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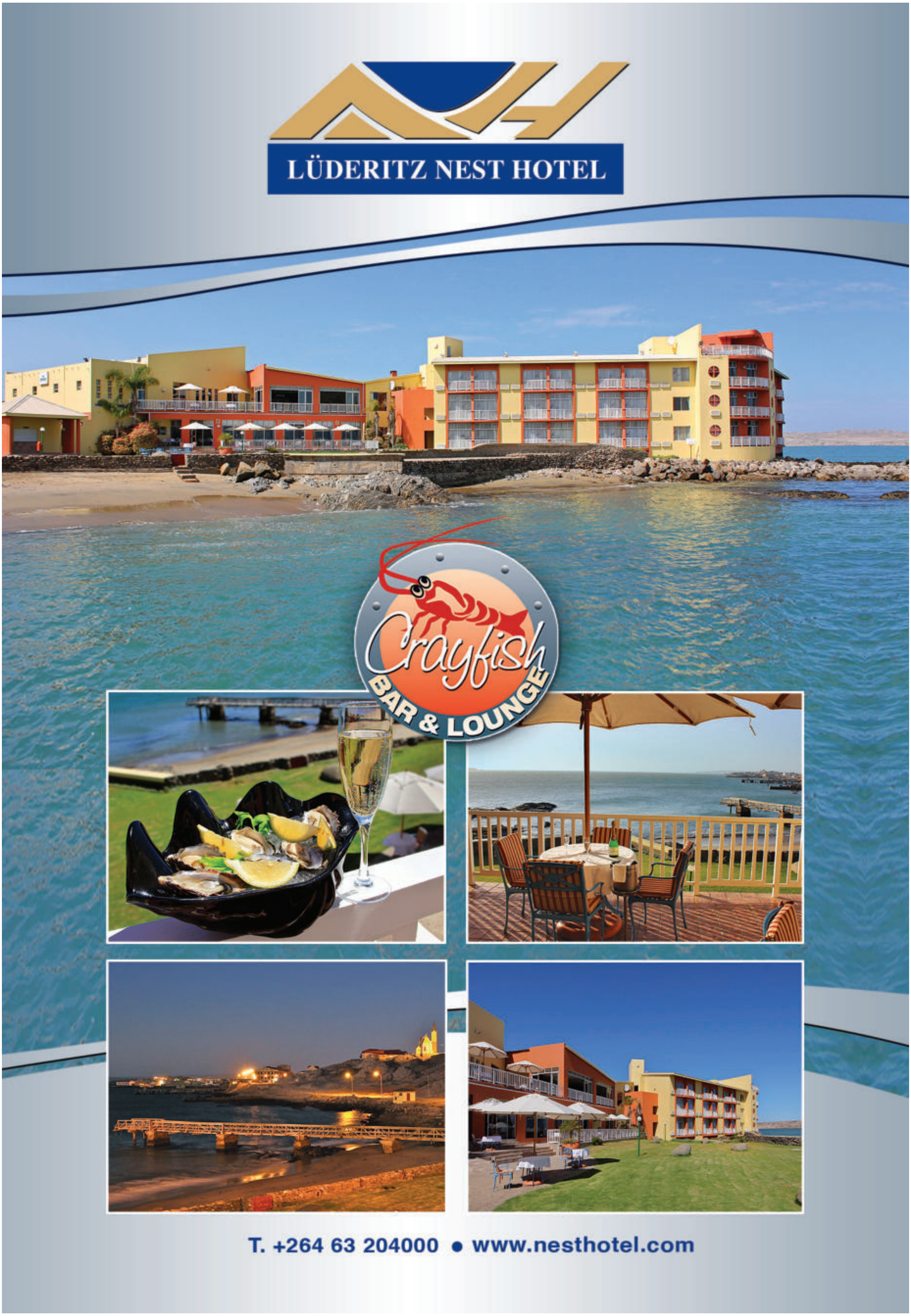
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Editorial

The Journal of the Namibia Scientific Society (ISSN: 1018-7677) is a cross-disciplinary journal, publishing research results in all fields related to Namibia. Issued since 1925, it is the longest-standing academic journal in Namibia and is distributed to libraries in various countries, e.g., Germany, South Africa, Kenya, Australia, Switzerland and USA. In currently 69 volumes, more than 370 articles have been published in research fields like Architecture, Climate/Weather, Conservation, (Desert) Fauna/Wildlife, Geography, Heritage Management, History (colonial times & independence struggle), (Eco) Tourism, and Vegetation, mostly in English and German.

All submitted articles must be based on original research and are subject to peer review. Nevertheless, as indicated by the slogan of the Namibia Scientific Society "Science for Society", the strength of the Journal also lies in its multi- and inter-disciplinary orientation. Always trying to strike a balance between scientific rigor on the one hand and readability on the other, the Journal is aimed at our members as well as interested readers worldwide. In addition to the printed edition, the Journal of the Namibia Scientific Society is currently undergoing digitization and will soon appear as an Open-Access eJournal.

This 69th volume of the Journal is a very special one: On the occasion of the 60th anniversary of the Gobabeb Namib Research Institute, all articles are related to this research station. The guest editor of this special issue is Scott Turner.

The main objective of research at Gobabeb is to increase knowledge about arid ecosystems and especially their amazing diversity, and to pass on these insights to specialists and decision-makers around the world. Research on the organisms of the Namib, as well as research on the ecology of deserts in Southern Africa, has mainly taken place at Gobabeb. The station is visited by more than 100 scientists each year for research purposes and, as a result, many publications have been produced over the past years. Thanks to the research at Gobabeb, the world's knowledge about desert animals and plants and their adaptation to extreme conditions has been vastly expanded. We are pleased that with this special issue we can contribute to spreading this knowledge as well.

The Namibia Scientific Society accompanied the founding of Gobabeb, and the ongoing fruitful partnership between the two institutions will continue in the future.

In the name of the Namibia Scientific Society, I would like to thank Scott Turner, the Gobabeb Namib Research Institute, especially Gillian Maggs-Kölling, and all authors.

I hope you will enjoy this special issue of the Journal of the Namibia Scientific Society.

Michael Backes

Namibia Scientific Society and Gobabeb: Science in Transition

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Keywords: Namib Desert, institutional history, partner organisations, research developments.

Abstract

The 60th anniversary of the Gobabeb–Namib Research Institute is an opportune time to look back on Gobabeb's institutional development and accomplishments and to look forward to future directions. Here we present a synopsis of the finding and founding of Gobabeb; the building of its research and training platforms; the reframing and transformation of the institution following Namibian independence, establishing the diverse funding to secure its future as a thriving research institution; and the development of relevant linkages and science networks, including the relationship to the Namibia Scientific Society.

Introduction

> '*When the station is built it will be the first in Africa, South of the equator, to concern itself solely with the study of desert conditions. It is to be hoped and expected that scientists of many disciplines besides the biological ones will come from other parts of the world to work in it*'
> (Lawrence, 1960).

An audacious aspiration, but six decades after its establishment in 1962, the Gobabeb–Namib Research Institute, a modest field station by international standards, off the beaten track in the middle of the Namib Desert, is thriving. Its extensive network of students, scientists, professional societies, collaborating institutions, decision-makers, and public sympathisers is prominent in Namibia, with many connections across southern Africa and globally. The Namibia Scientific Society (NSS) has been a partner in developing this network, involved in finding and founding Gobabeb and participating in each other's development ever since.

With this article, introducing a collection of papers celebrating Gobabeb's 60th anniversary, we provide a synopsis of this institution's development from 1962, and end with an outlook on its future. Our overview draws on a wealth of publications, several previous overviews (Lawrence, 1960; Fitzsimons, 1961; Lawrence, 1977; Seely, 1979; Brain, 1990; Seely, 1990; Seely & Sguazzin, 1992; Seely et al., 2000; Henschel & Lancaster, 2013), and other narratives.

Early scientific endeavour in the Namib

Since the 19th century, accounts of exploration along the arid western coastline of southern Africa have described a unique environment that has intrigued naturalists and collectors. Early scientific discoveries closely follow the activities of early traders, missionaries, and other intrepid explorers of the unknown, who often collected curiosities and commented on them in journals, both personal and scientific. These investigations accelerated during the early colonial era.

In 1925, the South West African Scientific Society was established to be a hub of scientific enquiry and evidence in Namibia. Many of the pioneering researchers of the Namib Desert worked in collaboration with members of this society. Local inhabitants had knowledge of the country, specific locations of interest, and how to traverse and survive the Namib, all crucial elements for successful research.

Finding Gobabeb: 1948–1961

The aftermath of World War II marked a turning point for scientific research in the Namib Desert. Teams of scientists from several countries spent over a decade on scientific explorations that crisscrossed the arid west of southern Africa, in South Africa, Namibia, and Angola, largely funded by private donations (Koch, 1963). The increasing interest in the Namib Desert made it imperative that a permanent scientific base station in the desert be established. The Transvaal Museum would play a leading role (FitzSimons, 1961), with the new station's focus being systematic biological research. The search was on to find the ideal location for such a desert research facility.

In 1959, these explorers "found" Gobabeb in the very middle of the Namib Desert, which they set out to investigate with enthusiasm (Anon., 1959; Brain, 1990). The scientific potential of the site was immediately recognised.

The management of the incipient research station fell jointly under the Windhoek Museum, S.W.A. Administration's Agriculture and Nature Conservation Department, the Transvaal Museum and the S.W.A. Scientific Society. From the outset, it was envisioned that the station and its facilities would be availed to all other accredited institutions or individuals wishing to conduct desert research there (FitzSimons, 1961).

Founding Gobabeb: 1962–1969

The Namib Desert Research Association was formed as a limited non-profit company to secure financial commitments for infrastructure and operations by the S.W.A. Administration, the South African Council for Scientific and Industrial Research (CSIR), and the South African Museums Association. Dr Eberhard von Koenen, a long-term associate of the NSS, was appointed Gobabeb's resident officer-in-charge, as later vividly described in his autobiography (von Koenen, 2009).[1] His tasks included putting a weather station into operation, establishing a secure water supply and a landing strip, and managing the building of a laboratory, offices and housing. Raising funds to build the research station was a challenge (FitzSimons, 1961), which was finally realised through support by von Koenen's patron, Erich Lübbert. At the official opening of Gobabeb on 08 October 1963, the President, H.C. Nöckler, spoke on behalf of the NSS (Nöckler, 1963). He announced the donation of a mechanical anemometer with a recording drum, the first of its kind in Namibia. This laid the foundation of Gobabeb's core datasets, which steadily built up over the following six decades.

In 1965, the Namib Desert Research Association morphed into the Desert Ecological Research Unit (DERU). The DERU managed the research programme under the aegis of the Transvaal Museum, with secure funding through the CSIR. Research at Gobabeb began to flourish, with entomologist Charles Koch appointed as the first Director. In addition to taxonomic, biogeographic, floristic and faunistic, climatic, microclimatic, and biogeophysical studies, the first ecophysiological research was conducted to understand how Namib Desert organisms coped with water scarcity and heat. This set the stage for desert ecology to take off as Gobabeb's claim to international scientific fame. Some 60 peer-reviewed papers were produced during these early years (ca. 9 peer-reviewed papers per annum).

[1] A 2005 video interview with Dr von Koenen, with updated German and English subtitles may be seen at the link https://vimeo.com/728408797. The interview was conducted by Erich Lübbert's grandson, Conrad Roedern, who kindly gave permission to release the interview.

Building a research platform: 1970–1990

Upon Koch's death in 1970, Mary Seely was appointed director of DERU. Since Charles Koch's 1961 overview of dune life (Koch, 1961), published in the NSS Journal, Gobabeb came to be regarded as a window into the fascinating mysteries of the dunes. As access to Gobabeb was restricted to staff, scientists, and park officials, the station itself became a mystery. Upon public demand, strongly expressed by members of the NSS, annual Open Days were arranged to showcase the research taking place and to lighten the mystery of Gobabeb. Public seminars were hosted in Windhoek by the NSS, and at the coast by the Swakopmund Scientific Society, to provide opportunities for Gobabeb staff and visiting scientists to share their knowledge. They also shared their findings through these societies' newsletters. Gobabeb's broadening visibility attracted documentary filmmakers, engendering worldwide interest in the Namib Desert that continues to the present.

Programmatic and financial commitment by South Africa's CSIR and its successor, the Foundation of Research Development (FRD) served as a springboard for attracting numerous international scientists, postdocs, postgraduate students and interns, building the virtual "critical mass" for science at Gobabeb. A key element of success from then until now was the constant stream of students and interns who became temporary residents at Gobabeb for several months to years. Interns provide the backbone of ongoing projects and conduct own studies for postgraduate qualifications. These "Gobabeb alumni" further spread the word of Gobabeb as a research destination.

Under Mary Seely's directorship, the 1970s and 1980s came to be Gobabeb's "first golden age", as Gobabeb staff and associated scientists and students generated a staggering 490 publications (averaging ca. 23 per annum), mostly on climate, geomorphology, geology, conservation, biodiversity, ecology, ecophysiology, archaeology and palaeontology. Remarkable discoveries were made, exemplified by tenebrionid beetles harvesting atmospheric water through fog-basking and constructing fog catchment sand trenches, and exploiting surface heat through thermal 'dancing' of lizards and spiders using heat to kill prey.

At the end of this phase of Gobabeb's history, the NSS served as a platform for taking stock of its achievements (Seely & Sguazzin, 1992).

Reframing: 1991–1997

Upon Namibia's independence in 1990, previous agreements concerning Gobabeb's management and funding by South African agencies were no longer valid, and a new arrangement was sought for research at Gobabeb to continue. A trust fund was established, managed by a new NGO, the Desert Research Foundation of Namibia (DRFN). The Transvaal Museum donated its library and research equipment to DRFN. Upkeep of the buildings and conservation programmes continued to be supported by the Namibian government through the Ministry of Environment and Tourism (MET). Despite no formal oversight agreement, Gobabeb continued to operate under dual management by DRFN and MET. Widespread public appreciation of its significance, including by NSS members, buoyed the motivation to continue Gobabeb's research mission. The station's long-term projects continued unabated, and visiting scientists refined previous discoveries and added new ones, resulting in 155 publications (22 per year). Namibian independence also heralded new opportunities for collaboration. International funding enabled Gobabeb to expand its field training programmes. Environmental education became a strong, post-independence priority.

Transforming: 1998–2001

The Gobabeb Trust was established in 1998 when MET and DRFN entered into a Joint Venture Agreement (JVA) concerning the operation of the Gobabeb Training and Research Centre. The NSS participated in the launch ceremony on 28 May 1998. The JVA introduced a new era, uniting the management of all facilities, programmes and relationships under one umbrella and allocating a discrete area within the Namib-Naukluft National Park (NNNP) for non-invasive research operations. Emmanuel Mwenya was appointed as Executive Director in the first four-year development phase, supported by German donor funds. The Southern African Development Community (SADC) designated Gobabeb as its Centre of Excellence for Dryland Environments. Mwenya, who had previously managed the Mashare Agricultural Development Institute in Rundu, introduced new agricultural directions to Gobabeb's portfolio in addition to its existing desert ecology programmes.

Gobabeb maintained its status as a productive research centre, with staff and visiting researchers generating 67 publications (ca.17 per year) during these four years. Gobabeb's research achievements were showcased in the NSS volume celebrating the journal's 75th anniversary (Henschel et al., 2000; Seely et al., 2000).

Developing a self-sustaining platform: 2002–2011

When Mwenya retired in 2002 due to ill health, Joh Henschel was appointed Director of Gobabeb with a mandate to develop its financial sustainability. The first step entailed completing improvements to the infrastructure—renovations, new buildings, a pilot hybrid solar-diesel energy supply and ground-cooling systems—in time for the official inauguration of the new Gobabeb on 9 May 2005. The inauguration was led by Prime Minister Nahas Angula, which also celebrated Mary Seely upon her retirement. A further German donor grant in 2006, and the award of a tourism concession in 2008, supported Gobabeb's efforts to become financially secure without donor support from 2009 onwards.

The financial model envisaged support for Gobabeb's operations through income generated by renting out the Amabilis lecture hall and newly built accommodation to paying clients. This allowed Gobabeb to organise and host international conferences, as well as various fundraising events, well-supported by NSS members. Training programmes, multiplied with field courses and experiential training, were provided to some 2000 students annually. Applied research initiated during Mwenya's time expanded and produced 144 publications between 2002 and 2011 (14 per year), extended across various disciplines.

In 2009, Gobabeb was commissioned to prepare a nomination dossier for the Namib Sand Sea as World Heritage Site. The Namib Sand Sea was subsequently inscribed in 2013 as one of only 21 properties world-wide under all four natural criteria. In celebration of Gobabeb's 50th anniversary, a special issue of the *Journal of Arid Environments* was compiled (Henschel & Lancaster, 2013).

When a new uranium rush commenced in the Namib from 2006 onwards, planning for a Namib Ecological Restoration and Monitoring Unit (NERMU) was initiated and became established at Gobabeb in 2012 in partnership with the Namibian Uranium Institute. Joh Henschel retired as Director in 2011 and is now part of the institution's team of research associates.

Back to its roots: 2012–2022

The last decade of operations at Gobabeb can best be described as a consolidation of the efforts of previous years, with a revival and expansion of its signature strength: research. With the appointment of Gillian Maggs-Kölling as Director in 2013, supported by Theo Wassenaar as Research Coordinator (2011-2017) and Eugene Marais as Research Manager (since 2017), a strategic decision was made to re-evaluate Gobabeb's role and core functions. Its research function was re-elevated to prominence, but without losing sight of the value of education and outreach, which remain firmly embedded within research operations. The training focus shifted to tertiary post-graduate level, where a critical need exists to polish promising young science talent. In 2022, Gobabeb now supports nine MSc and three PhD student associates,[2] who will, upon completion of their tenure, join the Namibian workforce as young science professionals. Research output is high with 317 peer-reviewed papers published during the past decade (32.y-1).

Following a review in 2017, the operating framework for Gobabeb was revised as a research collaboration agreement between the Gobabeb Trust and the Ministry of Environment Forestry and Tourism (MEFT). This arrangement allows continued access to the facilities in the NNNP for the operations of Gobabeb–Namib Research Institute for the foreseeable future.

2 https://gobabeb.org/research/student-research-profiles

Despite a long and mutually supportive partnership over many decades, Gobabeb and the NSS only signed a formal MoU on 05 December 2017. The main purpose of this agreement was to formalise the sharing of scientific information and promoting scientific engagement with the general public. Successful field excursions to Gobabeb for NSS members were organised in 2017 and 2019. In 2021, the NSS facilitated the participation of Prof. Eric Holm on the biannual excursion, who shared reminiscences from his tenure as the first, full-time technical scientific assistant at Gobabeb in 1968. These recent joint activities reaffirm the potential benefit for both Gobabeb and NSS, particularly in sharing scientific information and the nurturing of scientific curiosity amongst the Namibian public.

Onward and upward into the future

After weathering two years of the COVID-19 pandemic, stringent *modus operandi* of frugality and flexibility again emphasised that the future of Gobabeb depends on three key and interdependent factors:

1. Financing and sustainability
2. Maintaining science outputs that are relevant and address a range of stakeholder needs
3. Strengthening and expanding Gobabeb's science network.

Sustainability remains a perennial challenge, and the future of Gobabeb will always hinge on a reliable funding stream. The challenge to secure core funding, as well as diversified income, is integral to the governance structure of the Gobabeb Trust and has to be addressed collectively as a primary goal in the immediate future. Although not an element of the MoU with NSS, joint fund-raising activities and possibly corporate investment through NSS membership may be one avenue towards a more secure financial future.

Funds sourced through competitive grants will continue to drive research operations. Gobabeb's scientific horizons have expanded by introducing increasingly sophisticated techniques and technologies. The application of tools like phylogenomics and big data analysis will allow for a deeper analysis of evolutionary patterns in the Namib. Tools like drones and acoustic monitoring allow for rapid, non-destructive data gathering, opening up new opportunities in ecological assessments. Coupled with consideration of evolving user needs, the continued relevance of Gobabeb's research activities will be ensured. Planned infrastructure expansion will allow for a larger postgraduate intake on-site, enabling a range of longer-term research studies, and concurrently accelerating the development of science talent for the future. The NSS partnership will persist as a prominent conduit for the sharing of research information to the general public.

Faster access to online resources and reliable internet connectivity to communicate with colleagues worldwide will overcome some of the challenges of operating in a remote location. With an expansion of information-sharing, ongoing development of Gobabeb's web and social media presence[3], and the NSS connection and promotion of citizen science, Gobabeb's network is anticipated to diversify and grow, as per the current trajectory. Methods for scholarly communication and learning have changed with the massive developments in Information Technology, and opportunities for extending the reach of research must be explored in order for Gobabeb to remain relevant in an increasingly complex, socially-networked global culture.

Conclusion

From a visionary idea and the grit to make it happen, to the tenacious commitment and responsiveness to change that has underpinned the continuation of Namib Desert science over six decades, Gobabeb has a proven track-record and global recognition as one of the world's oldest arid lands field research stations. It stands as a beacon of scientific endeavour and is poised to continue this legacy into the future.

> '*Those of us who remain to watch the light which shines from the tower in the Namib will do so with feelings of deep sympathy and concern, trusting that in an uncertain and changing world it will stand and hold fast to the aims of its founders*'
> (Lawrence, 1977).

Acknowledgements

Over the years, numerous individuals and organisations, including a host of benefactors, were involved in developing Gobabeb–Namib Research Institute. The achievements were only possible thanks to assiduous teamwork involving many people, often provided selflessly and without acclaim, at local, national and international levels. This paper is dedicated to Mary Seely for her devotion to Gobabeb and its partnership with the Namibia Scientific Society.

References

ANONYMOUS, 1959. Field Expedition to the Namib Desert. *Bulletin of the Transvaal Museum* No. 3, July 1959: 2.

BRAIN, C.K. 1990. Twenty-five years of Namib Desert research: a personal perspective. *Namib ecology 25 years of Namib research.* 1st ed. Pretoria: Transvaal Museum.

[3] https://gobabeb.org

FITZSIMONS, V. 1961. The Namib Desert Research Station. *J. S.W.A. Scientific Society,* 15, 71–72.

HENSCHEL, J.R. & LANCASTER, N. 2013. Gobabeb–50 years of Namib Desert research. *Journal of Arid Environments,* 93, 1–6.

HENSCHEL, J.R., SEELY, M.K. & ZEIDLER, J. 2000. Long-term ecological research at Gobabeb: gaining and applying knowledge about a highly variable environment. *Journal of the Namibia Scientific Society,* 48, 89–114.

KOCH, C. 1961. Some aspects of abundant life in the vegetationless sand of the Namib Desert dunes. *Journal S.W.A. Scientific Society,* 15, 9–34.

LAWRENCE, R.F. 1960. The Namib Desert Biological Station. *South African Journal of Science,* 56, 90.

LAWRENCE, R.F. 1977. A history of the Namib Desert Research Station to 1970. *Namib Bulletin,* 3–5.

NÖCKLER, H.C. 1963. Zur Einweihung der Wüstenforschungsstation Gobabeb. *Bulletin.* Swakopmund: Society for Scientific Development.

SEELY, M.K. 1979. Ecology of a living desert: twenty years of research in the Namib. *South African Journal of Science,* 75, 298–303.

SEELY, M.K. 1990. The Desert Ecological Research Unit of Namibia: current status of ecological research in the Namib. *Namib ecology 25 years of Namib research.* 1st ed. Pretoria: Transvaal Museum.

SEELY, M.K., HENSCHEL, J.R., ZEIDLER, J. & SHANYENGANA, E.S. 2000. Namib research: its development at Gobabeb and implications for Namibia. *Journal of the Namibia Scientific Society,* 48, 62–88.

SEELY, M.K. & SGUAZZIN, T.M. 1992. Gobabeb: arid zone research in Namibia. *Journal of the Namibian Scientific Society,* 43, 133–145.

VON KOENEN, E. 2009. Die Anfänge von Gobabeb über die Pionierzeit 1961–63. *In:* ROEDERN, C. (ed.). Windhoek: Solar Age Namibia.

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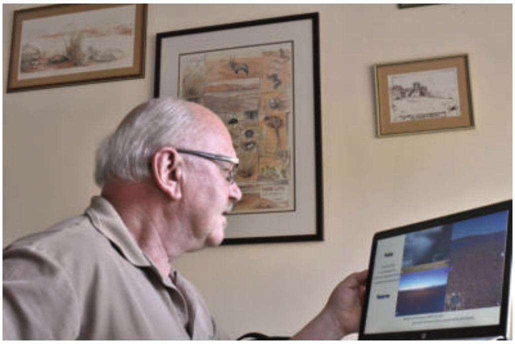

Joh Henschel has 45 years of experience as desert ecologist, starting at Gobabeb–Namib Research Institute as intern in 1977, postdoc 1986, research coordinator 1996, and executive director 2002–2011, then managed the Arid Lands Node of the South African Environmental Observation Network until his retirement in 2020. He has published 135 scientific papers and book chapters and over 230 popular science articles. His current projects include Namib tenebrionid beetle population dynamics, diversity, reproduction and ecophysiology, the ecology of the Namib dune field and fairy circles, the ecology of Karoo brown locusts and the Kimberley tri-biome programme. He currently lives in the Western Cape, South Africa.

Gillian Maggs-Kölling

Gillian is currently the Executive Director of Gobabeb, employed in this capacity since 2013. She previously headed the National Botanical Research Institute for 23 years, and served three years as responsible official for the research portfolio within the Directorate of Forestry. With her botanical background, the Namib flora is a special interest; she is particularly passionate about arid-adapted melon taxa. She is inspired by those individuals, past and present, whose combined legacy lives on in this unique research facility, and the breath-taking awe-someness of the Namib Desert.

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A Decade of Microbiome Research in the Namib Desert

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Key words: Namib Desert, Soil; Microbiomics, Microbial ecology, Aridity.

Introduction

The Namib Desert, one of the oldest drylands on Earth with an estimated age of 43 million years, lies along the entire coast of Namibia, from the Kunene River and the Angolan border in the north (S 17.27°) to the Orange River and the South African border in the south (S 28.64°). This coastal desert is a land of two halves. Much of the northern sector, from the Kuiseb River (S 23.11°) to the Angolan border, is a flat calcrete gravel desert (Eckardt et al. 2013). The southern sector, from the Kuiseb River to the South African border, is largely sand dunes (the Namib 'Sand-Sea', a UNESCO World Heritage Site).

The climate of the Namib Desert, in terms of water relations, is distinctive (Eckardt et al. 2013). The Atlantic coastal regions, which are strongly influenced by the coastal upwelling of the cold southern Atlantic Benguela current, receive minimal rainfall, but are regularly inundated with fog which rolls in from the sea overnight and can penetrate inland for up to 60 km. Many of the coastal species, both plants and animals, are specially adapted to capture fog water. The interior hyper-arid regions of the Namib Desert receive no fog and little rain, while the eastern zone receives 'regular' seasonal rainfall. Although a strong driver of plant and insect species diversity, the effect of water-input zonation on the microbiology of the desert soils remained largely unknown until teams of researchers led by Prof. Don Cowan, initially from the University of the Western Cape (2009 to 2012) and subsequently from the University of Pretoria (2013 to 2022), undertook annual research expeditions to the Gobabeb Research Station (now, Gobabeb-Namib Research Institute; https://gobabeb.org/) to unravel the microbial ecology of the Namib Desert.

