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The Holocene 2006 16: 931
DOI: 10.1177/0959683606hl984ed

The Holocene 16,7 (2006) pp. 931–935

Editorial: Late Holocene oceanographic and climate change from the western European margin: the results of the HOLSMEER project

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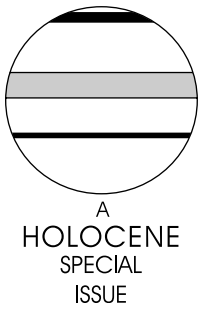

Abstract: The underlying aim of the HOLSMEER project has been to improve our understanding of natural climate variability through the search for, interpretation and quantification of, climatic variability in very high-resolution shallow marine records from Atlantic Europe covering the last 2000 years. This has been achieved through detailed analyses of a series of coastal and shallow marine sites spanning the Atlantic seaboard from Iberia to western Norway, and extending across to Iceland. HOLSMEER partners have documented pronounced instability in the thermohaline circulation (THC) during the period immediately prior to the recent significant anthropogenic impact on the environment. For the first time we have been able to document that these changes in the coastal ocean are correlated with significant changes in terrestrial palaeoclimate proxies, notably during the last 1000 years. The notable changes are the significance of warm sea surface temperatures (SST) associated with active THC between AD 700 and 1000, a transition phase to much colder SST and reduced THC between AD 1000 and AD 1300, colder SST through to AD 1900 followed by an active re-establishment of warm surface water circulation during the twentieth century. These switch-like reorganizations of the climate system have influenced the entire seaboard from western Iberia to western Norway, and have forced changes in ocean productivity, iceberg frequency and sea ice coverage. These changes have also directly influenced sea level through steric effects. The project has also resulted in significant advances in the establishment of new palaeoclimate proxies, including transfer functions related to benthic foraminifera, diatoms and dinoflagellate cysts. Annual growth band series from fossil specimens of the long-lived bivalve mollusc *Arctica islandica* from the northern North Sea have been successfully cross-matched, and independently verified by radiocarbon dating, to provide the longest *Arctica* chronology, and the first floating chronology constructed entirely from marine fossils.

Key words: Holocene, palaeoclimate, marine, thermohaline circulation, sea level, Arctica islandica, transfer function, HOLSMEER project, North Atlantic Ocean, western European margin.

Introduction, aims and objectives

The HOLSMEER project (2001–2004) was funded by the Energy, Environment and Sustainable Development programme of the EU Fifth Framework within Key action 2.1.4 'Climate variability and abrupt climate changes'. The rationale behind the project was that modelling predictions of the response of the climate system to anthropogenic forcings are most severely inhibited by inadequate understanding of natural climate variability. HOLSMEER aimed to improve our understanding of this natural variability through the search for, interpretation and quantification of, climatic variability in very high-resolution shallow marine records from Atlantic Europe covering the last 2000 years. We used long-term instrumental time series of marine and atmospheric parameters to calibrate the marine palaeoclimate observations, so extending the marine record to the period before systematic recording of environmental parameters was undertaken. This provides a basis for establishing the natural variability of the oceanic component of the climate system in the North Atlantic region prior to significant anthropogenic forcing of the environment.

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10.1177/0959683606hl984ed

The objectives of HOLSMEER were: (1) to generate high-resolution quantitative palaeoceanographic/palaeoclimatic data from NE Atlantic coastal/shelf sites for the last 2000 years using a multidisciplinary approach. (2) To develop novel palaeoclimatic tools for shallow marine settings by (i) calibrating the proxy data against instrumental data sets, (ii) contributing to transfer function development, and (iii) extrapolating back beyond the timescale of the instrumental data using the palaeoclimate record. (3) To investigate the link between late Holocene climate variability detected in the shelf/coastal regions of western Europe and the variability of the oceanic heat flux associated with the North Atlantic thermohaline circulation, and to compare such variability with existing high-resolution terrestrial proxies to help determine forcing mechanisms behind such climate change. (4) To lay a foundation for the identification of hazards and resources linked with, or forced by, such climate change.

