ELSEVIER

Marine Geology 191 (2002) 87–94

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Editorial

Quaternary shelf sea palaeoceanography: recent developments in Europe

J.D. Scourse[a,*], W.E.N. Austin[b]

[a] School of Ocean Sciences, University of Wales (Bangor), Menai Bridge, Anglesey LL59 5EY, UK
[b] School of Geography and Geosciences, University of St. Andrews, St. Andrews, Fife KY16 9AL, Scotland, UK

Accepted 29 August 2002

Abstract

High-quality palaeoceanographic reconstructions based on sequences preserved in shallow marine environments demonstrate that these constitute significant archives of climatic and oceanographic change. Such sequences are important, first, because their often very high-resolution, sometimes laminated, nature enables high-frequency cycles to be resolved and provides the basis for establishing spatial and temporal variability in the marine radiocarbon reservoir effect. Second, sea-level index points from shelves are important for the validation of glacio-hydro-isostatic geophysical models and for understanding sea-level change during early deglaciation. Third, shallow marine sequences contain excellent records of land–ocean interaction, often preserving paired terrestrial–marine proxies in the same stratigraphic sequence. A new development in shelf sea palaeoceanography is documenting the long-term dynamics of shelf sea stratification. This is the dominant hydrodynamic phenomenon of tide-dominated shelf seas in the middle and high latitudes and has a profound influence on productivity and therefore global change through the carbon cycle. Detailing the evolution of seasonal stratification during eustatic highstands is therefore of relevance to the climate system.

Keywords: palaeoceanography; shelf sea; radiocarbon; isostatic modelling; seasonal stratification

---

1. Introduction

The collection of papers in this issue on *Shelf Sea Palaeoceanography: The Quaternary Record* arise out of a symposium held at the Geoscience 2000 meeting organised at the University of Manchester by the Geological Society of London. The meeting itself, and the published contributions, highlight the results of recent intensive research in Europe on the palaeoceanographic potential of shallow marine sequences funded both by national research agencies, notably in Scandinavia and the UK, and by the EU. Several seminal studies outside Europe in recent years have illustrated the significance of high-resolution records from shallow marine contexts, most notably the work on the shelf basins, such as the Santa Barbara Basin off California (Cannariato and Kennett, 1999; Cannariato et al., 1999; Bull et al., 2000; Emmer and Thunell, 2000; Field and

---

* Corresponding author. Fax: +44-1248-716-367.
E-mail address: j.scourse@bangor.ac.uk (J.D. Scourse).

0025-3227/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0025-3227(02)00526-1

Baumgartner, 2000; Hendy and Kennett, 2000; Kennett et al., 2000; Kiefer et al., 2001; Pisias et al., 2001), the semi-enclosed Cariaco Basin in Venezuela (Hughen et al., 1996, 1998a,b, 2000) and the laminated fjord sequence from Saanich Inlet, British Columbia (Blais-Stevens et al., 1997, 2001; Dean et al., 2001; Nederbragt and Thurow, 2001). It is difficult to underestimate the significance of these investigations in the context both of palaeoceanographic change and of helping to resolve uncertainties surrounding the marine radiocarbon reservoir effect. Indeed, it is the impact of these studies, and the potential of similar future studies, that has driven the recent developments and focus towards shallow drilling as part of the Integrated Ocean Drilling Program (IODP).

In Europe, these studies have helped to counteract the widespread conviction that shallow marine environments are effectively unconformities in the making (e.g. Curry, 1989) and therefore unlikely to contain depositional basins recording the palaeoceanography of shelf seas, or as archives recording adjacent oceanic fluxes of heat and salt. Of course, whilst large areas of continental shelves are indeed zones of net erosion, work in Europe in the 1980s and 1990s demonstrated that depositional basins covering at least the Holocene do exist (Hald and Vorren, 1987; Hald et al., 1991; Peacock et al., 1992; Scourse and Austin, 1994; Austin and Scourse, 1997). This realisation, along with the examples cited above, has stimulated intensified research activity in this field, some of the results of which are published here. These depositional basins are now the focus of intense research interest in the context of very high-resolution time series of Holocene climate variability (as in the EU HOLSMEER project; http://www.bangor.ac.uk/os/holsmeer) as these proxies can be compared against instrumental records of observed changes in temperature, salinity and nutrient status.

