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EXTREME FLOODS AROUND AD 1700 IN THE NORTHERN NAMIB DESERT, NAMIBIA, AND IN THE ORANGE RIVER CATCHMENT, SOUTH AFRICA – WERE THEY FORCED BY A DECREASE OF SOLAR IRRADIANCE DURING THE LITTLE ICE AGE?

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Abstract: We review recent advances in the study of palaeofloods and in the reconstructions of climate features from sedimentary archives in the Namib Desert. Global environments are known to have varied over the past millennia, but the spatial patterns of these variations have remained poorly understood. We used palaeoflood sediments to reconstruct rainfall patterns over the last 500 years (Little Ice Age). During the Little Ice Age, the northern Namib Desert and the Orange River catchment experienced palaeofloods that exceeded those of the millennium prior and of the two centuries since. During the last two centuries, floods remained well below the Little Ice Age maximum levels. The patterns of hydrological changes imply dynamic responses of rainfall to solar irradiance forcing changes involving the Benguela El Niño oscillation.

Key words: palaeofloods, slackwater deposits, tropical-temperate-trough, solar irradiance, Little Ice Age, Namib Desert

INTRODUCTION

Slackwater deposits (SWDs) and floodout deposits (FODs) have been useful to reconstruct the palaeohydrology in arid and semi-arid regions, because they document extreme discharge events (Baker, 1987; Zawada, 2000; Benito et al., 2009; Heine and Völkel, 2009; Heine, 2010). SWDs are fluvial silts that accumulate in stable bedrock-controlled reaches. FODs are silts, sands and gravels, deposited in the unconfined lower reaches of the rivers mainly on plains. In the Namib Desert, SWDs and FODs are widespread in canyons, valleys and on plains (Heine and Völkel, 2009). Floods (and droughts) represent extreme hydrological conditions, and it is important to assess their magnitude and frequency under an anticipated climate change scenario.

Recently published palaeoclimatic records from all over the world indicate that major external forcing factors were important for the climate system (Jones et al., 2009); e.g., an imprint of solar irradiance was documented on east African rainfall (Verschuren et al., 2000), on sea-surface temperature in the North Atlantic (Jiang et al., 2005), on upwelling intensity variations off northwest Africa (McGregor et al.,

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2007), on summer temperature reconstructions of northwest Russia (Kononov et al., 2009), on wet phases in England and Denmark (Mauquoy et al., 2008), and on the intensity of north Atlantic hurricanes (Nyberg et al., 2007). The Little Ice Age (LIA) extreme floods were reported from the lower Orange River (Zawada, 2000) and the Hoanib River valley of the northern Namib Desert (Vogel and Rust, 1987; Heine, 2004a). According to Heine (2004b), the patterns of palaeohydrological change in the Namib Desert, reconstructed from fluvial flood sediments, bear distinctive similarities with radiative forcing. Minimum sunspot numbers correlate with maximum extreme flood events during the LIA. More recently, feedbacks of variations of solar activity to palaeoenvironmental changes during the Holocene (Little Ice Age, Mediaeval Warm Period, 2700 Event) have been observed in hyrax middens by Chase et al. (2010) in Namibia. Furthermore, strong correlations are evident between marine and terrestrial records, documenting the influence of the Benguela upwelling system on regional climates (Chase et al., 2010).

For a long time, little was known about floods in the Namib Desert (Namibia) and in the Orange River catchment (South Africa), as long instrumental records of hydrological changes do not exist. Recently, the investigation of arid zone fluvial systems in general and of the southern African arid areas in particular have made significant advances (for an overview, see Heine, 2010). A concentration of extreme floods occurred during the Little Ice Age in the Namib valleys and the Orange River valley (Fig. 1). Here, we present a synopsis of our research. We refer (i) to the *desert flash flood series* model (Heine and Völkel, 2009) in combination with radiocarbon and OSL dating, and (ii) to reconstructed changes in magnitude and frequency of fluvial systems that are draining toward the Atlantic coast in southern Africa, to identify suitable locations for reconstruction of palaeofloods associated with the LIA. We conclude from these regional results which precipitation patterns might have been responsible for exceptional floods during the LIA. Moreover, we would like to contribute to a continued refinement of palaeoclimate reconstructions through expanded proxy databases and a better understanding of the influence of radiative forcing on large-scale climate dynamics (cf. Jones et al., 2009; Mann et al., 2009).

THE LITTLE ICE AGE (LIA)

The Little Ice Age (ca. AD 1250-1850) has long been considered as the coldest interval of the Holocene. The greatest cooling over the extratropical Northern Hemisphere continents occurred during the interval from AD 1400 to 1700 (von Storch et al., 2004; Mann et al., 2009). The patterns of temperature change imply dynamical responses of climate to natural radiative forcing changes involving El Niño and the North Atlantic Oscillation–Arctic Oscillation (Mann et al., 2009). Because of its proximity to the present, there are many types of valuable resources for reconstructing temperatures from this time interval. Although reconstructions differ in the amplitude of cooling during the LIA (e.g., Borgaonkar et al., 2002) and temperatures were spatially and seasonally more heterogeneous over the past millennium than previously thought (Jungclaus, 2009), the LIA can be seen as a global climatic feature. Moreover, almost all reconstructions agree that maximum cooling occurred in the mid-15th, 17th and early 19th centuries (Crowley et al., 2008). Reconstructed climates are coherent with series of solar activity indicating that solar activity may have been one major driving factor of past climates (Kononov et al., 2009).

On the other hand, significant volcanism occurred during the LIA. A new study has successfully calibrated the Antarctic sulfate record of volcanism from the 1991 eruptions of Pinatubo and Hudson (Chile) against satellite aerosol optical depth (AOD) data (AOD is a measure of stratospheric transparency to incoming solar radiation). AOD ice core reconstruction compared with temperature

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reconstruction shows over the interval AD 1630 – 1850 a striking agreement between 16 eruptions and cooling events (esp. cooling event 1641–42, from 1667 till 1700+) (Crowley et al., 2008). This interval of significant tropical eruptions occurred almost exactly at the beginning of the coldest phase of the LIA in Europe (Late Maunder Minimum). This suggests that solar irradiance changes may not have been the sole cause of this cooling.

