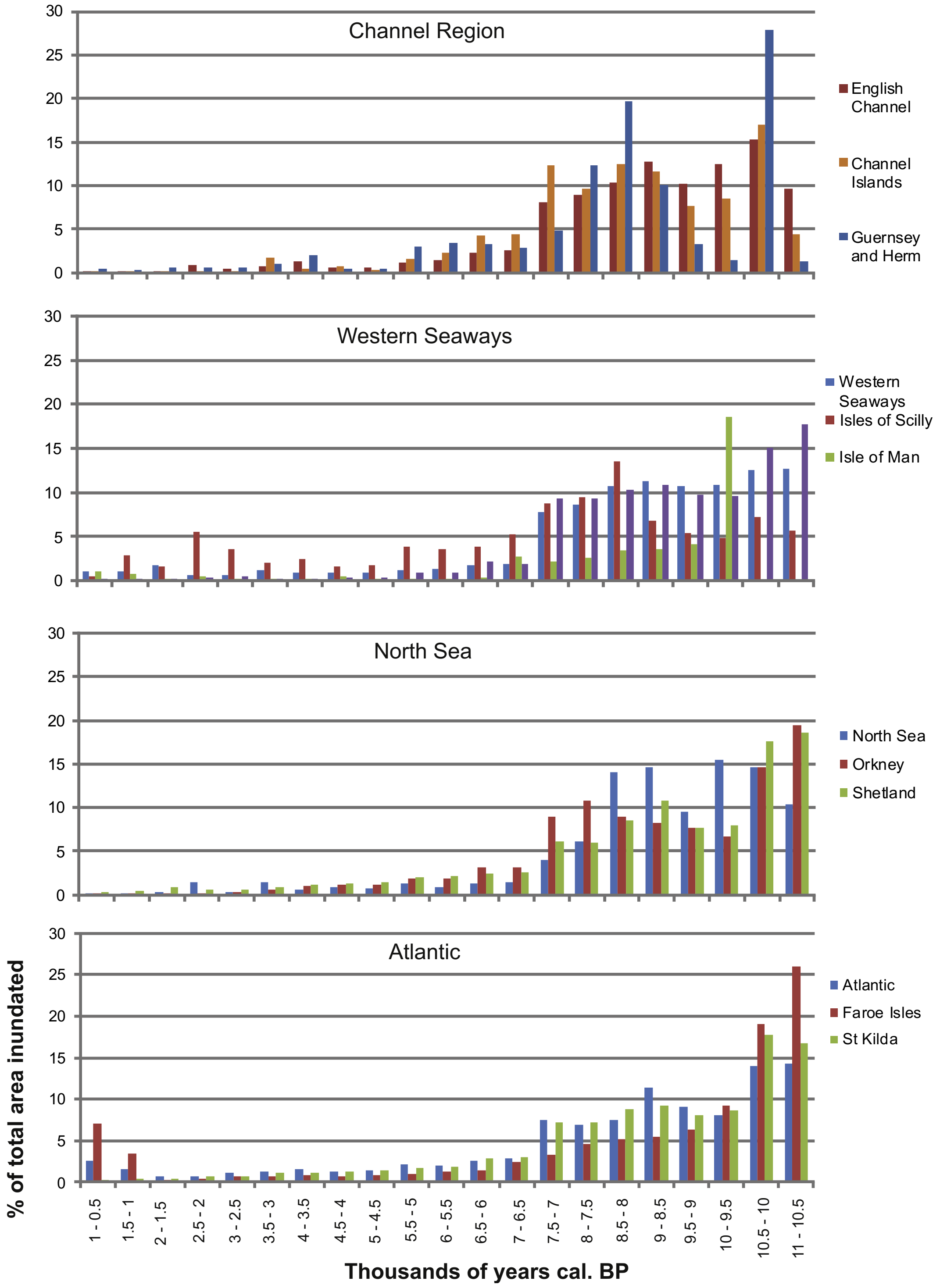

Fig. 8. Graphs showing the percentage of total area inundated over the 11,000 years modelled for each of the interaction zones.

plain which surrounded the Outer Hebrides is significantly diminished in size and the islands are approaching their present configuration. The local topography of Guernsey and Herm mean that they experience an increase in the rate of change over this period, with a larger relative area being submerged than in the previous two millennia. Similarly the rate of change increases within Scilly, but still lies below that seen in the earlier Holocene.