Why are studies of sedimentary sequences in shallow marine environments important? First, sedimentation rates in shallow marine basins can be orders of magnitude greater than in the more intensively investigated deep-sea environments, so permitting detailed high-resolution studies of palaeoenvironmental and palaeoceanographic change, enabling high-frequency cyclicities to be detected and their amplitude resolved. In some settings these high sedimentation rates are counteracted by thick mixed layers arising from extensive bioturbation (e.g. Kershaw et al., 1983), but ultra-high-resolution studies are enhanced by the preservation of laminated sequences from low-oxygen environments, notably silled fjords or sea lochs and in anoxic shelf basins. These sequences are critical for ^{14}C calibration and documentation of spatial and temporal change in the marine reservoir effect, and in the mid to high latitudes provide a viable equivalent to shallow water tropical corals.

Second, cyclic global sea-level changes in excess of 120 m between glacial and interglacial stages every 100 000 years result in evacuation and flooding of continental shelves with dramatic impacts on climate and, in particular, primary production and the carbon cycle (Walsh, 1988). Detailed records of glacio-eustatic change have emerged from coral-based studies in low latitude shallow marine environments (Fairbanks, 1989; Bard et al., 1996). These are not only critical for constraining eustatic input functions for glacio-hydro-isostatic models, but they provide key constraints on the palaeoceanography of shelf seas, both in terms of routeways (Larsen et al., 1999; Ahmad et al., 1995) and tidal dynamics which often control regional hydrography and primary production (Austin, 1991; Scourse and Austin, 1995). Glacio-hydro-isostatic model data (Lambeck, 1995, 1996) for the NW European continental shelf provide predictions of shoreline migration from the Last Glacial Maximum (21 ka BP) to the mid-Holocene (5 ka BP). These models combine the effects of deglacial eustatic and isostatic signals, and provide key evidence on mantle rheology and constraints on ice loads. Whilst these models are well-constrained by ^{14}C-dated index points for the Holocene (10–5 ka) from estuarine and shallow embayments in unglaciated areas and for the Late Glacial (14–10 ka) from uplifted shorelines in glacially loaded areas, they are currently less well-constrained otherwise because data from offshore cores has hitherto been lacking. These are critical because both isostatic

