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A multi-proxy palaeolimnological study to reconstruct the evolution of a coastal brackish lake (Lough Furnace, Ireland) during the late Holocene

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ABSTRACT

This study examines the evolution of Lough Furnace, a coastal brackish lake in the west of Ireland, using high-resolution sensors in the water column and palaeolimnological examination of the sediment archive. Palaeoenvironmental reconstructions suggest that meromixis formed as a result of sea level rise prior to ca. 4000 cal. yr BP. Increased seawater inflow has progressively led to permanent water stratification, which caused the onset of anoxia, making the monimolimnion a harsh environment for biological life. Diatom floristic interpretations suggest a progressive upcore increase in salinity, which is paralleled by a reduction in cladocera remains. Diagenetic processes have not altered the sediment organic matter signature. Organic matter mainly derives from freshwater DOC and appears to be linked to the presence of peat bogs in the catchment as confirmed by the C/N ratio. Upcore variations in the C/N ratio with a ca. 800-year periodicity have been interpreted as the result of alternating dry and wet climatic phases during the late Holocene, which appear synchronous with the NAO and long-term solar cycles. The current hydrology is largely controlled by freshwater inflow, which determines permanent meromictic conditions. Overturns are rare, requiring a specific combination of factors such as exceptionally dry and warm summers followed by cool autumns. According to the climate projections for the next century in Ireland, permanent meromictic conditions will probably continue.

1. Introduction

Coastal lagoons formed at the land–sea interface are rare habitats representing only 5.3% of European coasts (Barnes, 1980). Coastal lagoons are common around the shores of the Baltic, Mediterranean and the Black Sea (Doody, 2005), whilst on the northwest European Atlantic they are naturally rare (Barnes, 1989; Joint Nature Conservation Committee, 1996).

The land–sea interface is an exceptionally dynamic zone that shows strong non-linear physical and biological forces from both terrestrial and marine environments (Talley et al., 2003). Lagoons are paralic systems (Guelorget and Perthuisot, 1992), characterised by marine, brackish and freshwater deposits. These environments are generally unstable and susceptible to variations in hydrological components making them the most changeable and vulnerable environments on Earth (Viaroli et al., 2007). The main natural hydrological components include droughts, flooding, storms and sea-level rise (Kennish and Paerl, 2010), all of which are likely to be impacted by increased global warming (IPCC, 2007; Dunne et al., 2008). The presence of both fresh water and marine water combined with lagoon geomorphology may lead to the development of ectogenic meromictic conditions, where an external source of saline water into a fresh water lake restricts water column circulation to a surface layer (Walker and Likens, 1975; Hakala, 2004). Salinity is the primary stratification driver and temperature and thermal circulation processes are impeded. Therefore, overturns are limited to the top layer (i.e. mixolimnion), whilst the bottom of the lake (i.e. monimolimnion) can develop anoxia that represents a threat to aquatic life.

Climate fluctuations have occurred over different time-scales, spanning decades to millennia. Lagoons are generally short-lived coastal features formed during the Holocene (Kjerfve, 1986) and represent unique habitats vulnerable to climate change. In particular they are endangered by progressive sea level rise, which has been recorded over the Holocene and is expected to continue into the future (IPCC, 2007; Bates et al., 2008; Dunne et al., 2008). Palaeoclimatic records suggest the existence of multiple periods of rapid climate change during the Holocene in North Atlantic Ocean land masses (Mayewski et al., 2004; Wanner et al., 2001). A transition to generally warm but relatively unstable conditions characterised the late Holocene (Moros et al., 2004; Turney et al., 2006; Swindles et al., 2010) that have been associated with solar variability (Mauquoy et al., 2008), changes in the strength of the thermohaline circulation (Bianchi and McCave, 1999) and the North Atlantic Oscillation (NAO) (Nesje and Dahl, 2003; Trouet et al., 2009). Changes in relative sea level (RSL) are part of a complex pattern