These objectives have been addressed through the investigation of three shallow marine high-resolution archives of climate variability covering the last 2000 years: (1) high-resolution shallow marine (fjord, sea loch, ria, shelf basin) sedimentary sequences; (2) annual growth bands of the long-lived clam, *Arctica islandica*, (sclerochronology); and (3) high-resolution saltmarsh sequences. Palaeoclimate data from (1) have been based on stable isotopes, foram/diatom/dinocyst transfer functions and alkenone $U^{K'}_{37}$ sea surface temperature index, and age models based on AMS ^{14}C, ^{210}Pb, ^{137}Cs and tephrochronology. Statistical techniques developed in dendroclimatology have been used to crossdate *Arctica islandica* growth band floating chronologies (2) and the growth bands have yielded palaeoenvironmental data via stable isotopes and trace element geochemistry. The sea-level component (3) has generated high-resolution records of sea surface variability linked to other palaeoenvironmental proxies. These archives have been investigated in a transect of five key target sites across the NE Atlantic selected strategically to maximise the pressure gradient poles (Iceland Low to Azores High) characteristic of North Atlantic Oscillation-type variability (Figure 1). These records have been independently calibrated with instrumental and proxy terrestrial time series of atmospheric and sea surface temperature (SST), sea ice cover, salinity, precipitation, sea level (tide gauge) and storm frequency. These calibrations, along with micropalaeontological transfer functions, have enabled quantification of the marine proxy records for the period between 2000 years ago and the start of the instrumental records, the oldest of which date to the late seventeenth century.

The aim of this set of papers is to provide detailed reports on individual aspects of the HOLSMEER project, and the aim of this introduction is to provide an integrative overview of the overall outcome of the project.

Marine sedimentary sequences and saltmarsh records

For the northern coastal sites (North Sea region, including the Norwegian Trench, Skagerrak and German Bight; Figure 1; Hebbeln *et al.*, 2006, this issue; Gyllencreutz *et al.*, 2006, this issue) it is obvious in all data sets covering the last 2000 years that a major environmental shift took place between AD 700 and 1000. At this time an intensification of the advection of Atlantic waters to the Norwegian margin is recorded, and sites all along the European margin record a significant warming in SST. This is associated with an intensification of the circulation in the Skagerrak as evidenced by a significant increase in bottom current strength leaving also a clear signal in the benthic foraminiferal fauna. This is by far the most pronounced change in the benthic foraminifera communities in the Skagerrak through the last 2500 years. At the same time there is a clear decrease in the productivity in the Skagerrak, showing that not only the bottom but also the surface waters are affected by this shift. These are also affected by a long-term decrease in sea surface salinity (SSS).

The end of this event in the Skagerrak coincides with the end of the period with very strong advection of Atlantic waters to the Norwegian margin, and is associated with cooling, while at the same time a low salinity pulse in the Skagerrak points to enhanced Baltic Sea outflow possibly associated with high continental precipitation as indicated by a record from the German Bight (Hebbeln *et al.*, 2006, this issue). This pronounced change to cooler SST between AD 1300 and AD 1900 is recorded across the whole of the region, including the Icelandic shelf, along the Norwegian margin and Norwegian Channel, in a Scottish sea-loch and at the Iberian margin sites (Eiríksson *et al.*, 2006, this issue; Lebreiro *et al.*, 2006, this issue; Figure 1). This cooling is consistent with previously published data from the north Icelandic shelf (Knudsen *et al.*, 2004) and the Voring Plateau (cores JM97-948/2A and MD95-2011; Andersson *et al.*, 2003), and is associated with periods of increased ice rafting and lowered salinity in the north, and enhanced upwelling in Ría de Muros on the Iberian margin. For the first time this cooling period has been documented in several spatially separated and well-dated marine records covering the eastern North Atlantic margin. On the Iberian margin this cooling is linked to colder subpolar waters being transported southwards with the Portuguese/Canary Current System to the Tagus Prodelta and thus to a strengthening of the eastern boundary current system. As other sedimentary parameters reveal increased supply of terrigenous material to the Iberian margin during the same period, we interpret this shift towards generally cooler SST, and increased precipitation on the western Iberian Peninsula, to be related to a reduction of the thermohaline circulation and an associated atmospheric reorganization. In timing this corresponds approximately to dates previously assigned to the so-called 'Little Ice Age' recorded in land archives (Jones *et al.*, 2001). In these open shelf sites the records have a tendency to display higher temperatures prior to AD 1300 and back to AD 900 than compared with the period AD 1300–1900. Before AD 900 the similarity of the records is less obvious, although common features can be recognized in some of the records, such as the lower temperatures prior to AD 400 followed by a slight increase in temperature from AD 400 to AD 600 in the Norwegian Channel and Tagus Prodelta records. Another important result is that most parameters show increased SST and intensified northward flow of Atlantic water in the twentieth century. Further, climate shifts of shorter duration (less than a couple of hundred years) are found superimposed on the long-term climate changes in all records. However, because of the chronological uncertainty of 100–300 years it is difficult to correlate such brief events between records.

