Northward shifts of Canadian late deglacial drainage routes caused a stronger and warmer Canaries Current that enabled Holocene monsoons and a savanna on the western Sahara

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Abstract

This paper proposes an explanation for the well-watered savanna on the presently barren western Sahara Desert during the mid-Holocene and near the ends of other earlier Canadian deglaciations. Between 7,500 and 4,000 years before present, a humidity index indicates moist conditions and a savanna in the western Sahara. During this interval, a stronger and warmer Canaries Current return flow of the Gulf Stream nullified the effect of cold water that upwells off the northwest African coast due to the westward movement of surface water by trade winds. The return flow was stronger than today because less eastward Gulf Stream flow was lost to the northward flow of the Atlantic Meridional Overturning Current. The Canaries Current was warmer than today because cold southern Canadian meltwater no longer entered the Gulf Stream, and the high latitude climate was warmer then. Similar conditions probably prevailed at the ends of many other deglaciations, which were separated by 20,000 to 70,000 years due to orbital factors and variable glaciation. The savanna connections across the Sahara would have allowed each Hominin population to evolve in the isolated Moroccan-Algerian coastal zone to extend its range into the larger Africa. The intermittent savannas could therefore have played a significant role in the evolution of the many Hominin species found in the African fossil record over the last three million years.

Keywords: Glacial climate change, Monsoons, Savannas, African refugia, Hominin evolution.

[I] Introduction

It has been known for some time that the expansion of the area affected by today's African monsoons allowed much of the Sahara Desert to become covered by a lush savanna during the Holocene and during the last interglacial 120-125 ka BP[1-4]. This might be expected because when Northern summers occurred near the orbital maxima of Sahara summer insolation, most recently at about 11.5 ka BP[5], the higher temperatures on the Sahara, Fig. 1, relative to the oceanic source of monsoon moisture should result in stronger monsoons. Consistent with this expectation and with deglacial climate of the Sahara, Yan and Petit-Maire[6] report that the maximum extent of the monsoon effect in eastern Africa was achieved at 8.5 ka BP at the latitude of Aswan, about 24°N. Nevertheless, Street-Perrott and Perrott[4] report that higher lake levels indicate increased precipitation as far north as the Mediterranean coast at 30°N. Furthermore, the Tjallingii humidity index for the western Sahara[7], Fig. 2, suggests that the northward extension of the interglacial monsoon limit of about 16°N into the western Sahara did not begin until 7.5 ka BP. This was 4 ka after the insolation maximum that would have strengthened the monsoon south of 16°N. The western Sahara is of particular interest because at the ends of earlier glacial cycles, as in the Holocene, the moisture from extended monsoons has nourished a savanna as far north as Morocco at 30°N that enabled the isolated Hominid populations that were evolving there to expand their range southward into the larger Africa, as proposed by Johnson and Berger[8]. This paper identifies the cause of the temporary savanna and develops an explanation for the delay in the appearance of the Holocene savanna on the western Sahara until 7.5 ka BP[7].
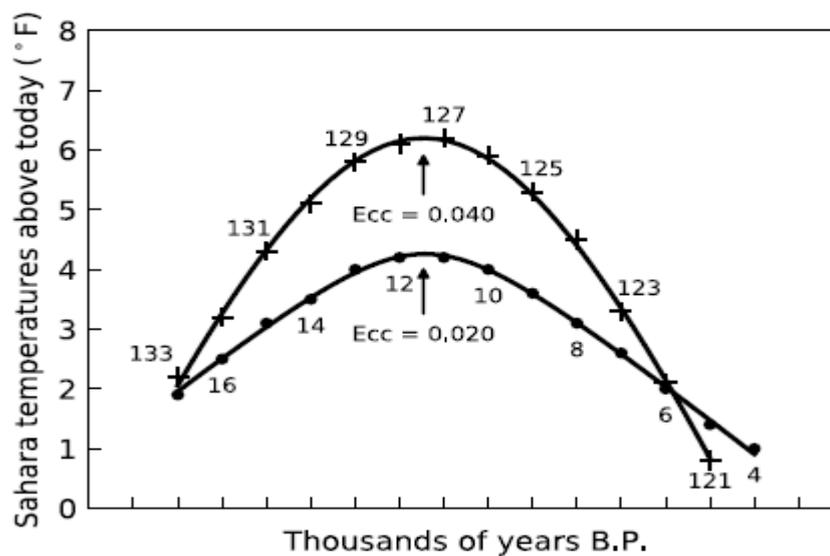
Figure 1: Estimated maximum summer temperatures on the Sahara as precession moves Northern summers through the orbital perihelion point closer to the sun[8] on two occasions with different orbital eccentricities when savannas on the Sahara are known to have occurred. The Sahara temperatures above today are proxy for monsoon strength relative to present. Ages are thousands of years before today. These calculations neglect any glacial climate cooling of the Sahara during summer.