Despite the Namib Desert having been an intense focus of research for nearly 70 years (Seely & Pallett 2012: Henschel & Lancaster 2013), prior to 2010 very little was known of

Plate 1: The quartz-rich gravel plains of the hyper-arid central Namib Desert

Plate 2: Dunes of the Namib Sand-Sea. The vegetated hummocks in the inter-dune valleys are clumps of speargrass (Stipagrostis sabulicola).

any aspect of the region's microbiology. The Namib Desert lichens have received the most attention (Wessels & Van Vuuren 1986; Wessels 1989; Schieferstein & Loris 1992; Büdel et al. 2011; Hinchcliffe et al. 2017). There have been a few early studies of fungal diversity and physiology (Jacobson et al. 1993; Jacobson 1997; Jacobson & Jacobson 1998; Stutz et al. 2000). These, and a single study of soil viral diversity (Prestel et al. 2008), represent the totality of 'microbial knowledge' of the region.

In 2010, we initiated an intensive (and extensive) program to fill out this sparse knowledge. We began using modern molecular phylogenetic methods. Initially based on 16S rRNA gene (prokaryote diversity) and ITS (lower eukaryote diversity) molecular fingerprinting and amplicon sequencing, our work subsequently expanded to include deep shotgun metagenome sequence analysis (yielding both phylogenetic and functional diversity data), total DNA-metavirome sequencing and metatranscriptome sequencing (sequencing of cDNA libraries from extracted and purified total mRNA, yielding high volumes of data on gene expression). One of the many factors that helped to drive this research program was the knowledge that, in desert ecosystems where the higher plants are sparsely distributed and/or very transitory, the soil microbial populations are disproportionately important in supporting essential ecosystem services such as carbon and nitrogen cycling.

Plate 3: The 2019 multi-national research team at Gobabeb. The authors are first on left, front row (DAC), hidden in the middle, middle row (J-BR).

Microbiology of Gravel Soils and Sand Dunes

Diversity

Over the past 12 years, we have performed a large number of phylogenetic surveys aimed at clarifying the microbial diversity of Namib Desert surface soils, in the context of spatial scales, geology and geomorphology, soil chemistry and soil-water relations. Much of this work is detailed in recent reviews and chapters (Cowan et al. 2015; Makhalanyane et al. 2015; Lebre et al. 2017; Ramond et al. 2019; Lebre et al. 2021; Cowan et al. 2020).

The dominant bacterial taxa of the Namib are those found in soils around the world: Actinomycetota, Pseudomonadota, Bacteroidota, Acidobacteriota and Cyanobacteria. Members of the phyla Chloroflexota, Deinococcota and Bacillota are more minor but significant contributors to the total bacterial diversity (Ronca et al. 2015; Armstrong et al. 2016; van der Walt et al. 2016; Gunnigle et al. 2017; Marasco et al. 2018; Leon-Sobrino et al. 2019). The presence of cosmopolitan phyla contrasts with analyses performed at higher taxonomic resolution (family, genus), which show large numbers of novel phylotypes, some of which cannot be assigned phylogenetically.

Edaphic fungal communities in the Namib desert are typically dominated by Ascomycota. The class Dothideomycetes was significantly more abundant in gravel plain soils than in dune soils, while Agaricostilbomycetes, Chytridiomycota and Sordariomycetes classes showed the opposite trend (van der Walt et al. 2016; Vikram et al., manuscript submitted).

Of the archaea, members of Euryarchaeota, Thermoproteota and Nitrososphaerota phyla composed a large majority of all archaeal sequences identified, ranging from 2% to 25% of the total prokaryotic communities. This makes the Namib Desert soils among the most archaea-rich of all desert soils worldwide (van der Walt et al. 2016). Members of the dominant archaeal taxon (Nitrososphaerota) are involved in nitrogen turnover, particularly ammonia oxidation.

Edaphic metaviromes were strongly dominated by sequences belonging to the most common soil dsDNA phage order, the Caudovirales, and representing the families *Siphoviridia, Myoviridae* and *Podoviridae* (Adriaenssens et al. 2015; Zablocki et al. 2016, 2017; Scola et al. 2018). This distribution is typical of soils worldwide.

Drivers of diversity and community assembly

The deterministic drivers of edaphic community assembly include historical water regime history (i.e., gravel plain vs riverbed and/or fog vs rain; Frossard et al. 2015; Scola et al. 2018; Naidoo et al. 2021), the presence and the influence of plant (Marasco et al. 2018) or soil origin (i.e., dune vs gravel plain vs riverbed; Gombeer et al. 2015) and soil physico-chemistries (e.g., Johnson et al. 2017; Scola et al. 2018). It is worth noting that Namib archaeal, bacterial and fungal communities were influenced by different physico-chemical variables (Johnson et al. 2017). In the fog zone, for example, salt concentration of the soil had a significant influence on edaphic communities (Stomeo et al. 2013; Scola et al. 2018).

Stochasticity[1] was also identified as an important driver of community assembly (Scola et al. 2018). Co-occurrence network analyses of soils and plant-associated soil niches suggest that biotic interactions (i.e. between different microbial taxa) also play an important role (Gunnigle et al. 2017; Marasco et al. 2018).

Functionality

While phylogenetic marker surveys provide comprehensive data on the presence and diversity of microorganisms, they yield no information on either the activity or functional capacity of the community. A range of methods, such as *in situ* enzyme assays, soil respirometry, metatranscriptomics (for functionality) or metagenomics (for a measure of the functional potential of a community) are used to assess community functions or functional potential.

Our studies of Namib gravel plain soils challenge the paradigm that desert soil microbial communities are completely dormant during long periods of drought. For example, 16S rRNA gene cDNA metabarcoding demonstrated that the dynamics of soil bacterial communities vary throughout the day. The Ascomycota were the most active fungal taxa, particularly during the cooler night hours (Gunnigle et al., 2107). A recent metatranscriptomic study also showed active nutrient cycling (C, N and P) in desiccated Namib soils (Leon-Sobrino et al. 2019). Under dry conditions, photoautotrophic carbon fixation was very limited, while chemoheterotrophic carbon acquisition pathways dominated. Transcripts for key dinitrogen fixation genes (*nifH*) were detected in very low numbers, while genes for nitrate and nitrite reduction enzymes (*nar* and *nir* genes, respectively) were abundantly expressed, suggesting that nitrate was the primary source of metabolic nitrogen in desiccated gravel plain soils (Leon-Sobrino et al. 2019).

A new paradigm for desert soil microbial energetics has emerged in the past 5 years. Following the discovery that carbon and energy acquisition in Antarctic soils was driven by Trace Gas Chemotrophy; i.e., assimilation and oxidation of atmospheric H_2 and CO driving high affinity CO_2 fixation (Ji et al. 2017), we demonstrated that Namib Desert soils also have this capability, as do other hot desert soils (Leung et al. 2020; Jordaan et al. 2020). Given that aerobic H_2 oxidation is hydro-genic (water-generating), this process may provide a hitherto unsuspected source of metabolic water for desert soil microbiomes (Bosch et al. 2021).

[1] Stochasticity: randomness, not affected by measurable factors such as rainfall, soil pH etc.

Cryptic Microbial Community Niches

Most microbial life is microscopic and invisible to the naked eye. In particular favoured niches, however, microbial consortia can form visible macroscopic structures. In the moister areas of the Namib, for example, biological soil crusts (BSCs) form on the soil surface. BSCs are complex assemblages of lichens, green algae and cyanobacteria (green photosynthetic filamentous bacteria). In the more arid areas of the Namib, conditions are too extreme for BSCs to survive. Life moves to the under-surfaces of quartz rocks and pebbles, forming microbial communities known as *hypolithons* (hypo–'under', lith–'rock'). These microbial communities are abundant across the geologically complex Namib Desert, but are generally invisible from the surface. Hypolithons are visible as black/green crusts adhering to the under-surfaces of rocks and at the rock-soil interface. Hypolithic communities are dominated by photosynthetic bacteria (mostly cyanobacteria), but include many other species of bacteria, fungi, viruses and phage, and even invertebrate 'grazers' such as springtails.

The hypoliths are the 'tropical rain-forests' of the Namib Desert. The hypolithic niche is a less extreme environment than the exposed soil surface. The overlying quartz is translucent, allowing light to penetrate and support cyanobacterial photosynthesis. This, in turn, supports all the other species in the community. The overlying rock also protects the hypolithon community from the extreme midday temperatures (the surface soil in the Namib can reach over 60°C), and from the desiccating effects of the very low humidity atmosphere (Bosch et al. 2022). The quartz rock also filters out potentially damaging short-wavelength solar radiation (Gwidzala et al. 2021).

Hypolithic communities are complex structural systems. Their composition is influenced by local aridity (Stomeo et al. 2013) and by selective recruitment of microbial taxa from the edaphic community (Makhalanyane et al. 2012). These communities are intimately associated with the surfaces of the quartz rock, penetrate into cracks and interstices (endolithy), are embedded in matrices of EPS (Extracellular Polysaccharide Substances) and are often lichenised, forming structured associations of filamentous fungi with cyanobacteria or green algae (de los Rios et al. 2021).

Hypolithons are thought to represent both biodiversity- and functional-hotspots in desert pavements (Vikram et al. 2016; Le et al. 2016; Ramond et al. 2022). Stable isotope analyses (Ramond et al. 2018) show that hypolithons were the major drivers of nitrogen fixation in Namib Desert soils, and that hypolithic cyanobacteria support entire sub-lithic food-webs (Valverde et al. 2015). Furthermore, hypolithic communities exhibited strongly mutualistic properties, with taxa belonging to the Cyanobacteria and α-Proteobacteria that have been identified as keystone species (Van Goethem et al. 2017).

We have sought to answer two simple questions about Namib hypolithic communities: how fast do hypolithic communities grow, and how does the growing community develop? We used artificial hypolithon arrays consisting of tiles and rocks to answer these questions. Arrays sited in the eastern rainfall zone showed hypolithic cyanobacterial biofilm growth

Plate 4: Upturned quartz rock, showing the green mat of microbial life on the underside and the soil below the rock

after just two years under the translucent rocks, and adhesion to the rock under-surface after three years. Conversely, a hypolithon array sited in the hyper-arid soils near Gobabeb showed no visual evidence of hypolithon growth even after seven years, although phylogenetic data suggested some enrichment of cyanobacteria in the soil after five years. We conclude that many decades are required for development into mature hypolithic communities, particularly in the more arid regions of the Namib Desert. Local soil aridity plays a significant role.

One of the many intriguing questions about hypolithic communities is whether the filtering of light by the overlying translucent rock has led to special genetic or physiological adaptations in the cyanobacterial phototrophs? For example, do hypolithic photoautotrophs have photosynthetic pigments which preferentially adsorb at the red-end of the PAR spectrum, or do they have photosystems adapted to work efficiently at very low light levels? A recent study using a range of fluorimetric and spectroscopic methods showed that chlorophyll contents were not light-adapted, but that stress-linked adaptations, such as the presence of helical carotenoid proteins, were characteristic of these communities (Gwidzala et al. 2021).

Other cryptic niches colonised by desert microbial communities include the pores (cryptoendolithic) or the cracks/fissures (chasmoendolithic) of various rocks types (e.g.,

Plate 5: An artificial hypolithon array

sandstone, granite and limestone). Endolith communities in central Namib Desert sandstones were dominated by the cyanobacterial genus *Chroococcidiopsis,* but community composition varied along an east-west precipitation gradient and was dependent upon substrate (Qu et al 2020).

Desert Plant-associated Microbiology

All plants have associated microbiomes, on leaf surfaces (epiphytes), inside cells and tissues (endophytes), and associated with root systems (the rhizosphere). The rhizospheric microbiome is thought to play key roles in supporting the plant host, while the microbiome benefits nutritionally from plant root exudates, making the rhizobiome a genuinely mutualistic association. Desert-adapted plants may harbour unique microbial populations, which may contribute to the host plant's resistance to drought.

We have investigated the microbiomes of one of the Namib's iconic inhabitants, the welwitschia (*Welwitschia mirabilis*, the only species within the Welwitschiaceae order). These slow-growing plants are endemic to the Namib Desert, and are ancient relatives of the pine-tree. They are dotted across barren and rocky landscapes, surviving extremes of heat and desiccation with apparent ease.

We found that very few microbial taxa were shared between the *Welwitschia* rhizosphere and the surrounding bulk soil (Valverde et al. 2016). The welwitschia root system therefore possesses its own unique microbial community, which almost certainly contributes to the survival of this unique plant. In contrast, foliar fungal distributions were cosmopolitan, with little evidence of adaptation to their host species (Kemmler et al. 2021).

Many desert plants have unusual modifications to their roots systems, such as cylindrical sheaths of mineral sand particles around the major roots (termed rhizosheaths). The rhizosheath is held in place by root hairs and cemented by extracellular polysaccharide 'glue' secreted by bacteria. *Stipagrostis* (the dominant grass of the gravel plains) rhizosheath microbiomes were about 1000-fold enriched compared with the surrounding sand, and were more organized: sand microbial community compositions were driven more by sand properties, and less by the plant species (Marasco et al. 2018).

Plate 6: Mature Welwitschia *plants: male (front) and female (behind)*

Plate 7: Stipagrostis *(speargrass) rhizosheaths*

Microbiology of Fairy Circles

For centuries, the enigmatic *fairy circles* of the Namib Desert have been the cause of wonder and argument. The indigenous peoples of the Namib thought that they were the work of dragons. In more recent times, theories of their origins have included the actions of UFOs, dancing fairies, radioactive hot-spots, natural gas seepages, poisonous residues of dead *Euphorbia* plants, the presence of colonies of sand termites or pathogenic fungi, or the result of natural plant self-organization processes. Scientific papers claiming to have discovered the true origins of fairy circles appear quite regularly, but with no real resolution of their origins. They remain a tantalizing enigma.

We have pursued the hypothesis that fairy circles are the result of microbial phytopathogenic processes. It has long been known that the abundance of culturable microorganisms differs within and at the edges of fairy circles (Theron 1979). Our own studies have focussed on the microbiology of the fairy circles that can be found in the gravel plains near the Gobabeb-Namib Research Institute. We demonstrated, using molecular fingerprinting, that soils from the centres and margins of the fairy circle had different bacterial and fungal communities compared to the "vegetated" surrounding soils (Ramond et al. 2014).

Plate 8: Fairy Circles scattered across the sands of the eastern Namib Desert

Fairy circles are found in both the gravel plains and on the margins of sand-dunes. If fairy circles are formed by microorganisms that prevent plant growth inside the circles, these microorganisms should be found in both habitats, irrespective of the geographical distance between them (~200 km, in this study). Even though the microbial communities from fairy circles in sand-dunes differed significantly from fairy circles in the gravel plains, we identified one archaeal, nine bacterial, and 57 fungal phylotypes that were consistently detected in all fairy circle soils throughout the Namib. These microbial taxa constitute putative candidates as the causative agents behind these enigmatic landscape features. We note that some of the identified taxa are closely related to well-known phytopathogens; i.e., microorganisms that are harmful to plants. However, proof of a phytopathogenic origin of fairy circles still requires the well-known Koch's postulates[2] to be fulfilled: in particular, we need to isolate the target microorganisms and prove in pot- and field-trails that they are toxic to plant growth.

[2] (i) The microorganism must be found in abundance in all organisms suffering from the disease, but should not be found in healthy organisms.
(ii) The microorganism must be isolated from a diseased organism and grown in pure culture.
(iii) The cultured microorganism should cause disease when introduced into a healthy organism.
(iv) The microorganism must be re-isolated from the inoculated, diseased experimental host and identified as being identical to the original specific causative agent.

Microbiology and Virology of Saline Springs, Salt Pans and Playas

The Namib Desert has numerous saline springs and salt pans with halite evaporates (often termed *playas*), located mostly near the coast (Eckardt & Drake 2010). These are caused by groundwater flowing westwards tens or hundreds of meters below the surface, until encountering a geological sill or dyke (Eckardt et al. 2022) which forces the water to emerge at the surface. Gradual mineral solubilisation and evaporative processes in the groundwater stream increase the salt concentrations, and the waters emerge as saline springs.

The emergent spring waters typically flow a few tens of hundreds of meters before sinking back into the sands. Before disappearing, and as the water evaporates, these saline streams support extensive salt crystallisation and hypersaline conditions in marginal pools. The result is a wide range of different saline water and soil habitats, which support a wide diversity of salt-adapted microorganisms (Johnson et al. 2017). These saline springs can also serve as essential water sources for local wildlife.

We have investigated several aspects of the microbiomics of saline spring eco-systems at Hosabes (near the Gobabeb-Namib Research Institute) and Eisfeld (east of Swakopmund), with a particular focus on the viral and phage communities. A survey of ssDNA viruses (Adriaenssens et al. 2016) demonstrated that a substantial majority of the

Plate 9: Hosabes saline spring and stream, with extensive crystalline evaporites

sequences identified were completely novel (i.e., not found in any of the public virome sequence databases). More recently, shotgun metagenomics identified host and viral taxa (Martinez-Alvarez et al. 2022), and characterised the functional potential of these organisms. Halite samples were dominated by extremely halophilic Euryarchaeota and Bacteriodota (*Salinibacter* species), with highly novel lineages of the Caudovirales phage. We also identified a potentially novel clade of Type II CRISPR-Cas genes, suggesting that these saline spring communities are involved in intense host-virus competition.

Microbial Community Responses to Water

Water, or rather the lack of it, is what makes a desert. The aridity of a desert is determined by the ratio of precipitation to potential evapotranspiration (P/PET). Very low precipitation (an average of a few mm of rain per year) and very high evapotranspiration qualifies the central Namib as *hyper-arid* ($P/PET < 0.05$).

Most microorganisms, when desiccated, transition into a dormant state, where residual metabolism (termed *anhydrobiosis*) is restricted to minimal (basal) metabolic processes necessary for the production of maintenance energy (Bosch et al. 2021). The extent of dormancy in desert soil microbiomes has never been resolved. Using metatranscriptomics methods, we were able to assess microbiome dormancy in Namib soils. While many of the major clades of bacteria show little or no gene expression in dry conditions (i.e., near or complete dormancy), a small fraction of the microbial species in dry desert soils retained metabolic activity (Gunnigle et al. 2017; Leon-Sobrino et al. 2019). Those 'active' species were part of the rare bacterial community, while the dormant fraction comprised the dominant taxa. We also showed that the magnitude of the microbiome response to precipitation depended on the water regime history of their environment of origin (riverbed vs gravel plain soils; Frossard et al. 2015).

Community gene transcription profiles (Leon-Sobrino et al. 2019) show that the active metabolic processes in microbiomes of desiccated soil were predominantly heterotrophic carbon acquisition (metabolizing fixed carbon from degrading lipids) and nitrogen acquisition by nitrate reduction (nitrate is often present at quite high concentrations in the driest desert soils). There was little evidence for the energy-expensive acquisition of atmospheric CO_2 assimilation (catalysed by RUBISCO) or atmospheric N_2 fixation (driven by nitrogenase).

In a desert, water changes everything! Heavy rains in the summer of 2011 triggered massive plant germination across the Namib, and for a while the depauperate desert became a prairie. This dramatic change in the landscape (and the desert biology) stimulated us to ask questions of how the addition of water (and the carbon rich plant biomass) might influence the soil microbiomes. A year-long field study (Armstrong et al. 2016) yielded some salutary lessons in experimental design. The single rain event (in month 11) triggered a massive shift in soil microbial community composition, coinciding with a dramatic increase in soil respiration as newly expanded microbial populations accessed previously dry and inaccessible organic substrates.

This study did not tell us how quickly a dry soil microbiome can respond to water inputs. We prepared several hundred litres of DNA-free artificial rainwater, and applied this to a 5m² area of desert soil, taking soils samples prior to the addition and at increasing intervals after the artificial 'rain event' and analysing them using metatranscriptomics methods. The results were dramatic! Just 10 minutes after water addition (our first sample), the metatranscriptome changed dramatically (Leon-Sobrino et al. 2021). Up-regulated genes included those for cellular motility, substrate import and export, and cell division, all changes which might be expected for a microbial community with sudden access to a liquid continuum and a newly available supply of energy rich organic substrates. The most prominently down-regulated genes were those encoding stress response elements, as cells transitioned from a high stress (desiccation stress, energy limitation and oxidative stress) environment to a more favourable habitat.

Desert Insects and Micro-arthropods

The Namib Desert has provided many famous examples of the unique diversity and physiology of its insects (Seely & Pallett 2012: Henschel & Lancaster 2013), particularly the iconic fog-harvesting beetles (Hamilton and Seely 1976). While insects have not been the primary focus of our desert ecology studies, we have always been aware that they are core components of the Namib's structured desert communities. At the urging of our New Zealand colleague, Professor Ian Hogg, we undertook a molecular bar-coding study of the Namib Desert's Collembola (Springtails).

The Namib Desert Collembola had been long thought to consist of only 4 species. We collected over 400 springtail specimens from 77 pit-fall traps across the desert, extracted genomic DNA and analysed the CO1 gene locus. The results were spectacular: GMYC

Plate 10: The central Namib Desert at Mirabeb, before and after the 2011 rains

(Generalized Mixed Yule Coalescent) analyses indicated a minimum of 30 putative species, 70% of which were found only at a single site (Collins et al. 2019). This study has raised many more questions than it has answered. Issues such as gene isolation and gene flow, distribution, dispersal and more all remain to be addressed and answered.

Conclusions

If there is a single lesson we can draw from a decade of microbiomics research in the Namib Desert, it is that, despite our extensive and intensive studies using state-of-the-art sequencing and bioinformatics technologies, our ignorance remains much greater than our knowledge. We have partially answered some of the simpler questions, particularly those relating to microbial community composition and compositional drivers. Yet, some of the results are contradictory, and some major taxonomic groups, such as the viruses, phages, and the microarthropods, remain grossly understudied. We know relatively little of the complex interactions within communities although we have exposed tantalizing hints suggesting that these interactions are critical elements of community function. We have barely scratched the surface of temporal effects on microbiome structure and function. We have very little kinetic data of any sort, from the functional rates of single taxa to the spatially integrated rates of key ecosystem services. We know little of the ways in which Namib Desert edaphic microbial communities may respond to changing climate parameters, over any timescale.

Our studies have also been spatially restricted: to an area of the central Namib Desert of less than 10,000 sq. km. and mostly at low spatial resolution (10 or 20 km sample site spacing). Given that the entire Namib Desert covers an area of approx. 81,000 sq. km, and microbial ecology studies of some major regions such as the Skeleton Coast National Park and the Namib Sand-Sea are almost completely non-existent, we can hardly claim to have comprehensively surveyed the microbial communities of the region.

This summary of our knowledge deficits is not intended to be pessimistic, but merely to highlight the potential for research over the next decade(s). The rapid development of sophisticated molecular and analytical tools can only accelerate the pace and value of such research, and the outcomes of such efforts are likely to be at least as exciting as those of the past decade, and probably much more so.

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Throughout more than a decade of Namib Desert microbiomics research, we have used an open collaborative model. Our annual field expeditions to the Gobabeb-Namib Research Institutions have been multi-partner team efforts, with collaborators from all around the world joining our expeditions of up to 30 researchers. Many of these visitors have become sustained long-term collaborators.

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References

ADRIAENSSENS, E., VAN ZYL, L., DE MAAYER, P., RUBAGOTTI, E., RYBICKI, E., TUFFIN, I.M., COWAN, D.A. (2015) Metagenomic analysis of the viral community in Namib Desert hypoliths. *Environmental Microbiology* 17: 480–495.

ADRIAENSSENS, E.M., VAN ZYL, L.J., COWAN, D.A., TRINDADE, M. (2016) Namib Desert salt pans: a novel lineage of haloarchaeal salterproviruses are a rich source of ssDNA viruses. *Viruses* 8(1): DOI: 10.3390/v8010014.

ARMSTRONG, A., VALVERDE, A., RAMOND, J.-B., MAKHALANYANE, T.P., JANSSEN, J., HOPKINS, D.W., ASPRAY, T.J., SEELY, M., TRINDADE, M.I., COWAN, D.A. (2016) Temporal dynamics of hot desert microbial communities reveal structural and functional responses to water input. *Scientific Reports* 6: 34434.

BOSCH, J., MARAIS, E., MAGGS-KÖLLING, G., RAMOND, J.-B., LEBRE, P.H., ECKARDT, F., COWAN, D.A. (in press) Water inputs across the Namib Desert: implications for dryland edaphic microbiology. Frontiers in Microbiology.

BOSCH, J., VARLIERO, G., HALLSWORTH, J., DALLAS, T.D., HOPKINS, D., FREY, B., KONG, W.D., LEBRE, P., MAKHALANYANE, T.P., COWAN, D.A. (2021) Microbial anhydrobiosis. *Environmental Microbiology* 23: 6377–6390.

BÜDEL, B., FRAHM, J.P., SIEGE, M. (2011) Lichens of the Namib Desert—A Guide to their Identification. *Herzogia* 24: 167–167.

COLLINS, G.E., HOGG, I.D., BAXTER, J.R., MAGGS-KÖLLING, G., COWAN, D.A. (2019) High levels of genetic variability and deeply divergent lineages among populations of Namib Desert Collembola. *Ecology and Evolution* 9: 4969–4979.

COWAN, D.A., HOPKINS, D.W., JONES, B.E., MAGGS-KÖLLING, G., MAJEWSKA, R., RAMOND, J.-B. (2020) Microbiomics of Namib Desert habitats. *Extremophiles* 24: 17–29.

COWAN, D.A., RAMOND, J.-B., MAKHALANYANE, T.P., DE MAAYER, P. (2015) Metagenomics of extreme environments. *Current Opinion in Microbiology* 25: 97–102.

DE LOS RIOS, A., GARRIDO-BENAVENT, I., LIMON, A., MAGGS-KOLLING, G., CASON, E.D., COWAN, D.A., VALVERDE, A. (2021) Novel lichen-dominated hypolithic communities in the Namib Desert. *Microbial Ecology* ePub, 10.1007/s00248-021-01812.

ECKARDT, F.D., DRAKE, N. (2010) Introducing the Namib Desert Playas. Sabkha Ecosystems. Springer.

ECKARDT, F., SODERBERG, K., COOP, L., MULLER, A., VICKERY, K., GRANDIN, R., JACK, C., KAPALANGA, T., HENSCHEL, J. (2013) The nature of moisture at Gobabeb, in the central Namib Desert. *Journal of Arid Environments* 93: 7–19.

ECKARDT, F.D., MAGGS-KÖLLING, G., MARAIS, E. (2022) A brief introduction to desert environments: Climate, geomorphology, habitats and soil processes. Ch. 1 in Microbiology of Hot Deserts, Ramond, J.-B., Cowan, D.A., Eds. Springer-Verlag, pp. 1–36.

FROSSARD, A., RAMOND, J.-B., SEELY, M., COWAN, D.A. (2015) Water regime history drives responses of soil Namib Desert microbial communities to wetting events. *Scientific Reports* 5: 571–578.