The Maunder Minimum (MM; ca. AD 1645–1715) was characterized by prolonged

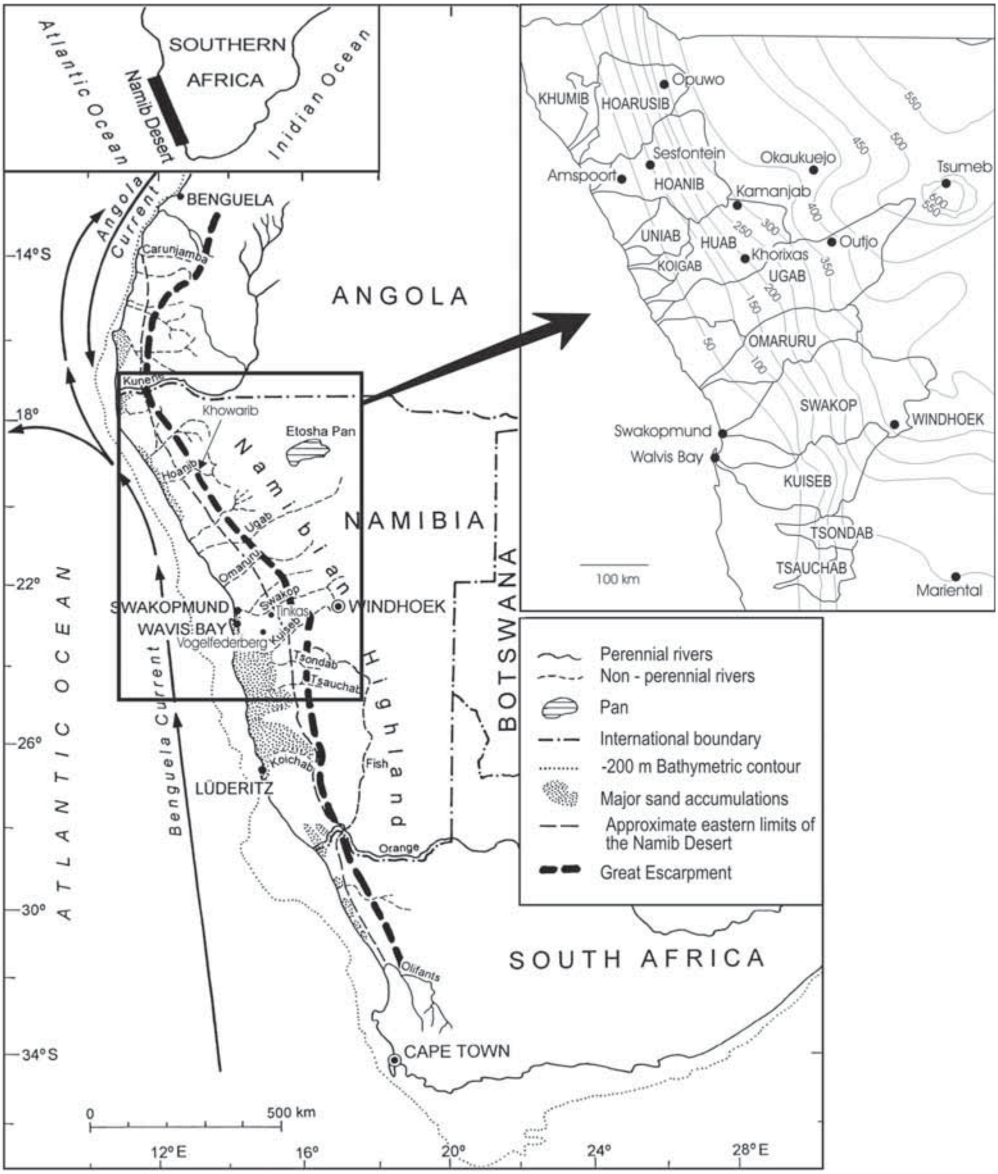

Figure 1. The Namib Desert and adjacent areas. Twelve major ephemeral rivers flow across western Namibia. Apart from Tsauchab and Tsondab, all ephemeral rivers may discharge into the Atlantic Ocean after extreme precipitation events. Inset map shows major drainage systems and isohyets (mm a^{-1})

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cold conditions. It is clear that the MM was a period of reduced solar irradiance, but the exact magnitude of the reduction remains in doubt. Lean (2006) mentioned a reduction of 0.15–0.4% of solar irradiance (at about AD 1700) compared to the measured minimum values of today. However, the IPCC simulations (Intergovernmental Panel on Climate Change; Jansen et al., 2007) are based on a 'low-amplitude' case (weaker solar irradiance forcing) with a Maunder Minimum reduction of only 0.08% compared to today (Jones et al., 2009). To resolve this question, the LIA in general and the Maunder Minimum in particular can serve as an example period to enable understanding of forcing-induced variations on the climate, in particular on atmospheric circulation and the hydrological cycle (Crowley et al., 2008; Raible et al., 2008).

STUDY AREA

In southwestern Africa, the Namib Desert stretches over 2,000 km along the Atlantic coast from southern Angola (14°S) to the Olifants River in South Africa (32°S) (Fig. 1). A swath of extreme aridity stretches from 40 to 120 km inland to the slopes of the Great Escarpment. The area of the Namib Desert is situated in a region of relative tectonic stability. The complex tectonic history of the principal Pan-African orogenic belts of the Namib Desert, reaching from the Kaoko Belt in the north to the Damara and Gariep Belt in the south, is summarized by Frimmel et al. (2011). The geology of the Namib Desert consists of a great variety of rock formations. North of Walvis Bay, folded metamorphic rocks of the Damara Supergroup and Gariep Complex predominate, with granite intrusions formed 850–500 million years ago around older metamorphic complexes (2,600–1,650 million years old). When the continent of Gondwana broke apart, masses of volcanic rocks were forced up through the crust of the earth. The Etendeka basalts of the Damara Igneous Province (~137–130 million years old) cover large areas (Luft et al., 2011) and remnants of intrusions of igneous rocks built conspicuous landmarks and hundreds of dykes and sills. The Namib Desert rocks are exposed in a rugged landscape of valleys, escarpments, mountains and plains. South of Walvis Bay, the older rocks of the Namib are covered mainly by the sandstones and sands of the Kalahari Group (70 million years – present) (Mendelsohn et al., 2002). North of the Namib Desert, the Kunene catchment comprises parts of the Archaean to Mesoproterozoic Angola Block.

The 0.9 million km^2 catchment of the Orange River comprises most of the interior of South Africa. Volcano-sedimentary rocks of the Neoproterozoic Gariep Belt are found in the lower reaches of the Orange River. Farther to the north and east of the Orange and Vaal Rivers, rocks of the Archaean to Mesoproterozoic basement (Kalahari Craton) are widespread. Continental sedimentary rocks of the Palaeozoic and Mesozoic eras (Permian to Triassic, sandstones, shales) cover large parts of the eastern and southern sections of the Orange River catchment. The mountainous parts of the eastern catchment show series of basaltic lava flows (Drakensberg Beds, ~180 million years old) with a maximum thickness of ~500 m. Since the Jurassic, this area has been subjected to regional tilting, resulting in an uplift of over three kilometres (Partridge and Maud, 2000).

In the Namib Desert, dominant soils are arenosols, gypsisols, leptosols, together with dune sands, gravel plains, and rock outcrops. In the escarpment areas and mountains, soils consist mostly of leptosols and regosols. On calcareous rocks, calcisols are common. Most soils are weakly developed and shallow. Fluvisols are found along the margins and valleys of larger river courses (Mendelsohn et al., 2002; Heine and Völkel, 2010). Arenosols and other weakly developed shallow soils are widespread in the lower Orange River catchment. Based on the weathering of the different parent rocks and aeolian dust input, the desert soils are composed of characteristic clay mineral assemblages. The Namib Desert soils can be divided into four

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clay mineral provinces (Heine and Völkel, 2010). In the Orange River Highveld catchment, black and (mainly) red montmorillonitic clayey soils (vertisols) and solonetzic soils are common. The same soils occur, together with ferrallitic soils, in the Drakensberg area (von M. Harmse, 1978).

