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Melt-Water-Pulse (MWP) events and abrupt climate change of the last deglaciation

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The last deglaciation is characterized by massive ice sheet melting, which results in an average sea-level rise of ~120－140 m. At least three major Melt-Water-Pulse (MWP) events (19ka-MWP, MWP-1A and MWP-1B) are recognizable for the last deglaciation, of which MWP-1A event lasting from ~14.2 to ~13.7 ka B.P. is of the most significance. However, the accurate timing and source of MWP-1A event remain debatable and controversial. It has long been postulated that meltwater of the last deglaciation pouring into the North Atlantic resulted in a slowdown or even a shutdown of the thermohaline circulation (THC) which subsequently affected the global climate change. Accordingly, the focus of this debate consists in establishing a reasonable relationship between MWP events and abrupt climate change. Here we summarize a variety of geological and model results for the last deglaciation, reaching a conclusion that the major MWP events did not correspond with the rigorous stadials, nor always happened within climate reversal intervals. MWP events of the last deglaciation had very weak influences on the intensity of the THC and were not able to trigger a collapse of the global climate. We need to reevaluate the influences of the temporal meltwater variability on the global climate system.

deglaciation, Melt-Water-Pulse, thermohaline circulation, abrupt climate change

Thermohaline circulation (THC) can be defined as currents driven by fluxes of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt[1]. In the subarctic regions of the North Atlantic, the Weddell Sea and the Ross Sea along the Antarctic continental shelf, the upper seawater chills and sinks as a result of increased density, forming the deep and bottom waters which then circulate between global oceanic basins. The deep and bottom water circulations are called the great ocean conveyor belt[2]. The North Atlantic Deep Water (NADW) is the most important component of the THC. The intensity of the NADW determines the state of the THC. Both geological records and modeled results suggest that the intensity and yielding rate of the NADW are responsible for the abrupt climate oscillations during the last glacial period[2,3]. There are three distinct circulation modes prevailing in the Atlantic, viz. stadial mode, interstadial mode and Heinrich mode. In interstadial mode, NADW forms in the Nordic Seas. In stadial mode, it forms in the subpolar open North Atlantic (that is, south of Iceland), and in Heinrich mode, it almost ceases and water of Antarctic origin fills the deep Atlantic basin[3].

Several general ocean circulation models and coupled ocean-atmosphere models have demonstrated that the THC is particularly sensitive to the freshwater fluxes in the high-latitude oceans[3,4]. In an early study, Broecker et al.[5] have postulated a mechanism of the relationship between NADW formation and freshwater fluxes, that the local net precipitation and continental runoff in the North Atlantic region alter the sea surface salinity and subsequently affect the production of NADW. When

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piling up to a critical point, the freshwater fluxes will trigger the THC and climate system to shift between different quasi-stable modes. Though this mechanism still needs to be elaborated, it emphasizes the important role of freshwater fluxes in triggering the abrupt climate changes and becomes a base of subsequent researches. Various numerical models almost hold the same evaluations on the effect of freshwater discharge to the ocean, that freshwater discharge reduces the NADW production and causes slow down or even shut down of the THC, resulting in a rapid cooling in the North Atlantic and the surrounding regions. The cooling then spreads to global oceans through ocean-atmosphere coupling effect. Although the northward meridional circulation weakens, heat from the low latitudes will be transported to the south and then warm Antarctica and the adjacent areas[6−10], forming a giant bipolar seesaw.

During the Last Glacial Maximum (LGM), North America and Scandinavia were covered by massive ice sheets. The Arctic Ocean and the Southern Ocean around the Antarctica were also overlaid by outspreading sea ice (Figure 1, Table 1). All these expanded ice sheets had melted during the last deglaciation, resulting in a global sea-level rise of 120—140 m[20−22]. Pouring of the meltwater into the North Atlantic and the ambient seas around Antarctic could definitely lead to significant changes of the THC and global climate. Clark et al.[2] once claimed “If we can identify the mechanisms that influenced the North Atlantic freshwater budget, then we could understand past changes in the THC”. Therefore, there must be some causal correlations between ice sheet melting, meltwater pulses, formation of the NADW and abrupt climate change.

1 Geological records and timing of MWP events

Meltwater discharge of the last deglaciation led to remarkable sea-level rise. Therefore, the reconstructed sea-level change from geological records is usually used to trace the rate and process of ice sheet melting. The last deglaciation extended from ~21 to ~6 ka B.P., corresponding with a sea-level rise of 120 m, with an average rate of 8 mm/a. In nature, sea-level does not rise at a constant rate. Coral records from the Barbados island clearly demonstrate that the last deglaciation was punctuated by two episodes of accelerated ice sheet melting and rapid sea-level rising, viz. MWP-1A (Melt-Water-Pulse) and MWP-1B intervals[23] (Figure 2). U/Th abso-