GOMBEER, S., RAMOND, J.-B., ECKARDT, F., SEELY, M., COWAN, D.A. (2015) The influence of soil physicochemistry on the edaphic bacterial communities in contrasting terrain types of the Central Namib Desert. *Geobiology* 13: 494–50.

GUNNIGLE, E., FROSSARD, A., RAMOND, J.-B., GUERRERO, L., SEELY, M., COWAN, D.A. (2017) Diel-scale temporal dynamics recorded for bacterial groups in Namib Desert soil. *Scientific Reports.* 7: 40189.

GWIZDALA, M., LEBRE, P.H., MAGGS-KÖLLING, G., MARAIS, E., COWAN, D.A., KRÜGER, T.P.J. (2021) Sub-lithic photosynthesis in hot desert habitats. *Environmental Microbiology* 23: 3867-3880 doi:10.1111/1462-2920.15505.

HAMILTON, W.J., SEELY, M.K. (1976) Fog basking by the Namib Desert beetle, *Onymacris unguicularis*. *Nature* 262: 284–285.

HENSCHEL, J.R., LANCASTER, N. (2013) Gobabeb—50 years of Namib Desert research. *Journal of Arid Environments* 93: 1–6.

HINCHCLIFFE, G., BOLLARD-BREEN, B., COWAN, D.A., DOSHI, A., GILLMAN, L.N., MAGGS-KOLLING, G., DE LOS RÍOS-MURILLO, A., POINTING, S.B. (2017) Advanced photogrammetry to assess lichen colonisation in the hyper-arid Namib Desert. *Frontiers in Microbiology* 8: 2083 doi: 10.3389/fmicb.2017.02083.

JACOBSON, K.M. (1997) Moisture and substrate stability determine VA-mycorrhizal fungal community distribution and structure in an arid grassland. *Journal of Arid Environments* 35: 59–75.

JACOBSON, K.M., JACOBSON, P.J. (1998) Rainfall regulates decomposition of buried cellulose in the Namib Desert. *Journal of Arid Environments* 38: 571–583.

JACOBSON, K.M., JACOBSON, P.J., MILLER, O.K. (1993) The mycorrhizal status of *Welwitschia mirabilis*. *Mycorrhiza* 3: 13–17.

JI, M., GREENING, C., VAN VONTERGHEM, I., CARERE, C., BAY, S., STEEN, J., MONTGOMERY, K., LINES, T., BEARDALL, J., VAN DORST, J., SNAPE, I., STATT, M., HUGENHOLTZ, P., FERRARI, B. (2017) Atmospheric trace gasses support primary production in Antarctic desert ecosystems. *Nature* 552: 400–403.

JOHNSON, R.M., RAMOND, J.-B., GUNNIGLE, E., SEELY, M., COWAN, D.A. (2017) Namib Desert edaphic bacterial, fungal and archaeal communities assemble through deterministic processes but are influenced by different abiotic parameters. *Extremophiles* 21: 381–392.

JORDAAN, K., LAPPAN, R., DONG, X., AITKENHEAD, IJ., BAY, SK., CHIRI, E., WIELER, N., MEREDITH, L.K., COWAN, D.A., CHOWN, S.L., GREENING, C. (2020) Hydrogen-oxidising bacteria are abundant in hot desert soils and strongly stimulated by hydration. mSystems *5*: e01131.

KEMLER, M., WINGFIELD, M.J., COWAN, D.A., SLIPPERS, B. (2021) Foliar fungi of the enigmatic desert plant *Welwitschia mirabilis* show little adaptation to their unique host plant. *South African Jounral of Science* 117: 1766.

LE, P.T.T., MAKHALANYANE, T.P., GUERRERO, L., VIKRAM, S., VAN DER PEER, Y., COWAN, D.A. (2016) Comparative metagenomic analysis reveals mechanisms for stress response in hypoliths from extreme hyperarid deserts. *Genome Biol. Evol.* 8: 2737–2747.

LEBRE, P., DE MAAYER, P., COWAN, D.A. (2017) Xerotolerant prokaryotes: surviving through a dry spell. Nature Reviews. *Microbiology* 15: 285–296.

LEBRE, P.H., COWAN, D.A., MAKHALANYANE, T.P. (2021) The hypolithic habitat: microbial communities under translucent rocks. Ch 1.2 in Life at rock surfaces: Life in Extreme Environments. Büdel, B., Friedl, T., Eds., De Gruyter Publ. 9: 39–56, ISBN 978-11-064261-2.

LEÓN-SOBRINO, C., RAMOND, J.-B., MAGGS-KÖLLING, G., COWAN, D.A. (2019) Nutrient acquisition, rather than stress response over diel cycles, drives microbial transcription in a hyper-arid Namib Desert soil. *Frontiers in Microbiology* 10: 1045.

LEÓN-SOBRINO, C., COCLET, C., MAGGS-KÖLLING, G., KAPITANGO, R., RAMOND, J.-B., COWAN, D.A. (2021) Temporal dynamics of microbial transcription in wetted hyperarid desert soils. *bioRxiv.*

LEUNG, P.M., BAY, S., MEIER, D., CHIRI, E., COWAN, D., GILLOR, O., WOEBKEN, D., GREENING, C. (2020) Energetic and trophic basis of microbial persistence in desert ecosystems. *mSystems* 5: e00495-19.

MAKHALANYANE, T., VALVERDE, A., GUNNIGLE, E., FROSSARD, A., RAMOND, J.-B., COWAN, D.A. (2015) Microbial ecology of hot desert edaphic systems. *FEMS Microbiology Reviews* 39: 203–221.

MAKHALANYANE, T.P., VALVERDE, A., LACAP, D., POINTING, S.B., TUFFIN, I.M., COWAN, D.A. (2012) Evidence of species recruitment and development of hot desert hypolithic communities. *Environmental Microbiology Reports* 5: 219–224.

MARASCO, R., MOSQUEIRA, M.J., FUSI, M., RAMOND, J.-B., MERLINO, G., BOOTH, J.M., MAGGS-KÖLLING, G., COWAN, D.A., DAFFONCHIO, D. (2018) Rhizosheath microbial community assembly of sympatric desert speargrasses is independent of the plant host. *Microbiome* 6: 215.

MARTINEZ-ALVAREZ, L., RAMOND, J.-B., VIKRAM, S., LEON-SOBRINO, C., MAGGS-KOLLING, G., COWAN, D.A. (2022) With a pinch of salt: metagenomic insights into Namib Desert salt pan microbial mats and halites reveal functionally adapted and competitive communities. *bioRxiv.*

NAIDOO, Y., VALVERDE PORTAL, A., PIERNEEF, R.E., COWAN, D.A. (2021) Differences in precipitation regime shape microbial community composition and functional potential in Namib Desert soils. *Microbial Ecolology* I08 June 2021, 10.1007/s00248-021-01785-w.

PRESTEL, E., SALAMITOU, S., DUBOW, M.S. (2008) An examination of the backeriophages and bacteria of the Namib Desert. *Journal of Microbiology* 46: 364–372.

QU, E.B., OMELON, C.R., OREN, A., MESLIER, V., COWAN, D.A., MAGGS-KÖLLING, G., *DIR*UGGIERO, J. (2020) Trophic selective pressures organize the composition of endolithic microbial communities from global deserts. *Frontiers in Microbiology* 10: 2952.

RAMOND, J.-B., BAXTER, J., MAGGS-KÖLLING, G., MARTÍNEZ-ALVAREZ, L., READ, D., LEÓN-SOBRINO, C., VAN DER WALT, A., COWAN, D.A. (2019) Microbial ecology of Namib Desert. Ch. 6 in *Extreme Environments.* Rampelotto PH, Ed., Springer, Publ. pp. 113–143.

RAMOND, J.-B., JORDAAN, K., DIEZ, B., HEINZELMANN, S.M., COWAN, D.A. (2022) Microbial biogeochemical cycling of nitrogen in arid ecosystems. *Microbiology and Molecular Biology Reviews* ePub. doi.org/10.1128/mmbr.00109-21.

RAMOND, J.-B., PIENAAR, A., ARMSTRONG, A., SEELY, M., COWAN, D.A. (2014) Niche-partitioning of edaphic microbial communities in the Namib Desert gravel plain Fairy Circles. *PLoS One* 9: 1–6.

RAMOND, J.-B., WOODBORNE, S., HALL, G., SEELY, M., COWAN, D.A. (2018) Namib Desert primary productivity is driven by cryptic microbial community N-fixation. *Scientific Reports* 8: 6921.

RAMOND, J.-B., MAKHALANYANE, T.P., TUFFIN, I.M., COWAN, D.A. (2015) Normalization of environmental metagenomic DNA enhances the discovery of novel microbial community members. *Letters in Applied Microbiology* 60: 359–366.

RONCA, S., RAMOND, J.-B., JONES, B.E., SEELY, M., COWAN, D.A. (2015) Microbial community structure along dune-interdune transects in the Namib Desert. *Frontiers in Microbiology* 6: 845.

SCHIEFERSTEIN, B., LORIS, K. (1992) Ecological investigations on lichen fields of the Central Namib. *Vegetatio* 98: 113–128.

SCOLA, V., RAMOND, J.-B., FROSSARD, A., ZABLOCKI, O., ADRIAENSSENS, E., JOHNSON, R.M., SEELY, M., COWAN, D.A. (2018) Namib Desert soil microbial community diversity, assembly and function along a natural xeric gradient. *Microbial Ecology* 75: 193–203.

SEELY, M., PALLETT, J. (2012) Namib: Secrets of a desert uncovered. Venture Pubs. 197 pp.

STOMEO, F., VALVERDE, A., POINTING, S.B., MCKAY, C.P., WARREN-RHODES, K.A., TUFFIN, I.M., SEELY, M., COWAN, D.A. (2013) Hypolithic and soil microbial community assembly along an aridity gradient in the Namib Desert. *Extremophiles* 17: 329–337.

STUTZ, J.C., COPEMAN, R., MARTIN, C.A., MORTON, J.B. (2000) Patterns of species composition and distribution of arbuscular mycorrhizal fungi in arid regions of southwestern North America and Namibia, Africa. *Canadian Journal of Botany* 78: 237–245.

THERON, G.K. (1979) Die verskynsel van kaal kolle in Kaokoland, Suidwes-Afrika. *Journal of the South African Biological Society* 20: 43–53.

VALVERDE, A., DE MAAYER, P., OBERHOLSTER, T., HENSCHEL, J., LOUW, M.K., COWAN, D.A. (2016) Specific microbial communities associate with the roots of *Welwitschia mirabilis*, a living fossil. *PLoS One* 11: e0153353.

VALVERDE, A., MAKHALANYANE, T.P., SEELY, M., COWAN, D.A. (2015) Cyanobacteria drive food-webs and functionality in niche soil communities. *Molecular Ecology* 24: 812–821.

VAN DER WALT, A., JOHNSON, R., COWAN, D., SEELY, M., RAMOND, J.-B. (2016) Unique microbial phylotypes in Namib Desert Fairy Circle soils. *Applied Environmental Microbiology* 85: 4592–4601.

VAN GOETHEM, M.W., MAKHALANYANE, T.P., COWAN, D.A., VALVERDE, A. (2017) Cyanobacteria and Alphaproteobacteria may facilitate cooperative interactions in niche communities. Frontiers in *Microbiology* 8: 2099.

VIKRAM, S., GUERRERO, L., MAKHALANYANE, T.P., LE, P.-T., SEELY, M., COWAN, D.A. (2016) Metagenomic analysis provides insights into functional capacity in a hyperarid desert soil niche community. *Environmental Microbiology* 18: 1875–1888.

VIKRAM, S., RAMOND, J.-B., ORTIZ, M., MAGGS-KÖLLING, G., PELSER, K., COWAN, D.A. Soil fungal diversity along a xeric stress gradient in the central Namib Desert. Manuscript under review.

WARREN-RHODES, K.A., MCKAY, C.P., BOYLE, L.N., WING, M.R., COWAN, D.A., STOMEO, F., POINTING, S.B., KASEKE, K.F., ECKARDT, F., HENSCHEL, J.R., ANISFELD, H., SEELY, M., RHODES, K.L. (2013) Physical ecology of hypolithic communities in the central Namib desert: the role of fog, rain, rock habitat and light. *Journal of Geophysical Research* 118: 1451–1460.

WESSELS, D.C.J. (1989) Lichens of the Namib Desert, South West Africa/Namibia. I. The chasmoendolithic habitat. *Dinteria* 20: 03–22.

WESSELS, D.C.J., VAN VUUREN, D.R.J. (1986) Landsat imagery-its possible use in mapping the distribution of major lichen communities in the Namib Desert, South West Africa. *Madoqua* 4: 369–373.

ZABLOCKI, O., ADRIAENSSENS, E., COWAN, D.A. (2016) Diversity and ecology of viruses in hyperarid desert soils. *Applied Environmental Microbiology* 82: 770–777.

ZABLOCKI. O,, ADRIAENSSENS, E., RAMOND, J.-B., FROSSARD, A., SCOLA, V., SEELY, M., COWAN, D.A. (2017) Extracellular virus diversity and biogeography in Namib Desert soils. *Genomic Announcements* 5: e01470-16.

ZABLOCKI, O., RYBICKI, E., COWAN, D.A. (2014) First report of a potyvirus infecting *Albuca rautanenii* in the Namib Desert. *Plant Disease.* 98: 1749.

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Don Cowan's research is in the fields of microbial ecology, microbial genomics and applied microbiology, where he and his team use modern 'omics' methods to understand the diversity and function of microorganisms in different environments. Much of his research focuses on the microbiology of extreme environments, including hot (Namib) and cold (Antarctic) desert soils. He also supervises research projects investigating the rhizospheric zones of economic crop plant species, and is currently leading the pan-African African Soil Microbiome project. He works with many other research laboratories in South Africa and across the world.

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1896-1900
Building of Fort by Schutztruppe as a Military Station

1905-1908
Magistrates Offices

1908
Renovated under supervision of Government Master builder Redecker

1920
School and hostel. More renovations and alterations

1960
A hostel until 1967, decays thereafter

04.08.1972
Local chemist Young starts the initiative "Save the Fort"

November 1972
Idea of establishing a Museum

21.03.1975
Building resorts under jurisdiction of the Monuments Council

1975-1976
± 2000 Portuguese refugees from Angola are housed in the Fort

18.02.1977
Tower roof replaced with concrete free of charge by company MLS

July 1977
Quote for renovation – R 16,481.00 received. Bulk paid by
Monuments Council, balance settled by donations

23.01.1978
Monuments Council takes over the renovated building

26.07.1978
Namibia Scientific Society officially accepts Umbrella Organisation

August 1978
Founding of Museums Committee, collection of display items

23.10.1983
Official opening of Museum

Kindly book at least 24 hours ahead of your visit:
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Validation of Satellite-Retrieved Land Surface Temperature (LST) Products at Gobabeb, Namibia

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Abstract

Global land surface temperature (LST) data derived from satellite-based infrared radiance measurements are highly valuable for various applications in climate research. LST is a fundamental state variable for land surface processes and has long been available from satellite observations in the thermal infrared (TIR). LST is also increasingly important for studies assessing land surface conditions, e.g., studies of urban climate, evapotranspiration, and vegetation stress. LST is usually retrieved from satellite-based radiance measurements in the infrared (IR) or microwave (MW) range and it is well suited to provide global coverage. Due to the spatial scale mismatch between ground and satellite-based measurements and the heterogeneity of natural land surfaces, the validation of satellite LST data sets is a challenging task. However, *in situ* validation is essential for obtaining quantitative information on the accuracy of LST satellite products. Permanent, continuous *in situ* measurements of up- and downwelling TIR radiance allow the analysis of long timeseries of satellite LST observations, which can reveal seasonal cycles and potential deviations; these can originate from surface anisotropy, topography, heterogeneous land cover, or spatial variations in soil moisture. Many of the validation results obtained over the Namib gravel plains demonstrate the maturity of the LST products investigated over the past 15 years. They also highlight the need to carefully consider their temporal and spatial properties when using them for scientific purposes. Total uncertainty of *in situ* LST obtained from the TIR radiance measurements at the Gobabeb wind tower is estimated as 0.8 ± 0.12°C, which is highly accurate for a bare soil site with diurnal LST amplitudes of up to 40°C. Analyses of spatial representativeness performed on the meter to kilometer scale near Gobabeb Namib Research Institute yielded an absolute bias of 0.5°C compared to *in situ* LST, a value mainly achieved thanks to the Namib's hyper-arid desert climate and the spatial homogeneity and temporal stability of the gravel plains. The Namib gravel plains were found to be suitable for validating LST with pixel sizes of up to 100 km^2 and the continued availability of the *in situ* measurements from Gobabeb is of high importance for accurately validating and monitoring current and future satellite LST products.

1 Introduction

Land surface temperature (LST), also called skin temperature, is the temperature of the Earth's surface (Dash et al. 2002, Hulley et al. 2019). LST is one of the main quantities governing the energy exchange between surface and atmosphere and it is a highly useful quantity for applications within climate research. This includes an improved understanding of the climatic effects of land use and land cover change (Mallick et al. 2012), drought monitoring (Rhee et al. 2010), detection of changes in land cover and energy balance (Mildrexler et al. 2011), monitoring of heatwaves (Dousset et al. 2010), estimation of evapotranspiration (Li et al. 2015), or investigations of urban heat islands (Weng 2009, Bechtel et al. 2019). Furthermore, it is used as input for land surface models (Reichle et al. 2010) and numerical weather prediction (Dash et al. 2002). The Global Climate Observing System (GCOS) specifies LST as an essential climate variable (ECV), i.e., important variables to understanding and prediction of Earth's climate (Guillevic et al. 2018).

LST is usually retrieved from remote sensing data in the thermal infrared (TIR) or microwave (MW) range and global coverage can be achieved by using satellite-based measurements. For a meaningful scientific use of satellite LST, information about the quality of the data sets has to be available. Therefore, the availability of long-term and quality-controlled observations of ECVs is very important. Such information can be obtained in several ways, most commonly from validation against *in situ* data, radiance-based validation, satellite-satellite intercomparisons, and time series analysis (Guillevic et al. 2018, Hulley et al. 2019).

Operational LST products are currently retrieved from a variety of space-borne TIR sensors, e.g., the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the Meteosat Second Generation (MSG) satellites, the Advanced Very High Resolution Radiometer (AVHRR) onboard the MetOp satellites (Trigo et al. 2021), the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard EOS-Terra and EOS-Aqua, the Sea and Land Surface Temperature Radiometer (SLSTR) onboard Sentinel-3A/B, and the various versions of the Thematic Mapper (TM) onboard the Landsat series.

For current TIR sensors, e.g. SEVIRI, MODIS and SLSTR, LST is most often estimated through the application of a Generalized Split-Window (GSW) formulation and similar. The uncertainty of LST retrievals depends on a wide range of factors such as land surface type (related to emissivity uncertainty), water vapor content in the atmosphere, or viewing geometry (Freitas et al. 2010, Ermida et al. 2017, Ghent et al. 2019). In order to ensure that LST retrievals are stable in time and consistently meet their expected accuracy, operationally derived LST have to be continuously monitored and assessed. Relative accuracy can be assessed by cross-validation between LST products obtained with different retrieval algorithms and/or for different sensors (Guillevic et al. 2018). Such exercises allow analyses of the consistency between different products but provide limited information on their actual accuracy. Therefore, *in situ* measurements ("ground truth") are ultimately needed for validating satellite LST and surface emissivity (LST&E) products (Guillevic et al. 2018, Göttsche et al. 2016). In principle, LST products can readily be validated with ground-truth radiometric measurements. Unfortunately, this so-called "temperature-based validation" is considerably complicated by the spatial scale mismatch between satellite and ground based sensors (Guillevic et al. 2018): areas observed by ground radiometers usually cover about $10\,m^2$, whereas satellite measurements in the thermal infrared typically cover between $1\,km^2$ and $100\,km^2$. Therefore, for *in situ* LST to be representative for the area observed by the satellite, they have to be obtained over areas that are sufficiently homogenous at the scale of the *in situ* measurements as well as on the satellite pixel scale. The size of the area that needs to be viewed by the validation instrument at the ground depends on within-pixel variability and how well this can be represented with *in situ* measurements. Therefore, for temperature-based validation, the accurate characterization of LST spatial variability is critical.

The Gobabeb LST validation station (23.551°S, 15.051°E, 450 m a.s.l.) lies about 2 km northeast of Gobabeb Namib Research Institute (https://www.gobabeb.org). Because of the hyper-arid desert climate, the site is temporally stable, which is essential for long-term validation studies (Göttsche et al. 2013, Göttsche et al. 2016, Masiello et al. 2018). While the *in situ* measurements are primarily performed to validate satellite LST derived by the Land Surface Analysis Satellite Application Facility (LSA SAF) from MSG/SEVIRI, they are equally suited to validate LST from other sensors (Trigo et al. 2021, Martin et al. 2019, Hulley et al. 2022). In the following sections, the two most popular LST retrieval algorithms are briefly introduced, *in situ* LST validation concepts are explained and results for Gobabeb are summarized. Finally, a table with the—quite numerous—abbreviations used in this article is provided.

2 Satellite LST Retrieval

LST from a satellite is estimated from top-of-atmosphere (TOA) radiance measurements, e.g. in MSG/SEVIRI's split-window channels 9 and 10 (Freitas et al. 2010). Most LST retrieval methods are based on measurements in two pseudo-contiguous TIR channels, *i.e.,* split-window algorithms, and exploit the differential absorption in the two bands for atmospheric correction (Dash et al. 2002, Hulley et al. 2019). The uncertainty associated with satellite LST retrievals lies typically between 1°C and 2°C.

2.1 Generalized Split Window (GSW) Algorithm

For current TIR sensors, e.g. SEVIRI, MODIS and SLSTR, LST is most often estimated through the application of a Generalized Split-Window (GSW) formulation (Wan 1997) or similar (Yang et al. 2020). LSA SAF adapted the GSW to the response functions of the SEVIRI channels (Freitas et al. 2010):

$$LST = (A_1 + A_2 \frac{1-\varepsilon}{\varepsilon} + A_3 \frac{\Delta\varepsilon}{\varepsilon^2}) \frac{T_{10.8} + T_{12.0}}{2} + (B_1 + B_2 \frac{1-\varepsilon}{\varepsilon} + B_3 \frac{\Delta\varepsilon}{\varepsilon^2}) \frac{T_{10.8} - T_{12.0}}{2} + C + \Delta LST \quad (1)$$

where ε is the average of the two channel-effective surface emissivities; Δε their difference ($\varepsilon_{10.8}$–$\varepsilon_{12.0}$); channel radiances are expressed as brightness temperatures $T_{10.8}$ and $T_{12.0}$; A_j, B_j, (j = 1,2,3) and C are the GSW parameters; and ΔLST is the uncertainty of the LST retrieval. The GSW parameters were calibrated for different ranges of satellite zenith angle and total column water vapor. In operational LST retrievals with such algorithms, total column water vapor is generally obtained from forecasts; in case of the LSA SAF, these are the three-hourly forecasts of the European Center for Medium-range Weather Forecasts (ECMWF). Since GSW algorithms are only applicable to clear sky conditions, cloudy pixels have to be removed through multispectral thresholding tests performed for the available sensor channels in the visible, near-infrared, and thermal atmospheric window (Bulgin et al. 2018). Recently a variety of similar LST retrieval algorithms for Sentinel-3A/B SLSTR was compared by (Yang et al. 2020): the most conclusive and accurate results over land were obtained for Gobabeb.

2.2 Temperature—Emissivity Separation (TES) Algorithm

Emissivity ε is a unitless measure ($0 \le \varepsilon \le 1$) indicating how effectively a surface radiates in comparison to an idealized 'black-body' (Dash et al. 2002, Hulley et al. 2019). Therefore, for LST retrieval from space-based and ground-based radiance measurements, accurate land surface emissivity (LSE) estimations are essential (Guillevic et al. 2018). Over semi-arid regions, where bare soils dominate and the atmosphere is generally dry, LST error is mainly controlled by uncertainty in LSE. Especially sites with larger fractions of bare ground are prone to be misrepresented in satellite-retrieved LSEs based on land cover classification and remotely sensed vegetation fraction: *in situ* measurements revealed that LSE estimations over arid regions can be wrong by more than 3%, causing LST uncertainties of up to 3°C (Schädlich et al. 2001, Göttsche & Hulley 2012). However, with algorithmic improvements, e.g., Temperature-Emissivity Separation (TES) (Gillespie et al. 1998, Hulley & Hook 2011) LST and LSE can be retrieved simultaneously from TIR data with an accuracy of 1.5%.

3 Determination of *in situ* LST

Continuous *in situ* observations from Gobabeb are available since the beginning of 2008. The main instrument for determining LST is the precision radiometer "KT15.85 IIP" produced by Heitronics GmbH, Wiesbaden, Germany. The radiometer measures the radiance between the wavelengths 9.6 µm and 11.5 µm, has a temperature resolution of 0.03°C, and an accuracy of ±0.3°C over the relevant temperature range (Göttsche et al. 2013). The drift of the KT15.85 IIP is less than 0.01% per month: this is achieved by linking the radiance measurements via beam-chopping (a differential method) to internal reference temperature measurements. The ground-observing radiometer at the Gobabeb wind tower is mounted at 25 m height, which results in fields of view (FOV) of about 12 m^2 (Figure 1). While atmospheric attenuation between the surface and the radiometer is negligible, the measurements contain surface emitted radiance (i.e., the target signal) as well as reflected downwelling 'sky radiance'. Depending on LSE and downwelling longwave radiance (e.g., a cold clear sky *vs.* a warm humid atmosphere), the reflected component can cause differences of several degrees Celsius (Schädlich et al. 2001). Therefore, an additional KT15.85 IIP measures downwelling longwave radiance at 53° zenith angle, which is representative of downwelling hemispherical sky radiance (Göttsche et al. 2013, Guillevic et al. 2018). For areas >10m^2 it was found that the gravel plains can be represented by a single 'surface end-member' consisting of a homogeneous mixture of bare soil (75% sand/gravel) and dry grass (25%).