At a coarse grain viewing, the models in Fig. 6 indicate that the majority of the total change to occur has now taken place. However, whilst true at the macro scale, at the regional level the specifics of local bathymetry and topography mean that coastline reconfiguration and seaway behaviour is still transforming. As water depths change previous shoals and shallows submerge and fish behaviour will have altered accordingly. The impacts of these changes are still most profoundly felt within the North Sea and English Channel regions. The cliff lined coast of Ireland and the rocky shores of Western Britain reduce the overall amount of change experienced along those coastlines. As such, a consistent difference is

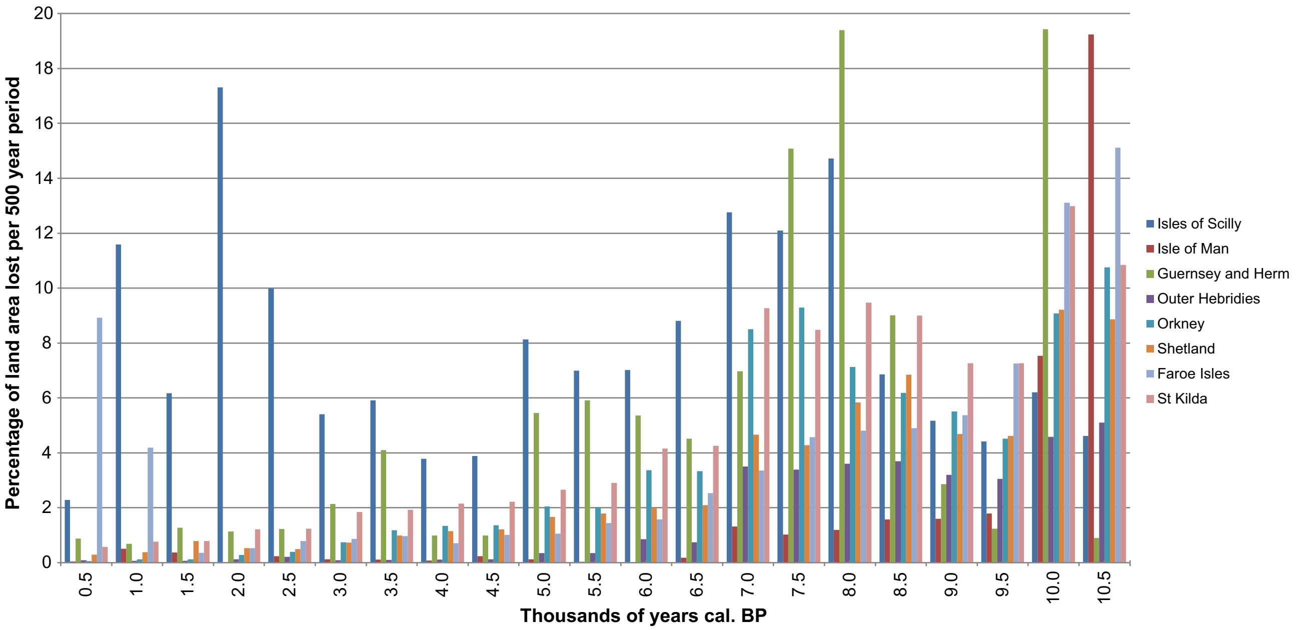

Fig. 9. Graph showing the percentage of available land area lost over each 500 year period for given island groups.

discernible between a persistent Irish and Atlantic façade and the more changeable low lying British and continental coastlines. However, within this space we still have to consider the nature of the newly submerged regions and their behaviour as seaways. The shallowly shelving land off North West England would have provided a potentially complex and dangerous mix of shallowly shelving, rapidly changing beaches and shoals. Thus although now maritime in nature, it (and other regions like it) may have become hard to navigate. Better understanding the complexities of these new maritime environments may well help us to unpick the variable timing and processes via which Neolithic practices become established around the British Isles and Ireland.

5.4. 4000–500 BP

Although the overall rate of change has slowed, exceptions still exist. The Isles of Scilly undergo profound change over this period, with the low-lying central region of the previous eras largest island submerging. The result is the transformation from a single large island with three attendant smaller islands, into the cluster of five major islands and c. 140 rocky islets that we see today. As Fig. 8 makes clear, the total percentage area of land lost per 500 years is considerable, marking this out as socially perceptible change, possibly within individuals' lifetimes. It also makes clear, as noted by Mulville (2007), that the Isles represent a significant archaeological resource for those interested in Holocene records of sea-level change and social impact. With shallow seas and observable submerged structures and peats, the rare opportunity exists to gain direct observations of changing human behaviour from submerged archaeological sites.

6. Conclusions

In this paper we have sought to achieve two goals: to present new palaeogeographic models, and to consider those models within their broader context. Examined on their own the images in Fig. 6 tell a story of large-scale change, of loss of land and creation of modern geographical boundaries. It is all too easy to transform these images into a story of catastrophe, of separation and compartmentalisation. Instead, close examination of both the models produced and the archaeological record reveals a more complicated picture of regional diversity and variable impact.

The archaeological narrative of Holocene sea-level change in North West Europe should not be limited to the loss of Doggerland, but benefits from comparison to the broader context. As Warren (2005), Tolan-Smith (2008) and Garrow and Sturt (2011) have noted, the populations who inhabited these landscapes were well able to navigate its changing geography and capitalise on the products of expanded marine areas. This is not to trivialise the impact that loss of land may have had on past populations, or to deny the possibility (indeed likelihood) that at times catastrophic changes did occur at a regional level, but to place it within a more reasoned framework. It is only through doing this that we can better proceed with understanding the record we currently hold. It is with this in mind that we hope the models made available here are widely used, modified, critiqued, updated and shared in an open format to help drive research in this area forward.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2013.05.023.

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