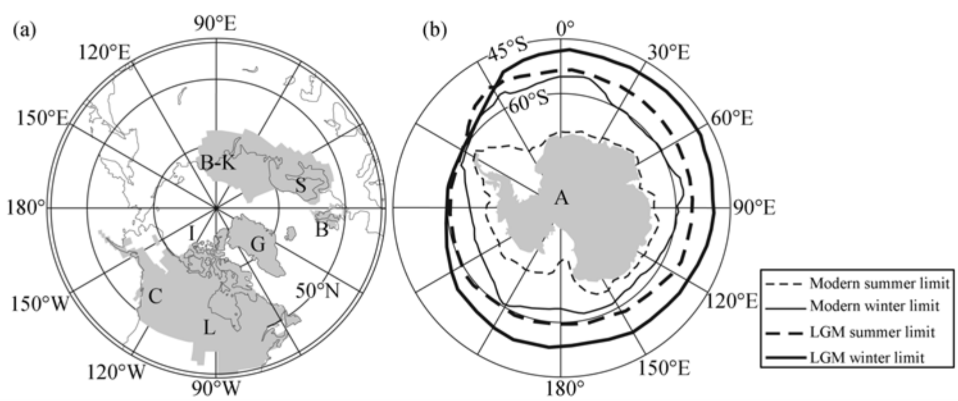

Figure 1 Geographical distribution of major ice sheets during the LGM. (a) L, Laurentide; C, Cordilleran; I, Innuitian; G, Greenland; B, British; S, Scandinavian; B-K, Barents and Kara, modified from ref. [11]. (b) A, Antarctica; LGM, last glacial maximum, modified from ref. [12].

Table 1 Assessment of the contribution of the melted ice sheets to sea-level rise during the LGM (modified from ref. [13]) (unit: m)

Ice sheet	CLIMAP Min Model[14]	CLIMAP Max Model[14]	Peltier[15]	Others' estimates
North America	77.0a)	92.0b)	64.3	82.7c)[16]
Greenland	1.0	6.5	6.0	1.9—3.5[17]
Eurasia	20.0	34.0	25.5	13.8—18.0[18]
Antarctica	24.5	24.5	17.6	14[19], or 13—21[17]
Others	5.0	6.0		
Total	127.5	163	113.5	

North America Ice Sheet includes Laurentide, Cordilleran and Innuitian ice sheets. Eurasia Ice Sheet consists of Scandinavian, British, and Barents-Kara ice sheets, but the CLIMAP minimum model only includes Scandinavian ice sheet. Contribution of Laurentide Ice Sheet is 76, 85 and 72. 4 m for a), b) and c) respectively.

lute dating on corals demonstrates that MWP-1A event happened between 14.2±0.1 and 13.7±0.1 ka B.P., leading to a sea-level rise of ~19 m in 500 years, with a rate of ~38 mm/a, and MWP-1B event happened between 11.5 and 11 ka B.P., corresponding to a sea-level rise of ~15 m, with a rate of ~30 mm/a[24,25]. MWP-1A event is also confirmed in the sea-level change record reconstructed from Tahiti corals of the southern Pacific. The new dating on Tahiti corals indicates that the sea-level jump with the largest amplitude commenced at ~14 ka B.P.[26]. Recent high resolution re-dating on Barbados corals suggests that the onset of MWP-1A event is younger than ~14.14 ka B.P.[22,27,28]. Comparison between coral records and Greenland ice core records indicates that MWP-1A event corresponds to the Older Dryas, a short cooling event within the Bølling-Allerød warming interval, whereas MWP-1B event corresponds to a tiny cooling event just after the termination of the Younger Dryas (YD) (Figure 3). In the new GICC05 timescale, Bølling warming event commenced at ~14.65±0.18 ka B.P. and the Older Dryas event started at ~14.05 ka B.P.[29].

Even within the early last deglaciation happened rapid ice sheet melting, which is documented in a long sea-level change record. Evidence of sedimentary facies from the shallow Bonaparte Gulf in north Australia proved that a rapid sea-level rise of ~10—15 m within a few hundred years terminated the LGM at ~19.0±0.25 ka B.P.[21]. Clark et al.[30] recognized this meltwater pulse event in sedimentary records along the Irish Sea

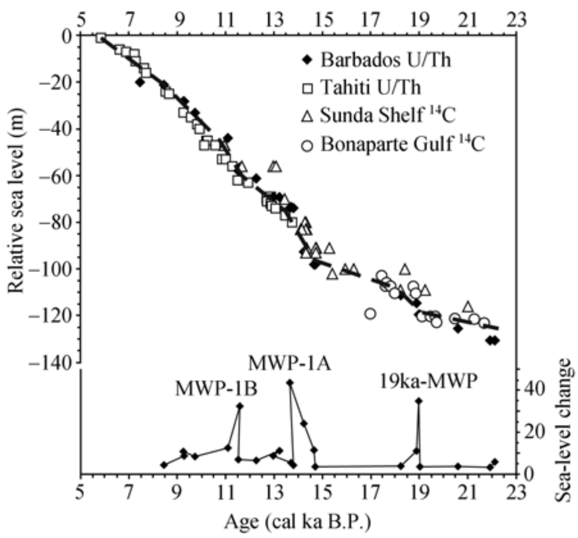

Figure 2 Sea-level rise during the last deglaciation derived from various geological records. Note that rate of seal-level rise is calculated from U/Th dating on corals from Barbados.