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involving seawater volume and mass change, tectonics and dynamic changes due to external forcing exerted on the sea surface (Chao et al., 2002; Mörner, 2006) whilst Glacio-Isostatic Adjustment (GIA) also played an important role (Horton 2006; Miettinen et al., 2007). A strong north–south trend in glacio-isostatic loading is evident in the British Isles, where uplift is evident in central and western Scotland and Northern Ireland and is coincident with submergence in southwest England and southern Ireland (e.g. Shennan and Horton, 2002; Roberts et al., 2006; Smith and Kamiya, 2006; Gehrels, 2010). The extent to which globally averaged sea levels have risen over the Holocene is unclear (Edwards, 2006). A number of global (Klemann and Wolf, 2007; NOAA, 2012) and local (e.g. Tushingham and Peltier, 1992; Shennan and Horton, 2002; Brooks and Edwards, 2006; Vink et al., 2007; Engelhart and Horton, 2011) RSL databases of the Holocene have been collated. Brooks and Edwards (2006) estimate a rise from ca. −6 m ca. 7000 cal. yr BP to ca. −2 m approximately 5000 cal. yr BP for Ireland and British Isles. However, despite a range of quantitative relative sea level data (e.g. Sinnott, 1999; Devoy et al., 2006), precise and reliable information about changes since the early Holocene for parts of the Irish coastline remains incomplete (Brooks et al., 2008).

A number of ecological studies have been conducted and published on Irish lagoons (e.g. Parker, 1977; Parker and West, 1979; Pybus and Pybus, 1980; Healy et al., 1982; Norton and Healy, 1984; Healy, 1997, 1999a,b; Oliver, 2005; Roden and Oliver, 2010). However, these inventorial surveys provided only a snapshot examination of physico-chemical and biological data. Long-term data sets are needed to aid in the understanding of coastal ecosystems (Talley et al., 2003). For almost all lakes, palaeolimnology is the only means of obtaining data on past trends (Battarbee, 1999). Coastal lagoons provide a suitable sedimentary environment for palaeoecological study because they are relatively sheltered from wave and tide exposure (Bennion and Battarbee, 2007) and are influenced by changes affecting both freshwater and marine environments (Ryves et al., 2004). Therefore, sediments contain the ontogeny (i.e. development through time) of basins themselves. Sediments also record information on atmospheric deposition and its terrestrial watershed (O'Sullivan, 2004) as well as changes derived from the marine environment (e.g. marine transgression). Palaeolimnology of coastal lakes also assists in determining the presence of marine or non-marine deposition, which in turn can be potentially linked back to climate patterns (Battarbee et al., 2002; Lotter, 2005). Many palaeoecological studies have successfully reconstructed the evolution of coastal lagoons by combining a number of proxies (e.g. Müller and Mathesius, 1999; Weckström, 2006; Cearreta et al., 2007; Blázquez and User, 2010). However, only a very small number of studies have been conducted on coastal lagoons in Ireland (Buzer, 1981; Holmes et al., 2007).

In a European context lagoons are recognised as vulnerable systems (Airoldi and Beck, 2007). The Habitats Directive (92/43/EEC) aims to maintain biodiversity through the conservation of natural habitats and by defining Special Areas of Conservation (SACs). Additionally, lagoons are included in the Water Framework Directive (WFD) (2000/60/EC) as priority habitats for conservation (Annex I). The Directive aims to achieve good ecological status in all relevant waters between 2015 and 2027 and requires baselines of reference conditions prior to anthropogenic impact to be identified. Moreover, the identification of natural background conditions and longer-term natural variability is often essential for conducting informed lake management programmes (Smol, 2008). In the absence of long-term data, and considering the dynamic nature of coastal lagoons, palaeolimnological reconstructions offer perhaps the only source of information regarding baseline reference conditions.