The climates of southern Africa are influenced by the position of the subcontinent in relation to the pressure and wind systems of the southern hemisphere. These correspond to the "high-sun" seasons (summer seasons) of the northern and southern hemispheres (Nicholson, 2000). South of 20° S, mean annual rainfall increases from the west to the east, and the 400 mm isohyet bisects southern Africa (Tyson, 1969). The western part is extremely arid along the Namib coast, getting semi-arid towards the interior of the subcontinent. The eastern part is sub-humid and gets wetter towards the east coast. This meridional distribution of rainfall reflects the replacement of the latitudinally moving convergence zone by the subtropical high pressure centres and, farther south, the disturbed westerly airstreams as the main controls of weather and climate (Tyson, 1969). This east-west contrast of the climate is intensified by the warm Agulhas Current, which flows from the north to the south in the Indian Ocean, and the northward cold Benguela Current of the Atlantic Ocean. The rainfall season along the Benguela coast occurs when sea surface temperatures (SSTs) reach their seasonal maximum (Nicholson, 2000). The aridity of the Namib Desert along the western coast gives way to a Mediterranean climate (winter rains) in the southwestern Cape. In general, winter rain does not affect the Namib Desert north of the Orange River mouth, however, occasionally rains may occur (Waibel, 1922).

While the large perennial Orange River drains great areas of the interior of South Africa, the Namib rivers are all essentially dry ephemeral rivers (Jacobson et al., 1995). Some rivers flow every year, some only occasionally. The waters of the ephemeral rivers only reach the sea after extreme rainfall in their catchments, some rivers end inland. Many years have no water flow in the Namib valleys (Mendelsohn et al., 2002). In the north, the Kunene River carries water throughout the year to the Atlantic Ocean.

METHODS

We used sedimentological and stratigraphical studies of SWD and FOD sequences combined with mapping of SWDs and FODs to reconstruct the Holocene palaeohydrology (Fig. 2, Heine and Völkel, 2009). We analysed the grain size distribution (standard techniques, sieve, pipette), carbonate content (Scheibler and Finkener technique, see Ellerbrock, 2000), content of organic material, colour (Munsell) and clay mineral associations (X-ray diffraction, Siemens X-ray unit D 5000) to describe and classify stratinomic features (Reineck and Singh, 1980; Miall, 1985), to differentiate between different fluvial flood sediments with different source areas (provenance), to reconstruct fluvial palaeoenvironments and to calculate theoretically palaeohydrological parameters, e.g., low discharge, high discharge or falling discharge, rate of sedimentation. Individual floods were characterized as 'moderate', 'high', 'extreme' and 'exceptional' by analyzing the height of their deposits above the present-day river bed. By investigating the relationships between heterogeneous deposits (cobble – gravel – sand – silt – clay) of ephemeral desert streams, a hierarchical analysis of the fluvial deposits of the Namib valleys was undertaken to deduce the sedimentary processes of their formation (Heine and Völkel, 2009). Ground Penetrating Radar (GPR) was used in fluvial and vlei sediments (gravel, sand, silt, clay) to illuminate the subsurface architecture of these deposits (Leopold et al., 2006). Moreover, detailed investigations of many soil sections of the central Namib Desert in the area of the Swakop and Kuiseb Rivers (Heine, 2004a, b) allow reconstructions of extreme rainfall events (sheet floods).

Radiocarbon and OSL dating was used to establish the palaeoflood record for six

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Figure 2. Remnants of the Orange River slackwater deposits (SWDs) in the Helskloof tributary valley (~17°28'E, 28°43'S, ~160 m a.s.l.) were dated by OSL to ca. 1.1±0.12 ka (cf. Table 1). The SWDs rest on local gravel of the Helskloof Valley. In 1978, the South African pioneers of palaeoecology, Eduard M. van Zinderen Bakker Sr. and Johanna A. Coetzee, together with Almut Heine used these SWDs as lunch table during their field work

Namib Desert valley catchments (Hoarusib, Hoanib, Swakop/Khan, Kuiseb, Tsondab, Tsauchab), the lower Kunene River valley and the lower Orange River valley. ^{14}C and AMS ^{14}C ages were determined by the laboratories in Hannover (M.A. Geyh, M. Frechen) and Erlangen (W. Kretschmer, A. Scharf). The ages younger than AD 1951 were inferred from a diagram by M.A. Geyh. OSL age determinations were carried out by the laboratories in Hannover (M. Frechen), in Cologne (U. Radtke), Pretoria (J.C. Vogel) and Ahmedabad (A. Singhvi). The optical dating techniques are described in Duller (2004) and Lian and Roberts (2006).

We compared the results of our investigations with those of many other studies of fluvial deposits in the Namib Desert valleys to synthesize a coherent interpretation of the data (cf. Heine and Völkel, 2009). Of great value are the observations of Hövermann (1978), Vogel and Rust (1987, 1990), Ward (1987), Eitel et al. (1999a,b, 2001, 2002, 2005, 2006), Krapf et al. (2003), and Pradeep et al. (2004).

RESULTS AND INTERPRETATION

From the Kunene Valley in the north to the Orange River in the south, palaeoflood sediments occur above the recent floodplains. Heine and Völkel (2009) and Heine (2010) suggest that most of the Holocene SWD and FOD sequences accumulated ~10,000 to 8,000 and ~2,000 to 0 years ago. The youngest accumulation phase occurred during the Little Ice Age (LIA) between 750 and 150 years ago. In the following, (i) we present a short description of the palaeoflood deposits of the Namib Valleys starting in the north and ending in the south, (ii) we reconstruct

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rainfall patterns over the last 500 years (Little Ice Age), and (iii) we discuss whether the patterns of hydrological changes imply dynamic responses of rainfall to solar irradiance forcing changes involving Benguela El Niño oscillation. In this paper, we discuss only sequences that are well-dated to the LIA.

THE KUNENE VALLEY

Brunotte and Sander (2000) investigated the floodplain sediments of the Kunene River between Ruacana (17°24'S, 14°13'E) and Epupa (17°00'S, 13°14.5'E) in detail. Floodplain sediments occur as small accumulation areas of up to 100 m wide between the current river channel and the valley slopes. These floodplain terraces can be traced downvalley all the way to the Kunene mouth. Fine-grained sediments of over 6 m thick are known. Beneath ca. 1.3 m depth, the sediments are weathered and estimated to be of early Holocene age (Brunotte and Sander, 2000). The upper sediments are stratified, sometimes humic layers can be observed. These silty to sandy flood sediments were deposited over large stretches alongside the slope base. Charcoal was deposited together with the flood sediments (SWD). Nineteen ^{14}C age determinations of fluvially transported charcoals and of charcoal of buried fire places reveal that the sedimentation processes occurred between AD 650–890 and 1525–1955 (Fig. 3). Most ages can be attributed to sedimentation processes during the LIA (Brunotte and Sander, 2000). The flood magnitudes were moderate; recent floods can reach the height of the floodplain. The clay minerals kaolinite (±30%) and smectite (±60%) dominate the samples (with some illite: ±10%). The clay