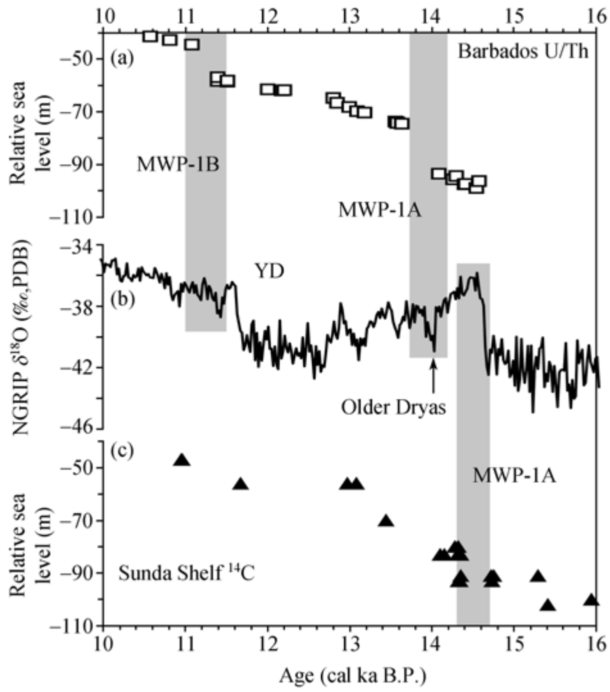

Figure 3 MWP-1A event in (a) Barbados coral records[22] and (c) Sunda shelf from the South China Sea. (b) NGRIP $\delta^{18}O$ record plotted against GICC05 timescale[29].

coast and named it 19ka-MWP event (Figure 2), which is considered to be caused by the retreat of the edge of the Northern Hemisphere ice sheets. Subsequently, the southeastern edge of the Scandinavian Ice Sheet is proved to once retreat very quickly during this period based on cosmogenic nuclide and radiocarbon dating results[31].

Of the three meltwater pulse events, the most significant MWP-1A event has been largely documented in a lot of sea-level change records. Still, the accurate timing of this event remains debatable. According to a number of AMS ^{14}C dating on mangrove roots, larger wood fragments and coarse-grained peaty detritus from the Sunda Shelf, Hanebuth et al.[32] found that MWP-1A event should happen between ~14.6 and 14.3 ka B.P., with a sea-level rising rate of 53.3 mm/a, which is higher than that derived from Barbados and Tahiti coral records. Taking this age, MWP-1A event should not commence in the Older Dryas cooling interval but in the inception of the Bølling warming period (Figure 3). A U^k_{37}-derived sea surface temperature profile of core 17940 in the northern South China Sea (SCS) exhibits an abrupt warming event at ~14.7 ka B.P., well defining the onset of the Bølling warming event of this region[33]. Synchronously, *n*-nonacosane concentration of this core was rapidly reducing, implying a fast drop of the terrigenous organic matter supply to the SCS[34]. The drop of *n*-nonacosane concentration in the SCS is interpreted as a result of reduced riverine runoff into the continental slope, which was caused by a sudden flooding of the exposed continental shelf and the subsequent rapid retreat of the shoreline[34]. The SCS records indicate the synchroneity of MWP-1A event and Bølling warming event[34]. However, the beginning of MWP-1A event lags the beginning of Bølling warming event by at least 400—500 years in the Barbados coral records.

Probably, both U/Th-dated Barbados coral records and ^{14}C-dated Sunda Shelf sediment records are defective. If sea-level rises at a rate of 10—20 mm/a or even higher, shallow-water coral reefs will be submerged and drown because of the lower accreting rate[35]. Submerged and drowned coral reefs have been found off Hawaii Island, which were considered to be caused by a catastrophic sea-level rise during MWP-1A event at ~14.7ka B.P.[35]. Therefore, the Barbados corals probably grew in the water shallower than 5 m undersea during MWP-1A interval, and the commencement of MWP-1A event should be earlier than that estimated from the coral records. A calibrated coral record shows that commencement of MWP-1A event is not earlier than 14.40 ka B.P. nor later than 14.23 ka B.P.[36]. This estimation of the timing of MWP-1A event still lags that derived from the Sunda Shelf records by ~200—400 years[36]. It is usually requested that we should convert ^{14}C ages to calendar ages before use by considering marine ^{14}C reservoir ages. However, precisely estimating the variable marine ^{14}C reservoir ages remains difficult[37]. During the MWP-1A event, marine ^{14}C clock ceased because of the turbulence of the THC, leading to a stagnant ^{14}C plateau lasting from ~14.9 to 14.2 cal. ka B.P.[38,39]. Based on more than 40 AMS ^{14}C ages, the interpolated age of the mid-point of the inception of the Bølling warming event at core 17940 from the northern SCS is estimated to be ~15970+285/–260 a B.P.[34,40], nearly ~1200 years older than that in the southern SCS[41]. This apparent offset is ascribed to an increase of the local marine ^{14}C reservoir age by ~1000 years in the northern SCS[34,40]. Because of the existence of so many uncertain factors, precisely estimating the accurate timing of MWP-1A event of the last deglaciation remains difficult.