3.1 LST Derivation from *in Situ* Measurements

Planck's law relates the radiance emitted by a black body (emissivity $\varepsilon = 1$) to its temperature (Dash et al. 2002, Hulley et al. 2019). However, most objects relevant to remote sensing applications are non-black bodies. Spectral emissivity $\varepsilon(\lambda)$ is defined as the ratio between the spectral radiance R_k emitted by surface component k at wavelength λ, and the spectral radiance emitted by a black body at the same wavelength and temperature. Spectral radiance emitted by a non-black body can be obtained by multiplying Planck's function $B(T_k, \lambda)$ with $\varepsilon(\lambda)$:

$$R_k(T_k, \lambda) = \varepsilon(\lambda) \cdot B(T_k, \lambda) \quad (2)$$

where R_k is in $W \cdot m^{-3} \cdot sr^{-1}$, T_k is the measured component temperature in Kelvins, and λ is the wavelength in meters. For a sensor located near the surface and measuring within an

(a) (b)

Figure 1: Land Surface Temperature (LST) at validation station Gobabeb. (a) wind tower (b) installation of different radiometers during the 2017 ESA FRM4STS field inter-comparison experiment

atmospheric TIR window, the influence of the atmosphere can be neglected. With known emissivity, the simplified radiative transfer equation (Dash et al. 2002, Göttsche et al. 2013) can be used to account for reflected downwelling TIR radiance from the atmosphere and for the non-black body behavior of the surface. Switching for simplicity to channel-effective values, a single surface component and dropping the variable dependencies, emitted blackbody-equivalent radiance *B* can be expressed as

$$B = \frac{R_L - (1 - \varepsilon) \cdot R_S}{\varepsilon} \tag{3}$$

where R_L is the upwelling land surface radiance and R_S the downwelling sky radiance; in practice, the latter is measured by a dedicated KT15.85 IIP radiometer aligned at the zenith angle of 53°. Once *B* is known, inverting Planck's law gives the surface temperature. The spectral response functions of the KT15.85 IIP radiometers are approximately symmetric and the Planck function as well as the spectral emissivity of natural surfaces varies slowly over the radiometer's spectral range, e.g. see (Hulley & Hook 2011). Therefore, LST is retrieved by evaluating Planck's function at the radiometer's center wavelength of 10.55 µm (Göttsche et al. 2013).

3.2 *In situ* LSE Determination

During December 2011, measurements with the "one-lid emissivity box" method (Figure 2a) were performed at Gobabeb to determine channel-specific emissivities for the KT15.85 IIP radiometer over relevant surface types. Combining box measurements from 2011 and 2012, the emissivity for the KT15.85 IIP radiometer at Gobabeb wind tower is estimated as 0.940 ± 0.015. With a dry grass fraction of 25%, LSE over the gravel plains is estimated as 0.944 ± 0.015 for SEVIRI channel 9. This value is in good agreement with results obtained for ASTER and MODIS (Göttsche & Hulley 2012). In June 2017 the French Aerospace Laboratory ONERA performed *in situ* measurements with a Fourier Transform IR (FTIR) spectrometer (Figure 2b) and confirmed these values (Göttsche et al. 2018). From the emissivity spectra obtained by ONERA, channel-specific emissivities of arbitrary TIR sensors can be determined. Based on these findings, total uncertainty of *in situ* LST at Gobabeb wind tower has been estimated as 0.80 ± 0.12°C (Göttsche et al. 2016).

(a) (b)

Figure 2: Land Surface Emissivity (LSE) determination at Gobabeb. (a) single-lid emissivity box (2011-12-22) and (b) BOMEM MR304SC FTIR spectrometer during field inter-comparison experiment (2017-06-28)

3.3 Spatial Homogeneity of LST

For reliable LST validation, the effect of the small-scale material variations (e.g., dry grass, rock outcrops) and topography needs to be fully characterized. Using a mobile radiometer system, various field experiments were performed during which the radiometer was driven along tracks of up to 40 km length (Figure 3). The results show a high level of homogeneity and a stable relationship between station LST and LST obtained along the tracks (Figure 4) with an absolute bias of about 0.5 °C (Göttsche et al. 2013, Göttsche et al. 2018).

Figure 3: Characterizing LST homogeneity of the gravel plains between Gobabeb and Mirabib. The five TIR radiometers participating in the ESA FRM4STS field inter-comparison experiment (Göttsche et al. 2018) provided spatially resolved in situ *LST along the driven track.*

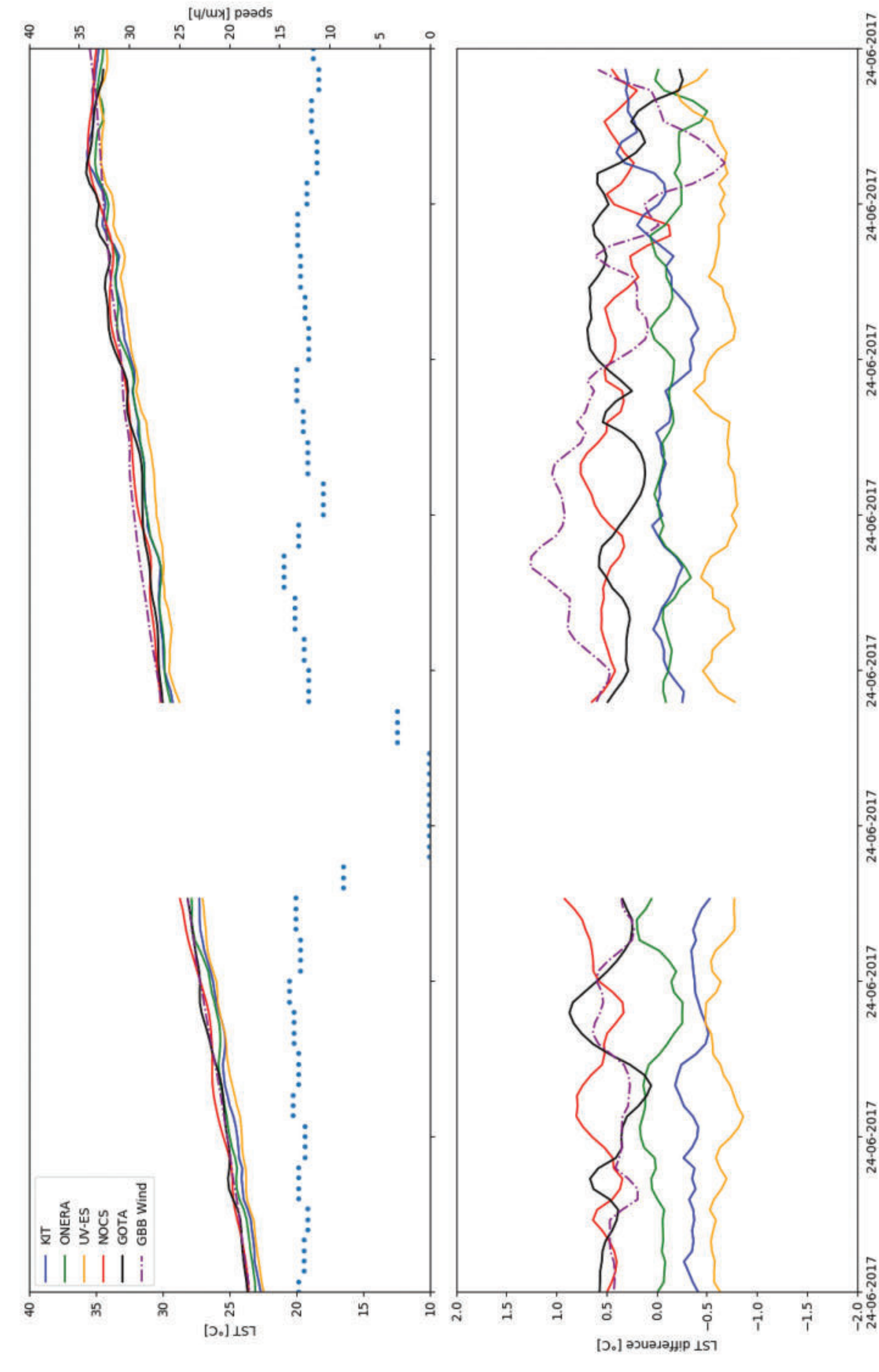

Figure 4 Top: In situ *LSTs obtained from the radiometers operated by different teams as they were driven across the gravel plains (see Figure 3)*; in situ *LST from Gobabeb wind tower (i.e. the permanent validation station) is also shown. Right axis indicates driving speed. Bottom: LST differences of the radiometers with respect to their average. Data courtesy: ESA FRM4STS project (Göttsche et al. 2018).*

4 Results

While the *in situ* validation of satellite LST data sets is a challenging task, it is needed to obtain quantitative information on their accuracy (Guillevic et al. 2018). The time series of *in situ* LST from Gobabeb starts in 2008 and has since then been used to validate a variety of LST products from numerous satellite sensors. *In situ* LSE at Gobabeb was obtained with the 'emissivity box method' as well as FTIR spectroscopy. (Göttsche & Hulley 2012) used this knowledge to validate six LSE products retrieved from MODIS, ASTER, and SEVIRI over the gravel plains and sand dunes near Gobabeb. LSE estimated with algorithms based on land cover classification and vegetation cover fraction data primarily depend on correct classifications and assigned bare-ground emissivities. In contrast, the physics-based ASTER-TES and MODTES algorithms were shown to correctly estimate LSE on the gravel plains and sand dunes: consequently, split window algorithms would benefit significantly from using MODTES LSE.

(Hulley et al. 2019) illustrate temperature-based validation with examples from the ESA FRM4STS LST Field Inter-comparison Experiment (FICE) performed on the Namib gravel plains near Gobabeb (Göttsche et al. 2018). During this experiment, *in situ* LST obtained from measurements with five different TIR radiometers were compared. Furthermore, *in situ* LSE were obtained with a Fourier Transform spectrometer and an 'emissiometer', which uses oscillating TIR radiance and digital signal processing to determine LSE. For a four day radiometer inter-comparison at Gobabeb's wind tower (Figure 1b), results showed that *in-situ* LST can be retrieved with RMSEs of about 0.5 K, if the instruments are well-aligned, have narrow spectral bands and view angles, observe areas of at least 2 m^2 and accurate emissivities are available. Furthermore, (Göttsche et al. 2018) investigated spatial LST variability near Gobabeb by driving the radiometers several times about 20 km across the Namib gravel plains (Figure 3): the five in-situ LST were first averaged individually over 200 m and yielded RMSEs of about 0.6 K compared to their mean (Figure 4).

(Freitas et al. 2010) quantified the uncertainty of the operational GSW algorithm used by LSA SAF to retrieve LST from MSG/SEVIRI. They quantified the uncertainty of the LST estimations by accounting for the algorithm's error statistics for globally representative atmospheric profiles and by carefully characterizing the uncertainty of the input data, particularly surface emissivity and total water vapor content. The retrieved values were also compared with a full seasonal cycle of *in situ* observations from Gobabeb, showing good agreement with root-mean-square differences between 1°C and 2°C. (Göttsche et al. 2013) used in-situ LST from Gobabeb wind tower to validate the MSG/SEVIRI LST product operationally derived by LSA SAF, which has a target accuracy of better than 2 K. For two years of SAF LST, the magnitude of the monthly biases was generally less than 1.0 K and RMSE below 1.5 K. SAF LST and *in situ* LST obtained for three days at another location on the gravel plains were also in good agreement with each other (bias 1.0 K); the corresponding bias between the SAF LST and Gobabeb wind tower LST for this period was even smaller (0.4 K). The bias between in-situ LST obtained along a 40 km track and at Gobabeb wind tower was 0.4 K with a standard deviation of 1.2 K, showing that the Gobabeb wind tower measurements are representative for large parts of the gravel plains. Thanks to SEVIRI's high temporal resolution (15 min), there are typically thousands of monthly match-ups with in-situ LST: ignoring rainy seasons, results for 2009–2014 showed that LSA SAF LST consistently met its target accuracy (Göttsche et al. 2016). (Trigo et al. 2021) validated LST retrieved from the geostationary MSG satellites and Metop polar orbiters. The in-situ validations performed for the two LST products included measurements from Gobabeb wind tower and revealed overall accuracies of 0.13°C for SEVIRI LST and 0.32°C for AVHRR-based LST. Better matches were usually found at night-time, highlighting the influence of LST spatial and temporal variability as well as viewing geometry on satellite daytime estimates. Both LST data sets were found to be consistent and to meet high accuracy standards. Furthermore, their ensured production throughout the sensors' lifecycles makes the two LST products good candidates for long term applications and studies.

(Jimenez-Munoz et al. 2014) analyzed the feasibility of applying the TES algorithm to MSG/SEVIRI data and its potential for improving LSA SAF's LST product over arid and semiarid areas. The so-called SEVTES algorithm was validated with *in situ* measurements from five stations in Africa; due to the high spatial homogeneity of the gravel plains the data from Gobabeb were crucial for the analysis. SEVTES-derived LSE were consistent with MODIS-TES and ASTER-TES retrievals and within 1%–2% of laboratory measurements.

(Martins et al. 2019) developed the first all-weather LST product based on visible and infrared observations by combining clear-sky LST and other satellite products retrieved from MSG/SEVIRI with LST estimated with a land surface energy balance (EB) model to fill gaps caused by clouds. The new product was compared with *in situ* observations from three dedicated LST validation stations, including Gobabeb wind tower, and indicated an accuracy between -0.8 K and 1.1 K and a precision between 1.0 K and 1.4 K.

(Masiello et al. 2015) developed a Kalman filter-based approach for the physical retrieval of LST and LSE from SEVIRI data and validated it with *in situ* LST from Evora and Gobabeb stations operated by KIT. For both sites the Kalman filter yielded a root mean square accuracy of 1.5°C and over the gravel plains at Gobabeb the emissivity retrieved in SEVIRI channel 10.8 μm was in excellent agreement with *in situ* observations. Furthermore, in order to speed up emissivity retrieval, a SEVIRI hyper-fast forward model has been developed (Masiello et al. 2019).

Using single-channel LST retrieval algorithms to ensure consistency across the Meteosat satellite series, (Duguay-Tetzlaff et al. 2015) generated a 30+ year LST climate data record and validated it over various sites, including Gobabeb; they showed that Meteosat single-channel and GSW retrievals are within 0.1–0.5 K except for very moist atmospheres. (Martin et al. 2019) systematically validated satellite LST data sets from several sensors

(AATSR, GOES, MODIS, and SEVIRI) against multiple years of *in situ* data from globally distributed stations. For the large data base of standardized satellite LST provided by the European Space Agency's (ESA) GlobTemperature project average accuracies were generally within ± 2.0 K during night, and within ± 4.0 K during day; however, time series analyses over individual stations also revealed seasonal cycles.

(Duan et al. 2019) validated the C6 MODIS LST product and identified surface emissivity as the largest uncertainty in the MODIS GSW algorithm; they also showed that adjustments of the GSW algorithm, e.g. incorporating dynamic LSE retrieved with the TES algorithm, can reduce LST errors over bare soil surfaces.

Within ESA's GlobTemperature project, (Ghent et al. 2017) validated LST from the Along-Track Scanning Radiometers (ATSR). The retrieval formulation was a nadir-only, two-channel, split-window algorithm, based on biome classification, fractional vegetation, and across-track water vapor dependences. One year of AATSR LST data (2009) were validated against *in situ* LST from "gold standard reference" stations, including Gobabeb, and showed average absolute biases of 1.00 K at daytime and 1.08 K at nighttime.

(Liu et al. 2015) used in-situ observations from Gobabeb wind tower to assess the quality of the S-NPP VIIRS LST Environmental Data Record (EDR). While ground observations from more vegetated areas indicated an overall accuracy of −0.41 K, validation results over arid regions in Africa suggested that VIIRS underestimated LST by 1.57 K. It was concluded that the VIIRS retrieval algorithm strongly depends on correct land cover classifications and, more generally, that surface type dependent algorithms have difficulties with large emissivity variations within a surface type.

(Sobrino et al. 2016) made synergistic use of MERIS and AATSR as a proxy for estimating LST from ESA's Sentinel 3 (S3) satellite. The proposed methodology for retrieving LST from S3 instruments is based on the SW technique with an explicit dependence on surface emissivity. LST retrievals with different input LSE are validated against *in situ* data measured along one year (2011) at five test sites, including Gobabeb wind tower. The results show that LST is retrieved with the proposed SW algorithm typically with RMSE below 2 K.

The official SLSTR LST product is a split-window (SW) algorithm (SWA) with an implicit use of LSE: this motivated (Yang et al. 2020) to investigate alternative SWAs with an explicit use of LSE. (Yang et al. 2020) studied seventeen algorithms for estimating LST from Sentinel-3 SLSTR data: nine of these exhibited low sensitivity to uncertainties in LSE and column water vapor content and were validated against in-situ LST from six sites. Among the land sites, the lowest RMSE of 1.65-1.79 K was obtained for Gobabeb.

(Masiello et al. 2018) developed a fully physical retrieval scheme for LSE spectra, which can be applied to high spectral resolution infrared observations from satellite sensors like IASI (Infrared Atmospheric Sounder Interferometer). The methodology retrieves the LSE spectrum, LST and atmospheric parameters simultaneously and has been developed within the general framework of Optimal Estimation. Applying the scheme to IASI data, it was shown the retrieved LSE spectra are independent of background information and in good agreement with *in situ* observations from Gobabeb (Göttsche et al. 2018). (Safieddine et al. 2020) developed an artificial neural network approach to retrieve LST from IASI data and validated their results against Gobabeb *in-situ* LST.

(Ermida et al. 2020) realized that the Landsat series of satellites have the potential to provide LST estimates at a high spatial resolution, which is particularly appropriate for local or small-scale studies. However, the available Landsat LST datasets generally require the users to handle large data volumes: this can be avoided by using the online platform Google Earth Engine (GEE), which allows users to perform big data analyses without the need for large local computing resources. (Ermida et al. 2020) provide a GEE repository for computing LSTs from Landsat 4, 5, 7, and 8. The retrieved Landsat LST were validated with in-situ measurements from twelve globally distributed sites and include Gobabeb wind tower as a desert site.

(Hulley et al. 2022) used Gobabeb in-situ LST to validate and assess LST and LSE products obtained from the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), which currently provides the highest spatial resolution TIR data (38 m × 69 m) available from space. ECOSTRESS LST showed good agreement with ground-based measurements (fourteen sites) with an average RMSE of 1.07 K and a mean absolute error (MAE) of 0.40 K. The multispectral and high-spatial-resolution characteristics of ECOSTRESS serve as a pathfinder to NASA's Surface Biology and Geology (SBG) mission.

(Göttsche & Olesen 2009) fitted a model of the diurnal temperature cycle (DTC) to *in situ* LST from Gobabeb wind tower to obtain parameters that summarize the surface's thermal dynamics. Modelling DTC is also useful for temporal compositing and for cloud screening. (Zhou et al. 2017) used *in situ* LST from Gobabeb to test and validate a method for correcting the thermal sampling depth (TSD) of passive microwave (PMW) observations over barren land. This is required since over arid regions MW radiation penetrates deeper into the ground than TIR radiation, which results in systematic LST differences. The core of the TSD correction (TSDC) method is a new formulation of the passive MW radiation balance equation, which links MW effective physical temperature to the soil temperature at a specific depth. The validation of the TSDC method with *in situ* LSTs from Gobabeb and yielded an RMSE of about 2–3 K and a slight systematic error, i.e. a similar accuracy as many TIR LST products.

5 Discussion

In situ validation of satellite LST remains a challenging task and requires continuous, high quality radiometric measurements from sites with a large, homogenous and temporary stable land cover. It is essential that the *in situ* measurements, which are usually performed over areas between 2 m^2 and 100 m^2, are also representative on the pixel scale, e.g. 1 km^2 to 25 km^2, of the satellite LST to be validated. Therefore, the vast and homogeneous gravel plains near the Gobabeb Namib Research Institute offer ideal conditions for validating satellite LST products up to pixel sizes of about 100 km^2, while at the same time covering a large diurnal temperature range and providing frequent clear-sky observations. The station design, in particular instrumentation and location, target specifically the validation of LST satellite products derived for pixel scales over 1 km, e.g., the precision radiometers used have particularly small drift, and the landscape surrounding the sites is homogeneous at the scale of several satellite pixels. Uncertainty analysis performed for one year of Gobabeb station data yielded an *in situ* LST uncertainty of 0.80 ± 0.12°C. This value is dominated by uncertainty in land surface emissivity within the radiometer's band, which for Gobabeb is estimated as ±0.015.

Continuous *in situ* measurements of up- and downwelling TIR radiance are performed at the Gobabeb wind tower since 2008. This allows analyses of long time series of satellite LST to be performed and can reveal potential deviations as well as seasonal cycles. *In situ* LST from Gobabeb have been used to validate a variety of satellite LST products and helped researchers to develop and evaluate new LST and LSE retrieval algorithms. The results obtained at Gobabeb highlight the need to carefully consider the temporal and spatial properties of LST and LSE when using them for scientific purposes.

Currently, several new TIR satellite missions are in preparation, e.g. the high-resolution French-Indian TRISHNA mission (Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment), or close to becoming operational, e.g. EUMETSAT's Meteosat Third Generation (MTG) with its main payload, the Flexible Combined Imager (FCI). LST products from these missions are of particular interest for African countries and the *in situ* emissivity spectra collected on the Namib gravel plains will help to validate their retrieved channel-effective emissivities. The continued acquisition of high-quality *in situ* LST at Gobabeb wind tower will ensure that current and new LST products, with their unprecedented temporal and spatial resolutions, can be monitored and achieve their target accuracies over a large temperature range.

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Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AATSR	Advanced Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
ECMWF	European Center for Medium-range Weather Forecasts
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FVC	Fraction of Vegetation Cover
GSW	Generalized split-window
IASI	Infrared Atmospheric Sounding Interferometer
LSA SAF	Land Surface Analysis Satellite Application Facility
LSE	Land Surface Emissivity
LST	Land Surface Temperature
Metop	Meteorological Operational satellite
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
NASA	National Aeronautics and Space Administration
SBG	Surface Biology and Geology
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SLSTR	Sea and Land Surface Temperature Radiometer
S-NPP	Suomi National Polar-orbiting Partnership
TES	Temperature-Emissivity Separation
TIR	Thermal Infra-Red
TOA	Top of Atmosphere
VIIRS	Visible Infrared Imaging Radiometer Suite

6 References

BECHTEL, B., DEMUZERE, M., MILLS, G., ZHAN, W., SISMANIDIS, P., SMALL, C. & VOOGT, J. (2019), SUHI analysis using Local Climate Zones—A comparison of 50 cities, *Urban Climate* 28, 100451.

BULGIN, C., MERCHANT, C., GHENT, D., KLÜSER, L., POPP, T., POULSEN, C. & SOGACHEVA, L. (2018), Quantifying uncertainty in satellite-retrieved land surface temperature from cloud detection errors, *Remote Sensing* 10(4), 616.

DASH, P., GOETTSCHE, F.-M., OLESEN, F.-S. & FISCHER, H. (2002), Land surface temperature and emissivity estimation from passive sensor data: Theory and practice-current trends, *International Journal of Remote Sensing* 23(13), 2563–2594. http://dx.doi.org/10.1080/01431160110115041.

DOUSSET, B., GOURMELON, F., LAAIDI, K., ZEGHNOUN, A., GIRAUDET, E., BRETIN, P., MAURI, E. & VANDENTORREN, S. (2010), Satellite monitoring of summer heat waves in the paris metropolitan area, *International Journal of Climatology* 31(2), 313–323.

DUAN, S.-B., LI, Z.-L., LI, H., GÖTTSCHE, F.-M., WU, H., ZHAO, W., LENG, P., ZHANG, X. & COLL, C. (2019), Validation of collection 6 MODIS land surface temperature product using *in situ* measurements, *Remote Sensing of Environment* 225, 16–29.

DUGUAY-TETZLAFF, A., BENTO, V.A., GÖTTSCHE, F.M., STÖCKLI, R., MARTINS, J.P., TRIGO, I., OLESEN, F., BOJANOWSKI, J.S., DA CAMARA, C. & KUNZ, H. (2015), Meteosat land surface temperature climate data record: Achievable accuracy and potential uncertainties, *Remote Sensing* 7(10), 13139–13156. http://dx.doi.org/10.3390/rs71013139.

ERMIDA, S.L., DACAMARA, C.C., TRIGO, I.F., PIRES, A.C., GHENT, D. & REMEDIOS, J. (2017), Modelling directional effects on remotely sensed land surface temperature, *Remote Sensing of Environment* 190, 56–69. http://dx.doi.org/10.1016/j.rse.2016.12.008.

ERMIDA, S.L., SOARES, P., MANTAS, V., GÖTTSCHE, F.-M. & TRIGO, I.F. (2020), Google Earth Engine open-source code for land surface temperature estimation from the Landsat series, *Remote Sensing* 12(9), 1471.

FREITAS, S., TRIGO, I., BIOUCAS-DIAS, J. & GÖTTSCHE, F.-M. (2010), Quantifying the Uncertainty of Land Surface Temperature Retrievals From SEVIRI/Meteosat, *IEEE Transactions on Geoscience and Remote Sensing* 48(1), 523–534. http://dx.doi.org/10.1109/TGRS.2009.2027697.

GHENT, D., CORLETT, G., GÖTTSCHE, F.-M. & REMEDIOS, J. (2017), Global land surface temperature from the along-track scanning radiometers, *Journal of Geophysical Research: Atmospheres*.

GHENT, D., VEAL, K., TRENT, T., DODD, E., SEMBHI, H. & REMEDIOS, J. (2019), A new approach to defining uncertainties for MODIS land surface temperature, *Remote Sensing* 11(9), 1021.

GILLESPIE, A., ROKUGAWA, S., MATSUNAGA, T., COTHERN, J.S., HOOK, S. & KAHLE, A.B. (1998), A temperature and emissivity separation algorithm for advanced spaceborne thermal emission and reflection radiometer (aster) images, *IEEE Transactions on Geoscience and Remote Sensing* 36(4), 1113–1126.

GÖTTSCHE, F.-M. & HULLEY, G.C. (2012), Validation of six satellite-retrieved land surface emissivity products over two land cover types in a hyper-arid region, *Remote Sensing of Environment* 124, 149–158. http://dx.doi.org/10.1016/j.rse.2012.05.010.

GÖTTSCHE, F.-M., OLESEN, F., POUTIER, L., LANGLOIS, S., WIMMER, W., SANTOS, V.G., COLL, C., NICLOS, R., ARBELO, M. & MONCHAU, J.-P. (2018), ESA FRM4STS Report from the Field Inter-Comparison Experiment (FICE) for Land Surface Temperature, Technical Report OFE-D130-LST-FICE-report-V1-Iss-1-Ver-1, Karlsruhe Institute of Technology, Karlsruhe, Germany. http://www.frm4sts.org/project-documents/.

GÖTTSCHE, F.-M. & OLESEN, F.-S. (2009), Modelling the effect of optical thickness on diurnal cycles of land surface temperature, *Remote Sensing of Environment* 113(11), 2306–2316. http://dx.doi.org/10.1016/j.rse.2009.06.006.

GÖTTSCHE, F.-M., OLESEN, F.-S. & BORK-UNKELBACH, A. (2013), Validation of land surface temperature derived from MSG/SEVIRI with in situ measurements at Gobabeb, Namibia, *International Journal of Remote Sensing* 34(9-10), 3069–3083. http://dx.doi.org/10.1080/01431161.2012.716539.

GÖTTSCHE, F.-M., OLESEN, F.-S., TRIGO, I., BORK-UNKELBACH, A. & MARTIN, M. (2016), Long term validation of land surface temperature retrieved from MSG/SEVIRI with continuous *in-situ* measurements in Africa, *Remote Sensing* 8(5), 1–27. Article number 410. http://dx.doi.org/10.3390/rs8050410.