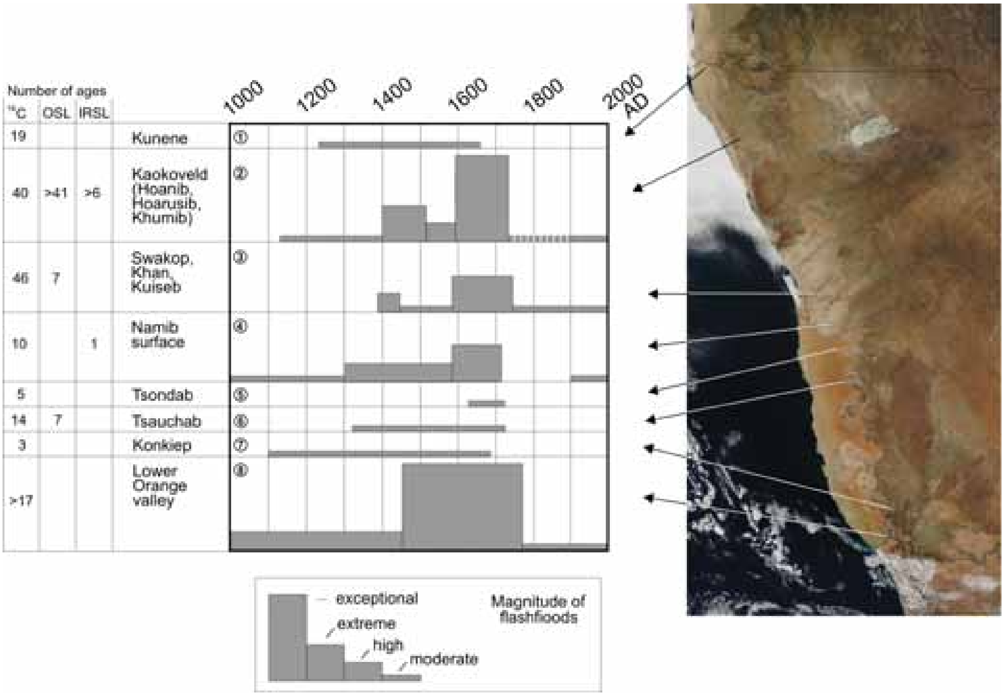

Figure 3. The youngest accumulation phase of slackwater deposits (SWDs) occurred during the Little Ice Age (LIA). The number of ^{14}C and OSL ages and magnitude of flash floods for different Namib Desert valleys are shown. During the LIA, the flash flood magnitude decreases from north to south. The Orange River flash floods of the LIA originate in the upper catchment (South African Highveld and Drakensberg Mountains)

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mineral composition of the Kunene River sediments reflects the origin of the floodplain silty sands in the tropical wet Angolan Highland (Heine and Völkel, 2010).

THE KAOKOVELD VALLEYS

The fluvial history of the Hoanib River has been described by many authors (amongst others, Vogel and Rust, 1987, 1990; Rust and Vogel, 1988; Eitel et al., 1999a,b, 2001, 2002, 2005, 2006; Krapf et al., 2003; Heine, 2004a,b, 2010; Leopold et al., 2006; Heine and Völkel, 2009). The so-called Amspoort Silts (19°21'S, 13°09.5'E) of the Hoanib River were first dated by ^{14}C to the LIA (Vogel and Rust, 1987). For a detailed description of the Amspoort Silts we refer to Eitel et al. (2005), Leopold et al. (2006) and Heine (2010). The palaeoclimatic interpretation of the Amspoort Silts was in doubt for many years (e.g., Heine, 2004a,b, 2010, Eitel et al. 2005, Leopold et al. 2006). By investigating the facies types of the Amspoort Silts and by elaborating the concept of a hierarchical dynamic stratigraphy to investigate the relationships between heterogeneous deposits of ephemeral desert streams (*desert flash flood series* model), Heine and Völkel (2009) documented that the distribution of the facies types shows that only very large, sediment-laden floods could have accumulated the SWDs of the Amspoort Silts and the related floodout deposits.

This is corroborated by the sequence of sheet flood deposits, channel gravels and slackwater deposits in backflooding areas of the Tsuxub mouth (Figs. 4, 5 and 6). The Tsuxub Valley joins the Hoanib River at Amspoort from the north. In the lower section of this tributary, the Amspoort Silts were laid down as SWDs on stratified gravel of the Tsuxub Valley without any intercalation of local Tsuxub gravel layers (TSFD in Fig. 6) with clayey Hoanib silts (Amspoort Silts). Only the gravel of the small Tsuxub channel do interfinger with the Hoanib SWDs, documenting fluvial processes in the Tsuxub catchment during the time of

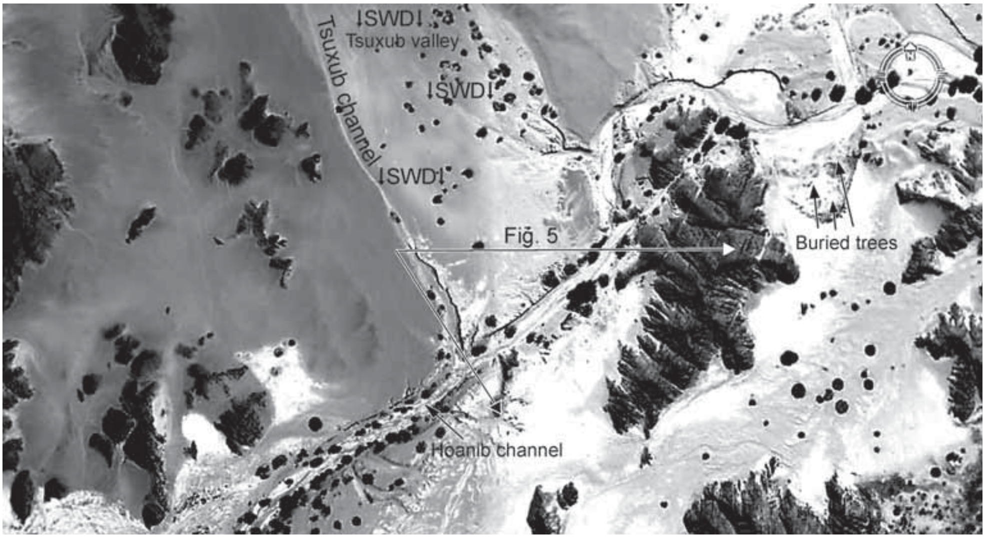

Figure 4. Satelite image of the Amspoort site. The Hoanib River channel runs from above right to lower left. The light colours show the distribution of the Amspoort slackwater deposits. The slackwater deposits reach upvalley in the Tsuxub tributary. In the tributary mouth, they are covered by sheet flood sediments of the Tsuxub (↓SWD↓). Occasionally (little) floods caused backward erosion and formed the Hoanib main channel and the small gullies of the tributaries.
The view shown in Figure 5 is indicated

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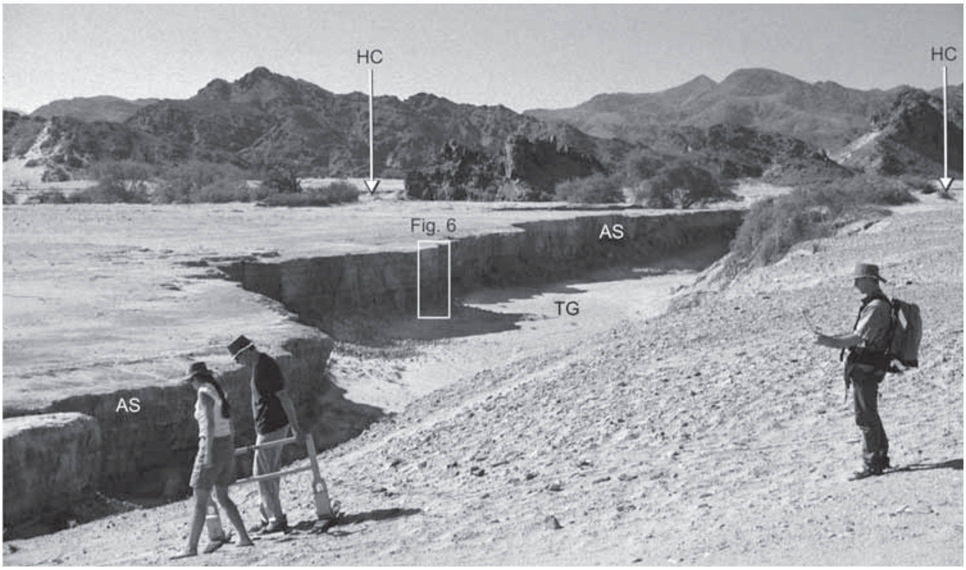