2 Source areas of MWP-1A event

Estimating the accurate timing of MWP-1A event is of great significance, because correlating MWP-1A event with the inception of Bølling warming event or with the Older Dryas event has entirely opposite meaning. If MWP-1A event corresponds with the inception of Bølling warming period, the NADW should be active, the meridional circulation be strong and the northward transport of tropical heat fluxes should warm the north Atlantic areas. This means that the largest freshwater discharge of the last deglaciation did not weaken but strengthened the NADW. However, correlating MWP-1A event with the Older Dryas also results in a big query. Why didn't this prominent freshwater discharge to the ocean give rise to a severe cold event like Younger Dryas or Heinrich 1 but the small Older Dryas lasting for only 100—150 years? Both speculations conflict with the conceptual model proposed by Broecker et al.[5]. Hence, we conclude that although sea-level change is a good index of the meltwater variability during the last deglaciation, it cannot be solely used as an index of the NADW variability and climate change. The total volume of the freshwater input is not important in triggering climate change. It is the location of the freshwater injection that plays a great role in triggering global climate change by altering the mode of the NADW[28]. Freshwater discharge to the Antarctic, or to the North Atlantic, or to the low latitudes, will produce completely different effects on ocean circulation. Model results indicate that the amplitude of the slowdown of the NADW induced by a fixed amount of freshwater to the high northern Atlantic is nearly 4—5 times that induced by the same amount of freshwater to the Gulf of Mexico[42]. Therefore, it becomes very crucial to locate the source of MWP-1A event.

The average meltwater flux to the oceans during the MWP-1A event is estimated to be ~0.5 Sv (Sv, Sverdrup, $1\text{Sv} = 10^6\ \text{m}^3\ \text{s}^{-1}$), with three possible sources.

(i) Laurentide Ice Sheet, the biggest ice sheet of the LGM, is the most possible source of the meltwater (Table 1) and therefore the foci of the research. Laurentide Ice Sheet possibly had three meltwater outlets during the Bølling warming episode. In the south, the meltwater could enter the Gulf of Mexico through the Mississippi drainage system. When melting made the southern edge of the ice sheet retreat to some places, the eastward meltwater could come into the northern Atlantic through the St Lawrence River and the Hudson Bay[43,45] (Figure 4). A negative excursion of the planktonic foraminiferal δ^{18}O from the Gulf of Mexico occurred during the Bølling warm interval, suggesting that the Laurentide southern margin had at least contributed to partial freshwater of the MWP-1A event via the Mississippi River. Unfortunately, there is no evidence to show that meltwater once injected to the north Atlantic via the eastern outlet[45]. One ice sheet melting model demonstrates that the meltwater of the MWP-1A event mainly came from the Northern Hemisphere ice sheets, of which the Laurentide Ice Sheet and the Eurasia Ice sheet contribute to a sea-level rise of ~16.5 m and ~4.6 m respectively[11]. Calculation from the other model displays an average freshwater flux of ~0.675 Sv from the Laurentide ice sheet between 15 and 14 ka B.P.[46]. This value, though overestimated, reflects the significant contribution of the Laurentide Ice Sheet to global sea-level change on the other hand. However, calculation from another model produces an opposite result that meltwater discharge to the oceans via the Mississippi drainage can only contribute to a sea-level rise of ~2.9 m, with an average flux of ~0.03 Sv during the MWP-1A interval[43].

Figure 4 Deduced drainage systems of the Laurentide Ice Sheet and the Lake Agassiz during the last deglaciation[44].

(ii) Eurasia Ice Sheet. Scandinavian and Barents Ice Sheets are close to the regions where the NADW sinks. Active NADW will release a huge amount of latent heat, which will cause the collapse of the ice sheets[47]. However, both geological records and model results reveal that the meltwater from Eurasia Ice Sheet has very restricted contribution to sea-level rise[31,48]. The Eurasia Ice Sheet never served as a primary source of MWP-1A event[11,43].

(iii) Antarctica Ice Sheet. Taking the Northern Hemisphere ice sheets as the primary source of the MWP-1A event will produce a self-contradictory interpretation that the massive freshwater inputs to the north Atlantic correspond with the strong THC during the Bølling warm interval. Accordingly, switching the source of MWP-1A event to the Antarctic continent seems to be attractive and reasonable. Clark et al.[49] proposed a way to test this possibility by introducing a new concept of “sea-level fingerprints”. It suggests that any ice mass will produce positive gravitational anomaly and draw ocean water toward it as a consequence of simple gravitational attraction. If this ice mass melts, then the gravitational “tide” will diminish and the sea-level around this ice mass will drop while the mean level of the global ocean will clearly increase. Consequently, different scenarios for the origin of the meltwater pulse (e.g., melting from Laurentide, Antarctica, or the Barents Sea) should produce distinct sea-level signatures or “fingerprints” over the course of the MWP-1A event. If taking the Antarctic Ice Sheet as the main source of the MWP-1A event, the modeled amplitudes of sea-level rise in the Barbados Island and the Sunda Shelf will be in good agreement with the geological records from coral and sediments[49]. Moreover, increasing the freshwater input to the Antarctic region will suppress the Antarctic intermediate and bottom water production but promote the NADW production, and finally make the north Atlantic gradually switch from the severe cold Heinrich1 mode to the Bølling warm mode[50]. This mechanism successfully avoids the paradox that the massive freshwater discharge to the north Atlantic corresponds with the strong THC during the Bølling warm interval. Other evidences from a modified glacial isostatic adjustment model also support this machanism[51]. Usually, results from this model show significant discrepancies with geological records. But revising this model by setting the Antarctic as the major source of the MWP-1A event (that, the Antarctic contributes to a sea-level rise of 15 m and the Northern Hemisphere contributes to 8 m) will eliminate this discrepancy, making the model results be in good agreement with the geological records[51].