[2] Method

The temporary savanna that developed late in the last deglaciation during the mid-Holocene (Fig. 2) on the usually barren western Sahara occurred because of a weaker North Atlantic Drift than today. A significant part of the Drift is the Atlantic Meridional Overturning Current (AMOC). The proposed explanation depends on the variable division of the Gulf Stream flow between its fraction of northward diversion as the AMOC, and the fraction of remaining eastward Gulf Stream flow that returns as the Canaries Current flow off the West African coast. This division depends largely on the rate of sinking of more saline winter-cooled surface water east of Greenland, which drives the AMOC. The winter sinking and the AMOC flow can be limited by Eurasian and North American meltwater discharges. To construct the explanation, the observed Holocene history of meltwater discharge routes to the Gulf Stream and the variable injection of cold meltwater into the Gulf Stream is used to argue that a humid interval on the western Sahara in the mid Holocene was a consequence of stronger and warmer eastward Gulf Stream flow to Europe and a resulting warmer Canaries Current than today that enabled monsoonal circulation on the western Sahara north of latitude 16˚N.

[3] Discussion and results

[3.1] A warmer Canaries Current is the key to savanna development.

The Holocene savanna development was enabled by monsoon precipitation brought about by a warmer and stronger Canaries Current after cold meltwater inputs to the Gulf Stream ceased. The Canaries Current flows southwestward along the coast of northwestern Africa. It forms the eastern rim of the North Atlantic Gyre that is centered in the Sargasso Sea. The northern rim of the gyre is occupied by the Gulf Stream, which today loses 13×10^6 m³sec⁻¹ to the AMOC flow, as estimated from the northward flow field of Greatbatch and Xu[9] across a marine cross section at 54.5˚N between longitudes 10˚W and 20˚W. Today, the Gulf Stream flow at the rim of the gyre that is not diverted northward is smaller relative to the AMOC flow. That smaller fraction continues eastward and then returns southwestward along the African coast as the Canaries Current. The strength of the Canaries Current is inversely related to the strength of the AMOC flow, which is partly and inversely dependent on the
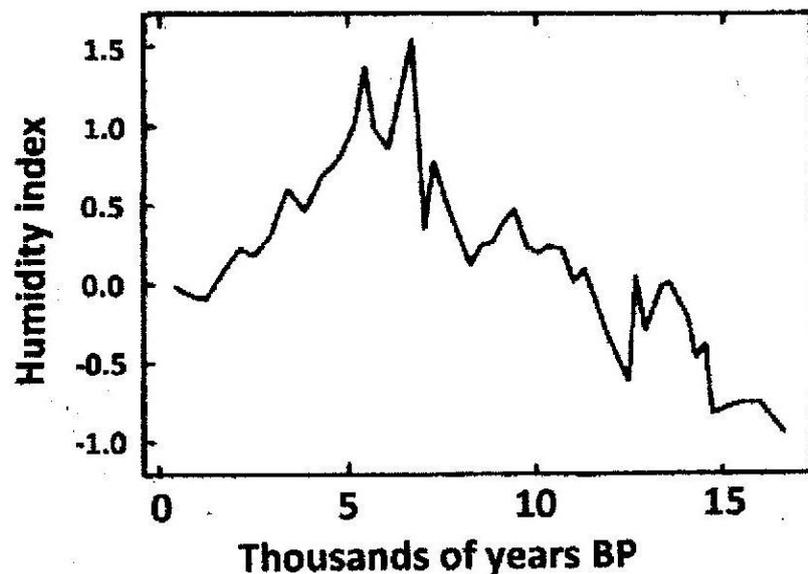
Figure 2: The part of the Tjallingii humidity index[7] for the Sahara after 15 ka BP. In the Holocene, the index began to rise well above today at 7.5 ka BP, indicating onset of monsoons on the Sahara and a savanna presence. The index was derived from wind-blown marine sediments obtained from a deep-sea core in the trade wind zone at latitude 20°45'N off the northwest African coast.
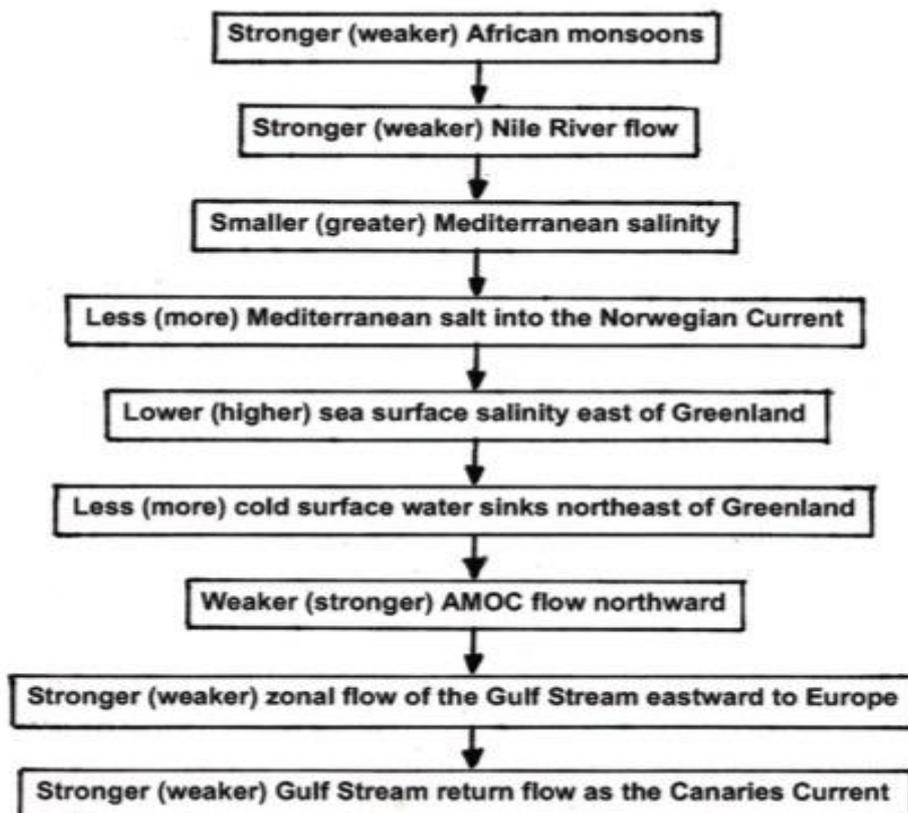
Figure 3: Block diagram showing the links between African monsoons and the Canaries Current by way of the Atlantic Meridional Overturning Current, or the AMOC. Evidence for these connections is presented in reference [8].