Figure 5. The Amspoort Silts (AS) are characterized by horizontal bedding and deposition in backflooding embayments. The gully is the tributary mouth of the Tsuxub River. The persons are working on the ground penetrating radar (GPR) profile of the site, which was described in detail by Leopold et al. (2006). AS, Amspoort Silts; HC, Hoanib channel, TG, Tsuxub gully

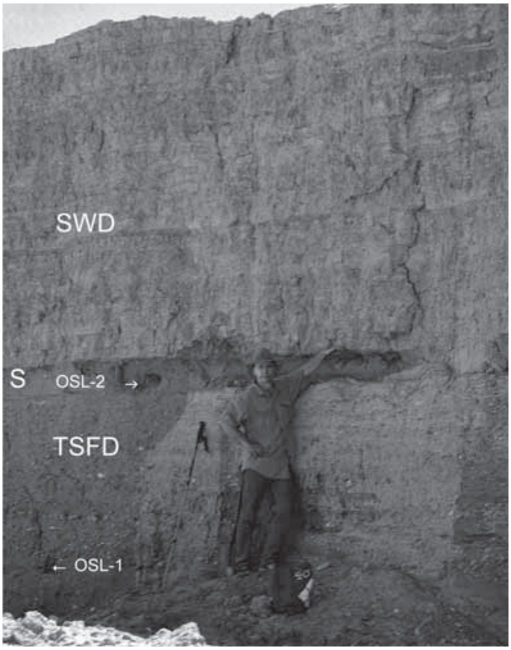

Figure 6. Amspoort Silt section. The horizontally fine-grained slackwater deposits (SWD) accumulated on top of tributary valley sheet flood deposits (TSFD). Both facies units are separated by a 0.3 m thick fluvial sand layer (S). OSL-1, OSL age ~4 ka BP; OSL-2, OSL age ~1 ka BP

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the deposition of the Amspoort Silts. The sheet flood sediments accumulated before ~1 ka. Between ~4 ka and ~1 ka, no more than 1.5 m of these sediments were deposited as result of rare precipitation events in the Namib Desert. The SWDs are definitely younger than 1 ka. Prior to this time, there was no major backflooding into the Tsuxub River mouth by the Hoanib River (cf. Leopold et al., 2006; Heine, 2010).

Since the first ^{14}C age determinations were obtained (Vogel and Rust, 1987, 1990), there has been no doubt about the age of the Amspoort Silt accumulation. In the meantime, at least 40 ^{14}C ages, >41 OSL ages and >6 IRSL ages have been published concerning the age of the Amspoort Silts (Fig. 3). The SWDs of the upper Hoanib catchment and the adjacent valleys of the Kaokoveld (e.g., Hoarusib, Khumib) (Heine, 2004a,b, 2010; Eitel et al., 2006) are not unique. SWDs accumulated in many valleys of the northern Namib during the LIA (Fig. 3). The LIA sequences of SWDs in the Hoanib and Hoarusib valleys are thicker than the other SWDs of the Kunene and than those of the central Namib Desert valleys (e.g., Swakop/Khan, Kuiseb). Also, the backflooding areas of the Hoanib reach farther into tributaries than those in valleys of the central Namib Desert valleys.

CENTRAL NAMIB DESERT VALLEYS

The Khan River is the largest tributary of the Swakop (Fig. 1). Heine (2004a) described a section of the youngest SWDs of the Khan valley about 1.7 km upstream of the confluence with the Swakop River. In addition to the ^{14}C ages, the OSL ages confirm the LIA age of the SWDs (04/9-2 and 04/9-4 of Table 1). Heine (2004a) presented evidence that the stacked SWDs of the Khan and Swakop valleys were accumulated mainly during the LIA. No remnants of SWDs were observed in heights above the recent channel floor that document larger flood palaeostages during the late Holocene than those recorded for the LIA. These results are corroborated (i) by SWDs of the Swakop River in the Namibian Highland (~ 22°18'S, ~16°13'E, ~1,200 m a.s.l.) where the largest peak discharges were dated to between 290±30 and 390±30 years ago (Greenbaum et al., 2007), and (ii) by detailed surveys of SWD sites along 120 km of the Kuiseb River Canyon (Grodek et al., 2009). The authors recognized a sequence of 13 palaeoflood deposits dated to the beginning of the 20th century and a sequence of 27 flood units dated back to ~800 years ago. The interrelationships of the SWDs along the Kuiseb indicate that a relatively recent flood, which occurred during the last two centuries, has been the largest of recent millennia. No SWDs were found in the valleys of the central Namib Desert that document in magnitude and frequency similar LIA floods like those in the Hoanib and Hoarusib valleys of the northern Namib. Further evidence for LIA floods in the central Namib Desert were recorded by Heine (2004a), who described soil sec-

Table 1. Dose rate data, including uranium, thorium, and potassium concentrations, calculated dose rate during burial, and resulting OSL ages. All uncertainties represent the 1σ confidence interval. The first 2 ages were calculated by A. Singhvi (Ahmedabab, India), the third age by A. Hilgers (Cologne, Germany).

Sample code	U (ppm)	Th (ppm)	K (%)	Water content (%)	Dose rate (Gy/ka)	Equivalent dose (Gy) Age (ka)		Age (ka)	
						Mean	Least 10%	Mean	Least (10%)
04/9–2	5.29±1.26	27.11±8.25	3.5	5	6.4 0.6	2.5 ± 0.1	0.8 ± 0.1	0.40 ± 0.04	0.13 ± 0.03
04/9–4	4.701.25	27.685.56	3.5	5	6.3 0.5	2.2 ± 0.3	0.8 ± 0.3	0.35 ± .05	0.13 ± 0.05
06/IV C-L1990	1.4±0.06	5.73±0.52	0.9	5	1.84 ± 0.1	–	–	1.10±0.12	

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tions, sediment sequences in small surface channels, cave deposits, groundwater table changes and tree trunks on the desert surface that were transported over many kilometres by occasional sheet floods. However, the SWDs of the Swakop/Khan and Kuiseb valleys prove that the LIA floods of the central Namib Desert did not reach the magnitude of the desert floods of the northern Namib. The highest Swakop SWDs in the upper catchment were found 7–8.5 m above the channel bed (Greenbaum et al., 2007), whereas in the lower reaches of the Swakop/Khan catchment SWDs of the same age (LIA) were deposited no higher than about 2–4 m above the channel bed in the river canyons (Heine, 2004a), documenting lower peak discharges. This is explained by flood water infiltration and transmission losses of the palaeofloods on their way through the desert (Jacobson et al., 1995; Efrat et al., 2009; Grodek et al., 2009). This indicates that the extreme rainfall events of the LIA did not affect the central Namib Desert in the same way as the northern Namib Desert.

