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The early Holocene sea level rise

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ABSTRACT

The causes, anatomy and consequences of the early Holocene sea level rise (EHSLR) are reviewed. The rise, of ca 60m, took place over most of the Earth as the volume of the oceans increased during deglaciation and is dated at 11,650–7000 cal. BP. The EHSLR was largely driven by meltwater release from decaying ice masses and the break up of coastal ice streams. The patterns of ice sheet decay and the evidence for meltwater pulses are reviewed, and it is argued that the EHSLR was a factor in the ca 8470 BP flood from Lake Agassiz-Ojibway. Patterns of relative sea level changes are examined and it is argued that in addition to regional variations, temporal changes are indicated. The impact of the EHSLR on climate is reviewed and it is maintained that the event was a factor in the 8200 BP cooling event, as well as in changes in ocean current patterns and their resultant effects. The EHSLR may also have enhanced volcanic activity, but no clear evidence of a causal link with submarine sliding on continental slopes and shelves can yet be demonstrated. The rise probably influenced rates and patterns of human migrations and cultural changes. It is concluded that the EHSLR was a major event of global significance, knowledge of which is relevant to an understanding of the impacts of global climate change in the future.

1. Introduction

The early Holocene, defined here as 11,650 to 7000 calibrated years before 1950 (BP), was a time of widespread environmental change as temperatures rose rapidly at the end of the last glaciation. A notable feature of this time was the ca 60m rise in sea levels over most of the Earth, as several studies imply (e.g. Fairbanks, 1989; Bard et al., 1996). This has attracted a great deal of scientific attention in recent years and we believe that it is timely to consider the published evidence for this rise and its impacts on the environment. We review the likely causes of the sea level rise, including its effects on the decay of coastal ice streams, before outlining the nature of the rise and its effects on coastlines. We then examine its possible consequences, in particular its relationship to climate, volcanic activity and submarine sliding, before considering its impacts on Mesolithic and Neolithic cultures. In a concluding statement, the paper summarises the changes described; comments on the relevance of studies of early Holocene sea level change as a key to understanding patterns and rates of change during glacial terminations; and concludes with a brief account of the extent to which an understanding of this phase of Earth history can prepare us for Earth system responses in the foreseeable future.

In the account which follows, sea level (SL) refers to the level of the sea surface without reference to the land and relative sea level (RSL) refers to the level of the sea as observed at the coastline. All dates given here are in sidereal (calibrated) years. Where original calibrated radiocarbon dates are not given in the published accounts quoted, calibrated dates have been obtained using Calib 6.0 (Reimer et al., 2009). All dates are given as before 1950: where 2000 AD is the datum (as with some ice core records), dates have been adjusted. Locations discussed are shown in Figs. 1, 3,5 and 7.

2. Definition

The early Holocene SL rise (here referred to by the acronym EHSLR) was a period of rapid rise over most of the Earth's oceans which took place between 11,650 BP and 7000 BP. Ocean volume had been increasing after the Last Glacial Maximum (LGM) according to the oxygen isotope record (e.g. Chappell and Shackleton, 1986; Cayre et al., 1999), but studies of low latitude coral records (e.g. Edwards et al., 1993; Montaggioni et al., 1997; Bard et al., 2010) indicate that the increase slowed during the Younger Dryas (ca 12,900–11,650 years BP based on Rasmussen et al., 2006 and Walker et al., 2009). By the start of the Holocene

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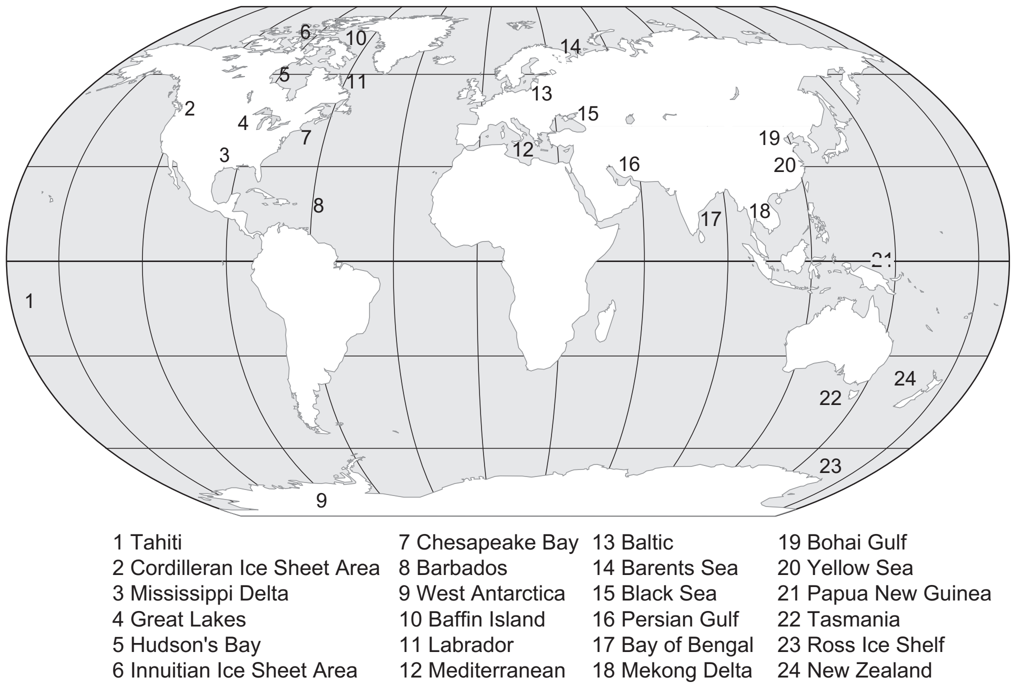