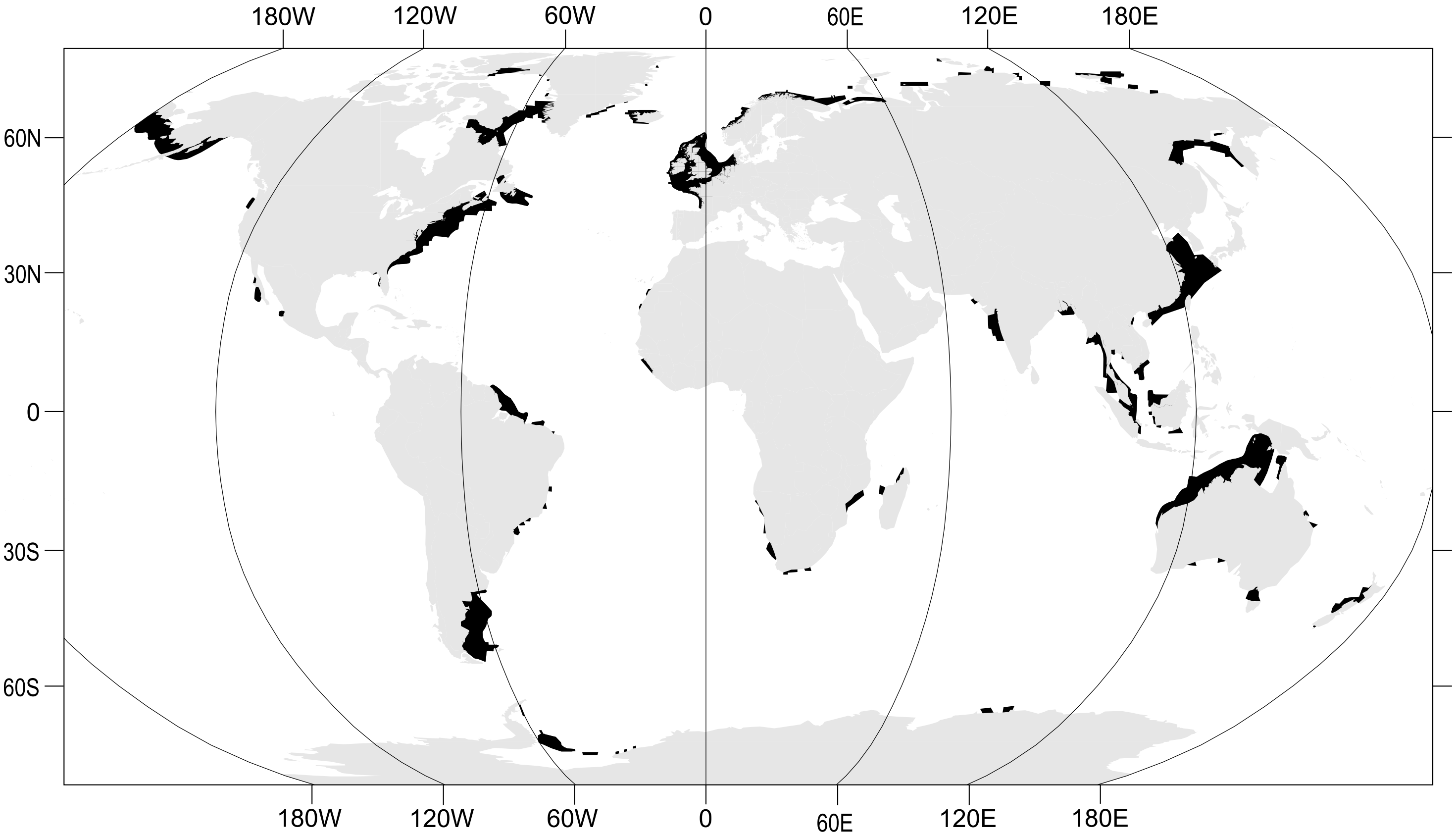

Fig. 1. Predicted global distribution of seasonally stratified shelf seas (adapted from Elliott and Li, 1999). Dark areas are shelf seas in which the stratification parameter $S = < 8$ (representative of conditions on the NW European shelf), where $S = \log_{10}(H/C_D U^3)$ (Pingree and Griffiths, 1978); H = water depth, C_D = bottom drag coefficient, U = amplitude of the tidal surface current.

and eustatic components show the greatest rates of change and, therefore, the most rigorous test of the geophysical models in the period 20–13 ka BP. Sea-level index points for this period are now offshore and can only be accessed by coring. New and recent studies are now addressing this need, notably in the North Sea (Shennan et al., 2000), on the Patagonian shelf (Guilderson et al., 2000) and on the Australian shelf (Yokoyama et al., 2000).

Third, marine sequences deposited close to land register the imprint of changes in terrestrial environments in parallel with those in the ocean. Land–ocean interactions are of great significance both as forcing agents of and as keys for unlocking archives documenting the climate system. For instance, the identification of geochemically distinct tephra layers both onshore and offshore enables documentation of spatial and temporal changes in the marine reservoir effect (e.g. Austin et al., 1995; Haflidason et al., 2000), which can be linked to palaeoceanographic change. The marine reservoir effect can therefore be seen not as merely a problem for the construction of age models but as a palaeoceanographic tool. Recent work on very high-resolution sequences of both Late Glacial and Holocene age containing multiple tephras from the north Icelandic shelf (e.g. Eiríksson et al., 2000a,b) is revealing a pattern of reservoir age shifts consistent with changes in current patterns, notably changes in the relative strength of the Irminger and East Greenland currents.

A particular focus of the Geoscience 2000 symposium was the documentation of the long-term dynamics of seasonal stratification in shelf seas. Such studies highlight the deficiencies of existing models of shelf sedimentation which rely purely on hydrodynamic controls. It is becoming clear that, in such settings, tidal dynamics have a critical part to play in controlling primary production and that the nature of organic particles and their processes of sedimentation are crucial for a complete understanding of sedimentary facies on continental shelves. In other words, biogeochemistry is at least as important as physical processes for understanding and interpreting shelf sequences. A background summary of shelf seasonal stratification is therefore given below.