To the south, the Tsondab and Tsauchab rivers originate in the Great Escarpment area, whereas the small Konkiep River channels east of Lüderitz drain only the eastern parts of the desert. All three laid down thin layers of SWDs that are found only a few metres above the recent channels. From the north to the south, the magnitude and frequency of occasional flood events during the LIA decreased. Moreover, in the Fish River Canyon, to date no SWDs of the LIA have been described.

ORANGE RIVER

Floods of the Orange River carry a relatively large suspended sediment load (Compton and Maake, 2007). Palaeoflood recurrence and magnitude were calculated from the SWDs of the Orange River (Zawada, 1995, 1997, 2000). The source of the suspended sediment load was determined by using variations in clay mineral assemblages (Bremner et al., 1990; Compton and Maake, 2007; Heine and Völkel, 2010). The SWDs of the lower Orange River valley dated to the LIA contain 75% smectite with relatively low percentage of illite (10%) and kaolinite (10%) as well as mixed-layer clay minerals (up to 5%). This assemblage documents the strong influence of soils and rocks of the upper reaches of the catchment, where smectite is abundant as a product of the weathering of the Drakensberg basalts and the sedimentary rocks (Heine and Völkel, 2010). The influence of suspended sediments from the lower Orange catchment including the large area of the Fish River and Molopo catchment in southern Namibia and Botswana is weak, as is evident from the clay mineral associations of the lower Orange tributaries with mainly illite (±85% in Fish River sediments) (Heine and Völkel, 2010).

The low magnitude of LIA floods in the southern and central Namib Desert contrasts with the extremely large floods of the lower Orange River Valley. Zawada (1997, 2000) identified, dated and flow-modelled thirteen palaeofloods that occurred over a period of 5,500 years (Fig. 7). During this time, the Little Ice Age floods were significantly larger than those before and after. About 100 km south of the lower Orange River, Benito et al. (2009) examined SWDs of the Buffels River. They recorded more than 25 palaeofloods during the last 600 years. The LIA floods cluster around AD 1400–1500 and AD 1700–1900. Since AD 1900, large floods decreased both in frequency and in magnitude (Benito et al., 2009). These observations corroborate the Orange River record.

DISCUSSION AND SUMMARY

In most catchments of the northern Namib Desert and the Orange River, the largest reconstructed Holocene flood events are considerably larger than the largest historically documented discharges, suggesting thereby catastrophic magnitudes being many times larger than any gauged or historically recorded flood. During the LIA, in the Namib Desert the palaeoflood magnitude recorded by the SWDs decreased from the north to the south (Fig. 3). A correlation of Holo-

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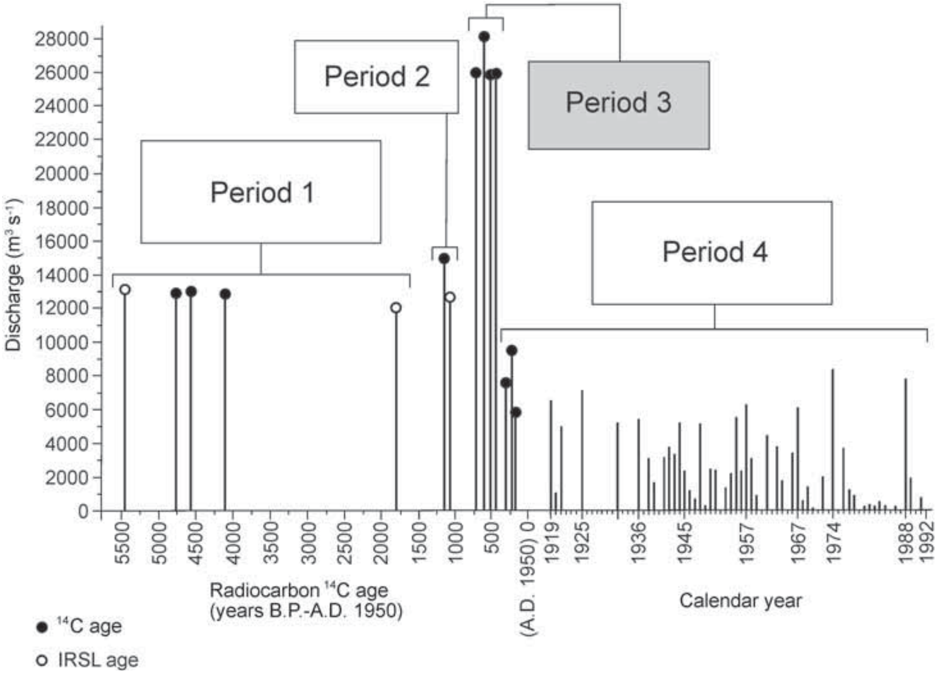

Figure 7. Zawada's (2000) compilation of the palaeoflood record for the lower Orange River [on x-axis left of 0 (A.D. 1950)] and with the annual peak-flow series gauged at Viooldrift for the period 1919–1992 [on x-axis right of 0 (A.D. 1950)]. Zawada (2000) subdivided the entire record into four palaeoflood periods characterized by a threshold discharge value. Period 1: the Orange did not experience a flood that exceeded the threshold discharge of 12,800 $m^3 s^{-1}$. Period 2: the Orange did not experience a flood that exceeded the threshold discharge of 14,700 $m^3 s^{-1}$. Period 3 (Little Ice Age: four ^{14}C ages range between AD 1453-AD 1785): the Orange did not experience a flood that exceeded the threshold discharge of 27,000 $m^3 s^{-1}$. Period 4: AD 1785-AD 1992; the Orange did not experience a flood that exceeded the threshold discharge of 9.500 $m^3 s^{-1}$. By far the most exceptional floods within the past 5,500 ^{14}C years occurred during the LIA (Period 3)

cene phases characterized by extreme flash flood events with the reconstructed Holocene climate history (temperature and precipitation) (Heine, 2005) show that weather conditions causing extreme floods occurred during diverse climatic phases. During the early Holocene, the extreme flood events occurred during warmer and wetter periods, whereas during the LIA the floods occurred during a relatively cool period.

A reconstruction of the palaeoflood hydrology of the Namib Desert valleys from SWDs dated to the LIA shows the following trend (Figs. 3 and 9): while the Kunene and the southern Namib rivers experienced moderate flood magnitudes, exceptional floods are recorded from the northern desert valleys and the upper Orange River. A decrease in flood magnitude from the north to the south can be observed for the desert valleys. The exceptionally extreme floods of the Hoanib and the upper Orange River apparently occurred between ca. AD 1450 and 1800 (Orange River, median date of AD 1619; Zawada, 2000) and around AD 1700 (Hoanib; Vogel and Rust, 1990). Rains to support such megafloods must have fallen in vast regions of a band stretching from the Drakensberg in the south to the northern Namib in the north (Fig. 8).

