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Runoff and precipitation dynamics in the Blue and White Nile catchments during the mid-Holocene: A data-model comparison

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A B S T R A C T

The Blue Nile is the major contributor of freshwater and sediments to the modern-day main Nile River and exerts a key control on seasonal flooding in the Nile valley. Recent studies have postulated that the relative contribution from the Blue Nile to the main Nile runoff might have been reduced during the mid-Holocene, at a time when higher boreal summer insolation stimulated enhanced precipitation in North Africa. Whether the decrease in the relative contribution from the Blue Nile resulted from a decrease in precipitation over the catchment, from an increase in White Nile runoff or from a combination of both is still a matter of debate. By comparing regional proxy-records with the output from a global atmospheric model zoomed on Africa, we propose that the reduced contribution from the Blue Nile at 6 ka originated from both a higher White Nile runoff and a lower Blue Nile runoff. Enhanced African and Indian monsoons at 6 ka induced a northern shift of the Intertropical Convergence Zone and an eastward shift of the Congo Air Boundary. Such an atmospheric configuration led to a negative anomaly of summer precipitation over the Blue Nile catchment that likely resulted in a reduction in the Blue Nile runoff. By contrast, a sustained positive anomaly of precipitation over the White Nile catchment during both summer and autumn most likely induced a higher main Nile runoff during the mid-Holocene. Using the model output, we propose a first synoptic view on regional rainfall dynamics that permits to reconcile contrasting proxy records.

1. Introduction

During the Holocene (i.e., the past 10 thousand years), the meridional migrations of the rainfall belt in the African subtropics lead to severe transformations of the climate and vegetation in this region (Gasse, 2000). After an arid interval during the Younger Dryas (ca. 12.5–11.5 ka), the northward migration of the rainfall belt allowed the development of savannah in parts of the Sahara Desert presently barren of any vegetation (Jolly et al., 1998). This greening of the Sahara occurred during the so-called African Humid Period (thereafter referred to as AHP), which lasted until the mid-Holocene, i.e. ~6000 years ago (6 ka) (Kuper and Kröpelin, 2006). The abundance of resources allowed herds of big game to thrive in the Sahara, which were used by hunter–gatherer populations for their subsistence (Drake et al., 2011).

After the mid-Holocene, the southward retreat of the rainfall belt provoked the disappearance of the vegetal and animal populations in the Sahara. It is also during this period (and perhaps during the AHP termination) that the transition between gathering and herding (pastoralism) occurred in northern Africa (Blanchet et al., 2014). In northern Sudan within the modern desert Nile, archaeological evidences faithfully track the progressive aridification of a series of secondary Nile channels from the early Holocene to the end of the AHP that were all active and allowed seasonal cultivation during the Neolithic period (Macklin et al., 2013). Such environmental and societal disruptions resulted in large-scale human migrations towards the banks of the Nile River, contributing to the rise of Pharaonic dynasties (Kuper and Kröpelin, 2006; Macklin et al., 2013; Macklin and Lewin, 2015). The AHP is therefore a key period in Earth's history to investigate the connexions between climatic changes and human societies dynamics.

Changes in boreal summer insolation exerted a major control on climatic conditions in northern Africa during the mid-Holocene by reducing latitudinal temperature gradients (e.g. Braconnot et al.,

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2007; Davis and Brewer, 2009; Bosmans et al., 2012). However, the geological record of environmental changes across Northeastern Africa is very heterogeneous, with large spatial and temporal offsets. Some records depict a progressive humid/arid transition following the changes in insolation (Fleitmann et al., 2003; Jung et al., 2004; Kröpelin et al., 2008; Weldeab et al., 2014), while other records point to a more rapid transition (Liu et al., 2007; Garcin et al., 2012; Tierney and deMenocal, 2013). Additionally, the humid/arid transition is not recorded synchronously over NE Africa, and is reported between 8.5 ka (Blanchet et al., 2013, 2014; Costa et al., 2014) and 5.5 ka (Garcin et al., 2012; Tierney and deMenocal, 2013). This large temporal variability might result from regional climatic processes or variation in the time resolution of palaeoclimatic archive (Tierney and deMenocal, 2013), or from climate-environment feedback processes (Claussen et al., 1999). Temporal offsets might also result from a time-trangressive retreat of the African monsoon following the gradual decline in insolation forcing, with equatorial latitudes becoming arid later than tropical latitudes (Shanahan et al., 2015).

In the Nile River catchment, the changes in humidity and palaeoenvironments also reveal a complex pattern (Blanchet et al., 2014). Today, the two main branches of the Nile River provide contrasting contributions to the main Nile flow. The Blue Nile and Atbara rivers are the main contributors and flow mostly during the boreal summer, while the White Nile provides a more constant input throughout the year and becomes a significant contributor during the drier months (see e.g. Woodward et al., 2007 for an extensive review). Over the course of the Holocene, the overall Nile runoff decreased steadily, following the reduction in the summer insolation and southward migration of the rainfall belt (Revel et al., 2010; Marriner et al., 2012). By contrast, the reconstructions of past changes in the relative contribution from both sources to the main Nile runoff exhibit large and sometimes rapid variations during the Holocene (Krom et al., 2002; Box et al., 2011; Blanchet et al., 2013; Flaux et al., 2013; Véron et al., 2013). Several hypotheses have been proposed to account for the changes in source contribution to the main Nile runoff: i) a shift in the seasonal distribution of precipitation towards the autumn equinox, favouring a stronger White Nile runoff (Blanchet et al., 2013), and ii) the development of an extensive vegetation cover on the Ethiopian Highlands that prevented erosion and lead to a lower Blue Nile runoff (with precipitation remaining high, e.g. Krom et al., 2002).