2. Seasonal stratification in shelf seas

Seasonal thermal stratification is the dominant hydrodynamic phenomenon of tide-dominated shelf seas in the middle and high latitudes (Fig. 1). In these settings, heating of the surface waters induces buoyancy and stability, but the turbulence generated by the action of bottom friction on ti-

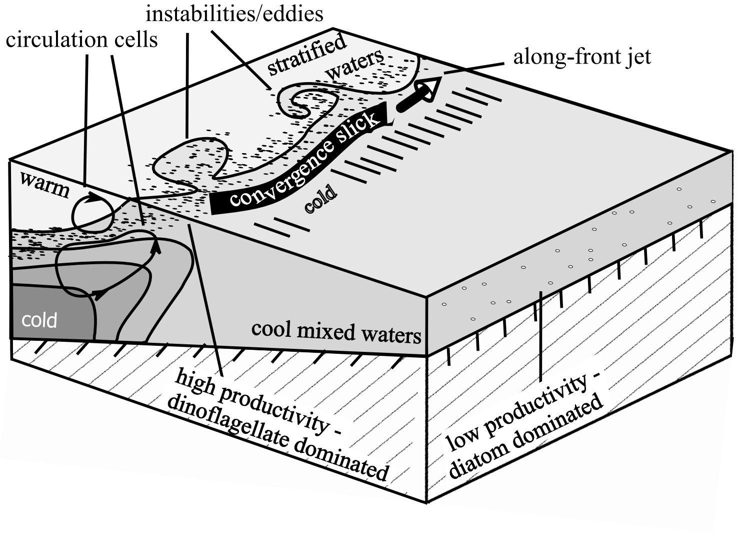

Fig. 2. Cartoon of the three-dimensional structure of a tidal front.

dal currents acts against this and may generate sufficient kinetic energy to maintain vertical mixing throughout the depth of the water column. During winter, the entire water column is mixed with relatively uniform temperature, salinity and density characteristics throughout. In early spring, when heat fluxes from the atmosphere to the sea surface, a warm surface layer develops. This layer is separated from the colder bottom waters by a sharp density gradient, the pycnocline, which restricts the exchange of heat and nutrients between the two water bodies (Fig. 2). In the Celtic Sea,