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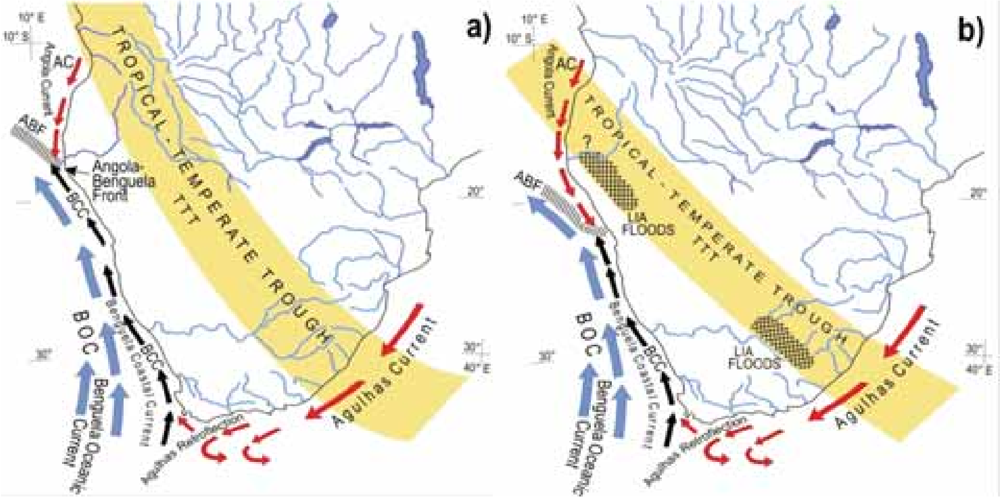

Figure 8. Ocean currents and situation of tropical-temperate-trough (TTT) during exceptional precipitation events in arid Namibia (a) during the last 100 years and (b) during the Little Ice Age (LIA) with areas afflicted by exceptional floods

SWDs were used by many authors as proxies to reconstruct palaeoenvironments of the Namib Desert (cf. Heine, 2010). Heine's (2010) review indicated that many of the preconceptions about SWDs as palaeoclimate databases are simplistic. SWDs are characteristic sediments of the *desert flash flood series* (Heine and Völkel, 2009). SWDs are fluvial deposits in deserts representing *a priori* not the climate, but atmospheric conditions prevailing in an area and at a certain time (weather). Well-dated sequences of individual slackwater layers can document time intervals of tens and/or hundreds of years with repeated flood events. Despite these flash flood events, the general climate trend can be one of greater aridity or of less precipitation overall. The current evidence generally indicates little climatic fluctuation during the Holocene with a progressive decrease in humidity (Heine, 2005;Chase et al., 2009, 2010). During the last 1000 years, the northern Benguela Current sea surface temperatures experienced a decline of about 1°C in comparison to the preceding 2000 years (Altenbach and Struck, 2006). During the last 500 years, the Namib Desert and adjacent areas in Namibia experienced more arid groundwater conditions than before (Vogel, 1989, 2003; Heine, 2005). The inferred increasing aridity of the central Namib Desert from dated *Acacia erioloba* trees stands in marked contrast to sedimentary fish scale records (Altenbach and Struck, 2006; Struck and Altenbach, 2006) from the Benguela Current off the Namib Desert, which show population changes of several fish species during the LIA, indicating wetter conditions in the 'hinterland' (see also Baumgartner et al., 2004). More LIA flash floods in the central Namib Desert are also documented by sheet flood sediments and flood-transported tree trunks on the Namib surface (Heine, 2004b). Chase et al. (2009) reported wetter conditions during the last 300 years, based on high-resolution stable carbon and nitrogen isotope records from hyrax middens. These data indicate that the decrease in flash flood frequency and magnitude (*desert flash flood series*) during the last 300 years should not be interpreted as a proxy of a more arid climate (Heine, 2005; Chase et al., 2010). It is possible that the LIA extreme flash floods, documented in the northern Namib Desert and in the upper Orange River catchment (Fig. 8), were caused by circulation anomalies over southern Africa and are unrelated to general trends of

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aridity in the region. A significant proportion of summer rainfall is derived from tropical-temperate troughs (TTTs), which extend both over continental southern Africa and over the adjacent southwestern Indian Ocean (Todd and Washington, 1998, 1999; Todd et al., 2004), and which are short-lived.

Using daily satellite rainfall estimates over both land and ocean, Todd et al. (2004) were able to resolve specific synoptic conditions (representing the dominant rainfall systems in southern Africa) and the associated atmospheric circulation structure. Todd and Washington (1999) and Todd et al. (2004) derived from these data that precipitation associated with TTTs over southern Africa is caused by distinct patterns of anomalous low-level moisture transport, which extends to the planetary scale. The principal mode of rainfall variability is a dipole structure with bands of rainfall oriented northwest to southeast across southern Africa (Fig. 8). The position of the temperate trough and the TTT cloud band shifts alternatively between the southwestern Indian Ocean and the southeast Atlantic Ocean. The synoptic scale TTT events are often controlled by large-scale planetary circulation patterns. Even in the 'high-sun' (summer) rainfall areas of the southern hemisphere, the westerlies are important for the development of rain-bearing disturbances, which take on a 'hybrid' character and combine features of tropical and mid-latitude systems (Nicholson, 2000). Tropical and extra-tropical dynamics are involved in producing these TTT cloud bands over southern Africa (Todd and Washington, 1999). These atmospheric dynamics influence the regional occurrence of the TTTs and, hence, the distribution of rainfall in the Namib Desert (cf. Heine, 2004b). The TTTs make only a small contribution to wet and dry months (and years) over southern Africa (Todd et al., 2004). Thus, studies of rainfall variability over months or years do not detect these TTTs, even though they may be a major cause of the flashfloods observed in the sedimentary record. A southward shift of the Angola-Benguela Front along the northern Namib coast brings warmer SSTs to the coastal Atlantic (Benguela El Niño / Atlantic El Niño; Nicholson, 2010) and can result in a shift of the TTT from the Angolan Highland farther to the west. Exceptional rainfall in the northern Namib Desert can be the consequence, as in early February of 1995, when heavy rains began to fall in the northwestern catchments of the Namib rivers. Rains fell throughout March and early April, often in massive afternoon and evening thunderstorms causing extreme floods in the Namib valleys (Jacobson et al., 1995). These exceptional rains were connected to SST anomalies of the southeast Atlantic, where an anomalous warming was recorded from December 1994 to June 1995. The peak of the warming occurred off the Kunene mouth in March 1995. Warming events tremendously disrupt the coastal ecosystems, reducing productivity and devastating the anchovy and sardine fisheries (Nicholson, 2010). This early 1995 rainy season did not cause abnormal precipitation in the central Namib at Gobabeb (Namib Desert Research Station at the Kuiseb River), nor extreme flooding of the Kuiseb valley (data of the Namib Desert Research Station). This documents the regional influence of the TTT bands over Namibia (Fig. 8).