Here, we aim at investigating the precipitation dynamics during the mid-Holocene in order to better understand the processes influencing the runoff dynamics in the Nile River catchment. First, we review available datasets of past humidity conditions from NE Africa in order to explore the potential forcing mechanisms and provide a synoptic picture of past humidity conditions in the region. This data-compilation is then compared to a simulation of mid-Holocene precipitation dynamics obtained using the LMDZ4 global atmospheric model (Contoux et al., 2013). This model has a zooming ability, which allows providing climatic variables for the preindustrial and the mid-Holocene at high-resolution above northern Africa, and therefore permits an investigation of the climatic processes influencing the precipitation dynamics in NE Africa.

2. Present-day climatic conditions

The annual rainfall dynamics above tropical Africa closely follow that of the insolation, with the northern tropics receiving rainfall during the boreal summer. Due to their latitudinal distribution and to local conditions, the sources of the Nile River have distinctive rainfall patterns: the Ethiopian Highlands (source of the Blue Nile and the Atbara River) receive large monsoonal rainfall during the boreal summer, while the Great Lakes region (source of the White Nile) has two rainfall peaks during the equinoxes, due to the biannual passage of the Intertropical Convergence Zone (ITCZ) over the area (Fig. 1). Williams et al. (1982) estimate that about two thirds of the main Nile mean annual discharge is inherited from the seasonal rains over the Ethiopian Highlands.

In the Ethiopian Highlands, the orography plays a crucial role in controlling the boreal summer rainfall. The main moisture sources are the eastern Mediterranean Sea (contributing for more than half of the moisture transported towards the Ethiopian Highlands), the Indian Ocean and the Atlantic Ocean (Fig. 1) (Viste and Sorteberg, 2013). About two thirds of the moisture released above the Ethiopian Highlands enter the region through the northeastern flanks of the Highlands. Convergence of moisture-laden winds coming from the Mozambique channel, and to a lesser extent from the eastern equatorial Atlantic, curl West and North of the orographic barrier represented by the Ethiopian Highlands, merge with moisture-laden winds originating from the eastern Mediterranean sea before converging towards the highland into a cyclonic-type circulation, locally constrained by orography (Viste and Sorteberg, 2013). The resulting precipitation rates above the Ethiopian Highlands are highly seasonal, and about an order of magnitude higher than at similar latitudes further to the West above the White Nile catchment. The importance of orography on precipitation rates above the Ethiopian Highlands is further highlighted using modelling studies of the Mio-Pliocene moisture transport into this region (Sepulchre et al., 2006). Removing the East African Rift and the associated Ethiopian orography induces a mostly zonal moisture transport during boreal summer, with an increased contribution from the Atlantic Ocean and a reduced contribution from the Indian Ocean to the Ethiopian highland summer rainfall.

At the source of the White Nile, high precipitation rates occur all year long, with two distinctive rainfall peaks at the equinoxes (Fig. 1). However, the seasonality of the White Nile flow is modulated by storage in lakes and swamps, notably in the Sudd region in South Soudan (Woodward et al., 2007). The Sudd region acts as a sediment trap where most of the sediment loaded upstream deposits in swamps; the White Nile can loose up to 50% of its water through evaporation in these swamps (Howell et al., 1988).

3. Material and methods

3.1. Proxy-data

We use ten datasets obtained from both marine and continental archives analysed using various geochemical and sedimentological proxies (Table 1 & Fig. 2a). Put together, these records provide a comprehensive picture of the spatial and temporal variations in palaeo-humidity during the Holocene in Northeastern Africa.

We use two records from the Mediterranean Sea. The first one is a sedimentary sequence collected from the Nile deep-sea fan, which was analysed using grain-size and radiogenic neodymium (Nd) and strontium (Sr) isotopes (resp., εNd and $^{87}Sr/^{86}Sr$) measurements, which allow tracking past changes in river runoff and fluvial sediment source (Blanchet et al., 2013). The second core was retrieved in the Levantine basin and was analysed using $^{87}Sr/^{86}Sr$ measurements to track the changes in fluvial sediment source (Box et al., 2011). The source rocks in the Blue and White Niles catchment areas have very different radiogenic isotope signatures (Padoan et al., 2011), which can be used to estimate the relative contributions from both sources to the main sediment flux. Although being slightly more radiogenic, the sediments originating from the source of the Atbara River cannot be distinguished from those originating from the Blue Nile (Padoan et al., 2011). At present, the seasonal pattern of contributions from the Atbara and the

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