The major changes identified, notably the transition from warmer to cooler conditions at and before AD 1300, are similar to data from Holocene deep sea records from the North Atlantic. Moros *et al.* (2004), in a review of sea surface temperatures and ice rafting across the North Atlantic, identify

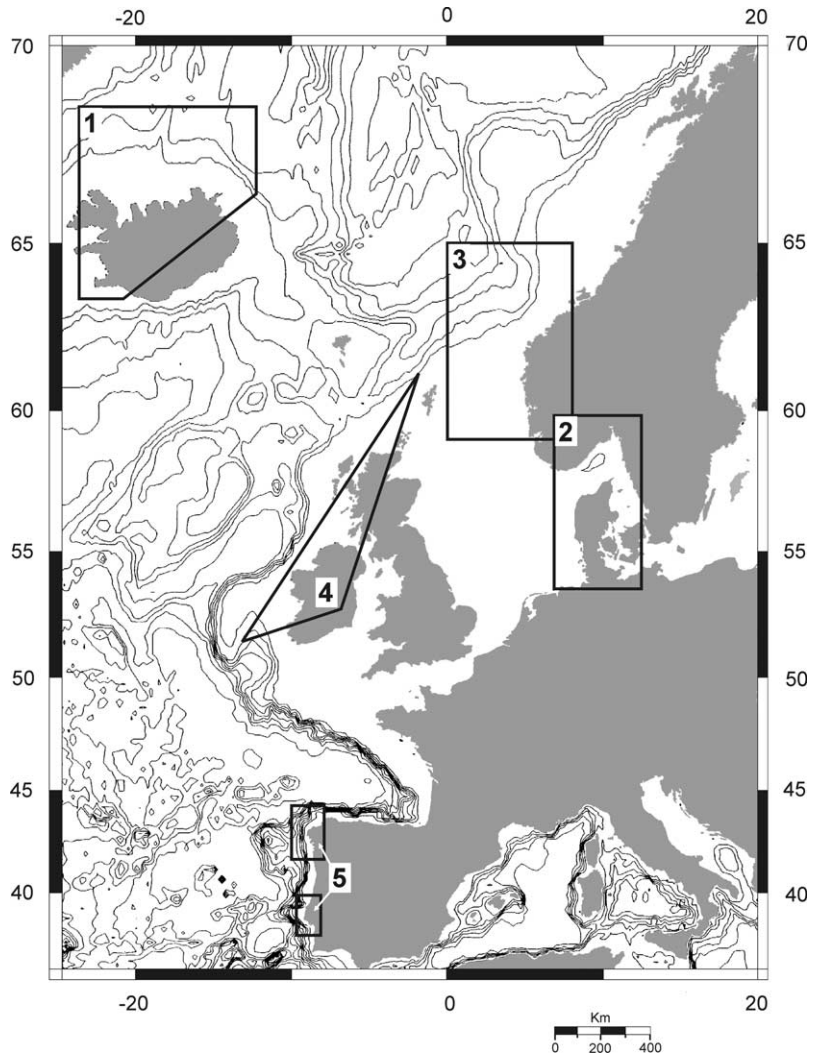

Figure 1 Location of key target sites used in the HOLSMEER project. 1, North and west Iceland; 2, Skagerrak and German Bight; 3, western Norway; 4, western British Isles; 5, western Iberia

a distinct SST decline between 2 and 0.5 kyr BP, which probably correlates with the cooling identified at higher resolution in the HOLSMEER records.

We have generated a high-resolution record of salinity variations linked to palaeoprecipitation in Central Europe from the German Bight for the past 800 years (Scheurle and Hebbeln, 2003; Scheurle *et al.*, 2005). Here $\delta^{18}O$ data are almost exclusively related to salinity variations as has been deduced from detailed correlations with instrumental records. The detailed salinity reconstruction for the German Bight is strongly controlled by Elbe river discharge that, in turn, is an integrated record of precipitation in Central Europe. The available record spans the last 800 years and indicates three periods of relatively high salinities (ie, low discharges and low precipitation): AD 1300–1400, AD 1590–1650 and AD 1800–1920.

An excellent saltmarsh sequence discovered at Viðarhólmi in western Iceland has yielded a sea-level record that, when detrended, shows a long-term sea-level fall between AD 500 and AD 1850 (Gehrels *et al.*, 2006, this issue). This corresponds with a long-term reduction of summer SST. This finding implies that thermal contraction (and expansion) contribute to sea-level variations in Icelandic coastal areas. Sea level began to rise abruptly around AD 1850 simultaneously in the northern Atlantic (Iceland) and the western Atlantic Ocean (Ireland and Portugal). This rapid sea-level rise is interpreted to be a response to an increase in global temperature.