All field observations and laboratory data corroborate the interpretation of the Amspoort Silts as sediments of large floods in the sense of the *desert flash flood series* (Heine and Völkel, 2009; Heine, 2010). Most of the Amspoort Silts were deposited during the LIA around AD 1700. This is corroborated by evidence from sedimentary records of fish scales in the Benguela coastal upwelling area (Baumgartner et al., 2004; Altenbach and Struck, 2006; Struck and Altenbach, 2006). During the last 3200 years, extreme hake dominance occurred only around AD 1700, which is interpreted as evidence for wetter conditions in the 'hinterland' of the northern Namib. The Orange River palaeoflood record provides further data (Fig. 7). Worldwide, the interval between AD 1650 and 1750, almost covering the Maunder Minimum (MM, ca. AD 1645–1715), appears to have been the coldest spell of

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the LIA. It is likely that the MM caused the greatest change in southern African palaeohydrology during the last three millennia. During the MM, bands with repeated rainfall events in the areas between the northern Namib Desert and the Drakensberg Mountains were caused by frequently occurring TTTs. The same period experienced arid conditions in the Kalahari area, where Lake Ngami was probably completely desiccated from AD 1670–1760 (Nicholson, 2000). In northeastern South Africa, very dry conditions have been inferred from cave speleothems (Holmgren et al., 1999), while in equatorial Africa the lake-level of Lake Naivasha was the highest ever during the last millennium (Verschuren et al., 2000). These LIA rainfall anomalies are similar to modern-day rainfall distributions that see wet conditions in some areas and dry condi-

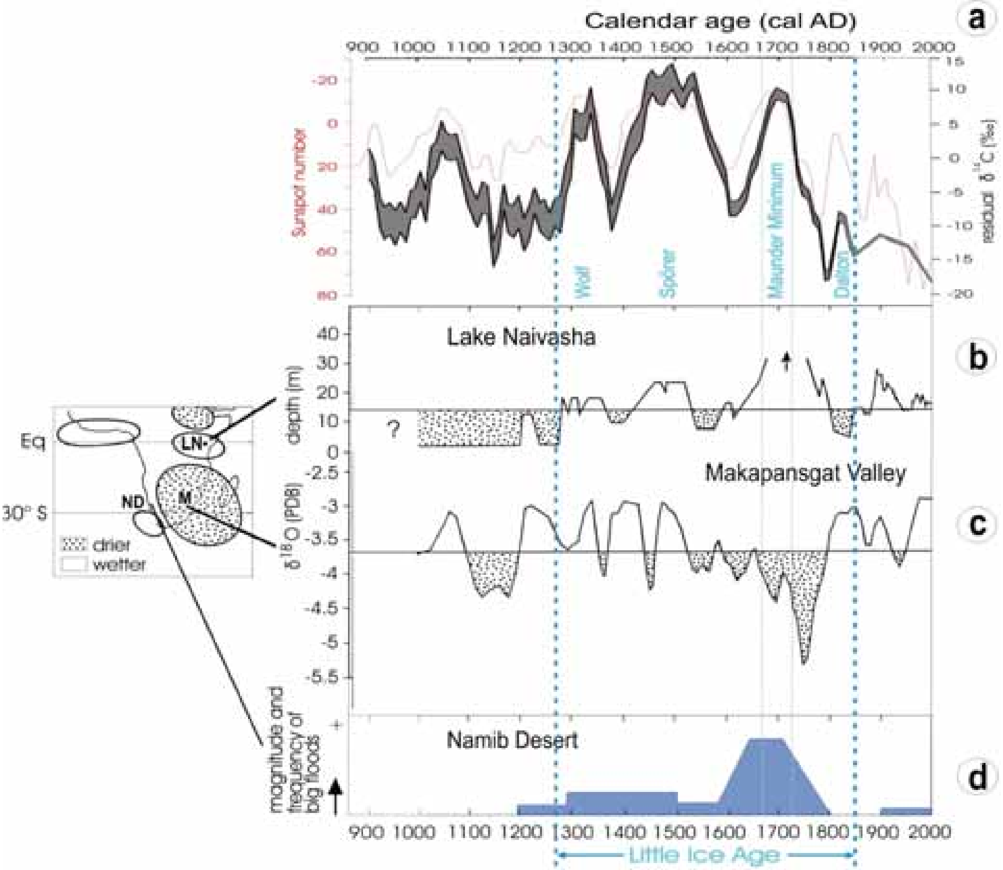

Figure 9. Comparison of records

(a) of sunspot numbers (red, Solanki et al., 2004) and residual δ14C (‰) representing solar irradiance (Mauquoy et al., 2002), (b) of lake-level fluctuations in East Africa (Lake Naivasha) (Verschuren et al., 2000), (c) of δ18O values from south African speleothem (Makapansgat) representing arid-humid changes (Holmgren et al., 1999; Tyson et al., 2002), and (d) Namib Desert flash-flood events since AD 1000. Several of these multidecadal changes in these records are coincident (e.g., during the Maunder Minimum), suggesting the possibility of a common response to radiative forcing on this time scale. Inset map shows the areas in southern and eastern Africa showing teleconnection patterns associated with Benguela El Niño situations which may be comparable with drier and wetter areas in southern and equatorial Africa during the Maunder Minimum. LN, Lake Naivasha; M, Makapansgat valley; ND, Namib Desert

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tions in others at the same time (Nicholson, 2000). An analysis of individual years in palaeoenvironmental geoarchives documented this pattern for decadal and shorter timescales (Nicholson, 2000) (Figs. 8 and 9).

The patterns of environmental change recently recorded in the Namibian hyrax middens document the relationship between the Benguela upwelling system and regional climates (Chase et al., 2010). Furthermore, $\delta^{15}N$ values from hyrax middens correlate strongly with reconstructions of sunspot numbers during the last 5,000 years, with good agreement for the LIA, Mediaeval Warm Period, and '2700 Event' (Chase et al., 2009, 2010). SSTs along the Benguela coast and adjacent Atlantic sectors appear strongly linked to rainfall variability in the Sahel, in East Africa, and in western equatorial Africa (Nicholson, 2010). Since sunspot numbers, which document variations in solar irradiance correlated with the SSTs of the Benguela Current as well as with $\delta^{15}N$ values from hyrax middens, it should be possible to correlate these sunspot numbers with palaeoclimatic reconstructions from Namibian SWDs, from South African speleothems (Holmgren et al., 1999; Tyson et al., 2002), and from East African lake-level fluctuations (Verschuren et al., 2000) as well (inset map of Fig. 9).

The data presented here emphasize the value of SWD records from the Namib Desert valleys as an indicator of past weather patterns. Correlations are apparent between marine and terrestrial records, indicating the relationship between the Benguela upwelling system and regional weather patterns. Like Chase et al. (2010), we conclude that the patterns of environmental change recorded in the Namibian SWDs can be correlated with records from many other places. We support the statements of Chase et al. (2010) 'that models of precessional insolation forcing of low-latitude Holocene climate are inconsistent with observations from tropical and subtropical Africa during the Holocene. Rather than being characterised by an anti-phase inter-hemispheric response to low-latitude precessional forcing, both the northern and southern African tropics experienced a wetter early Holocene followed by a trend of progressive aridification (cf. Heine, 2005), suggesting that high-latitude rather than direct low-latitude insolation forcing dominated regional climates.' Earth–Sun interactions in the form of solar forcing are a potentially important factor driving climate change on decadal-centennial-millennial timescales in both the northern and southern tropics (Chase et al., 2010). Continued refinement of palaeoclimate reconstructions through expanded proxy databases and refinements of CFR (climate field reconstruction) methodology (Mann et al., 2009), improved estimates of past radiative forcing (Lean, 2006) and a better understanding of the influence of radiative forcing on large-scale climate dynamics should remain priorities as scientists work toward improving the regional credibility of climate model projections (Mann et al., 2009).

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