African monsoon with its eastward winds originating south of latitude 16˚N, as indicated by the links in Fig. 3. The Canaries Current temperature can be lowered by the effects of glacial climate and cold meltwater entering the Gulf Stream in addition to trade wind upwelling.

[3.2] Why there is no connecting savanna today.

There is no savanna on the Sahara today because the sea surface temperature is too cold. The water along the coast that is blown westward by trade winds is replaced by upwelling of cold deep-water, and the Canaries Current is now too weak to counteract the upwelling effect. The lower temperatures are significantly colder than the sea surface to the west, consistent with the mean annual isotherms in the Bartholomew Atlas[10]. The 70˚F isotherm lies well north of latitude 30˚N over most of the Atlantic, but as it approaches the Moroccan coast it turns sharply southward and does not intersect the coast until it reaches the northern edge of the monsoon zone at about 16˚N. This implies that the surface water temperature along the coast from Morocco to 16˚N is less than 70˚F and is up to 10˚F colder than water to the west. The air passing over the colder water does not apparently contain enough water vapor to drive the summer monsoon circulation, and the Sahara coast is too far south to receive the winter rains that fall in northern Morocco and northern Algeria. The weak Canaries Current resulting from today's strong AMOC flow is illustrated in Fig. 4. The dry climate of the western Sahara is analogous to that of other coasts adjacent to flows of colder water. Examples include the Baha peninsula of northern Mexico, the desert coasts of Chile and Peru, and the narrow waterless Namib strip on the coast of southwest Africa[10].

[3.3] Why there was no savanna on the Sahara until late in the deglaciation.