Some geological records also support this mechanism that the major source of the MWP-1A event is located in the Antarctic. For example, the ice-rafted-detritus (IRD) was found to increase in abundance between 14.2 and 13.5 ka B.P. in the south Atlantic, which is comparable to the Heinrich events in the north Atlantic[52]. This event is named “SA0”, an indication of massive collapse of the Antarctic ice sheets during the MWP-1A event[52]. In addition, the benthic foraminiferal $\delta^{18}O$ of site MD95-2042 in the North Atlantic region resembles the air temperature change over Antarctica during the last glaciation[53], revealing a close relationship between global ice volume change and the air temperature change over Antarctic. During the inception of the Bølling warm interval, Antarctic was warming up and sea-level was rising at a rate of 40 mm/a; then, the north Atlantic region began to warm up while the Antarctic region switched to the Antarctic Cold Reverse (ACR) period, with the sea-level rising rate decreasing to 17 mm/a[50,54].

Even so, contradiction in interpretation still exists. Some explicitly inverse evidences suggest that the Antarctica Ice Sheet is unlikely to be the primary or sole source of the MWP-1A event. Assuming that the freshwater of MWP-1A event comes from the Northern Hemisphere, Peltier[11] got similar “sea level fingerprints” to that of Clark et al.[49] based on ICE-4G and ICE-5G models. Since the discrepancy between the two kinds of “fingerprints” is within the errors of geological records, the method used by Clark et al.[49] to determine the source of the MWP-1A event is questionable. The Antarctica Ice Sheet only contributed to a sea-level rise of 13－21 m, whereas the sea-level had increased by 20 m during the MWP-1A event (Table 1). If Antarctica really served as the main source of the MWP-1A event, it is requested that all expanded ice mass must rapidly melt within 500 years, which is obviously inconsistent with the commonsense. Both geological records and model results demonstrate that melting of the Antarctica Ice Sheet is a slowly gradual process since the last deglaciation. Melting process of the most parts of the Antarctic ice sheet had extended to the mid-Holocene[55,56], and even now, some parts of the Antarctic Ice Sheet are slowly melting[17].

The source of the MWP-1A event still remains an enigmatic question, although a variety of simulations and reconstructions from geological records have been employed to tentatively answer this question. Taking the Northern Hemisphere ice sheet as the major source of the MWP-1A event gives rise to active NADW during the Bølling warm period, which conflicts with the traditional speculation proposed by Broecker et al.[5]. And, taking the Antarctic Ice Sheet as the major source requires a premise that MWP-1A event and Bølling warm event should commence synchronously, which means that the Antarctic meltwater triggers the warm climate in the Northern Hemisphere. In order to match the Sunda shelf records, Weaver et al.[50] even proposed a regional carbon reservoir age of 200 years in Barbados to replace the previously established age of 400 years. But, new paired $^{230}Th/^{234}U/^{238}U$ ages and ^{14}C ages of the Barbados corals suggest that the local carbon reservoir age is still 365±60 years, being identical to the previous value[27].

3 Younger Dryas event and meltwater discharge

Younger Dryas (YD) is the most significant and abrupt climate reversal event of the last deglaciation. Geological records of this event have been found all over the Northern Hemisphere. Marine records indicate that YD event corresponds with a dramatic slowdown or even a shutdown of the NADW[28,57,58], which should be induced by a massive freshwater discharge to the North Atlantic[5]. Before injecting to the oceans, the meltwater from Laurentide Ice Sheet accumulated in the Lake Agassiz, the biggest prehistoric freshwater lake in the North American continent during the last deglaciation[59] (Figure 4). Before the commencement of the YD event, the freshwater from the Lake Agassiz entered the Gulf of Mexico via the Mississippi drainage system[45]; when Laurentide Ice Sheet retreated and the eastward outlet was open, the Lake Agassiz freshwater flowed into the north Atlantic via the St Lawrence valley and subsequently triggered the cold YD event by reducing the NADW production[45] (Figure 4). This postulation obtains geochemical support from the planktonic foraminiferal $\delta^{18}O$ in the sediments of the Gulf of Mexico. Moreover, model results also demonstrate that as much as 9500 km^3 freshwater (an average flux of 0.3 Sv) from Lake Agassiz was released to the North Atlantic via the St Lawrence valley before the YD event (12.9 ka B.P.)[60,61].