GUILLEVIC, P., GÖTTSCHE, F., NICKESON, J., HULLEY, G., GHENT, D., YU, Y., TRIGO, I., HOOK, S., SOBRINO, J.A., REMEDIOS, J., ROMÁN, M. & CAMACHO, F. (2018), Land Surface Temperature Product Validation Best Practice Protocol. Version 1.1.0. In P. Guillevic, F. Göttsche, J. Nickeson & M. Román (Eds.), Best Practice for Satellite-Derived Land Product Validation (p. 58): Land Product Validation Subgroup (WGCV/CEOS), Technical report. https://lpvs.gsfc.nasa.gov/LSTE/LSTE_home.html.

HULLEY, G.C., GHENT, D., GÖTTSCHE, F.M., GUILLEVIC, P.C., MILDREXLER, D.J. & COLL, C. (2019), *Land Surface Temperature,* Elsevier, pp. 57–127.

HULLEY, G.C., GÖTTSCHE, F.M., RIVERA, G., HOOK, S.J., FREEPARTNER, R.J., MARTIN, M.A., CAWSE-NICHOLSON, K. & JOHNSON, W.R. (2022), Validation and quality assessment of the ECOSTRESS level-2 land surface temperature and emissivity product, *IEEE Transactions on Geoscience and Remote Sensing* 60, 1–23.

HULLEY, G.C. & HOOK, S.J. (2011), Generating Consistent Land Surface Temperature and Emissivity Products Between ASTER and MODIS Data for Earth Science Research, *IEEE Transactions on Geoscience and Remote Sensing* 49(4), 1304–1315. http://dx.doi.org/10.1109/TGRS.2010.2063034.

JIMENEZ-MUNOZ, J.C., SOBRINO, J.A., MATTAR, C., HULLEY, G. & GÖTTSCHE, F.-M. (2014), Temperature and Emissivity Separation From MSG/SEVIRI Data, *IEEE Trans. Geosci. Remote Sensing* 52(9), 5937–5951. http://dx.doi.org/10.1109/TGRS.2013.2293791.

LI, Z., JIA, L. & LU, J. (2015), On uncertainties of the Priestley-Taylor/lst-fc feature space method to estimate evapotranspiration: Case study in an arid/semiarid region in northwest China, *Remote Sensing* 7(1), 447–466. http://www.mdpi.com/2072-4292/7/1/447.

LIU, Y., YU, Y., YU, P., GÖTTSCHE, F. & TRIGO, I. (2015), Quality Assessment of S-NPP VIIRS Land Surface Temperature Product, *Remote Sensing* 7(9), 12215–12241. http://dx.doi.org/10.3390/rs70912215.

MALLICK, J., SINGH, C.K., SHASHTRI, S., RAHMAN, A. & MUKHERJEE, S. (2012), Land surface emissivity retrieval based on moisture index from LANDSAT TM satellite data over heterogeneous surfaces of Delhi city, *International Journal of Applied Earth Observation and Geoinformation* 19, 348–358. http://dx.doi.org/10.1016/j.jag.2012.06.002.

MARTIN, M.A., GHENT, D., PIRES, A.C., GÖTTSCHE, F.-M., CERMAK, J. & REMEDIOS, J.J. (2019), Comprehensive in situ validation of five satellite land surface temperature data sets over multiple stations and years, *Remote Sensing* 11(5), 479.

MARTINS, J.P.A., TRIGO, I.F., GHILAIN, N., JIMENEZ, C., GÖTTSCHE, F.-M., ERMIDA, S.L., OLESEN, F.-S., GELLENS-MEULENBERGHS, F. & ARBOLEDA, A. (2019), An all-weather land surface temperature product based on MSG/SEVIRI observations, *Remote Sensing* 11(24), 3044.

MASIELLO, G., SERIO, C., VENAFRA, S., LIUZZI, G., GÖTTSCHE, F., TRIGO, I. & WATTS, P. (2015), Kalman filter physical retrieval of surface emissivity and temperature from SEVIRI infrared channels: a validation and intercomparison study, *Atmospheric Measurement Techniques* 8(7), 2981–2997. http://dx.doi.org/10.5194/amt-8-2981-2015.

MASIELLO, G., SERIO, C., VENAFRA, S., LIUZZI, G., POUTIER, L. & GÖTTSCHE, F.-M. (2018), Physical retrieval of land surface emissivity spectra from hyper-spectral infrared observations and validation with *in situ* measurements, *Remote Sensing* 10(6), 976.

MASIELLO, G., SERIO, C., VENAFRA, S., POUTIER, L. & GÖTTSCHE, F.-M. (2019), SEVIRI hyper-fast forward model with application to emissivity retrieval, *Sensors* 19(7), 1532.

MILDREXLER, D.J., ZHAO, M. & RUNNING, S.W. (2011), Satellite finds highest land skin temperatures on earth, *Bulletin of the American Meteorological Society* 92(7), 855–860. http://dx.doi.org/10.1175/2011BAMS3067.1.

REICHLE, R.H., KUMAR, S.V., MAHANAMA, S.P.P., KOSTER, R.D. & LIU, Q. (2010), Assimilation of satellite-derived skin temperature observations into land surface models, *Journal of Hydrometeorology* 11(5), 1103–1122. https://doi.org/10.1175/2010JHM1262.1.

RHEE, J., IM, J. & CARBONE, G.J. (2010), Monitoring agricultural drought for arid and humid regions using multi-sensor remote sensing data, *Remote Sensing of Environment* 114(12), 2875–2887.

SAFIEDDINE, S., PARRACHO, A.C., GEORGE, M., AIRES, F., PELLET, V., CLARISSE, L., WHITBURN, S., LEZEAUX, O., THÉPAUT, J.-N., HERSBACH, H., RADNOTI, G., GOETTSCHE, F., MARTIN, M., DOUTRIAUX-BOUCHER, M., COPPENS, D., AUGUST, T., ZHOU, D.K. & CLERBAUX, C. (2020), Artificial neural networks to retrieve land and sea skin temperature from IASI, *Remote Sensing* 12(17), 2777.

SCHÄDLICH, S., GÖTTSCHE, F. & OLESEN, F.-S. (2001), Influence of Land Surface Parameters and Atmosphere on METEOSAT Brightness Temperatures and Generation of Land Surface Temperature Maps by Temporally and Spatially Interpolating Atmospheric Correction, *Remote Sensing of Environment* 75, 39–46. http://www.sciencedirect.com/science/article/pii/S0034425700001541.

SOBRINO, J., JIMÉNEZ-MUÑOZ, J., SÒRIA, G., RUESCAS, A., DANNE, O., BROCKMANN, C., GHENT, D., REMEDIOS, J., NORTH, P., MERCHANT, C., BERGER, M., MATHIEU, P. & GÖTTSCHE, F.-M. (2016), Synergistic use of MERIS and AATSR as a proxy for estimating Land Surface Temperature from Sentinel-3 data, *Remote Sensing of Environment* 179, 149–161. http://dx.doi.org/10.1016/j.rse.2016.03.035.

TRIGO, I.F., ERMIDA, S.L., MARTINS, J.P., GOUVEIA, C.M., GÖTTSCHE, F.-M. & FREITAS, S. C. (2021), Validation and consistency assessment of land surface temperature from geostationary and polar orbit platforms: SEVIRI/MSG and AVHRR/metop, *ISPRS Journal of Photogrammetry and Remote Sensing* 175, 282–297.

WAN, Z. (1997), A physics-based and algorithm for and retrieving land-surface and emissivity and and temperature from eos/modis and data, *IEEE Transactions on Geoscience and Remote Sensing* 35(4), 980–996.

WENG, Q. (2009), Thermal infrared remote sensing for urban climate and environmental studies: Methods and applications and and trends, *ISPRS Journal of Photogrammetry and Remote Sensing* 64(4), 335–344. http://dx.doi.org/10.1016/j.isprsjprs.2009.03.007

YANG, J., ZHOU, J., GÖTTSCHE, F.-M., LONG, Z., MA, J. & LUO, R. (2020), Investigation and validation of algorithms for estimating land surface temperature from Sentinel-3 SLSTR data, *International Journal of Applied Earth Observation and Geoinformation* 91, 102136.

ZHOU, J., ZHANG, X., ZHAN, W., GÖTTSCHE, F.-M., LIU, S., OLESEN, F.-S., HU, W. & DAI, F. (2017), A thermal sampling depth correction method for land surface temperature estimation from satellite passive microwave observation over barren land, *IEEE Transactions on Geoscience and Remote Sensing* 55(8), 4743–4756.

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Tenebrionid Beetle Diversity Increases with Aridity Across the Namib Desert

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Abstract

Darkling beetles (Tenebrionidae: Coleoptera) are commonly associated with hot arid lands worldwide. In southern Africa, the number of species is reported to increase along the east-to-west gradient in aridity. The highest diversity is found in the Namib Desert, which occupies a 100 km by 2,000 km hyperarid strip along the west coast, from South Africa to the south into southern Angola. We sought to confirm this regional diversity pattern by collecting tenebrionids with pitfall traps at five SASSCAL observatories along a transect stretching from the hyperarid desert interior (MAP 25 mm, CV 130%) to semiarid conditions 260 km inland (MAP 343 mm, CV 36%). We collected tenebrionids during 11–20 month-long trapping sessions and identified species from seven tenebrionid tribes and subtribes which were previously recorded in half-degree squares across the arid western half of the southern Africa region. Even though there was a six-fold decrease in tenebrionid abundance, all diversity indices increased with increasing aridity (e.g. α-diversity inland: 1.40, desert interior 3.71). Community structure was very different in the interior highland plateau compared to the desert (ß-diversity 0.52–0.69), while adjacent sites in the desert differed less (ß-diversity 0.26–0.29). In the desert, tenebrionids were recorded most

frequently at sheltered sites where windblown detritus is trapped, while in the interior, more were recorded away from sheltered locations where they might encounter sit-and-wait predators. Geomorphological processes and heterogeneous moisture conditions over space and time could explain how so many Namib Desert endemic tenebrionids evolved and coexist.

Introduction

Darkling beetles (Coleoptera: Tenebrionidae) played a key role in the motivation for establishing a field station at Gobabeb in 1962. It was Charles Koch's extensive expeditions to the Namib, between 1948–1959 in pursuit of these beetles, that led him and his team to Gobabeb (Koch 1962). Their importance for research at Gobabeb is reflected in the fact that tenebrionids have been the subject of one in eight publications of the Gobabeb Namib Research Institute since its inception (Henschel & Lancaster 2013).

Research on Namib tenebrionids has since expanded far beyond taxonomy, biogeography and diversity studies to include life history, behaviour, physiology, ecology and ecophysiology in pursuit of answers to questions concerning these beetles' abilities to thrive in hyperarid conditions (Holm 1970; Seely 1973; Hamilton & Seely 1976; Seely & Hamilton 1976; Wharton & Seely 1982; McClain et al. 1985; Hanrahan & Seely 1990; Nicolson 1990; Rasmussen et al. 1991; Roberts 1991; Nicolson 1992; Ward & Seely 1996; Rössl 2000; Cloudsley-Thompson 2001; Parenzee 2001; Mitchell et al. 2020; Duncan 2021; Henschel 2021).

Namib tenebrionids are conspicuous, large, apterous omnivores—essentially detritivores—that integrate factors such as the availability of detritus and various soil characteristics such as moisture, hardness, and grain size composition (Koch 1961; Penrith 1979; Prendini 2001). They have unusual capabilities to obtain moisture and food from sources not conventionally accessible to many other surface-active animals. They can withstand long periods without these resources, even at high-temperature extremes, and actively search for scarce resources. They are generally long-lived with lifespans of several years, mainly as adults that can repeatedly reproduce with small clutches whenever resources permit.

There are over 300 tenebrionid species in the Namib, 200 of them endemic (Koch 1962; Schulze 1974; Penrith 1977, 1979; Endrödy-Younga 1982). Within walking distance of the Gobabeb Namib Research Institute field station, which is located in the most arid part of the desert, there are at least 82 species of tenebrionids (Henschel et al. 2003), and 54 at one site on the gravel plains (Henschel 2021). This diversity is especially remarkable because of the Namib's extremely low productivity (Seely & Louw 1980), more so considering how different it is for other desert taxa studied across this climatic gradient. For example, the highest levels of endemism in ants (Marsh 1986), moths (Mey 2010), plants (Yeaton 1988; Jürgens et al. 2013), birds and reptiles are associated with the Great Escarpment beyond the eastern border of the Namib (Simmons et al. 1998).

A frequently-posed question concerns why the diversity of tenebrionids increases with aridity across southern Africa (Koch 1962; Holm & Scholtz 1980; Crawford & Seely 1987). This question has yet to be answered satisfactorily. To better understand the relationship of the Namib tenebrionid community with aridity, we examined the general pattern of tenebrionid diversity across the arid western half of the southern African region (AWSAR, Table 1). We also examined tenebrionid diversity in more detail across the central Namib Desert (CND). Based on the pulse-reserve dynamics associated with the Namib (Henschel 2021), we predicted that 1) tenebrionid diversity correlates with rainfall variability, which correlates with aridity; and 2) tenebrionid abundance decreases with aridity due to declining productivity.

Methods

General diversity pattern

The distribution of tenebrionid species across the AWSAR between latitude 13–34.5°S and longitude 11.5–25.5°E was compiled from literature where overviews of their distribution were readily accessible from museum records (Koch 1955; De Moor 1970; Penrith 1975, 1977, 1979, 1980, 1981a, b, c, 1982a, b, c, 1983a, b, 1984, 1986a, b, c, 1987; Penrith & Endrödy-Younga 1994; Endrödy-Younga 1996, 2000). The tribes/subtribes for which this was possible, referred to as focal taxa, were Adesmiini, Caenocrypticini, Cryptochilini, Sepidiini: Molurina (in part), Sepidiini: Trachynotina (in part), Pedinini: Platynotina, and Zophosini. The number of focal species recorded in each half-degree latitude and longitude square (HDS) was correlated with the mean annual precipitation (MAP) obtained from WorldClim for each HDS (Fick & Hijmans 2017).

To compensate for the uneven sampling of tenebrionids, the distribution of each focal species across HDS cells was interpolated by broadening the footprint of a record and

Table 1: List of acronyms

Acronym	Meaning
AWSAR	arid western half of the southern African region
CND	central Namib Desert
CV	coefficient of variation
HDS	half degree square of latitude and longitude
MAP	mean annual precipitation
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management

bridging small locality gaps within the AWSAR boundaries. The linear interpolation process used a rule-based cellular automaton in Microsoft-Excel with two steps. The first extended occupancy to blank HDS cells adjacent to occupied cells. The second used the outcome of the first step to test whether a blank cell was located between two occupied cells. If so, the intervening blank cell was listed as occupied. The outcome yielded a putative distribution map for each species. Overlaying the 579 putative distribution maps of focal species provided a map of potential diversity at a spatial resolution of HDS cells.

Detailed diversity pattern compared to ecological parameters

We examined the diversity trends and community patterns of focal taxa in greater detail across a 260 km long climatic gradient from near the coast of the CND eastwards across the Great Escarpment to the highland plateau, Khomashochland, in Namibia. We focused on the differences in hydrological regimes in terms of quantity and frequency of free moisture and primary productivity across this transect. Using pitfall traps, we examined beetle populations at five study sites (observatories) located at about 23°S latitude and half a degree longitude apart along a west to east transect. The transect represents a strong precipitation gradient, with extreme aridity at the western end on the coast (although tempered by frequent fogs for up to ~80 km inland, i.e. the two most western observatories) and a semiarid climate at the eastern end. At each site, we compared records from traps placed in the open versus in the proximity of shelter in different vegetation communities at each site (Jürgens et al. 2010).

The diversity pattern and underlying ecological factors were examined more closely by investigating tenebrionid communities along a transect across the CND. This study was conducted between 2004–2009 at five SASSCAL observatories (Kleinberg, Gobabeb, Ganab, Rooisand, Claratal) (Jürgens et al. 2010), distributed half a degree longitude apart at about 23°S latitude along a climatic gradient reaching from the foggy Atlantic coast (altitude 188 m a.s.l.) to the west across the CND plains, over the Great Escarpment, to the Khomashochland of the Namibian Highland Plateau (altitude 1865 m a.s.l.) to the east (Figure 1, Table 2).

These five sites straddle different climatic zones, which were chosen using data from a minimum of 23 years of data (maximum 58 years) obtained from: the Namibian Meteorological Services; Gobabeb Namib Research Institute; (Lancaster et al. (1984); SASSCAL weathernet (http://www.sasscalweathernet.org/index.php?MIsoCode=NA). The precipitation gradient across the study area (Table 2) stretches from Walvis Bay on the coast (Mean Annual Precipitation MAP=10.4 mm, CV=157%) to Windhoek on the highlands 260 km inland (371.4 mm, 35%).

At each observatory, we placed three roof-covered pitfall traps within each of six grid hectares chosen as focal study sites (Table 2). One covered trap was placed into or adjacent to shelter on the south side of shrubs or rocks or a south-facing slope (hereafter referred to as "sheltered traps"; Figure 2). A second trap was unsheltered on open ground

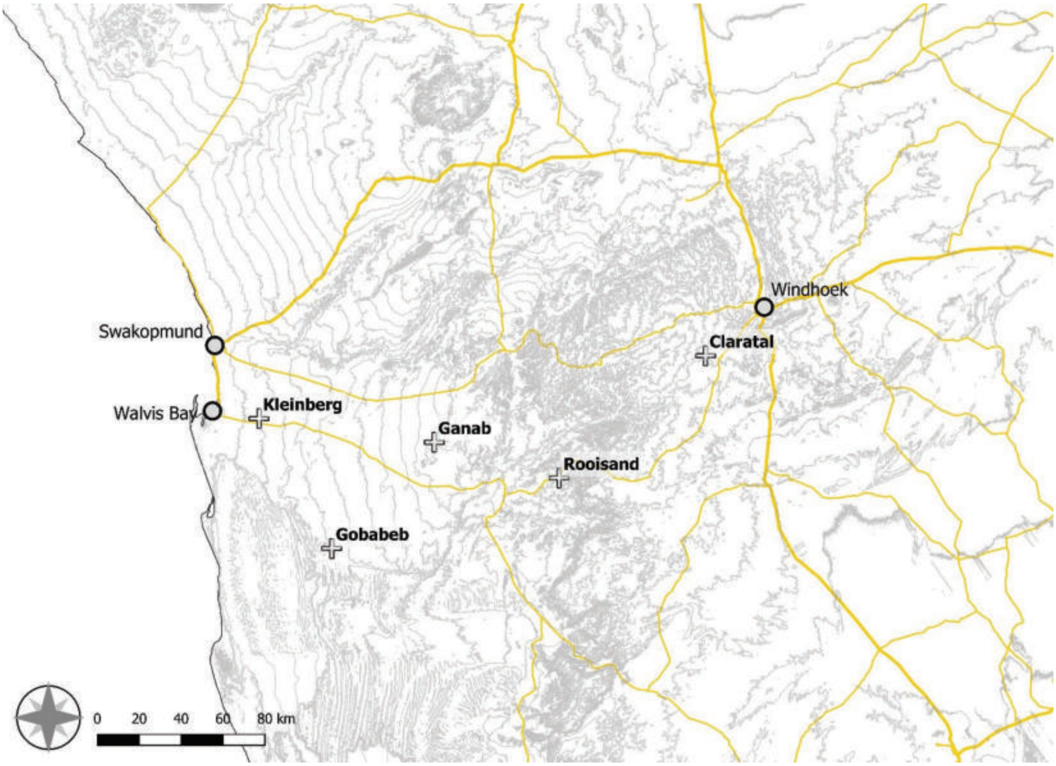

Figure 1: The central Namib part of the study area, showing the locations of the five SASSCAL observatories where we collected data across the Namib Desert (Kleinberg, Gobabeb, Ganab), at the base of the escarpment (Rooisand), and on the highland plateau (Claratal)

with north-facing slope. A third trap was placed in the open with south-facing slope, a short distance from shelter. The pitfall traps of 20 cm depth and 10 cm diameter contained mono-ethylene glycol as a preservative (Henschel et al. 2010). Standard trapping sessions were about a month long and were operated at irregular intervals as practically and logistically possible (Figure SM2). When not collecting, traps were closed with lids pegged into the ground. Collected specimens were sorted to order level in the laboratory and preserved in alcohol. Tenebrionid beetles were later separated from other beetles and were identified, ideally by comparing them to expert-verified voucher specimens or museum collections where available.

A list of focal species expected to occur at the observatories was compiled from the museum dataset mentioned above. Since previous records were not collected at exactly the current locations, the potential occurrence of a focal taxon in the adjacent half-degree latitude and longitude and small locality gaps between records was also considered. However, ultra-psammophilous species known to be confined to the Namib Sand Sea were excluded. For this reason, distribution data for Gobabeb were from the half-degree square north

Table 2: Characterisation of the study sites in terms of location, rainfall (MAP), variability of rainfall (CV), fog nights per annum, and habitat characteristics in the six focal grid hectares in terms of the ground substrate (Gravel, Rocks, Sand), drainage lines (None, Lines), and shrubs (Bare, Few, Dense)

Characteristic	Kleinberg	Gobabeb	Ganab	Rooisand	Claratal
latitude	22.989838	23.532409	23.12182	23.294542	22.779382
longitude	14.725183	15.04689	15.53844	16.104978	16.774852
distance from coast (km)	21	54	108	167	230
altitude (masl)	188	419	995	1160	1865
aridity index[1]	0.011	0.016	0.074	0.11	0.21
MAP (mm)	15.5	25.3	57.2	111.3	343.2
CV of MAP (%)	117%	130%	111%	54%	36%
n for MAP (y)	38	58	39	26	55
fog nights	76	37	3	0	0
plant richness[2]	4	33	53	95	205
lichen richness[3]	12	5	1	20	14
Lepidoptera richness[4]	-	45	149	131	227
grid hectare 1	G-N-D	R-N-D	G-N-D	R-N-D	G-N-D
grid hectare 2	G-N-D	R-N-D	G-N-D	R-N-D	S-L-D
grid hectare 3	G-N-B	G-N-B	G-N-D	S-L-D	G-N-D
grid hectare 4	G-L-D	G-N-B	S-L-F	G-N-D	R-N-D
grid hectare 5	G-L-D	R-N-F	S-L-F	R-N-D	S-L-D
grid hectare 6	G-N-B	R-N-F	G-N-D	G-N-D	G-N-D
ground cover[1]	50% lichen	0.2% grass	2.2% grass	7.6% grass	18% grass

[1] Trabucco & Zomer (2018).
[2] Schmiedel et al. (2010), Strohbach and Luther-Mosebach in (Jürgens et al., 2010).
[3] Wirth et al. (2010), Zedda and Rambold in Jürgens et al. (2010).
[4] Mey (2010).

(gravel plains), not south (dunes) of the Gobabeb observatory. Since we only used pitfall traps to record tenebrionids, we did not expect to collect all species that occur at a site as many more species are typically recorded where multiple methods are applied, especially when these include visual searching (Henschel et al. 2010).

We analysed only trapped tenebrionids listed as potential species from focal taxa (Table SM1). In other words, when referring to tenebrionids from the current study area, this should be understood as a subset of focal species from the 100 tenebrionid species that potentially occurred there, based on previous records from the tribes/subtribes Adesmiini, Caenocrypticini, Cryptochilini, Sepidiini: Molurina (in part), Sepidiini: Trachynotina (in

Figure 2: Pitfall traps were placed either in sheltered locations near shrubs or rocks (left) or unsheltered in the open (right) with a third trap at a short distance from shelter. The examples shown are from the Gobabeb Observatory.

part), Pedinini: Platynotina, and Zophosini (Table SM1). Other tenebrionids that could not be reliably identified to species level were grouped with other beetles and not analysed in detail.

Observatories were compared in terms of various diversity indices (Table 3) using only (a) species observed in the current study; (b) previously documented species; and (c) species with potential occurrence, as explained above. Abundance data, standardised relative to effort, were tracked in terms of season (early summer Oct-Dec, late summer Jan-Mar, early winter Apr-Jun, late winter Jul-Sep), shelter (sheltered, near shelter, fully exposed), and microhabitat conditions such as substrate characteristics, topographical features of water runoff (drainage lines), and the relative density of perennial plants. Species accumulation curves were used to indicate how the number of recorded species related to the trapping effort (Thompson et al. 2003) so the current data could be viewed in the context of the regional diversity. The asymptote of this curve, i.e. the number of species at each site, was calculated using the first-order jackknife estimator of species richness (Smith & Pontius 2006) (Table 3).

Table 3: Diversity indices as applied in this study

Property	Abbreviation, Equation, Definition
Species richness	S = number of species at a defined location
$S_{documented}$	Species previously recorded in the half-degree square (HDS) of Observatory[+]
$S_{potential}$	Species recorded in adjacent HDS or small gaps between records (excluding ultra-psammophilous species)[+]
$S_{observed}$	Tenebrionids of focal taxa identified at observatories in the current study
$S_{jackknife}$	$S_{jackknife}=S_{observed}+((n-1)/n)(\Sigma r_i)$, where n=number of samples, r_i=species unique to only one sample[#]
Simpson diversity	$\lambda=\Sigma(n_i(n_i-1)/N(N-1)))$, and n_i = abundance of species i, N = total abundance
Shannon evenness	$J'=H'/\ln(S)$ where H' = -sum(P_i x lnP_i), and P_i = proportion of species i
Fisher's α	$\alpha=N(1-x)/x$, where x varies with S/N*
ß-diversity	$\beta_T=(g(H)+l(H))/2a$, where g(H)=species gained, l(H)=species lost, a=average S (ß-diversity is an index of change in species composition between sites)

[+] (Koch, 1955; Penrith, 1977, 1979, 1980, 1981a, b, c, 1982b, c, 1983a, b, 1984, 1986a, b, c, 1987; Penrith & Endrödy-Younga, 1994; Endrödy-Younga, 2000).
[#] (Smith & Pontius, 2006).
[*] (Magurran, 1991; Hayek & Buzas, 1997).

Results

General Diversity Pattern

There were 579 focal species of tenebrionids across the AWSAR. The patchiness of diversity records (Figure 3a) reflects sampling bias that was not quantified, but its effects could be reduced by interpolation (Figure 3b). HDS cells with zero species records were probably not sampled. The collective distribution of tenebrionids in HDS cells across the AWSAR was negatively correlated ($r = -0.49$, $p<0.05$) with MAP (Figures 3 & 4). Most (62%) of cells with the highest quartile of diversity were located in the lowest quartile of MAP (χ^2 = 126, $p<0.001$). Half of the top 10-percentiles of diversity (19-38 species) occurred where MAP was <122 mm.

Diversity was significantly higher in the Namib Desert, which covers 11% of the AWSAR, than in the remaining 89% of the area (χ^2 = 684, $p<0.001$). The Namib contained 334 (52%) of the focal species, at least 177 (59%) of which were endemic.