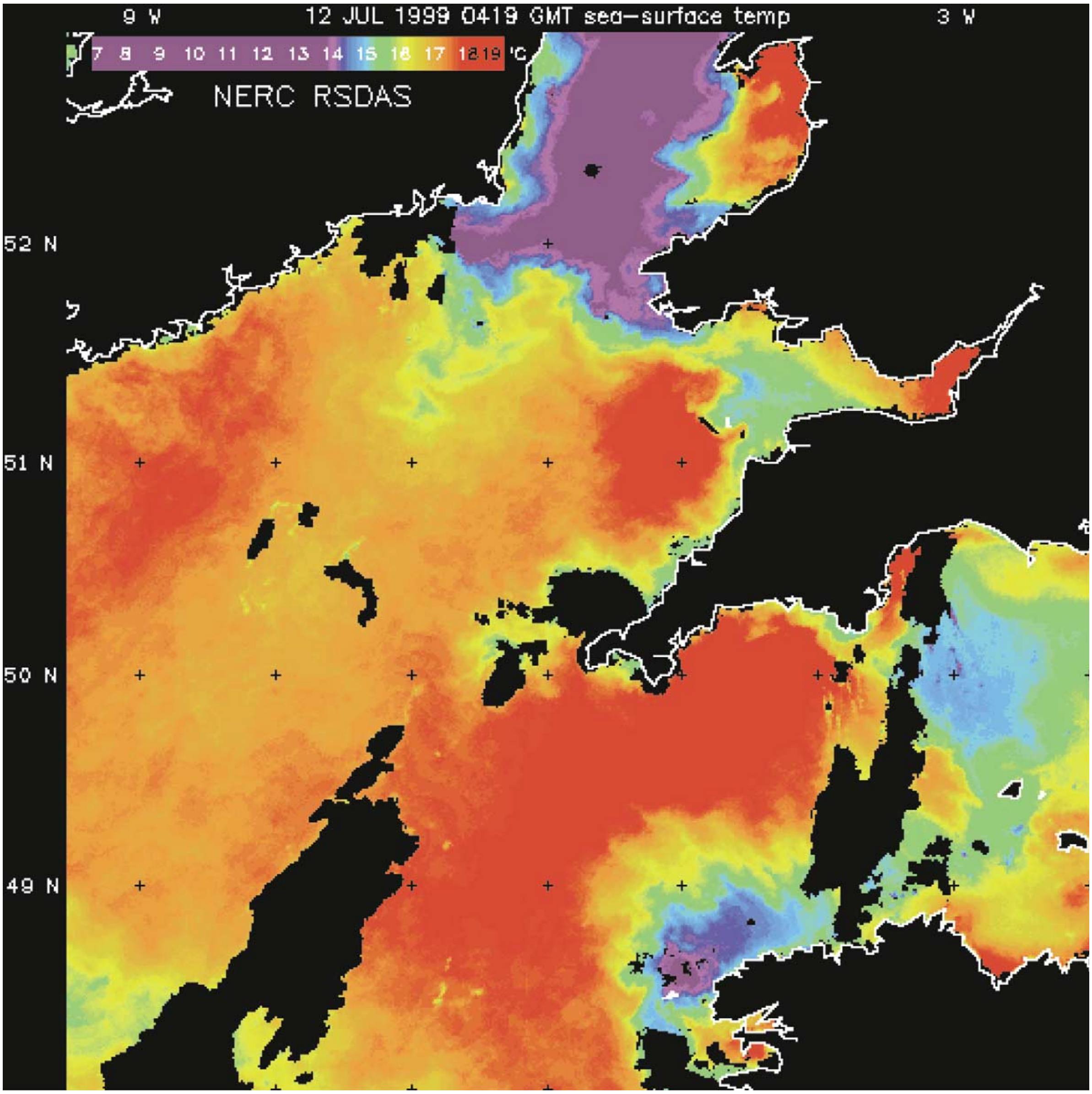

Fig. 3. AVHRR SST satellite image of Celtic Sea taken at 0419 GMT on 12 July 1999. The temperature gradient representing the Celtic sea front is shown clearly. Black areas represent cloud or land; temperature scale shown at top of image. Reproduced with the kind permission of the Remote Sensing Data Analysis Service (RSDAS) at the Plymouth Marine Laboratory (NERC), UK.

where salinities are generally high throughout, the pycnocline generally coincides with the thermocline, defined as the sharp temperature gradient between the surface and bottom waters (Elliott et al., 1991). In autumn, as atmospheric cooling begins, the surface layer loses heat both upwards and downwards. Eventually the two layers become equal in temperature, the thermocline disintegrates and the whole water column becomes, once again, mixed by convective overturning. Variations in tidal mixing and water depth result in some areas of the shelf becoming stratified whilst adjacent waters are mixed; the transition between the two is marked by a strong horizontal gradient known as a front.

The Celtic Sea front is one such shelf sea front extending between Britain and Ireland and curving southwards, at around 51°N, along the British coast (Fig. 3). This intensively researched front (Pingree, 1975, 1979; Simpson, 1976; Simpson et al., 1978; Simpson and Bowers, 1979, 1981; Wang et al., 1990; Elliott and Li, 1991; Elliott et al., 1991) can be recognised in summer by temperature measurements across the boundary area and may sometimes be recorded by satellite imagery which detects the sharp, horizontal, surface temperature gradients (Fig. 3; Simpson and Bowers, 1979). The mixed zone is confined to the shallower (generally < 100 m) inshore waters in the north and east of the study area, whilst the deeper water over the central and outer shelf stratifies during the summer months.

Much of the enhanced biological productivity of shallow water marine environments is associated with seasonal thermal stratification (Holligan, 1981; Scott et al., in press). The effects of vertical stability on phytoplankton distributions during the summer months on the NW European shelf are well-established (Pingree et al., 1975, 1976; Houghton, 1988). Nutrient renewal along fronts during the summer due to mixing by wind and tide combined with surface stabilisation during settled weather and neap tides intermittently create conditions suitable for rapid phytoplankton growth (Pingree et al., 1975; Tett et al., 1986). Such growth in turn leads to enhanced particulate flux to the sea bed in the vicinity of the frontal region (Jones et al., 1998). Given the spatial extent of seasonal stratification on a global scale, detailing the evolution of this phenomena is therefore of relevance to the carbon cycle, to climate change on a global scale and, in particular, to the modulating effect of sea level on global change. Whilst the example given here relates to seasonal stratification in the Celtic Sea, the principles invoked are applicable to tide-dominated shelf seas worldwide and therefore have implications for the significance of this phenomenon associated with eustatic highstands in the global climate system during the Quaternary.