However, such an interpretation has been strongly challenged recently by a series of new findings. For example, the aerial survey shows no images of remaining flooding channels to the St Lawrence valley during the last deglaciation but obvious images of a wide and linear northward spillway to the Arctic Ocean[62]. This geomorphic evidence indicates that the meltwater drainage from glacial Lake Agassiz likely passed into the Arctic Ocean rather than the North Atlantic. Furthermore, numerous dating evidences imply that both the eastward and the northward outlets of the Lake Agassiz were closed before the YD event[62]. Thus, it is likely that the meltwater triggering the YD event did not come from the Lake Agassiz. To overcome this contravention, Broecker[59] proposed another speculation that the Lake Agassiz meltwater escaped beneath the Laurentide Ice Sheet to the ocean. Based on results of an integrated model, Tarasov et al.[44] speculated that the freshwater discharge which triggered the YD event did not come from the Lake Agassiz but from the Canadian Keewatin ice dome. This huge ice dome had kept a high freshwater supply during the entire YD episode. Meltwater from this ice dome first flowed into the Arctic Ocean and then passed through Fram Strait to enter the Greenland-Iceland-Norwegian seas, where the modern NADW forms[44,63] (Figure 4). However, this speculation conflicts with our commonsense that the northern part of the Laurentide Ice Sheet did not melt until the late deglaciation, a time when the subarctic areas warmed up.

The YD event (~12.8−11.6 ka B.P.) had lasted for ~1200 years. Geological records of sea-level change show a sea-level rise of ~10 m for the YD event, with an average freshwater flux of less than 0.1 Sv[64]. Even an overestimation of the freshwater flux by Clark et al.[60] is no other than 0.17 Sv, which means that there was not much meltwater supply throughout the YD interval. If the freshwater discharge really triggered the YD event, the limited meltwater should come from some places close to the regions of the NADW production. Greenland and Eurasia Ice Sheets are likely the candidates. It is noticed that a negative excursion did occur in the planktonic foraminiferal $\delta^{18}O$ from the southeast shelf of the Greenland during the commencement of the YD event, an indication of the melting of the marine portions of Greenland Ice Sheet as well as the seawater dilution in this region[65]. However, no such a record can be found in the Barents Ice Sheet[48]. Some others speculate that iceberg armadas which spilled out of the Arctic could provide meltwater to trigger the YD event. Naturally, melting of the icebergs floating in the sea won't cause a sea-level rise[64]. We conclude that all ice sheets from the Northern Hemisphere should contribute to the sea-level rise during the YD event. The Allerød warm interval before the YD event is characterized by high temperature which accelerates ice sheet melting. When the high northern latitudes switched from the Allerød warm interval to the severe cold YD episode, melting of the ice sheet would reduce greatly.

If the freshwater discharge is responsible for the YD event, it should be unique to the termination of the last glacial cycle[59]. If not, was there any YD-type climate reverse event happened during the other transitional periods from glacial to interglacial? Obviously, the timing of the abrupt climate change in the Southern Hemisphere is opposite to that in the Northern Hemisphere during the last deglaciation. For example, the ACR event corresponds with the Bølling-Allerød warming event of the Northern Hemisphere, and warming of the Austral climate after the ACR event is consistent with the cold YD event of the Northern Hemisphere[54,66]. Unfortunately, the lack of long enough sequences restricts our understanding on this question. The longest ice core profile of the North Greenland Ice core Project (NGRIP) only extends to ~120 ka B.P., not reaching the penultimate termination[67]. Stalagmite records of Hulu and Dongge caves from the south China do not reveal any climate reversal event during Termination II[68,69]. But, stalagmite $\delta^{18}O$ records from Shennongjia area in the central China reveal some climate reversal events during the Termination III, which are similar to the Bølling-Allerød warming event, the YD event and the early Holocene Climate Optimum event of the last deglaciation[70]. Atmospheric methane (CH_4) concentration trapped in the bubbles of the Antarctic ice cores reflects wetland areas and productivity in the tropics and the Northern Hemisphere, and can serve as good proxy of the Northern Hemisphere climate change. However, the Antarctic methane concentration does not display any climate reversal event during Termination II−VII[71]. Although during Termination III, the Vostok $\Delta^{40}Ar$, a proxy of air temperature over Antarctica, exhibits a climate reversal event as in Termination I, the δD, also a proxy of air temperature over Antarctic, does not exhibit the same event[72,73]. Similarly, the δD record from Dome C shows no cold reversal events during Termination II—IX[74,75]. Why do some glacial terminations display YD-type cold reversal events in the late Pleistocene but some don't? There seems to be no definite answer to this question. By a one-dimensional coupled ice-sheet-bedrock model, Sima et al.[76] found that the YD event actually resulted from an intermittent re-start of self-sustained oscillations of the large-scale oceanic circulation. Furthermore, any deglaciation could produce a YD-type cold climate reversal event, and some deglaciations could even produce 2—3. Therefore, the YD-type event is not unique to the termination of the last glacial cycle but implicit to all terminations. If the mechanism of the YD event consists in the oceanic circulation, we need to reevaluate the role of the meltwater drainage in triggering the YD event.

4 Correlations of MWP events with abrupt climate change

In summary, correlation of meltwater discharge with abrupt climate reversal events is not as simple as considered by Broecker et al.[5]. The prominent MWP-1A and MWP-1B events of the last deglaciation do not correspond with the severe cold episodes in the Northern Hemisphere. Likewise, two rigorous stadials, the YD and Heinrich1 events, are not associated with the massive meltwater discharge to the global oceans. Although 8 episodes of massive meltwater discharge to the North Atlantic via the St. Lawrence or Hudson Rivers happened between 7 and 18 ^{14}C ka B.P.[60] and each corresponds with a cold climate interval, the freshwater flux variability and the cooling of the cold event is inconsistent in amplitude. The most significant freshwater discharge from the Lake Agassiz occurred at ~8.4 ka B.P., pouring as much as 163000 km^3 meltwater into the Hudson Strait[61]. Although this event corresponds with the "8.2 ka" cold event, the cooling extent of this event is not comparable to that of the YD event. Model results show that the Lake Agassiz only poured as much as 9500 km^3 freshwater during the YD event[61].