Abundance and Diversity across the Central Namib

Beetle abundance was lowest at Gobabeb, increasing eastwards and westwards (Table 4). Records of museum collections (Table SM1) indicated that the number of species previously recorded in the vicinity of observatories in the CND (Kleinberg, Gobabeb, Ganab)

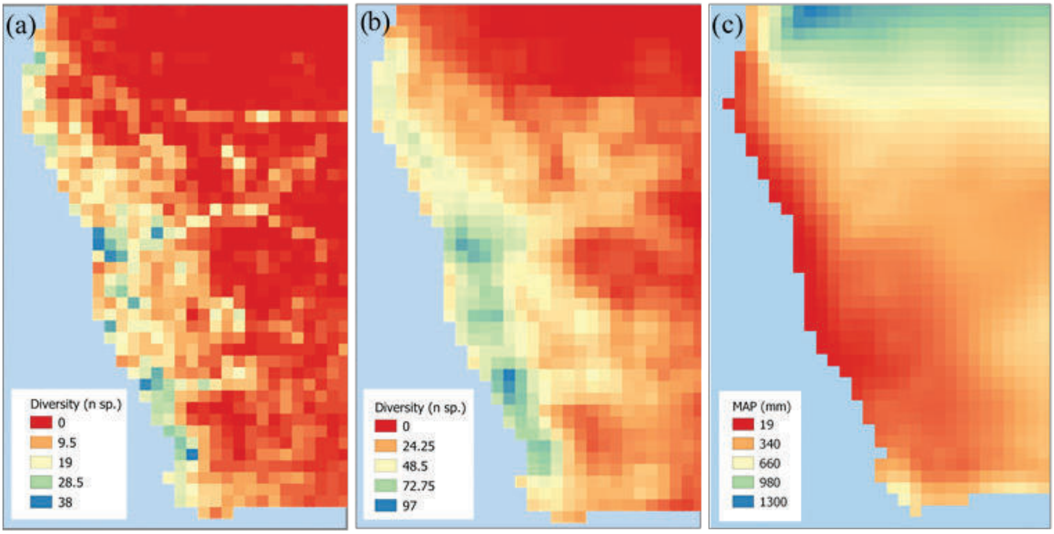

Figure 3: Map of half degree latitude/longitude cells across the AWSAR showing (a) the actual diversity of tenebrionids, (b) the potential diversity of tenebrionids, and (c) mean annual precipitation (MAP)

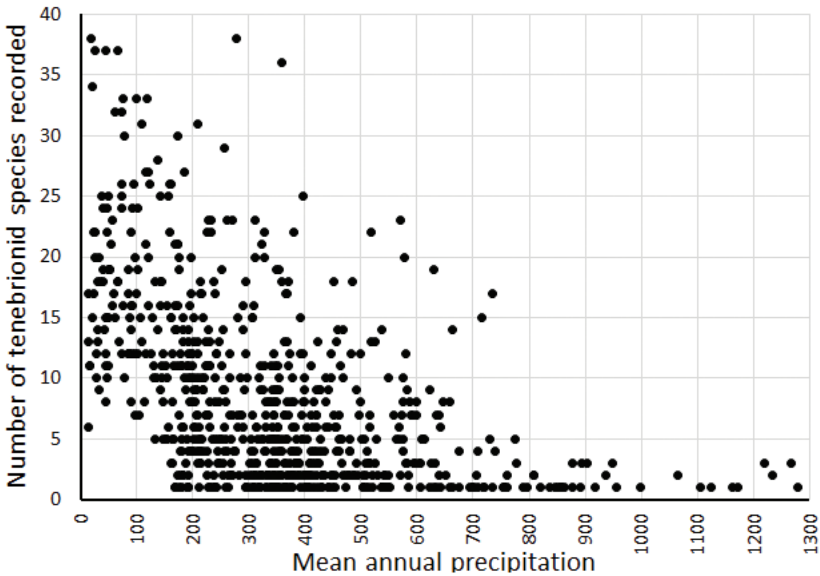

Figure 4: Number of focal species recorded vs MAP in HDS across the AWSAR

Table 4: Abundance, species richness and diversity of tenebrionid beetles of focal species currently observed or collected at the five study sites or previously recorded in the vicinity. Indices are explained in Table 2.

Measure	Total	Kleinberg	Gobabeb	Ganab	Rooisand	Claratal
Distance from coast (km)		21	54	108	167	230
Trapping Sessions (Samples)		18	20	16	14	11
Total Abundance						
Other beetles	16512	270	122	2504	12227	1389
Tenebrionids	11119	2872	1062	1729	1802	3654
Mean±SE per session		160±45	53±11	108±27	129±47	332±137
Species Richness						
$S_{potential}$	101	58	66	60	65	65
$S_{documented}$	64	30	35	26	18	21
$S_{observed}$	30	13	21	22	17	11
$S_{jackknife}$		18	27	26	22	14
Diversity						
Simpson λ	0.12	0.50	0.19	0.26	0.32	0.40
evenness J’	0.75	0.33	0.69	0.61	0.60	0.52
Fisher’s α	3.75	1.76	3.71	3.55	2.60	1.40
ß-diversity						
Kleinberg		-				
Gobabeb		0.29	-			
Ganab		0.37	0.26	-		
Rooisand		0.53	0.37	0.28	-	
Claratal		0.58	0.69	0.52	0.57	-

was higher (26–35) than further inland (18–21). The trend in diversity roughly formed a mirror image of the trend in abundance, with the highest species richness (observed and jackknifed) in the two middle sites and a decline both westwards and eastwards (Table 4). However, at Kleinberg, near the coast, the species accumulation curve did not level out (Figure 5). This site may thus have more rare species, as was also indicated by museum records of the focal taxonomic groups (Table SM1). The first order Jackknife estimates of species richness indicated that with the current methods, 3–6 more species should have been recorded at each site (Table 4).

All diversity indices were highest at Gobabeb, the next highest at Ganab, and declining stepwise eastwards (Table 4). At Kleinberg, where 96% of the samples comprised *Zophosis amabilis* and *Cauricara eburnea*, both diversity and evenness were generally low despite the high richness (Table 5). By contrast, 95% of the total abundance was

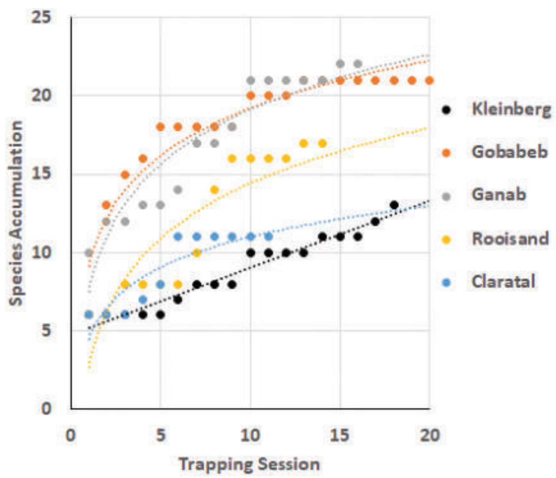

Figure 5: Species accumulation curves for the five study sites, showing logarithmic trendlines except for Kleinberg, where the trendline was linear, reflecting that species accumulation was not beginning to show saturation over 18 trapping sessions

reached with 11 species at Gobabeb and Ganab, nine at Rooisand, and five at Claratal (Table 5).

While abundance was positively correlated with MAP (r=0.80), α-diversity correlated negatively with MAP (r=-0.62) and positively with the CV of MAP (r=0.62) (Figure 6). The previously recorded number of species ($S_{documented}$ in Table 4) correlated even more strongly with MAP-CV (r=0.90) and was also negatively correlated with MAP (r=-0.63).

Trapping Location, Shelter and Season

The trapping records were unevenly spread across grids (χ^2: 168-969, df=5, p<0.001), degree of shelter (χ^2: 106-665, df=2, p<0.001), and season (χ^2: 105-696, df=3, p<0.001) (Figure 7). Of the three traps in each grid, the highest capture rates were in the sheltered traps at all sites except Claratal, where most captures were in unsheltered traps out in the open without a roof (Figure 7). At Kleinberg, the highest capture rates were in grids devoid of perennial vegetation or drainage lines, i.e. open gravel plains where the lichen cover was highest (Table 2, Figure 7). In contrast, at Gobabeb, the capture rate was lowest on the open plains without shrubs or rocks, intermediate on granite rocks where there were shrubs and highest on a quartz hill, where shelter and potential food in terms of accumulated detritus and hypolithic cryptophytes were highest. At Ganab, tenebrionid abundance was highest in a grid with a shrub-lined wash. At Rooisand, the highest captures were in a grid with a *Commiphora glandulosa-Adenolobus gariepensis* shrub community on a gentle slope with calcrete stones. At Claratal, a high abundance of tenebrionids was associated with *Acacia karroo – Cynodon dactylon* plant communities.

Table 5: Number of individuals of different tenebrionid species recorded at the five study sites

			←West				East→
	Species	Total	Kleinberg	Gobabeb	Ganab	Rooisand	Claratal
Widespread	*Physosterna cribripes*	823	8	17	796	1	1
	Zophosis kochi	331	1	2	6	19	303
	Epiphysa arenicola	145	53	13	78	*	1
	Zophosis infanda	205	2	1	2	-	200
	Gonopus tibialis	21	9	*	10	*	2
Widespread in Namib Desert, not on plateau	*Zophosis damarina*	199	13	16	65	105	-
	Metriopus depressus	132	2	99	16	15	-
	Stenocara gracilipes	242	12	10	7	213	-
	Onymacris rugatipennis	187	2	168	15	2	-
	Zophosis amabilis	2,201	1,768	401	*	32	-
	Physadesmia globosa	377	4	28	345	-	-
	Zophosis moralesi	72	3	52	17	-	-
Fog zone	*Cauricara eburnea*	1,048	995	53	-	-	-
	Zophosis dorsata	2	-	2	-	-	-
	Gonopus puncticollis	1	-	1	-	-	-
	Brinckia debilis	1	*	1	-	-	-
Namib interior and escarpment	*Zophosis mniszechi*	152	-	11	80	61	-
	Eustolopus octoseriatus	119	-	73	38	8	-
	Zophosis devexa	119	-	28	90	1	-
	Cauricara velox	131	-	82	2	47	-
	Zophosis lamentabilis	13	-	3	9	1	-
Eastern Namib and escarpment	*Cryptochile consita*	1,007	-	-	35	972	-
	Zophosis orbicularis	7	-	*	7	-	-
	Zophosis cerea	1	-	*	1	-	-
Eastern Namib and plateau	*Zophosis testudinaria*	28	-	1	6	-	21
	Renatiella fettingi	2,290	-	-	12	143	2,135
	Somaticus aeneus	161	-	-	92	25	44
	Metriopus hoffmannseggi	910	-	-	-	95	815
	Stenocara aenescens	123	-	-	-	62	61
Plateau	*Somaticus bisbicostatus*	71	-	-	-	-	71
	Total	11,119	2,872	1,062	1,729	1,802	3,654

* known to occur at the site, but not recorded in the current study

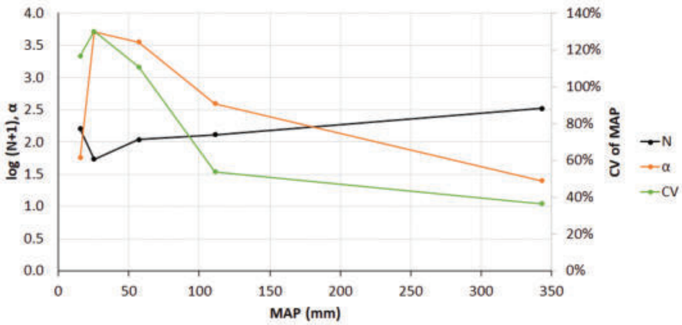

Figure 6: Tenebrionid abundance (log N+1), α diversity, and the coefficient of variation (CV) of MAP plotted against MAP (mm) at the five observatories. Alpha diversity correlated negatively with abundance (r=-0.94) and MAP (r=-0.62) and positively with the CV of MAP (0.62)

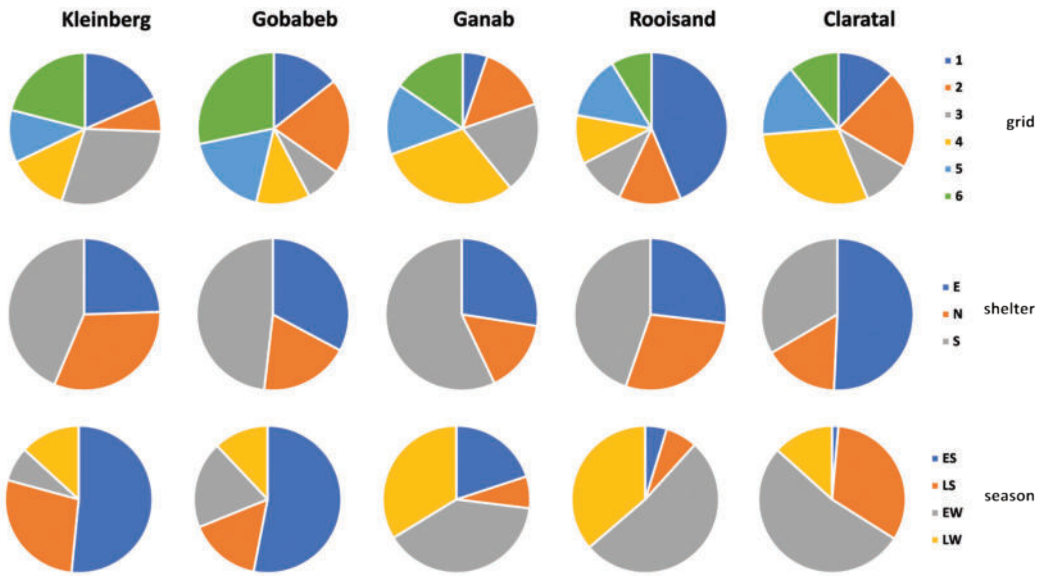

Figure 7: Proportion of tenebrionid beetles collected in traps deployed in different grids (1–6 of each Observatory, Table 1), sheltered (S), near shelter (N), or fully exposed in the open (E), and in different seasons, early summer (ES: OND), late summer (LS: JFM), early winter (EW: AMJ), or late winter (LW: JAS)

The seasonal capture rate differed between sites, with Kleinberg and Gobabeb recording over half of all abundance in early summer (Figure 7), which is the season with the highest occurrences of fog. At Ganab and Rooisand, in contrast, abundance was highest during early and late winter. At Claratal, abundance was highest during late summer and early winter, with 85% of the captures recorded.

Although a few widespread species occurred across the gradient (Table 5), the species composition differed considerably between observatories, with β-diversity ranging from 0.26 (between Gobabeb and Ganab) and 0.69 (between Gobabeb and Claratal, Table 4). While *Zophosis amabilis* was the most abundant species recorded during this study at Kleinberg and Gobabeb, only the fog-zone-associated *Cauricara eburnea* was co-dominant with *Zophosis* at Kleinberg. At Gobabeb, many other species were co-dominant, and diversity was high, although abundance was only a third of that recorded at Kleinberg. A different set of large-bodied species dominated at Ganab, while at Rooisand, the dominant set of species was relatively small-bodied and differed from Claratal (Table 5). β-diversity was high between Claratal and all other sites (Table 4), reflecting a vastly different beetle community on the highland plateau than in the lowland desert and adjacent escarpment (Table 5). Kleinberg was the next distinctive site, with high β-diversity to sites outside the fog zone (Table 4 & 5).

The full complement of species can be sorted into seven groups based on their affinity for the fog zone, the Namib interior, the escarpment, or the plateau (Table 5). Only five species occurred across the whole transect (with some gaps in the record), while a further seven appeared to be limited to below the plateau or below the escarpment (Table 5). Four species occurred mostly in the fog zone, which covers the first two sites, although only one (*C. eburnea*) was truly abundant (Table 5). Eight species were confined to the Namib interior and escarpment, essentially avoiding the fog zone (Table 5). Of the last six species, five occurred from the Namib interior up to the plateau, and one was recorded only on the plateau at Claratal (Table 5). The majority (19 out of 30) of the species were limited to the Namib and adjacent escarpment (Table 5).

Discussion

Our datasets at two different scales showed that tenebrionid diversity increased across an east-to-west gradient of increasing aridity across the western half of southern Africa. This trend was especially pronounced across the Namib Desert, with tenebrionids being more diverse but less abundant within the desert than in the adjacent hinterland. Our estimate of endemism for the Namib Desert matches a previous estimate by Koch (1962) of about 200 endemic species, who had also included several other tribes in his study. This concentration of species indicates that the Namib Desert is a hotspot of tenebrionid diversity.

Over the past eight decades, the area between Namibia's capital city, Windhoek, and the country's main harbour at Walvis Bay has been intensively studied by scientists. This has provided valuable datasets for exploring the factors that might underlie the beetle biodiversity patterns across the Namib in this area. Over a distance of 300 km, MAP rises over 20-fold from Kleinberg near the coast to Claratal on the plateau, while the trend for variation in MAP goes in the opposite direction. Across this area, the number of tenebrionid species and all diversity indices increased from the foggy coast to the Namib interior (Gobabeb and Ganab) and decreased from there across the Great Escarpment to the Khomashochland (Table 4). Abundance had the opposite trend: declining from the western Namib to the middle zone (Gobabeb) and increasing over sixfold from there to the easternmost site (Claratal).

The coastal location (Kleinberg) fell out of the general longitudinal pattern. The regular occurrence of fog at this observatory supported an abundance of terricolous crustose and foliose lichens covering about half of the ground surface (Zedda and Rambold in Jürgens et al. (2010)) which increased the availability of water and food for tenebrionids (Lalley et al. 2006). The low eveness of diversity at Kleinberg was caused by particularly high abundances of two species, *Zophosis amabilis* and *Cauricara eburnea,* both known to feed on lichen (Wessels et al. 1979) with their populations tracking fog frequency (Seely et al. 2005; Henschel 2021). At Kleinberg, the numerous rare species would require considerably more trapping effort than the 18 traps deployed during 18 month-long trapping sessions to record the true species complement.

Coincident with the patterns in community structure, there were clear changes in composition over the transect, with high β-diversity indices between adjacent sites. The most marked difference between adjacent communities (ß = 0.57) was between the two sites located in the Thornbush Savanna, Rooisand at the foot of the escarpment, and Claratal, above the escarpment. The change in altitude thus had an even larger effect on species composition than the biome transition between Ganab and Rooisand (ß = 0.28). For many organisms, the mountainous terrain of the escarpment may act as a dispersal barrier, explaining abrupt changes in species composition seen along the escarpment (Barnard et al. 1998; Simmons et al. 1998; Mendelsohn et al. 2002; Jürgens et al. 2010). The mechanism behind the marked filtering effect that altitude plays on species pools is poorly understood for most invertebrate taxa beyond the general knowledge that species or their phenological and phenotypic characteristics often occur within very narrow climatic zones (Andrewartha & Birch 1954; Cheli et al. 2021; Lopez et al. 2021). These relationships with a range of micro and meso-climatic variables that vary with altitude are important to understand, as the fortunes of many species will be determined by the fine details of how aspects such as temperature and moisture levels will vary in the future (Roitberg & Mangel 2016; Figueroa et al. 2021; Tocco et al. 2021).

The trend in tenebrionid diversity from west to east is opposite to that of other taxa, a phenomenon that Koch had already noted during his surveys of Tenebrionidae across the arid west of southern Africa (Koch 1962). While species richness of other insects decreases with decreasing MAP from east to west, e.g. Lepidoptera (Mey 2010), tenebrionid richness increases. The taxonomic groups we included in our analysis of transect data represent only part of the tenebrionid species and did not include several species recorded close to the current observatories with different sampling methods that were continuous over decades (e.g., Henschel et al. 2003; Henschel 2021). Nevertheless, the west to east trend across the transect is similar to that previously recorded across the area (Table SM1). It is consistent with the overall picture of the 579 taxa for which distribution records were mapped across the AWSAR (Figure 3, SM1). However, there are many more tenebrionid species in the region. Alone in Namibia, some 743 known tenebrionid species or taxonomic entities are recorded from this family (Marais 1998; Irish 2012). Ongoing studies are identifying more tenebrionid taxa in the Namib Desert, including previously little-studied groups, e.g. Tentyriini (Schawaller 2012) and Cossyphodini (Schawaller 2013), and taxonomic revisions, e.g. Platynotina (Kamiński & Iwan 2013) and Molurina (Kamiński et al. 2021).

In sparsely vegetated areas, shelter appears to be premium, and our capture rates were higher at shelters such as shrubs or rocks. These provide some shade during the day and are places where locally generated or windblown detritus collects. The preference for open spaces at Claratal could perhaps be due to reduced predation risk away from structures where sit-and-wait predators lurk.

The seasonal patterns of tenebrionid abundance (activity) relate to the expected highest occurrence of moisture. At Kleinberg and Gobabeb, this would be when fog is most frequent, i.e., at the end of winter and the beginning of summer (September to December, Lancaster et al. (1984)). The occurrence of rains in late summer and early winter, driven by Tropical Temperate Troughs (Eckardt et al. 2013), and the resulting moderate temperatures and lingering soil moisture conditions during winter (Henschel 2021) could explain the relatively high activity of tenebrionids during winter at Ganab and Rooisand. At Claratal the tenebrionid activity was highest during the first half of the calendar year when most rains fell, and plant productivity was highest (Strohbach and Luther-Mosebach in Jürgens et al. (2010)).

Our finding that diversity correlates with the variability of MAP can possibly be explained by the intervals between rainfall events becoming longer with increasing aridity. This allows for dividing activity times more finely into temporal niches. Multiple successive time-niches used by populations of different tenebrionid species with divergent rates of growth and decline serially changes community composition, thus enhancing the coexistence of many species, resulting in the highest diversity at the driest location (Henschel 2021).

The extraordinarily high level of endemism in the desert is probably related to the great age of the Namib (Ward & Corbett 1990). As substrate specialists (Prendini 2001), isolated populations of tenebrionids are subject to geomorphological processes such as dune-field dynamics (Koch 1961; Endrödy-Younga 1982) or other changes in substrate configuration (Penrith 1979, 1986a). Divergence of isolated populations would lead to the speciation of endemics at local levels.

At a landscape level, the scale of ten to tens of km, an interplay of temporal and spatial rainfall variability may come into play. In the Namib, rainfall is highly variable over time (Table 2) and across space (Henschel et al. 2005), and in terms of rainfall, the Namib Desert is heterogeneous, irrespective of geophysical conditions. Therefore, populations of tenebrionids in adjacent landscapes could be in a very different status, e.g. irrupting in one area while crashing or in a bottleneck condition in another. This heterogeneity may constrain gene flow across the area and promote population differentiation even across geographically similar interconnected areas.

The increase of tenebrionid diversity with increasing aridity across the Namib Desert remains a fruitful topic for further research despite significant advances in understanding since Koch first noted it 60 years ago.

Supplementary Material

This can be downloaded at:
http://data.sasscal.org/metadata/view.php?view=doc_data&id=7301

Contents:

- **Figure SM1**: Number of tenebrionid species of focal taxa recorded in half-degree squares of latitude and longitude (HDS) across the western half of southern Africa between latitude 13-34.5°S and longitude 11.5-25.5°E.
- **Table SM1:** Tenebrionids recorded at five SASSCAL observatories and in their half-degree squares of latitude and longitude (HDS).
- **Figure SM2:** Total abundance (log N) of focal tenebrionids recorded at different SASSCAL observatories during month-long trapping sessions conducted at various times between April 2004 and March 2009.
- Site-specific overviews of tenebrionids recorded at west-to-east (WET) SASSCAL Observatories across the central Namib
- Files:
  - Tenebrionid beetle data BIOTA-WET 2004–2009.
  - Tenebrionid beetle metadata BIOTA-WET 2004–2009.

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References

ANDREWARTHA, H.G. & BIRCH, L.C. 1954. *The distribution and abundance of animals,* Chicago & London, University of Chicago Press.

BARNARD, P., BROWN, C.J., JARVIS, A.M., ROBERTSON, A. & VAN ROOYEN, L. 1998. Extending the Namibian protected area network to safeguard hotspots of endemism and diversity. *Biodiversity and Conservation,* 7, 531-547.

CHELI, G.H., CARRARA, R., BANDIERI, L. & FLORES, G.E. 2021. Distribution and environmental determinants of darkling beetles assemblages (Coleoptera: Tenebrionidae) in Peninsula Valdes (Argentinean Patagonia). *An Acad Bras Cienc,* 93, e20201282.

CLOUDSLEY-THOMPSON, J.L. 2001. Thermal and water relations of desert beetles. *Naturwissenschaften,* 88, 447–460.

CRAWFORD, C.S. & SEELY, M.K. 1987. Assemblages of surface-active arthropods in the Namib dunefield and associated habitats. *Revue de Zoologie Africaine,* 101, 397–421.

DE MOOR, P.P. 1970. Monograph of the Praeugenina (Coleoptera: Tenebrionidae, Strongyliini). *Transvaal Museum Memoir,* 17, 1–203.

DUNCAN, F.D. 2021. Respiratory Strategies in Relation to Ecology and Behaviour in Three Diurnal Namib Desert Tenebrionid Beetles. *Insects,* 12, e1036.

ECKARDT, F.D., SODERBERG, K., COOP, L.J., MULLER, A.A., VICKERY, K.J., GRANDIN, R.D., JACK, C., KAPALANGA, T.S. & HENSCHEL, J.R. 2013. The nature of moisture at Gobabeb, in the central Namib Desert. *Journal of Arid Environments,* 93, 7–19.

ENDRÖDY-YOUNGA, S. 1982. Dispersion and translocation of dune specialist tenebrionids in the Namib area. *Cimbebasia (A),* 5, 257–271.

ENDRÖDY-YOUNGA, S. 1996. Revision of the tribe Caenocrypticini (Coleoptera: Tenebrionidae: Tentyriinae). *Transvaal Museum Monograph,* 11, 1–74.

ENDRÖDY-YOUNGA, S. 2000. Revision of the subtribe Gonopina (Coleoptera: Tenebrionidae, Opatrinae, Platynotini). *Annals of the Transvaal Museum,* 37, 1–54.

FICK, S.E. & HIJMANS, R.J. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology,* 37, 4302–4315.

FIGUEROA, L.L., MARAN, A. & PELINI, S.L. 2021. Increasing temperatures reduce invertebrate abundance and slow decomposition. *PLoS One,* 16, e0259045.

HAMILTON, W.J.I. & SEELY, M.K. 1976. Fog basking by the Namib Desert beetle, *Onymacris unguicularis. Nature,* 262, 284–285.

HANRAHAN, S.A. & SEELY, M.K. 1990. Food and habitat use by three tenebrionid beetles (Coleoptera) in a riparian desert environment. *Namib ecology 25 years of Namib research.* 1st ed. Pretoria: Transvaal Museum.

HAYEK, L.-A.C. & BUZAS, M.A. 1997. *Surveying natural populations,* New York, Columbia University Press.

HENSCHEL, J.R. 2021. Long-Term Population Dynamics of Namib Desert Tenebrionid Beetles Reveal Complex Relationships to Pulse-Reserve Conditions. *Insects,* 12, 1–25.

HENSCHEL, J.R., BURKE, A. & SEELY, M. 2005. Temporal and spatial variability of grass productivity in the central Namib Desert. *African Study Monographs,* Suppl. 30, 43–56.

HENSCHEL, J.R., GROHMANN, C., SITEKETA, V. & LINSENMAIR, K.E. 2010. Monitoring tenebrionid beetle biodiversity in Namibia. *African Study Monographs,* 40, 91–102.

