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Ice sheets and rapid climate change

P.U. Clark (1)

(1) Oregon State University, Corvallis, OR, USA

Ice sheets have the potential to induce rapid climate change through their release of freshwater to sites of intermediate or deepwater formation, with attendant changes in ocean heat transport. The paleo record has suggested four specific mechanisms of release: an ice-sheet instability resulting in abrupt release of icebergs (Heinrich events), intervals of extreme mass loss expressed as rapid sea-level rise (meltwater pulses), rearrangement of continental runoff (routing events), and abrupt discharge of proglacial lakes (floods). (1) Heinrich events (HE's) are commonly cited as representing an ice-sheet surge that triggers a large reduction in the Atlantic Meridional Overturning Circulation (AMOC). There appears to be little change in sea level at the time of HE's, and many records suggest sea-level rise prior to HE's during marine isotope stage 3, contrary to the direction required by the binge-purge instability hypothesis. Moreover, HE's occur at times of maximum expression of the bipolar seesaw (cold north, warm south), suggesting the AMOC had collapsed by the time of an HE. One explanation of HE's consistent with these relations is an ice-shelf collapse induced by oceanic forcing associated with subsurface warming that develops when the AMOC collapses. (2) The $\sim$20-m sea-level rise during meltwater pulse (MWP) 1A $\sim$14.5 ka indicates an extraordinary episode of ice-sheet collapse, with an associated freshwater flux to the ocean ($\sim$0.5 Sv for 300 yr) that is thus far unprecedented in paleo-records. The debate over MWP-1A centers on its timing, source and its affect on climate. I summarize key points in this debate, and conclude that a dominant (but unlikely sole) source from Antarctica coincident with the start of the Bolling remains the most consistent explanation of the data. (3) The most well-known routing event involved retreat of the Laurentide Ice Sheet (LIS) that redirected continental runoff from the Mississippi to the St. Lawrence River, triggering the Younger Dryas. Recent challenges to this hypothesis have suggested that the routing went to the Arctic Ocean instead. I review recent

paleoceanographic evidence that supports the conventional south-to-east routing and not the south-to-north routing. (4) The most well-known flood is the sudden drainage of Lake Agassiz that is widely identified as the cause of the 8.2 ka event. This event was unique to the last stages of the LIS, however, and similar such events should only be expected in association with similar such ice-sheet configurations. If other floods occurred at other times, they were likely much too small to impact climate.