Production of the NADW sharply declined and even ceased during the YD and Heinrich1 intervals[28,57] (Figure 5(e)), which is clearly documented in the atmospheric $\Delta^{14}C$ records. The THC not only controls global heat and moisture distribution but also pumps the ^{14}C from the atmosphere and surface seawater into the oceanic interior through deep water formation in the high latitudes. Nearly 80% of the modern ^{14}C pumped into the deep sea is transported via the NADW. Once the NADW formation suffocates, newly produced ^{14}C will reside in the atmosphere and in the surface ocean[77]. The atmospheric $\Delta^{14}C$ concentration had kept at a high level during the Heinrich1 event, and then decreased till the onset of the Bølling warm interval (Figure 5(c)). The atmospheric $\Delta^{14}C$ concentration had gradually increased by 70±10 ‰ during the first 200 years of the YD event, and then had gradually declined for the next 1100 years (Figure 5(c))[78,79]. The revised Barbados coral records[36] indicate that MWP-1A event should commence just 200—400 years after the onset of the Bølling warming event, a time when the north Atlantic warmed up and massive ice sheets melted, indicating the Northern Hemisphere origin of the meltwater of MWP-1A event. However, the THC had only slightly slowed down during the MWP-1A interval under a background of holistic weakening of the THC for the Bølling-Allerød warm interval (Figure 5(b) and (e)). Here, the atmospheric $\Delta^{14}C$ concentration slightly decreased and marked ^{14}C plateaus occurred all over the global oceans (Figure 5(c) and (d))[39], which implies that the massive meltwater discharge in the northern hemisphere reduced the intensity of the NADW production and wrecked the ventilation of the oceans, subsequently triggering the Older Dryas event. Still, the reconstructed amplitude variability of the freshwater discharge of MWP-1A event is too small to correspond with its important role expected in models. Similar paradox in interpretation also exists for MWP-1B event. Though it corresponds with a minor cooling event just after the termination of the YD event, it seems to have no discernible influence on the THC (Figure 5).

In general, collapse of the Northern Hemisphere ice sheet during the last deglaciation should be ascribed to the continuous increase of atmospheric CO_2 concentration, the increase of the Northern Hemisphere summer insolation and the released latent heat during the sinking of the NADW. The atmospheric CO_2 concentration had rapidly increased by 11—15 ppmv during the MWP-1A and MWP-1B intervals (Figure 5(f)). It is likely that the rapid ice sheet melting was caused by greenhouse effects of CO_2 which is tightly related to the air temperature over Antarctica[80]. A study in the Indo-Pacific Warm Pool reveals that the atmospheric CO_2 concentration changed synchronously with the tropical sea surface temperature during the last two glacial-interglacial transitions but exceeded the global ice volume change by