HENSCHEL, J.R. & LANCASTER, N. 2013. Gobabeb—50 years of Namib Desert research. *Journal of Arid Environments,* 93, 1–6.

HENSCHEL, J.R., MTULENI, V., PALLETT, J. & SEELY, M.K. 2003. The surface-dwelling arthropod fauna of Gobabeb with a description of the long-term pitfall trapping project. *Journal of the Namibia Scientific Society,* 51, 65–92.

HOLM, E. 1970. *The influence of climate on the activity patterns and abundance of xerophilous Namib Desert dune insects.* M.Sc., University of Pretoria.

HOLM, E. & SCHOLTZ, C.H. 1980. Structure and pattern of the Namib Desert dune ecosystem at Gobabeb. *Madoqua,* 12, 3–39.

IRISH, J. 2012. *Family Tenebrionidae in Namibia* [Online]. Windhoek: Namibia Biodiversity Database. Available: https://biodiversity.org.na/taxondisplay.php?nr=3201 [Accessed 2022-02-18T19:06:44+02:00 2022].

JÜRGENS, N., OLDELAND, J., HACHFELD, B., ERB, E. & SCHULTZ, C. 2013. Ecology and spatial patterns of large-scale vegetation units within the central Namib Desert. *Journal of Arid Environments,* 93, 59–79.

JÜRGENS, N., SCHMIEDEL, U. & HOFFMAN, M.T. (eds.) 2010. *Biodiversity in southern Africa,* Göttingen & Windhoek: Klaus Hess Publishers.

KAMIŃSKI, M.J., GEARNER, O.M., KANDA, K., SWICHTENBERG, K., PURCHART, L. & SMITH, A.D. 2021. First insights into the phylogeny of tok-tokkie beetles (Tenebrionidae: Molurina, Phanerotomeina) and examination of the status of the Psammodes vialis species-group. *Zoological Journal of the Linnean Society*, 191, 883–901.

KAMIŃSKI, M.J. & IWAN, D. 2013. Taxonomy, Distribution and Ecological Niche Models of the Afrotropical Platynotoid Platynotina (Tenebrionidae: Pedinini). *Annales Zoologici,* 63, 653–733.

KOCH, C. 1955. Monograph of the Tenebrionidae of southern Africa: Tentyriinae, Molurini, Trachynotina, Somaticus Hope. *Transvaal Museum Memoir,* 7, 1–242.

KOCH, C. 1961. Some aspects of abundant life in the vegetationless sand of the Namib Desert dunes positive psammotropism in tenebrionid-beetles. *Journal S.W.A. Scientific Society,* 15, 9–34.

KOCH, C. 1962. The Tenebrionidae of southern Africa XXXI. comprehensive notes on the tenebrionid fauna of the Namib Desert. *Annals of the Transvaal Museum,* 24, 61–106.

LALLEY, J.S., VILES, H.A., HENSCHEL, J.R. & LALLEY, V. 2006. Lichen-dominated soil crusts as arthropod habitat in warm deserts. *Journal of Arid Environments,* 67, 579–593.

LANCASTER, J., LANCASTER, N. & SEELY, M.K. 1984. Climate of the central Namib Desert. *Madoqua,* 14, 5-61.

LOPEZ, H., HERVIAS-PAREJO, S., MORALES, E., DE LA CRUZ, S. & NOGALES, M. 2021. Interpopulation Plasticity in a Darkling Beetle Life-History along a Whole Oceanic Island Altitudinal Gradient. *Insects,* 12, e1137.

MAGURRAN, A.E. 1991. Diversity indices and species abundance models. *In:* MAGURRAN, A.E. (ed.) *Ecological diversity and its measurement.* 2nd ed. London: Chapman & Hall.

MARAIS, E. 1998. Insect diversity. *In:* BARNARD, P. (ed.) *Biological diversity in Namibia, a country study.* Windhoek, Namibia: Ministry of Environment and Tourism.

MARSH, A.C. 1986. Ant species richness along a climatic gradient in the Namib Desert. *Journal of Arid Environments,* 11, 235–241.

MCCLAIN, E., SEELY, M.K., HADLEY, N.F. & GRAY, V. 1985. Wax blooms in tenebrionid beetles of the Namib Desert: correlations with environment. *Ecology,* 66, 112–119.

MENDELSOHN, J., JARVIS, A., ROBERTS, C. & ROBERTSON, T. 2002. *Atlas of Namibia,* Cape Town, New Africa Books (Pty) Ltd.

MEY, W. 2010. Basic pattern of Lepidoptera diversity in Namiba. *In:* JÜRGENS, N., SCHMIEDEL, U. & HOFFMAN, M.T. (eds.) *Biodiversity in southern Africa 2: patterns and processes at regional scale.* Göttingen & Windhoek: Klaus Hess Publishers.

MITCHELL, D., HENSCHEL, J.R., HETEM, R.S., WASSENAAR, T.D., STRAUSS, W.M., HANRAHAN, S.A. & SEELY, M.K. 2020. Fog and fauna of the Namib Desert: past and future. *Ecosphere,* 11, 1–40.

NICOLSON, S.W. 1990. Water relations of the Namib tenebrionid beetles. *Namib ecology 25 years of Namib research.* 1st ed. Pretoria: Transvaal Museum.

NICOLSON, S.W. 1992. Diuresis in the desert? unexpected excretory physiology of a Namib Desert beetle. *South African Journal of Science,* 88, 243–245.

PARENZEE, L. 2001. *Use of tenebrionid beetles as indicators of habitat quality.* M.Sc. Archive, University of the Witwatersrand.

PENRITH, M.-L. 1975. The species of *Onymacris* Allard (Coleoptera: Tenebrionidae). *Cimbebasia, Series A,* 4, 47–97.

PENRITH, M.-L. 1977. The Zophosini (Coleoptera: Tenebrionidae) of western southern Africa. *Cimbebasia Memoir,* 3, 7–291.

PENRITH, M.-L. 1979. Revision of the Western Southern African Adesmiini (Coleoptera: Tenebrionidae). *Cimbebasia,* Ser-A 5, 1–94.

PENRITH, M.-L. 1980. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 1: introduction. *Cimbebasia Series A,* 6, 1–16.

PENRITH, M.-L. 1981a. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 2: the subgenus *Zophosis* Latreille, and seven related south-western African subgenera. *Cimbebasia Series A,* 6, 17–109.

PENRITH, M.-L. 1981b. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 3: seven aberrant Namib subgenera. *Cimbebasia, Series A,* 6, 111–124.

PENRITH, M.-L. 1981c. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 4: twelve subgenera from arid southern Africa. *Cimbebasia Series A,* 6, 125–164.

PENRITH, M.-L. 1982a. The genus *Calaharena* (Coleoptera: Tenebrionidae: Opatrini: Stizopina). *Cimbebasia,* 5, 251–255.

PENRITH, M.-L. 1982b. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 5: a derived subgenus from northern Africa. *Cimbebasia,* 6, 165–226.

PENRITH, M.-L. 1982c. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 6: the subgenus *Hologenosis* Deyrolle. *Cimbebasia,* 6, 227–289.

PENRITH, M.-L. 1983a. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 7: the African species of subgenus *Oculosis* Penrith. *Cimbebasia,* 6, 291–367.

PENRITH, M.-L. 1983b. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 8: the Palaearctic species group of the subgenus *Oculosis* Penrith, the subgenus *Cheirosis* Deyrolle, and a monotypical subgenus from Socotra. *Cimbebasia,* 6, 369–384.

PENRITH, M.-L. 1984. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 9: the remaining species of the subgenus *Septentriophosis* Penrith. *Cimbebasia Ser. A,* 6, 385–416.

PENRITH, M.-L. 1986a. Relationships in the tribe Adesmiini (Coleoptera: Tenebrionidae) and a revision of the genus *Stenodesia* Reitter. *Annals of the Transvaal Museum,* 34, 275–302.

PENRITH, M.-L. 1986b. Revision of the genera Bombocnodulus Koch and Brinckia Koch (Coleoptera: Tenebrionidae: Molurini). *Journal of the Entomological Society of Southern Africa,* 49, 55–85.

PENRITH, M.-L. 1986c. Revision of the Zophosini (Coleoptera: Tenebrionidae) part 10: key to the subgenera, supplement, evolution and biogeography of the tribe, and catalogue. *Cimbebasia,* 6, 417-502.

PENRITH, M.-L. 1987. Revision of the genus *Tarsocnodes* Gebien, (Coleoptera: Tenebrionidae: Molurini) and description of a monotypical genus from the kalahari. *Cimbebasia Ser. A,* 7, 235–270.

PENRITH, M.-L. & ENDRÖDY-YOUNGA, S. 1994. Revision of the subtribe Cryptochilina (Coleoptera: Tenebrionidae: Cryptochilini). *Transvaal Museum Monograph,* 9, 1–144.

PRENDINI, L. 2001. Substratum specialization and speciation in southern African scorpions: the Effect Hypothesis revisited. *In:* FET, V. & SELDEN, P. A. (eds.) *Scorpions 2001: In Memoriam Gary A. Polis.* Plymouth: British Arachnological Society.

RASMUSSEN, J.L., SEELY, M.K. & PIETRUSZKA, R.D. 1991. The reproductive behavior of six species of Namib Desert tenebrionid beetles (Coleoptera: Tenebrionidae). *Journal of Insect Behavior,* 4, 567–582.

ROBERTS, C.S. 1991. *The surface and subsurface environments and the physiological and behavioural ecology of dune-living beetles in the Namib Desert.* M.Sc. thesis, University of the Witwatersrand.

ROITBERG, B.D. & MANGEL, M. 2016. Cold snaps, heatwaves, and arthropod growth. *Ecological Entomology,* 41, 653–659.

RÖSSL, R. 2000. *Reproduktionsbiologie, Entwicklungsbiologie und Ökologie von sympatrischen Tenebrionidae (Coleoptera: Insecta) des Kuiseb bei Gobabeb in der Namib Wüste / Namibia.* PhD thesis, Rheinische Friedrich-Wilhelms-Universität.

SCHAWALLER, W. 2012. A new genus and species of Tentyriini (Coleoptera: Tenebrionidae) from sand dunes in Namaqualand, South Africa. *Zootaxa,* 3514.

SCHAWALLER, W. 2013. Cossyphodini (Coleoptera: Tenebrionidae: Pimeliinae) in South Africa, Namibia and adjacent regions: New species and records, key to genera, and Old World species catalogue. *Zootaxa,* 3721, 351–64.

SCHMIEDEL, U., DENGLER, J., LUTHER-MOSEBACH, J., GRÖNGRÖFT, A., MUCHE, G., PETERSEN, A., STROHBACH, B.J. & JÜRGENS, N. 2010. Patterns and dynamics of vascular plant diversity along the BIOTA transects in southern Africa. *In:* JÜRGENS, N., SCHMIEDEL, U. & HOFFMAN, M. T. (eds.) *Biodiversity in southern Africa 2: Patterns and processes at regional scale.* Göttingen & Windhoek: Klaus Hess Publishers.

SCHULZE, L. 1974. The Tenebrionidae of Southern Africa. 43. Description of some larvae of the Zophosini with observations on the possible origin of phylogenetic evolution of dune-living genera (Coleoptera). *Annals of the Transvaal Museum,* 29, 71–98.

SEELY, M.K. 1973. Factors controlling reproduction of certain Namib Desert tenebrionids. *Madoqua Series II,* 2, 63–65.

SEELY, M.K. & HAMILTON, W.J.I. 1976. Fog catchment sand trenches constructed by tenebrionid beetles, *Lepidochora,* from the Namib Desert. *Science,* 193, 484–486.

SEELY, M.K., HENSCHEL, J.R. & HAMILTON, W.J.I. 2005. Long-term data show behavioural fog collection adaptations determine Namib Desert beetle abundance. *South African Journal of Science,* 101, 570–572.

SEELY, M.K. & LOUW, G.N. 1980. First approximation of the effects of rainfall on the ecology and energetics of a Namib Desert dune ecosystem. *Journal of Arid Environments,* 3, 25–54.

SIMMONS, R.E., GRIFFIN, M., GRIFFIN, R.E., MARAIS, E. & KOLBERG, H. 1998. Endemism in Namibia: patterns, processes and predictions. *Biodiversity and Conservation,* 7, 513–530.

SMITH, C.D. & PONTIUS, J.S. 2006. Jackknife Estimator of Species Richness with S-PLUS. *Journal of Statistical Software,* 15, 1–12.

THOMPSON, G.G., WITHERS, P.C., PIANKA, E.R. & THOMPSON, S.A. 2003. Assessing biodiversity with species accumulation curves: inventories of small reptiles by pit-trapping in Western Australia. *Austral Ecology,* 28, 361–383.

TOCCO, C., FOSTER, J., VENTER, N., COWIE, B., MARLIN, D. & BYRNE, M. 2021. Elevated atmospheric CO2 adversely affects a dung beetle's development: Another potential driver of decline in insect numbers? *Glob Chang Biol,* 27, 4592–4600.

TRABUCCO, A. & ZOMER, R.J. 2018. *Global Aridity Index and Potential Evapo-Transpiration (ET0) Climate Database v2* [Online]. CGIAR Consortium for Spatial Information (CGIAR-CSI). Available: https://cgiarcsi.community/data/global-aridity-and-pet-database/ [Accessed 14 August 2022].

WARD, D. & SEELY, M.K. 1996. Competition and habitat selection in Namib desert tenebrionid beetles. *Evolutionary Ecology,* 10, 341–359.

WARD, J.D. & CORBETT, I. 1990. Towards an age for the Namib. *Namib ecology 25 years of Namib research.* 1st ed. Pretoria: Transvaal Museum.

WESSELS, D.C.J., WESSELS, L.A. & HOLZAPFEL, W.H. 1979. Preliminary report on lichen-feeding Coleoptera occurring on *Teloschistes capensis* in the Namib Desert, South West Africa. *The Bryologist,* 82, 270–273.

WHARTON, R.A. & SEELY, M.K. 1982. Species composition of and biological notes on Tenebrionidae of the lower Kuiseb River and adjacent gravel plain. *Madoqua,* 13, 5–25.

WIRTH, V., MÜLLER, J., PFIZ, M., LORIS, K. & KÜPPERS, M. 2010. Lichen distributionj along an ocean-inland transect in the fog zone of the Central Namib. *In:* JÜRGENS, N., SCHMIEDEL, U. & HOFFMAN, M.T. (eds.) *Biodiversity in southern Africa 2: Patterns and processes at regional scale.* Göttingen & Windhoek: Klaus Hess Publisher.

YEATON, R.I. 1988. Structure and function of the Namib dune grasslands: characteristics of the environmental gradients and species distributions. *Journal of Ecology,* 76, 744–758.

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Anibtanab: An Earlier and Middle Stone Age Site in the Namib Sand Sea

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Keywords: Earlier Stone Age, Middle Stone Age, Namib Desert, archaeology, Sand Sea, Anibtanab, arid landscapes, lithic technology.

Abstract

The archaeological site of Anibtanab is an interdunal pan locale on the northern margin of the Namib Sand Sea, situated roughly 1.5 km south of the !Khuiseb River and about 40 km east of Gobabeb. The site was first investigated by Shackley (1985) who reported earlier and middle stone age tools scattered across the approximately 1,500 m x 1,000 m pan. Shackley's brief mention provides typologies and total number of tools but no additional descriptions of the technology. In 2021, the site was revisited and a new sample of lithics was analyzed. This paper presents the preliminary results of this analysis, which provides a more detailed understanding of the Anibtanab site to inform future studies of the numerous archaeological pan sites in the Namib Sand Sea.

Introduction

The Namib Sand Sea holds a potential wealth of archaeological data that is only just beginning to be understood. Dozens of surface artifact scatters have been identified, but very few have been systematically studied. One such site on the northern edge of the Namib Sand Sea is Anibtanab. Located about 1.5 km south of the !Khuiseb River ravine and about

40 km to the east of Gobabeb, Anibtanab is a large interdunal pan, roughly 1,500 m by 1,000 m in size (Figures 1 and 2). The site is located favorably near seasonal water sources, raw materials for stone tools in the form of large quartzite cobbles, and vegetation, veld foods and longer lasting pools along the !Khuiseb.

The first archaeological report from the site was published by Myra Shackley in 1985, under the site name Zebravlei. She indicated that it was also called Mniszechi's Vlei by researchers from Gobabeb working in the area. We prefer to retain the historical local name "Anibtanab" for the area (Anon 1911, Stapff 1887), as Mniszechi's Vlei has no historical or contextual relevance. Shackley reports a Middle Stone Age (MSA) scatter with the highest density of artifacts in the central portion of the pan. Shackley recorded artifacts while walking five southwest to northeast transects of 500 m (Shackley 1985). One hundred and twenty seven artifacts were recorded, including points, blades and various flake types. No materials diagnostic of the Earlier Stone Age such as handaxes or cleavers were recorded. Total numbers and raw material types were not provided, nor were any size data, but the sample was 27% core types, 37.2% flake types, and 15.8% formal tools (Shackley 1985). The remaining portion was fragmented or debris types.

In 2013, Ted Marks, accompanied by the former director at Gobabeb, Mary Seely, revisited Anibtanab while undertaking an archaeological inventory of the northern Namib Sand Sea. Marks took X-ray fluorescence (XRF) measurements of minor and trace element concentrations in a sample of 16 quartzite artifacts from the site. These data were compared with a library of XRF measurements on unmodified quartzite cobbles from gravels throughout the central Namib. Using canonical discriminant analysis, he determined that the sampled quartzite artifacts at Anibtanab most likely originated from quartzite gravels derived from the Karpfenkliff conglomerate along the lower reaches of the !Khuiseb valley (Marks et al. 2014).

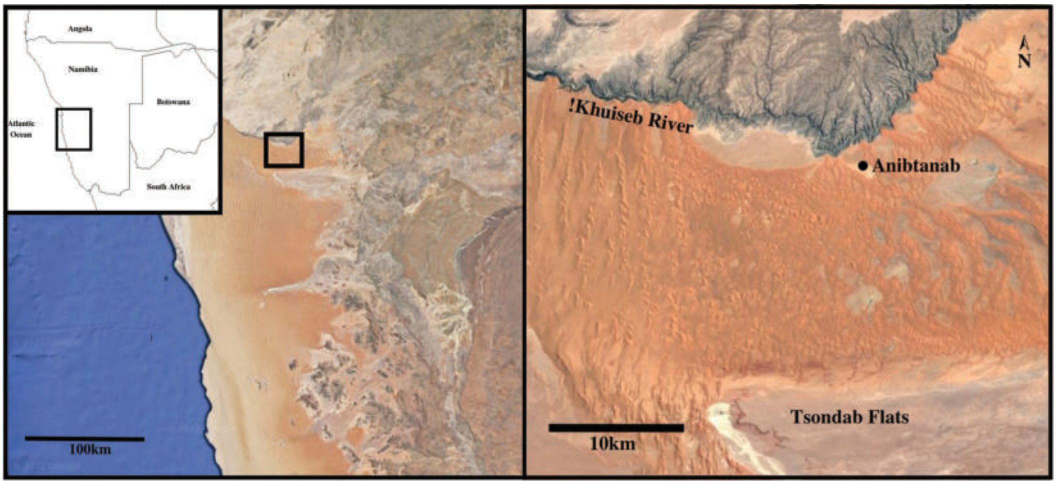

Figure 1: The site of Anibtanab in the Northern Sand Sea, 1.5 km south of the !Kuiseb River

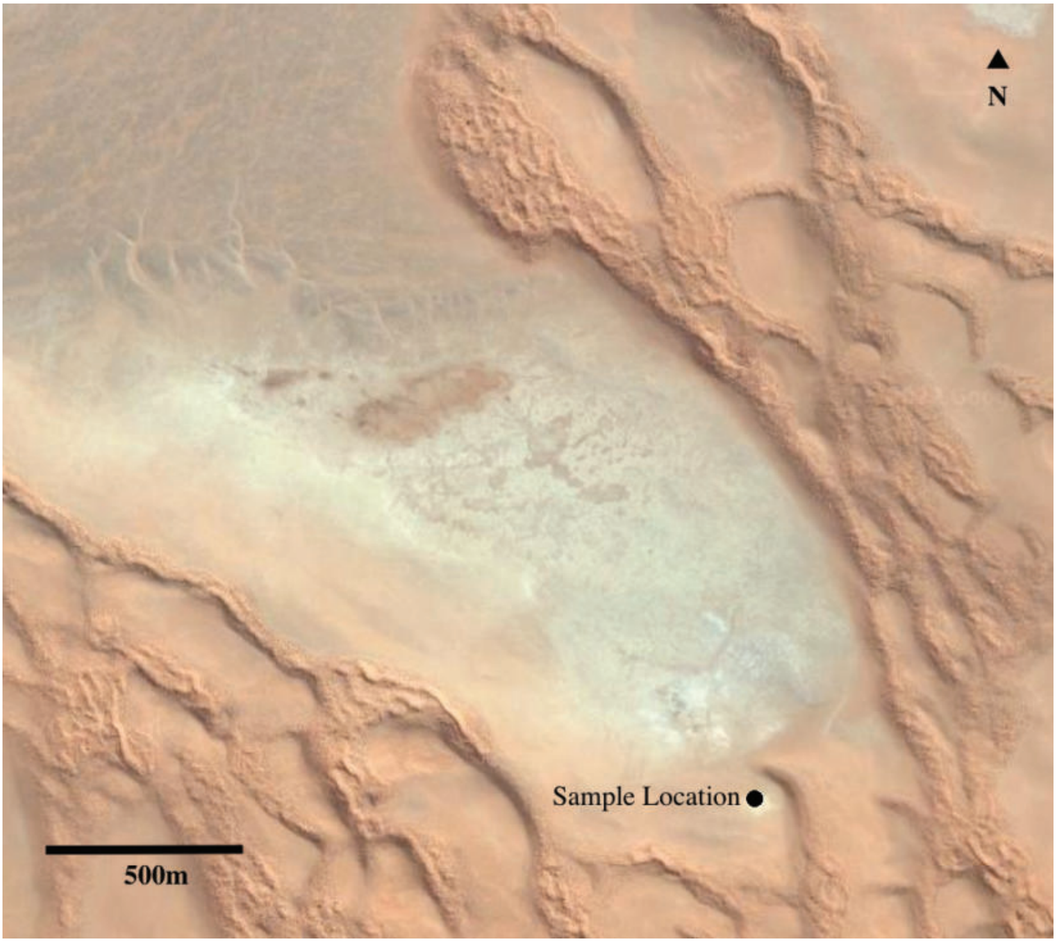

Figure 2: Anitanab interdunal pan

The limited data from previous studies offer clues to understanding prehistoric occupations of the Namib Sand Sea. However, numerous difficulties arise when studying surface archaeological sites, many of which involve localized taphonomic, depositional, and multiple occupation issues (Fanning et al. 2009). However, newly emerging methods and improving surface material dating technology have prompted a recent increase of interest in surface materials (Fanning et. al. 2009, Marks 2015, Gliganic et. al. 2021).

In recent decades, past fluvial episodes in the Namib Desert have been accurately dated (reviews in Stone et. al. 2010, Stone & Thomas 2012), though the full extent of wet conditions leading to substantial runoff and open water within dune areas is still unknown. Information from archaeological and geomorphological studies can supplement one another, where artifacts may provide broad chronologies of alluvially deposited gravels, cobbles, pebbles, or sediments. Modern dating methods for alluvial sediments may define likely wet periods conducive to hominin occupation. Establishing the relationships between climatic events and patterns of hominin occupation is therefore a key research goal for studies in the Namib Sand Sea.

Anibtanab is the first of many of these interdunal sites to be reinvestigated with the goal of gaining a better understanding of the movements of hominins in this challenging dune landscape. This paper provides preliminary technological data on an interdunal pan, which has never been fully described in previous studies (Shackley 1985). The site marks a northeastern locality from which a new project (Survey and Archaeology of the Namib Desert Surface) will continue mapping sites towards the southwest and along the ancient Tsondab River flats.

Methods

The site was revisited in July 2021. A preliminary artifact evaluation of the pan surface was first conducted for a general overview of the stone tool technology present and to assess the exposed geological deposits. The southern portion of the pan appears to have the highest density of artifacts. It was determined that a random sample of artifacts would be assessed within that portion of the pan.

A 10 m^2 area was measured off at a randomly generated location in the southern portion of the pan, near where the gravel plain meets the dunes. Stone artifacts were first flagged within the sample grid and data were collected (Figure 3). Standard measurements were taken on each artifact including maximum length (for flakes measured from the striking platform to the distal termination), maximum width (perpendicular to the maximum length at the midpoint of the length), and maximum thickness (at the midpoint of the maximum length). On flakes, the number of faces on the striking platform and the number of dorsal scars were recorded. Each artifact was assigned a typology (Leakey 1971, Kuman 2001, Marks et al. 2014). All flaking debris was classified as a single type, namely shatter. Measurements were not taken on fragmented pieces such as flake fragments (which include the blob of percussion) or incomplete flakes (medial or distal pieces of a flake).

All artifacts were returned to their original position after data collection. A low density of fossilized faunal remains was scattered throughout the sample area. The fossils were highly fragmented and were weathered to a white patination. No clearly identifiable fossils were observed. Fossil remains were flagged for a collective scatter photograph but not collected or assessed.

The Assemblage

The sample assemblage contained 209 total artifacts (Table 1). The majority were produced from quartz (n = 196, 93.7%) while only thirteen artifacts (6.2%) were produced

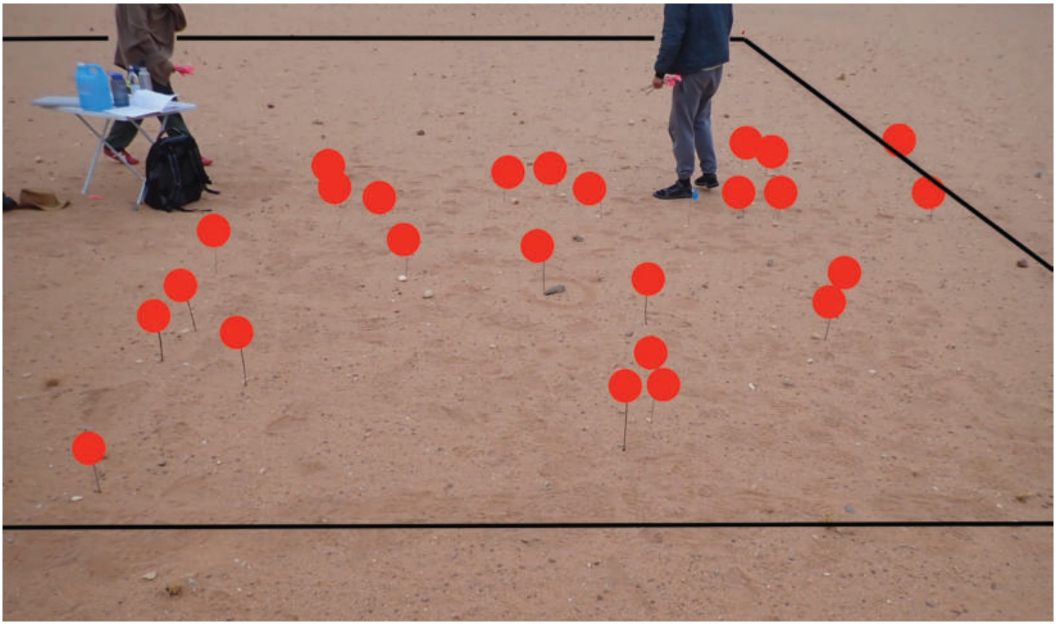

Figure 3: Flagging artifacts within the 10x10 m sample area. The tops of the flags are shown as red dots to enhance them.

from quartzite. The majority of the collection was flaking debris (n = 129, 61.7%) followed by various flake types (n = 58, 27.7%). Cores and formal tools each had eleven artifacts with each category representing 5.2% of the total. The assemblage was fairly well represented in the expected size distribution (Figure 4). The smallest fraction (< 9 mm) was not present, which was likely due to wind erosion that smooths and moves the smallest material, making it almost impossible to distinguish from natural lithic debris.