Acknowledgements

We gratefully acknowledge support from NERC, research Grant GR3/11467 (J.D.S., W.E.N.A. and Kennedy). This paper is a contribution to IGCP projects 396 (Continental shelves during the Quaternary) and 437 (Coastal environmental changes during sea-level highstands in the late Quaternary). The satellite image was processed by the Plymouth Marine Laboratory Remote Sensing Group from data supplied by the NERC Dundee Satellite Receiving Station and kindly supplied by Dr Tim Smythe. The Marine Studies Group, the Quaternary Research Association and financial support from Amerada Hess Limited are gratefully acknowledged.

References

Ahmad, S.M., Guichard, F., Hardjawidjaksana, K., Adisaputra, M.K., Labeyrie, L.D., 1995. Late Quaternary paleoceanography of the Banda Sea. Mar. Geol. 122, 385–397.

Austin, R.M., 1991. Modelling Holocene tides on the NW European continental shelf. Terr. Nova 3, 276–288.

Austin, W.E.N., Scourse, J.D., 1997. Evolution of seasonal stratification in the Celtic Sea during the Holocene. J. Geol. Soc. London 154, 249–256.

Austin, W.E.N., Bard, E., Hunt, J.B., Kroon, D., Peacock, J.D., 1995. The ^{14}C age of the Icelandic Vedde Ash: implications for Younger Dryas marine reservoir age corrections. Radiocarbon 37, 53–62.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G., Rogerie, F., 1996. Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. Nature 382, 241–244.

Blais-Stevens, A., Clague, J.J., Bobrowsky, P.T., Patterson, R.T., 1997. Late Holocene sedimentation in Saanich Inlet, British Columbia, and its paleoseismic implications. Can. J. Earth Sci. 34, 1345–1357.

Blais-Stevens, A., Bornhold, B.D., Kemp, A.E.S., Dean, J.M., Vaan, A.A., 2001. Overview of Late Quaternary stratigraphy in Saanich Inlet, British Columbia: results of Ocean Drilling Program Leg 169S. Mar. Geol. 174, 2–26.

Bull, D., Kemp, A.E.S., Weedon, G.P., 2000. A 160 ky-old record of El Niño–Southern oscillation in marine production and coastal runoff from Santa Barbara Basin, California, USA. Geology 28, 1007–1010.

Cannariato, K.G., Kennett, J.P., 1999. Climatically related millennial-scale fluctuations in strength of California-margin oxygen-minimum zone during the past 60 ky. Geology 27, 975–978.

Cannariato, K.G., Kennett, J.P., Behl, R.J., 1999. Biotic response to late Quaternary rapid climate switches in Santa Barbara Basin: ecological and evolutionary implications. Geology 27, 63–66.

Curry, D., 1989. The rock floor of the English Channel and its significance for the interpretation of marine unconformities. Proc. Geol. Assoc. 100, 339–352.

Dean, J.M., Kemp, A.E.S., Pearce, R.B., 2001. Palaeo-flux records from electron microscope studies of Holocene laminated sediments, Saanich Inlet, British Columbia. Mar. Geol. 174, 139–158.

Eiríksson, J., Knudsen, K.L., Haflidason, H., Henriksen, P., 2000a. Late-glacial and Holocene palaeoceanography of the North Icelandic shelf. J. Quat. Sci. 16, 23–42.

Eiríksson, J., Knudsen, K.L., Haflidason, H., Heinemeier, J., 2000b. Chronology of late Holocene climatic events in the northern North Atlantic based on AMS ^{14}C dates and tephra markers from the volcano Hekla, Iceland. J. Quat. Sci. 16, 573–580.

Elliott, A.J., Li, Z., 1991. Thermocline depths and water temperatures at selected sites in the NW European shelf seas. Mar. Pollut. Bull. 22, 282–286.

Elliott, A.J., Li, Z., 1999. Temperature simulation in the NW European shelf seas. Coast. Estuarine Stud. 56, 175–193.