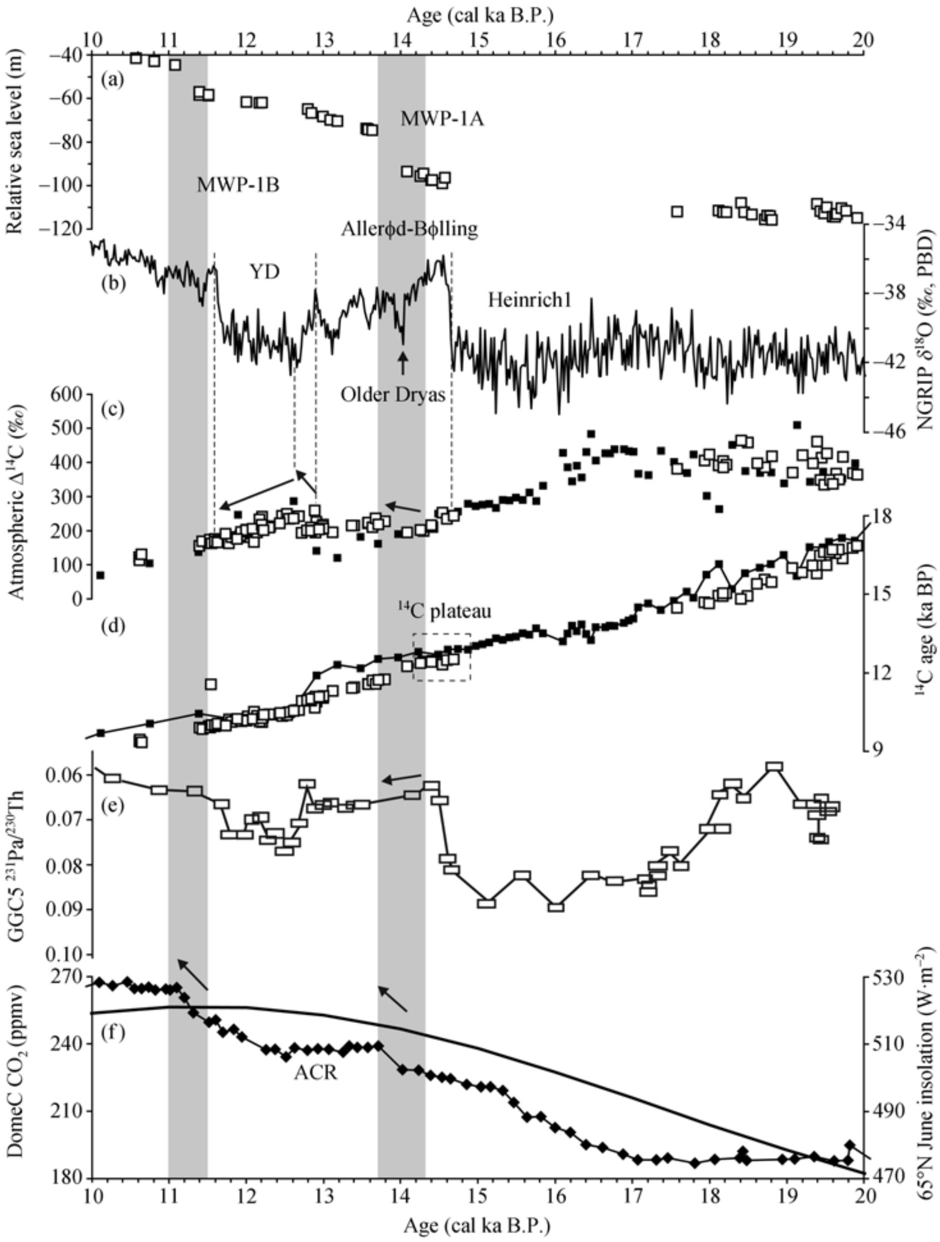

Figure 5 (a) Relative sea-level changes between 20 and 10 ka B.P. derived from Barbados coral records[22]; (b) NGRIP δ^{18}O record plotted against GICC05 age model[29]; (c) and (d) atmospheric Δ^{14}C record and radiocarbon calibration data. Solid squares denote planktonic foraminiferal radiocarbon calibration data of ODP site 1002C from the Cariaco Basin in the Atlantic[38], and open squares denote radiocarbon calibration data from Barbados corals[27]; (e) ^{231}Pa/^{230}Th record of core GGC05 from the northern Atlantic. It reflects the variability of the THC intensity[57]; (f) atmospheric CO_2 concentration record (line interrupted by diamond symbols) from Dome C ice core, Antarctica[80] and June insolation (solid line) at 65°N[81].

2000—3000 years[82]. Deep-sea temperature also warmed up by ~2℃ between 19 and 17 ka B.P., which leads to the rise in atmospheric CO_2 and tropical-surface-ocean warming by ~1000 years[83,84]. Thus, Stott et al.[84] concluded that increasing austral spring insolation combined with sea-ice albedo feedbacks appear to be the key factors responsible for the deep ocean warming. Just after the warm of deep-sea temperature occurred the rise in atmospheric CO_2 and the melt of the northern hemisphere ice sheet. Therefore, it is the Southern Ocean and the tropics that played the most important roles in leading the climate change of the last deglaciation. The negative feedbacks of the meltwater fluxes on the changes of the THC and the climate system are not as significant as that proposed in the climate models.

5 Conclusions

Massive meltwater fluxes from the ice sheets of both hemispheres have resulted in a global sea-level rise of ~120 m since the last deglaciation, corresponding to the dramatic changes of global THC. The surface system of the Earth has undergone a significant process of self-adjustment since the last deglaciation and has just recovered from the rigorous glacial cooling.

Various climate models unexceptionally stress the sensitivity of the NADW to the freshwater discharges. Most studies always attempt to reveal the interactions between meltwater drainage, strength of the NADW production and abrupt climate changes of the last deglaciation. Basically, there are two major viewpoints related to the timing and source of the MWP-1A event. One point of view insists that MWP-1A event happened just 200—400 years after the onset of Bølling warming event, and that warming of the north Atlantic made the Northern Hemisphere ice sheet the source of MWP-1A event and subsequently triggered the Older Dryas cooling event. Whereas for the other point of view, MWP-1A event is considered to be synchronous with the onset of Bølling warm event, and the meltwater from Antarctic strengthened the NADW production, leading the Northern Hemisphere into a warm state. The first point of view inherits the ideas of Broeck et al.[5], but with a shortage that the slight cooling during the Older Dryas event is not considered to be consistent with the massive freshwater discharge of MWP-1A event. For making up this shortage, the second point of view advances the commencing time of MWP-1A event onwards by several hundred years based on evidences from some geological records and further sets the remote Antarctic Ice Sheet as the main source of freshwater. However, by integrated summarization of the data set, we find that cold climate reversal events are not consistent with freshwater discharge events in the amplitudes of variability during the last deglaciation. We need to reevaluate the impact of the freshwater discharge on the THC and rapid climate changes. Is there any other unknown mechanism responsible for the abrupt switches of the THC and climate between different modes? The Southern Ocean and the tropics should be noticed considerably due to their important roles in leading the climate of the last deglaciation.

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