During the last deglaciation the AMOC flow was quite weak or absent until late in the deglaciation due to low salinity meltwater discharged into the high latitude North Atlantic as the continental ice was removed. Consequently, the Canaries Current was quite strong as suggested in Figure 5. But it was also quite cold due to Gulf Stream mixing with the cold Northern Gyre water, and the inputs of cold meltwater directly from the North American ice sheet into the Gulf Stream, mainly through the St. Lawrence Valley. However, late in the deglaciation as the southern edge of the ice sheet moved northward, cold meltwater no longer entered the Gulf Stream. The Canaries Current remained stronger until the far northern Canadian deglaciation was complete and meltwater ceased to enter the high latitude North Atlantic by way of Hudson Strait, thus allowing the AMOC flow to further increase, making the Canaries Current unable to sustain the savanna. The Sahara humidity is even lower today (Fig. 2) because the orbital insolation in summer is now less than it was at 4 ka BP, as linked in Fig. 3.

[3.4] How and where the Holocene savanna was established.

[3.4.1] The first requirement for a warmer Canaries Current late in the last deglaciation: The elimination of cold meltwater from the Gulf Stream.

During the long intervals of glacial ice sheet growth, the seasonal meltwater and generally cold climate would have kept the Gulf Stream and Canaries Current cold with insufficient water vapor to drive the monsoon winds and nourish a savanna on the Sahara. During glacial cycles with large ice sheet extent, much of the southern Canadian melt water was impounded and drained through giant Lake Agassiz. For a time earlier in the deglaciation the impounded Agassiz drainage occurred to the Arctic by way of the Mackenzie River Valley and therefore kept the AMOC flow small and the marine climate cold. But as the elevation of the southern edge of the Canadian ice sheet fell, all the southern Canadian melt water discharge returned to the St. Lawrence Valley and ensured a continuing cold Canaries Current. However, meltwater would have ceased to enter the Gulf Stream after the southern front of the Laurentide Ice Sheet had retreated to northern Canada and no cold meltwater drainage then occurred through the St. Lawrence Valley. The deglacial event that explains most of this drainage change is the final diversion of the great Lake Agassiz discharge of meltwater from the St. Lawrence Valley outlet into Hudson Bay after the bay became ice-free. This event occurred at 8.4-8.2 ka BP[12]. As the

residual Canadian ice sheet melting continued, the last significant meltwater discharge through the St. Lawrence Valley would have ended about 7.5 ka BP when the Tjallingii Humidity index[7] rose from 0.5 to 1.5, suggesting
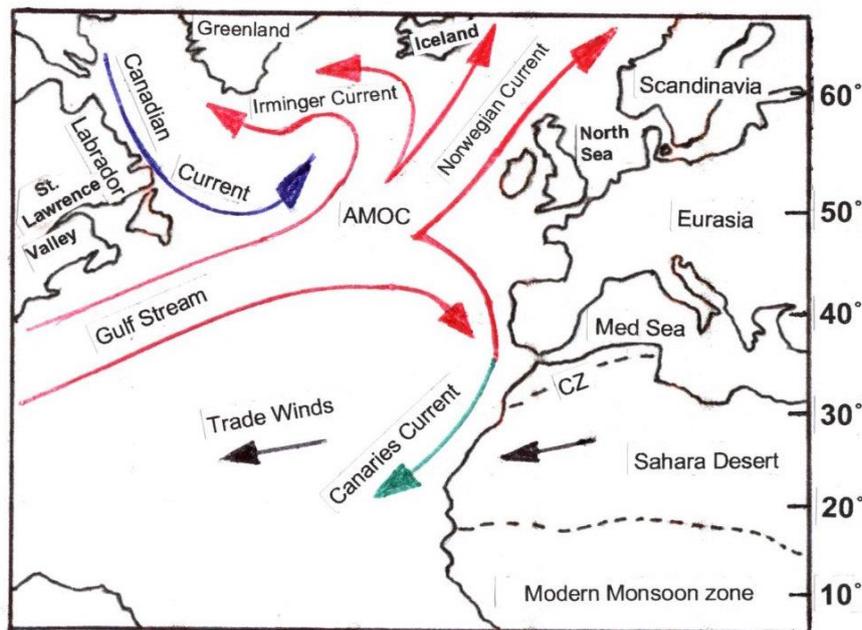