The aim of this paper is to reconstruct the evolution of Lough Furnace, a brackish coastal lagoon on the western coast of Ireland, during the late Holocene using a multiproxy palaeolimnological approach. Particular attention was focussed on the reconstruction of meromixis formation as a result of the relative sea level rise. The palaeolimnological investigation of this hydrologically complex system was furthermore augmented using high-resolution time series data on salinity, temperature and dissolved oxygen measured through the water column over a two-year period, to better understand modern and future system dynamics. The influence of climate variability on the palaeohydrology of Furnace and the future hydrological scenarios given the predicted global warming make this study highly relevant.

2. The study area

Lough Furnace is located in the Burrishoole catchment (N 53°55′22″, W 9°34′20″) at the north-eastern corner of the Clew Bay (northwest Ireland) (Fig. 1a). The geology of the catchment is dominated by metamorphic rocks of late Precambrian age (Long et al., 1992), represented by schists, gneiss and quartzites (Whelan et al., 1998). Catchment land cover consists of peat bog and forestry (Bossard et al., 2000). The upper part of the catchment is considered to be one of the best examples of an active blanket bog (NPWS, 2001), which represents 71% of the catchment today (Bossard et al., 2000) whilst forest plantations occupy 23% of the catchment (Forest Inventory and Planning System, unpublished data). Pollen records from the Late Glacial suggest early development of woodland, its subsequent decline and then the development of peat and bog ca. 5000 cal. yr BP (Browne, 1986). Anthropogenic influences of fire and grazing probably accelerated deforestation (Coxon et al., 1991). From the 13th to the 18th centuries the Burrishoole Channel was an important port, which facilitated trade with northern Mayo through the Nephin Beg mountains (Synge, 1963). Since the mid-1950s the Burrishoole catchment has been an important site of fisheries research, with fish census and catchment monitoring being conducted by the Marine Institute.

Furnace is part of the Clew Bay Complex SAC (site code 1482) and is described as a good example of a deep, stratified, saline coastal lake in a very natural state (NPWS, 2001). The lake has a surface area of 141 ha, a maximum depth of 21 m, a diameter of 1850 m, and it is approximately 800 m wide on average. Furnace is located to the south of the catchment (Fig. 1b) and receives highly coloured drainage waters (52–112 mg l^{-1} PtCo; Marine Institute, unpublished data) that strongly limit the photic zone depth (ca. 1.7 m). The Burrishoole Channel connects Furnace to the sea in Clew Bay and semidiurnal tides flow northward into the lake.

Furnace is a permanently meromictic lake and only a single water column overturn is known to have occurred on the 12th September 1995 (Salmon Research Agency, 1995). This caused a major fish kill that wiped out trout and char that were caged in the lake at the time. Measurements of oxygen revealed an epilimnion depleted in oxygen (<2 mg l^{-1} DO) whilst the temperature profile showed isothermal conditions (ca. 17 °C). The summer of 1995 was exceptionally hot with average air temperatures of ca. 17 °C and low rainfall (175 mm) (Marine Institute, unpublished data). The water temperature within the hypolimnion from June to August 1995 was 4–5 °C warmer than any previously recorded measurements (Salmon Research Agency, 1995). Due to the negligible input of freshwater in the summer of 1995, the halocline progressively disappeared and stratification was maintained by the thermocline only (Salmon Research Agency, 1995). As the weather cooled in the early autumn, isothermal conditions were mainly responsible for the mixing event, which moved anoxic water upward from the monimolimnion. An examination of summer rainfall records (i.e. the sum of precipitation in June, July and August) from 1960 (Marine Institute, unpublished data) suggests that rainfall in 1976, 1983 and 2006 was lower than 1995, but no overturns were documented. Therefore, it is likely that the combination of the disappearance of both halocline and thermocline together with the contribution of a northerly wind caused the 1995 event (Russell Poole, pers. comm.). Similar lagoon dynamics were documented by Lamont et al. (2004), who found that the upwelling of anoxic water depends on the coincidence of strong winds and low levels of precipitation, which results in a weak salinity stratification. The fish kill associated with the 1995 overturn was probably due to the upwelling of hydrogen sulphide rather than anoxic waters. The permanent or extended stratification of