Fig. 1. Some locations discussed in this paper. Other locations are shown in Figs. 3, 5 and 7.

ocean volume was again increasing rapidly. However, by ca 7000 BP a sharp change in the rate of rise in both ocean volume and SLs took place, and the overall rise after ca 7000 BP became an order of magnitude less, as reflected in models for areas where RSL approaches global mean SL (e.g. Fleming et al., 1998; Milne et al., 2005).

3. Causes of the early Holocene sea level rise

The increase in ocean volume in the early Holocene was primarily driven by meltwater release as atmospheric temperatures rose and ice sheets decayed. Steric effects were of much less significance. Thus Milne et al. (2009) observed that although sea temperatures rose, steric effects including thermal expansion were probably "within data uncertainty" (p. 474), since because of the oceans' very large thermal inertia, ocean temperatures would have varied less than atmospheric temperatures. Proxy records from a number of sources and locations document the increase in atmospheric temperatures during the early Holocene. Data from Greenland ice cores (e.g. Johnsen et al., 1992, 2001; Dansgaard et al., 1993; Cuffey et al., 1995; Taylor et al., 1993; Stuiver and Grootes, 2000; Rasmussen et al., 2006) imply a remarkably rapid rise in temperature. Taylor et al. (1997) observe that at GISP2, temperatures rose by ca 15 °C over 1500 years following the end of the Younger Dryas, with abrupt steps at 11,660, 11,645 and 11,612 BP. They place the transition between the Younger Dryas and Holocene as having taken place over as little as 40 years, and it has been suggested that by as early as ca 9500 BP, global temperatures were close to pre-industrial levels (Mackay et al., 2003). This period of rapid warming initiated the further decay of glaciers and ice sheets which had begun after the LGM.

The rapid decay of ice sheets and glaciers at the end of the last glaciation has been remarked upon in many accounts (e.g. Denton et al., 2010). Factors which would have contributed to the decay include the topographic setting of the ice masses and the effects of local and regional meteorology and climate. The EHSLR probably had an effect on the break up of coastal ice streams. Where such streams terminate in ice shelves, as recent studies (e.g. De Angelis and Skvarca, 2003; Dupont and Alley, 2005) show, the shelf often buttresses the ice stream through "back pressure", and the break up of buttressing ice shelves may speed up the flow of contiguous ice streams. In the early Holocene, with thinning of ice masses and a rise in RSL, the break up of ice shelves would have been noticeable, with the speeding-up or even surging of ice streams, leading to their disintegration. In the following section we review the pattern of retreat in both hemispheres and discuss meltwater pulses associated with the retreat.

3.1. *The decay of glaciers and ice sheets*

3.1.1. *The northern hemisphere*

At the start of the Holocene, ice sheets and glaciers were still widespread. In North America, the Cordilleran Ice Sheet, which had been rapidly retreating since the LGM, still terminated in coastal ice streams along the Pacific coast. Clague and James (2002) remark that the Pacific margin of the ice sheet was probably disrupted by the rising SL, presumably at least in part by the break up of ice shelves and contiguous coastal ice streams. They also observe that the rapid glacio-isostatic uplift in the southern areas of the former ice sheet indicates that it retreated rapidly, with the discharge of lakes on the southern margin of the ice sheet notably contributing to the output of meltwater (Blais Stevens et al., 2003). Clague and James (2002) maintain that by as early as ca 10,800 BP, Cordilleran glaciers were little more extensive than at the present day.

Across the Canadian Arctic Archipelago, the Innuitian Ice Sheet, contiguous with the Laurentide Ice Sheet to the South, was extensive during the Younger Dryas, but began to disintegrate rapidly by ca 11,600 BP, "gutted" by rising temperatures and rising SLs (England et al., 2006). The pattern of disintegration of this widely marine based ice mass probably involved the break up of ice shelves resulting in more rapid flow of the ice streams and by ca 8900 BP the fjord areas were ice-free. In contrast, the Greenland Ice