Figure 4: Today's principal oceanic currents in the higher latitudes of the North Atlantic. CZ is the isolated coastal zone with winter rains. Blue and green are colder surface waters. Because the AMOC is strong, the Canaries Current is weak and cannot counteract the trade wind upwelling effect of cold deep water. The Irminger Current is a mix of cold Canadian Current water and Gulf Stream water that forms the Northern Gyre.
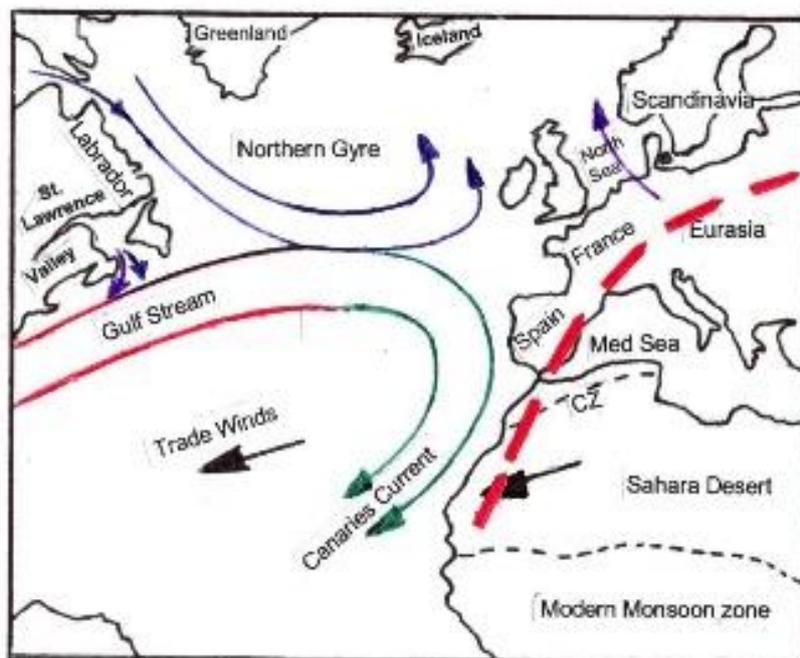

Figure 5: Principal oceanic currents and melt water discharges during deglaciation when the high latitude North Atlantic was cold and there was little or no AMOC flow. Deglacial debris has been carried by ice bergs from Canada across the Atlantic to the sea bed near Ireland[11]. The deglaciation was especially rapid at the end of the preceding major deglaciation at 128 ka BP. Heavy red arrows mark the path of the summer jet stream and

warm winds driven by the cold ocean/warm land temperature gradient. This jet stream probably contributed strongly to the rapid Eurasian deglaciations that ended before deglaciations ended in Canada.

that monsoon activity began in the western Sahara. The onset of the monsoon winds north of 16˚N would have been favored by positive feedback. When west-to-east monsoon flow began, less trade wind upwelling would have occurred. This would have accelerated the warming of the Canaries Current, which suggests that a very rapid onset of monsoons and savanna on the western Sahara may have occurred.
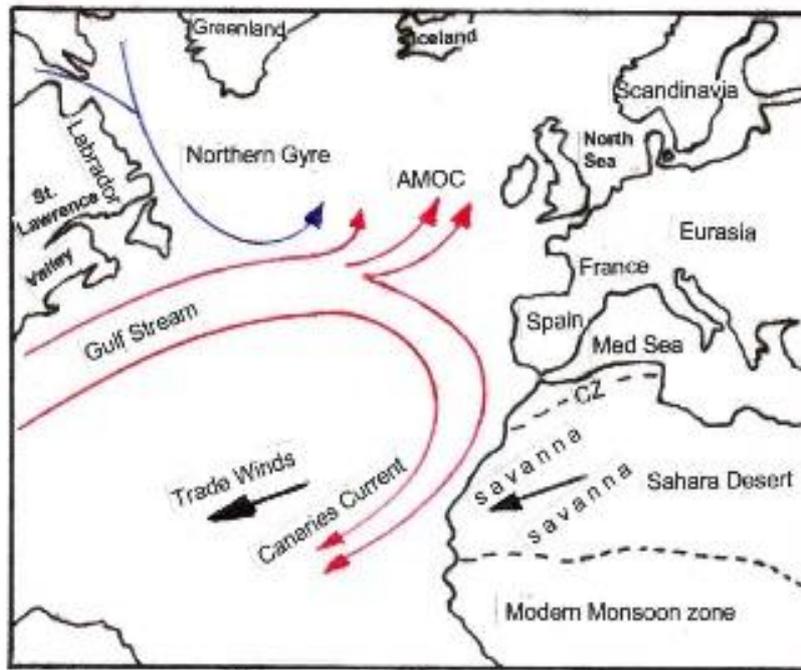

Figure 6: Oceanic circulation during the mid-Holocene and other times of savannas on the Sahara. The final melt water that mixed into the AMOC and partly limited its flow was discharged through Hudson Strait at the north end of Labrador. A partial AMOC flow would probably have prevented mixing of cold Northern Gyre water into the stronger residual Gulf Stream flow that continued toward Spain. The residual flow then warmed the Canaries Current despite the upwelling of water along the western African coast.