Elliott, A.J., Clarke, T., Li, Z., 1991. Monthly distributions of surface and bottom water temperatures in the northwest European shelf seas. Cont. Shelf Res. 11, 453–466.

Emmer, E., Thunell, R.C., 2000. Nitrogen isotope variations in Santa Barbara Basin sediments: implications for denitrification in the eastern tropical North Pacific during the last 50 000 years. Paleoceanography 15, 377–387.

Fairbanks, R.G., 1989. A 17 000-year glacio-eustatic sea-level record: influence of glacial melting rates on the Younger Dryas and deep ocean circulation. Nature 342, 637–642.

Field, D.B., Baumgartner, T.R., 2000. A 900 year stable isotope record of interdecadal and centennial change from the California Curent. Paleoceanography 15, 695–708.

Guilderson, T.P., Burckle, L., Hemming, S., Peltier, W.R., 2000. Late Pleistocene sea level variations derived from the Argentine Shelf. Geochemistry, Geophysics, Geosystems 1, Paper number 2000GC000098 (online).

Haflidason, H., Eiríksson, J., van Krefeld, S., 2000. The tephrochronology of Iceland and the North Atlantic region during the Middle and Late Quaternary: a review. J. Quat. Sci. 15, 3–22.

Hald, M., Vorren, T.O., 1987. Stable isotope stratigraphy and paleoceanography during the last deglaciation on the continental shelf off Troms, northern Norway. Paleoceanography 2, 583–599.

Hald, M., Labeyrie, L.D., Poole, D., Steinsund, P.I., Vorren, T.O., 1991. Late Quaternary paleoceanography in the southern Barents Sea. Nor. Geol. Tidsskr. 71, 141–144.

Hendy, I.L., Kennett, J.P., 2000. Dansgaard-Oeschger cycles and the California Current system: planktonic foraminiferal response to rapid climate change in Santa Barbara Basin, Ocean Drilling Program hole 893A. Paleoceanography 15, 30–42.

Holligan, P.M., 1981. Biological implications of fronts on the northwest European continental shelf. Phil. Trans. R. Soc. London A 302, 547–562.

Houghton, S.D., 1988. Thermocline control on coccolith diversity and abundance in Recent sediments from the Celtic Sea and English Channel. Mar. Geol. 83, 313–319.

Hughen, K.A., Overpeck, J.T., Peterson, L.C., Trumbore, S., 1996. Rapid climate changes in the tropical Atlantic Ocean region during the last deglaciation. Nature 380, 51–54.

Hughen, K.A., Overpeck, J.T., Lehmann, S.J., Kashgarian, M., Southon, J.R., 1998a. A new C-14 calibration data set for the last deglaciation based on marine varves. Radiocarbon 40, 483–494.

Hughen, K.A., Overpeck, J.T., Lehmann, S.J., Kashgarian, M., Southon, J., Peterson, L.C., Alley, R., Sigman, D.M., 1998b. Deglacial changes in ocean circulation from an extended radiocarbon calibration. Nature 391, 65–68.

Hughen, K.A., Southon, J.R., Lehmann, S.J., Overpeck, J., 2000. Synchronous radiocarbon and climate shifts during the last deglaciation. Science 290, 1951–1954.

Jones, S.E., Jago, C.F., Bale, A.J., Chapman, D., Howland, R., Jackson, J., 1998. Aggregation and resuspension of suspended particulate matter at a seasonally stratified site in the southern North Sea: physical and biological controls. Cont. Shelf Res. 18, 1283–1310.

Kennett, J.P., Cannariato, K.G., Hendy, I.L., Behl, R.J., 2000. Carbon isotopic evidence for methane hydrate instability during Quaternary interstadials. Science 288, 128–133.

Kershaw, P.J., Swift, D.J., Pentreath, R.J., Lovett, M.B., 1983. Plutonium redistribution by biological activity in Irish Sea sediments. Nature 306, 774–775.

Kiefer, T., Sarnthein, M., Erlenkeuser, H., Grootes, P.M., Roberts, A.P., 2001. North Pacific response to millennial-scale changes in ocean circulation over the last 60 kyr. Paleoceanography 16, 179–189.

Lambeck, K., 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. J. Geol. Soc. 152, 437–448.