Novel palaeoclimate proxies

HOLSMEER has made important contributions to the discovery and development of novel palaeoclimate proxies from shallow marine archives. Important developments in transfer functions related to benthic foraminifera (Sejrup *et al.*, 2004), diatoms (Jiang *et al.*, 2001, 2002) and dino-flagellate cysts (Marret *et al.*, 2004) have been achieved. The consortium have also provided new data on the relationships between the seasonal dynamics of temperature, salinity and oxygen isotopes in shelf seas, and the registration of these dynamics in the isotopic content of benthic foraminifera (Scourse *et al.*, 2004; Austin *et al.*, 2006, this issue). Annual growth band series from fossil specimens of the long-lived bivalve mollusc *Arctica islandica* from the northern North Sea have been successfully cross-matched (using SHELLCORR, a bespoke statistical tool developed within the project), and independently verified by radiocarbon dating, to provide the longest *Arctica* chronology and the first floating chronology constructed entirely from marine fossils (Scourse *et al.*, 2006, this issue). The record covers the period from AD 1000 to 1400

and integrates a 267-yr series from the longest-lived specimen yet recorded from the North Sea. This breakthrough in cross-matching demonstrates that *Arctica islandica* can fulfil its potential as the 'tree of the sea' to provide an absolute timescale for the marine environment. High-resolution $\delta^{18}O$ and Sr/Ca ratios from *Arctica* growth bands have helped confirm the annual nature of the growth bands and improved interpretation of very narrow 'doublet' bands whose chronological significance has hitherto been uncertain.

Conclusions of the HOLSMEER project

(1) A major environmental shift in the NE Atlantic took place between AD 700 and 1000. At this time an intensification of the advection of Atlantic waters to the Norwegian margin occurred, and sites all along the European margin record a significant warming in sea surface temperatures (SST). This is associated with an intensification of the circulation in the Skagerrak as evidenced by a significant increase in bottom current strength leaving also a clear signal in the benthic foraminiferal fauna.

(2) A pronounced change to prevalent cold SST between AD 1300 and 1900 is recorded across the whole of the region, including the Icelandic shelf, along the Norwegian margin and Norwegian Channel, in a Scottish sea-loch and at the Iberian margin sites. It is associated with periods of increased ice rafting and lowered salinity in the north, and enhanced upwelling off Iberia. For the first time this cooling period has been documented spatially in several well-dated marine records covering the eastern North Atlantic margin.

(3) We interpret these events to be linked to the dynamics of the North Atlantic thermohaline circulation and the associated atmospheric circulation changes.

(4) Before AD 900 the similarity of the records is less obvious, although some common features can be recognized, such as the lower temperatures before AD 400 followed by a slight increase in temperature from AD 400 to 600 in the Norwegian Channel and Tagus Prodelta records.

(5) All records show increased SSTs and intensified northward flow of Atlantic water in the twentieth century.

(6) A detailed salinity reconstruction for the German Bight for the past 800 years is strongly controlled by Elbe river discharge that, in turn, is an integrator of the precipitation in Central Europe. The record indicates three periods of relatively high salinities (ie, low discharges and low precipitation): AD 1300–1400, AD 1590–1650 and AD 1800–1920.

(7) An excellent saltmarsh sequence discovered at Viðarhólmi in western Iceland has yielded a sea-level record that, when detrended, shows a long-term sea-level fall between AD 500 and 1850. This corresponds with a long-term reduction of SST. This finding implies that thermal contraction and expansion contribute to sea-level variations in Icelandic coastal areas.

(8) Sea level began to rise abruptly around AD 1850 simultaneously in the northern Atlantic (Iceland) and the western Atlantic Ocean (Ireland and Portugal).

(9) Important developments in transfer functions related to benthic foraminifera, diatoms and dinoflagellate cysts have been made.

(10) Annual growth band series from fossil specimens of the long-lived bivalve mollusc *Arctica islandica* from the northern North Sea have been successfully cross-matched, and independently verified by radiocarbon dating, to provide the longest *Arctica* chronology, and the first floating chronology constructed entirely from marine fossils.

Acknowledgements

The HOLSMEER project was supported by European Union Fifth Framework project (EVK2-CT-2000-00060).

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