[3.4.2] The second requirement for a warmer Canaries Current: Partial restoration of the AMOC flow.

In the second requirement, the partial restoration of the AMOC flow caused a stronger Canaries Current than today that counteracted the cold upwelling water off the western Sahara coast. After the meltwater discharge ceased through the St. Lawrence Valley, meltwater would have continued to be discharged through Hudson Strait north of Labrador, Fig. 6. This water reduced the salinity of the Northern Gyre, which contributed water by mixing into the northward AMOC flow, and thus reduced the sea surface salinity east of Greenland. Consequently, while the Canadian ice sheet was finally melting away, the AMOC flow remained somewhat weaker than today, the resulting stronger Gulf Stream flow that continued eastward to Europe fed into the Canaries current, mixing into and warming the coastal water. When the melting of the last remnant of the great ice sheet in northern Canada ceased, probably soon after 5 ka BP, the AMOC flow increased, the Canaries Current became weaker and colder, and the savanna that connected the Moroccan coastal zone to the larger Africa could no longer be sustained.

[3.4.3] The connecting savanna was probably limited to the western Sahara.

The Holocene savanna between the Moroccan coastal zone and the larger Africa may have been limited to the western Sahara because the Canaries Current source of monsoon moisture came from the mid latitude Gulf Stream. Therefore, the Canaries Current was not as warm as the oceanic tropical source of monsoon water vapor south of latitude 16˚N where monsoons extend all the way across Africa. Consequently, the Sahara monsoons

were less humid, and would have lost most of their water vapor more quickly than did the monsoons south of 16°N. The Sahara monsoons therefore may not have contributed to what was probably an extension of the southerly monsoons to a maximum limit in Egypt far to the east at Aswan at 24°N[6]. This maximum occurred at 8.5 ka BP. But at that date cold Canadian melt water was still entering the Gulf Stream through the St. Lawrence outlet because the northward outlet into Hudson Bay was not fully open until 8.2 ka BP[12], and the Tjallingii humidity index for the Sahara (Fig. 2) was little higher then than it is today. This humidity index, with a maximum of 1.5 at 5.5 ka BP, may therefore reflect moisture conditions only in the western Sahara, as in Fig. 6.

[4] Conclusions.

[4.1] Generalizing the savanna occurrences.

The savanna on the Sahara is also found at an earlier time at 125-120 ka BP[3] near the end of the preceding major Northern Hemisphere deglaciation. The Tjallingii humidity index[7] for the western Sahara also suggests characteristically humid intervals at 105 and 83 ka BP at the ends of minor cyclic deglaciations[8] when glacial ice would have remained in Canada after Eurasian ice was removed. During the last interglacial in Europe, new major ice sheet growth was initiated in Canada about 3 ka before new ice sheet growth began in Eurasia(13, 14), and ice sheet volume in North America would have become correspondingly larger. Judging from the climate mechanisms that initiated and ended ice sheet growth[14], the longer duration of deglaciations in Canada than in Eurasia was probably the case for most Northern Pleistocene glacial cycles. Therefore, the critical interval of final melt water drainage through Hudson Strait that enabled the Holocene savanna on the western Sahara probably occurred also at the end of most other Pleistocene glacial cycles.

[4.2] Significance for Hominid evolution.

Over the last 800 ka there were probably as many as 18 brief intervals of savannas on the Sahara[8], or by extrapolation, possibly as many as 60 such savanna intervals in the entire Pleistocene. At the end of each glacial cycle interval, the small Hominin population that had been living and evolving on the Moroccan-Algerian coast and which had been isolated by the barren Sahara, would have extended their range southward into the larger Africa. The genetic changes that would have occurred with the hybrid mixing of the northern and southern populations would likely have had important consequences for the evolution of the *Homo sapiens* version of mankind that we have today.

Acknowledgement.

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