Lambeck, K., 1996. Glaciation and sea-level change for Ireland and the Irish Sea since late Devensian/Midlandian time. J. Geol. Soc. 153, 853–872.

Larsen, E., Funder, S., Thiede, J., 1999. Late Quaternary history of northern Russia and adjacent shelves: a synopsis. Boreas 28, 6–11.

Nederbragt, A.J., Thurow, J.W., 2001. A 6000 yr varve record of Holocene climate in Saanich Inlet, British Columbia, from digital colour analysis of ODP Leg 169S cores. Mar. Geol. 174, 95–110.

Peacock, J.D., Austin, W.E.N., Selby, I., Harland, R., Wilkinson, I.P., Graham, D.K., 1992. Late Devensian and Holocene palaeoenvironmental changes on the Scottish Continental Shelf west of the Outer Hebrides. J. Quat. Sci. 7, 145–161.

Pingree, R.D., 1975. The advance and retreat of the thermocline on the continental shelf. J. Mar. Biol. Assoc. UK 55, 965–974.

Pingree, R.D., 1979. Baroclinic eddies bordering the Celtic Sea in late summer. J. Mar. Biol. Assoc. UK 59, 689–698.

Pingree, R.D., Griffiths, D.K., 1978. Tidal fronts in the shelf seas around the British Isles. J. Geophys. Res. 83, 4615–4622.

Pingree, R.D., Pugh, P.R., Holligan, P.M., Forster, G.R., 1975. Summer phytoplankton blooms and red tides along tidal fronts in the approaches to the English Channel. Nature 258, 672–677.

Pingree, R.D., Holligan, P.M., Mardell, G.T., Head, R.N., 1976. The influence of physical stability on spring summer and autumn phytoplankton blooms in the Celtic Sea. J. Mar. Biol. Assoc. UK 56, 845–873.

Pisias, N.G., Mix, A.C., Heusser, L., 2001. Millennial scale climate variability of the northeast Pacific Ocean and northwest North America based on radiolaria and pollen. Quat. Sci. Rev. 20, 1561–1576.

Scott, G.A., Scourse, J.D., Austin, W.E.N., in press. The distribution of benthic foraminifera in the Celtic Sea: the significance of seasonal stratification. J. Foraminiferal Res.

Scourse, J.D., Austin, W.E.N., 1994. A Devensian Late-glacial and Holocene sea-level and water depth record from the central Celtic Sea. Quat. Newsl. 74, 22–29.

Scourse, J.D., Austin, R.M., 1995. Palaeotidal modelling of continental shelves: marine implications of a land-bridge in the Strait of Dover during the Holocene and middle Pleistocene. Geol. Soc. London Spec. Publ. 96, 75–88.

Shennan, I., Lambeck, K., Flather, R., Horton, B., McArthur, J., Innes, J., Lloyd, J., Rutherford, M., Wingfield, R., 2000. Modelling western North Sea palaeogeographies and tidal changes during the Holocene. Geol. Soc. London Spec. Publ. 166, 299–319.

Simpson, J.H., 1976. A boundary front in the summer regime of the Celtic Sea. Estuarine Coastal Mar. Sci. 4, 71–81.

Simpson, J.H., Bowers, D., 1979. Shelf sea fronts' adjustments revealed by satellite IR imagery. Nature 280, 648–651.

Simpson, J.H., Bowers, D., 1981. Models of stratification and frontal movements in shelf seas. Deep-Sea Res. 28, 727–738.

Simpson, J.H., Allen, C.M., Morris, N.C.G., 1978. Fronts on the continental shelf. J. Geophys. Res. 83, 467–4614.

Tett, P., Edwards, A., Jones, K., 1986. A model for the growth of shelf-sea phytoplankton in summer. Estuarine Coastal Shelf Sci. 23, 641–672.

Walsh, J.J., 1988. On the Nature of Continental Shelves. Academic, San Diego, CA.

Wang, D., Chen, D., Sherwin, T.J., 1990. Coupling between mixing and advection in a shallow sea front. Cont. Shelf Res. 10, 123–136.

Yokoyama, Y., De Deckker, P., Lambeck, K., Fifield, L.K., 2000. Timing of the Last Glacial Maximum from observed sea-level minima. Nature 406, 713–716.