Flakes

Flakes were produced on quartz and quartzite with the majority on quartz (Table 2; Figure 5; 93%). The most frequent platform types on quartz were single (n = 19) and cortical platforms (n = 20). A fully cortical dorsal surface was the most frequent dorsal face type.

Quartz flakes represented the largest raw material category (average length 3.66 cm, width 2.79 cm, thickness 1.16 cm). The most significant difference between quartz and quartzite flakes was the width (Figure 6). Quartzite flakes comprised a very small sample (n = 4) and were on average much wider than long implying they were side struck. These subtle differences were more likely to reflect dissimilarities in the morphology of quartz vs. quartzite pebbles rather than any real differences in technological strategies in dealing with the two raw materials. This is, however, a question for future examination.

Table 1: Sample assemblage typology totals

	Quartz n (%)	Quartzite n (%)	Total n
Formal Tools			
Handaxe	0 (0)	1 (100)	1
Denticulate	6 (100)	0 (0)	6
Scraper	4 (100)	0 (0)	4
Total	10 (91)	1 (9)	11 (5.2)
Core Types			
Casual Core	6 (85.7)	1 (14.3)	7
Centripetal Core	2 (100)	0 (0)	2
Irregular Core	2 (100)	0 (0)	2
Total	10 (91)	1 (9)	11 (5.2)
Flakes			
Cortical Platform	19 (95)	1 (5)	20
Single face Platform	20 (91)	2 (9)	22
Two+ Faces Platform	3 (75)	1 (25)	4
Indeterminate	12 (100)	0 (0)	12
Total	54 (93)	4 (7)	58 (27.7)
Debris/Incomplete			
Core Fragment	5 (100)	0 (0)	5
Flake Fragment	33 (92)	3 (8)	36
Incomplete Flake	14 (88)	2 (12)	16
Shatter	64 (97)	2 (3)	66
Split Cobble	3 (100)	0 (0)	3
Split Pebble	3 (100)	0 (0)	3
Total	122 (95)	7 (5)	129 (61.7)
Total	**196 (93.7)**	**13 (6.2)**	**209 (100)**

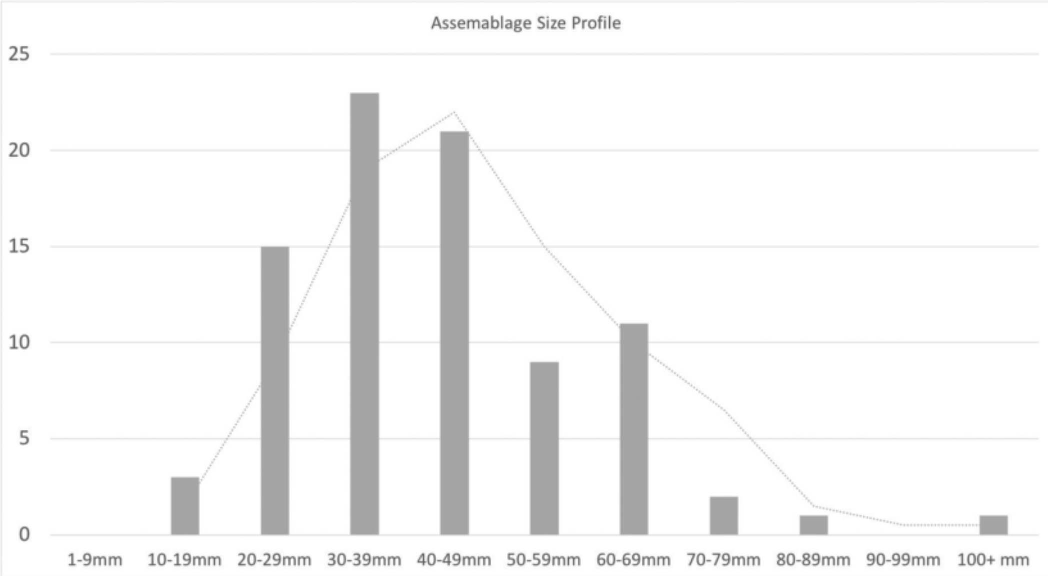

Figure 4: Assemblage size distribution with average trendline

Formal Tools

The only biface that was within the sample area was produced on a quartzite flake measuring 14 x 6.8 x 3.2 cm (Figure 7). Weighting 332 g, it had a total of twelve removals still visible on both faces. This is the only diagnostic of tools from the ESA, however its age cannot be determined.

The only other tool types present were denticulates (n = 6) and scrapers (n = 4). These are produced only on quartz. Denticulates are distinguished from the finer retouch of scrapers by a wider and deeper "notch-like" removal or removals on the flakes edge. These formal tools are more likely to represent an MSA occupation at the site.

Discussion

The northern region of the Namib Sand Sea, specifically south of the !Khuiseb and north of the former Tsondab course, is characterized by large pans on plains between the red, linear aeolian dunes. Some of these pans, like Anibtanab, may hold water during wet years and certainly did so in the distant past, though amount of rainfall needed and the duration of such seasonal ponding are unknown. The pans are also of interest as many of them contain surface scatters of artifacts from the ESA and MSA periods, indicating an ancient hominin association with more extreme parts of the Namib Desert. Almost no archaeological

Table 2: Flake types

Platform Type	**Quartz**	**Quartzite**	**Total n**
Cortical Platform	19 (95)	1 (5)	20
Single face Platform	20 (91)	2 (9)	22
Two+ Faces Platform	3 (75)	1 (25)	4
Indeterminable	12 (100)	0 (0)	12

Dorsal Ridges	**Quartz**	**Quartzite**	**Total n**
Cortical	16 (100)	0 (0)	16
One single ridge	4 (100)	0 (0)	4
Two ridges	11 (92)	1 (8)	12
Three+ ridges	6 (86)	1 (14)	7
Indeterminable	17 (89.5)	2 (10.5)	19

Quartz Flakes Average Sizes

	Max. (cm)	Avg. (cm)	Min. (cm)	S.D.
Length	7.5	3.66	1.1	1.22
Width	5.8	2.79	1.1	1.04
Thickness	3.7	1.16	0.4	0.6

Figure 5: Flakes made on quartz. Some minor edge damage is present and likely due to both natural weathering (i.e. animal trampling). (Scale in cm)

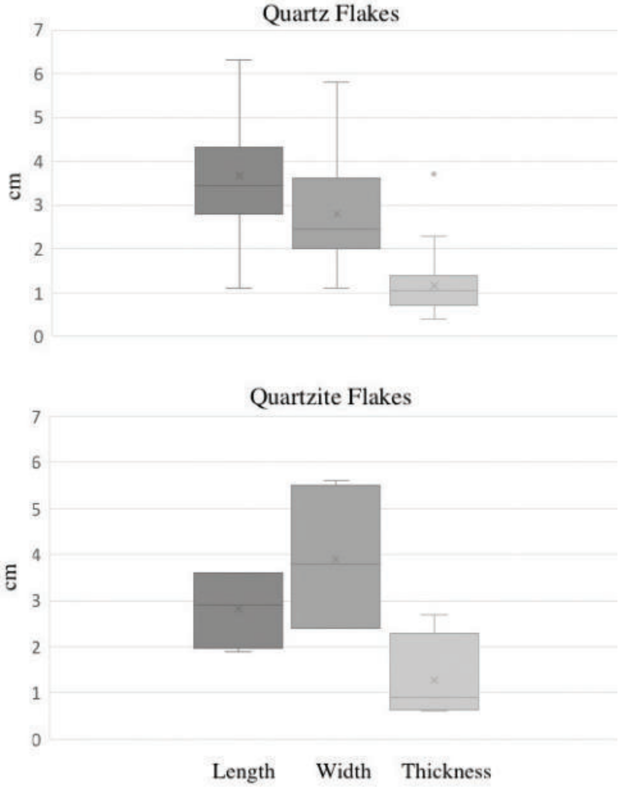

Figure 6: Flake size profiles

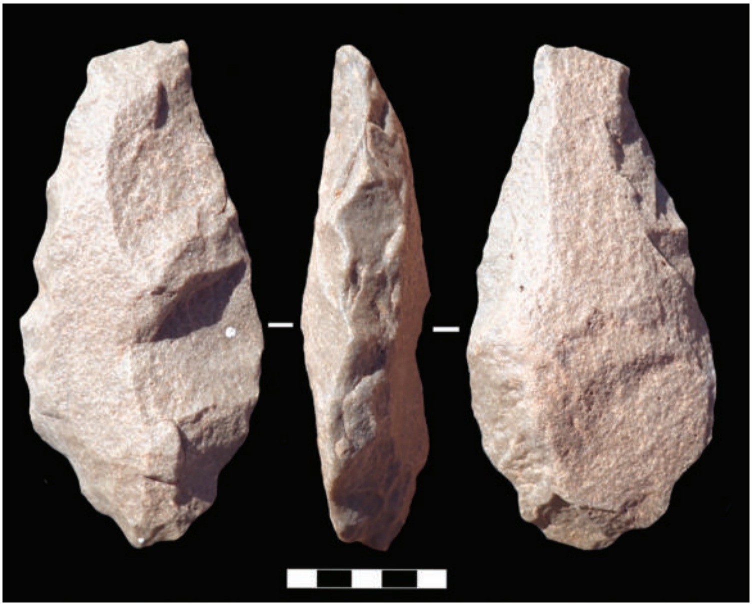

Figure 7: Handaxe produced on quartzite (scale in cm)

research has been conducted on these pan sites since the mid-1980s, largely due to the notion that only limited data can be extracted from surface sites, as well as the general challenges of accessing sites in a remote and demanding desert environment. However, interest in such sites is increasing as better methods and dating techniques continue to evolve (Knight and Stratford 2020). The archaeological record of the Namib Sand Sea may thus continue to yield important clues into human adaptations to this unique environment, as well as to broader questions of human evolution in Southern Africa.

Elsewhere, on the edge of the Namib Sand Sea, other surveys have been conducted. For example, Hardaker conducted extensive surveys of the ESA and MSA surface record along the Sand Sea's eastern margin (Hardaker 2011, Hardaker 2020), while others have recorded ESA along the coastal regions (Corvinus 1983). Though hundreds of lithic scatters were identified, detailed collection descriptions are not provided and the relative dating methods that were used are problematic (Knight & Stratford 2020).

One of the long-term goals of our current archaeological project is to understand hominin occupation within the Namib Sand Sea, particularly its northern part. It is of paramount importance that careful mapping of all the lithic scatters is conducted, whether multiple technologies are present on a single surface or not. A full description of sample surveys from various sites provides a starting point to build such a database.

The Middle Stone Age technology of Anibtanab is most comparable to an archaeological assemblage from the !Nara Valley site (23°33'S, 14°57'E). !Nara Valley is an MSA surface site located on the !Khuiseb 60 km downstream (northwest) of Anibtanab (Shackley 1985). Like Anibtanab, it is situated just south of the river.

The !Nara Valley assemblage resulted from a 100 m^2 sample grid selected in an area of the pan identified as having a dense artifact concentration. The sample area produced 202 stone artifacts including flakes, cores, and tools. The average flake size at !Nara Valley is only slightly larger than the Anibtanab flakes, but it is unclear if this is because Shackley incorporated all the raw material types into that average. Like Anibtanab, the !Nara Valley site is dominated by quartz. Shackley argued that 27% of these are flake types associated with a "Mossel Bay Industry" (Shackley 1985), though there are still many discussions as to what characterizes this industry (Thompson et al. 2010, Wurz 2013). Though an undated surface assemblage and likely visited on multiple occasions, if Shackley's comparison of the assemblage to the "Mossel Bay Industry" is confirmed, that might place the assemblage roughly in the Late Middle Pleistocene and could provide a possible clue to the age of the Anibtanab MSA component.

Similarities in the ecological setting exist between the two sites as well. !Nara Valley is situated along a through-route between dunes likely to be used by game to access the !Khuiseb River (Shackley 1985). The site also allows access to both raw materials, water, and other resources from the !Khuiseb. The same is true of Anibtanab where the site is located between the dunes and the plant and water resources of the !Khuiseb valley in an area extensively utilised by game. Shackley (1985) interprets the limited variation of formal tool types at !Nara Valley to be indicative of specificity of the site's usage, specifically for hunting game moving to and from the river. Together, these similarities may indicate patterns of MSA land use practices, where hominins positioned themselves at the boundaries between the comparatively lush riparian corridors and the dune and gravel plain environments farther afield, to access resources from both ecological zones. This pattern of intensive use of ecotones has been noted at other MSA sites in the wider Central Namib region (Marks 2015, Marks 2018).

Another much smaller surface scatter of comparable technology is Bubuses (23°22'S, 14°52'E), which lies 75 km northwest of Anibtanab and also only a short distance (600 m) south of the !Khuiseb. A long linear dune separates the site from the river. Bubuses' small assemblage consists of only 28 artifacts, mostly on quartz. Irregular core types (n = 3) and chopper cores (n = 6) dominate the core types totaling 32.1% of the artifacts (Shackley 1985). The technology is attributed to the MSA. However, the artifacts exhibit more abrasion (rolling), possibly indicating their association with the Gobabeb Gravels, which may place them closer to the Pleistocene-Holocene transition (Shackley 1985). Though Bubuses demonstrates another MSA locality in the Sand Sea, south of the !Kuiseb with an assemblage of artifacts largely produced on quartz, it is too small of a sample to make further comparison to Anibtanab.

Conclusion

Anibtanab is one of many hundreds (potentially thousands) of archaeological surface sites in the interdune pans of the Namib Sand Sea. Previous archaeological work in the 1970s identified a few of the sites, but further work is needed. These early site descriptions also lack full technological discussions, which complicates cross site comparisons based on those data.

The sample studied from Anibtanab is dominated by quartz flakes that are most likely associated with a Middle Stone Age chronology. The only definitive tool of the Earlier Stone Age found within the sample is a handaxe produced on quartzite. A lone handaxe is not comparable to other ESA sites. However, the quartzite flakes within the sample have a different size profile than the quartz flakes, being much wider than long, which may indicate that they are associated with a different occupation. Paired with evidence of quartzite being more frequently used during the ESA at other sites in the northern part of the Namib Sand Sea sites, they may be of ESA origin.

It therefore can be concluded that Anibtanab is a primarily a Middle Stone Age site, situated close to the modern !Khuiseb River, providing access to riparian resources and water. A smaller and Earlier Stone Age component exists but at low frequency.

There are still a great number of unresolved questions at Anibtanab and similar sites in the Namib Sand Sea. The primary unknowns center around chronology and paleoenvironmental conditions. We still have only a preliminary hypothesis for a mid to late Pleistocene hominin presence at sites in the Namib Sand Sea, during which it is quite likely that periods of human occupation were highly sensitive to fluctuations between wet and dry conditions. Broader environmental and demographic fluctuations outside the Namib Desert may also have influenced differences over time in the spatial distribution of MSA versus ESA sites in the region. It would go a long way towards helping us understand broader questions of the adaptations of early humans in this part of Africa if it was possible to associate patterns of site use, technological practices, and fine-scale environmental variability. As more sites are identified and studied, the data from the Anibtanab assemblage offer a strong starting point for future comparative studies of Namib Sand Sea surface collections, as well as of stratified assemblages.

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References

ANONYMOUS. (1911) Karten von Deutsch-Südwestafrika. Blatt 19. Kuiseb-Unterlauf 1:400000.

CORVINUS, G. (1983) *The Raised Beaches of the West Coast of South West Africa/ Namibia: An Interpretation of their Archaeological and Paleontological Data.* Verlag C.H. Beck. Munich.

FANNING, P.C., HOLDAWAY, S.J., RHODES, E.J., BRYANT, T.G. (2009) The Surface Archaeological Record in Arid Australia: Geomorphic Controls on Preservation, Exposure, and Visibility. *Geoarchaeology: An International Journal,* Vol 24. No. 2. 121–146.

GLIGANIC, L.A., MEYER, M.C., MAY, J-H., ALDENDERFER, M.S., TROPPER, P. (2021) Direct dating of lithic surface artfiacts using luminescence. *Science Advances:* 7. June.

HARDAKER, T. (2011) *New Approaches to the Study of Surface Palaeolithic Artefacts: A pilot project at Zebra River, Western Namibia.* BAR International Series 2270.

HARDAKER, T. (2020) A geological explanation for occupation patterns of ESA and early MSA humans in Southwestern Namibia? An interdisciplinary study. *Proceedings of Geologists' Association* 131: 8–18.

KNIGHT, J. and STRATFORD, D. (2020) Investigating lithic scatters in arid environments: The Early and Middle Stone Age in Namibia. *Proceedings of the Geologists' Association* 131:6.

KUMAN, K. (2001) An Acheulean factory site with prepared core technology near Taung, South Africa. *South African Archaeological Bulletin* 56 (173&174): 8–22.

LEAKEY, M.D. (1971) *Olduvai Gorge: Volume III, Excavations in Beds I and II, 1960–1963.* Cambridge: Cambridge University Press.

MARKS, T., MARAIS, E., SEELY, M., and MCCALL, G. (2014) *Revisiting the Early Stone Age of the Namib Sand Sea: New Research at Namib IV and Mniszechi's Vlei.* Paper presented at the 2014 meetings of the Paleoanthropology Society.

MARKS, T. (2015) Middle and Later Stone Age Land Use Systems In Desert Environments: Insights from the Namibian Surface Record. *South African Archaeological Bulletin:* 70 (202). pp. 180–192.

MARKS, T. (2018) *Bedtime for the Middle Stone Age: land use, strategic foraging, and lithic technology at the end of the Pleistocene in the Namib Desert, Namibia.* Ph.D. Dissertation, University of Iowa. Available online.

SHACKLEY, M. (1985) Palaeolithic Archaeology of the Central Namib Desert. *Cimbebaisa.* Memoir No. 6.

STAPFF, F.M. (1887) Karte des unteren Khuisebtals. Petermanns Geographische Mitteilungen 33, 202–14.

STONE, A.E.C. and THOMAS, D.S.G. (2012) Casting new light on late Quaternary environmental and palaeohydrological change in the Namib Desert: A review of the application of optically stimulated luminescence in the region. Journal of Arid Environments. pp 1–19.

STONE, A.E.C., THOMAS, D.S.G., and VILES, H.A. (2010) Late Quaternary palaeohydrological changes in the northern Namib Sand Sea: New chronologies using OSL dating of interdigitated aeolian and water-lain interdune deposits. Palaeogeography, Palaeoclimatology, Palaeoecology. 288. pp. 35–53.

THOMPSON, E., WILLIAM, H.M., MINICHILLO, T. (2010) Middle and late Pleistocene Middle Stone Age lithic technology from Pinnacle Point 13B (Mossel Bay, Western Cape Province, South Africa) Journal of Human Evolution 59(3-4) pp 358-377.

WURZ, S. (2013) Technological Trend in the Middle Stone Age of South Africa between MIS 7 and MIS 3. *Current Anthropology* Vol. 54. Supplement 8, December.

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New Research at Mirabib Rockshelter

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Abstract

Mirabib Rockshelter, located near the Kuiseb River in the Namib-Naukluft National Park, is one of the best known archaeological sites in the Namib Desert. Previous excavations in the 1970s revealed a complex history of occupation stretching from the early Holocene until the proto-historical period. New research at Mirabib has pushed its chronology back to ca. 18–21 ka BP and revealed new insights into human adaptations in the region. While the site has yielded exceptionally well-preserved evidence going back to the terminal Pleistocene, there is still a great deal of untapped potential for learning more about human life in the Namib in the distant past.

Introduction

Mirabib Rockshelter is a large archaeological site located in the gravel plains of the central Namib Desert in western Namibia. Excavations over the past fifty years at Mirabib have revealed extensive and well-preserved Late Stone Age deposits as well as tentative Middle Stone Age artifacts from the lowermost levels. The site's unique environmental setting, diverse history of occupation, intact strata, and well-preserved organic remains makes it easily one of the most important archaeological sites currently known from this part of Namibia.

Mirabib sits within an expansive granite and schist *inselberg* complex approximately thirty miles east of the Gobabeb Namib Research Institute and ten kilometers north of the Kuiseb River valley (Figure 1). From the perspective of hunter-gatherers, the Mirabib inselbergs are a very advantageous point on the otherwise open, flat landscape, offering

Figure 1: Mirabib Rockshelter in the central Namib Desert

good views of animal movements over a broad expanse of the Central Namib. The rock outcrops themselves are dotted with small hollows and overhangs which offer protection from sun and strong winds. Though the climate today is one of the most arid regions in Africa with around 50mm of precipitation per year, rare but intense rainstorms in the summer can bring centimeters of precipitation in a short period of time. These events can fill small rock hollows in the Mirabib inselberg, providing a relatively reliable source of water that can persist through the dry season. As a result, endemic animals regularly frequent the area. The combination of water, shelter, and nearby food resources at Mirabib makes it an exceptionally attractive spot in the Central Namib for hunter-gatherers, and likely has been so for tens of thousands of years.

In and around the Mirabib inselberg group, more than a dozen small rockshelters bearing evidence of Late Stone Age human activity lying on the surface can be found. The main rockshelter discussed in this article faces southeast on the edge of the largest rock formation in the group (Figure 2). The rockshelter itself consists of a broad gallery eroded out of a softer schist layer in the granite, creating an overhang approximately fifteen meters deep from the opening to the back wall and about twenty-five meters wide. The sheltered area was originally perhaps as much as 100-200 meters longer than it is today, but a section of the roof to the west of the excavated area collapsed at an unknown time likely before the mid-Holocene, leaving the present relatively small shelter area open. There is a strong possibility that archaeological deposits could be well preserved beneath the enormous blocks of roof fall. Though it would be an extremely large undertaking, excavating underneath the fallen roof material is a tantalizing possibility for future research at the site.

In the area of the rockshelter open currently, excavations were originally undertaken in the early 1970s, led by Dr Beatrice Sandelowsky of the State Museum of South West Africa, now the National Museum of Namibia (Sandelowsky 1974, Sandelowsky 1977). Her team excavated a 14 meter^2 trench down to bedrock from the back of the shelter to approximately the front of the overhanging rock. Her excavations identified at least six natural strata dating between 1.5 ka and 8.0 ka BP. In 2013, a joint team from the University of

Figure 2: Mirabib Rockshelter in the northern Namib-Naukluft National Park

Iowa, Tulane University, and the University of Namibia led by Drs. Ted Marks and Grant McCall opened a new 1 by 1 meter test pit slightly to the east of Sandelowsky's excavation (Marks 2018). The more recent excavations confirmed the stratigraphy from the previous excavations, obtained new dates and artifact samples, and demonstrated that the deposits at Mirabib are significantly deeper in certain areas of the rockshelter than Sandelowsky originally proposed. Our team employed Optically Stimulated Luminescence (OSL) dating, a technique that was not available when Sandelowsky's original excavation took place, to the sediments from the lower layers. As a result, the chronology of the site has been extended as far back as 18 to 21 ka BP, with major occupation phases at around 1.5 ka–5.0 ka BP, 5.6–8.3 ka, and 10.3–12.1 ka BP (Figure 3).

The Late Pleistocene

The lowermost stratum (designated as stratum G) at Mirabib is now dated to about 19.6±1.4 ka BP, during the late Pleistocene. The environmental conditions that prevailed roughly 18–21 ka BP in this part of the Namib are complex and not clearly resolved. There were likely rapid transitions between humid conditions and extreme aridity. However, geomorphological evidence from the nearby Kuiseb River suggests what was perhaps, counterintuitively, a more attractive habitat for humans in the Namib compared to today. The aggradation of the Homeb silt deposits in the Kuiseb and other stream systems in western Namibia supported vegetation and fauna in a long "green corridor" through the desert. Filled in with silt to a higher elevation, the riparian corridor was a relatively wider and more productive habitat than the valley is today (Srivastava et al. 2006, Miyamoto 2010).

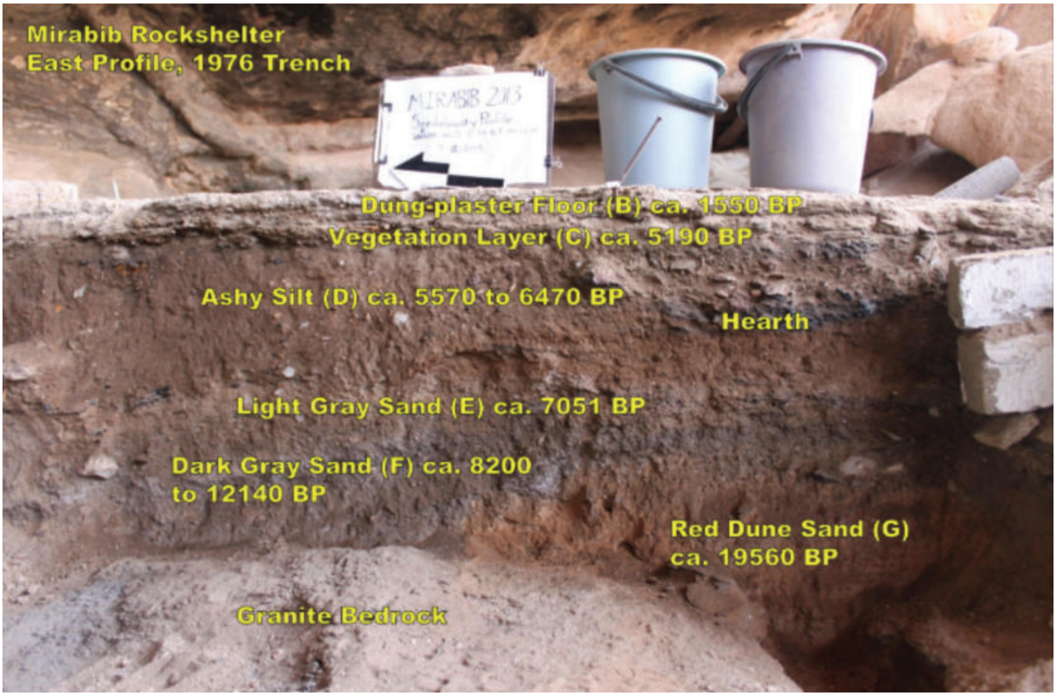

Figure 3: Profile of Sandelowsky's excavation trench reopened in 2013 showing the OSL and radiocarbon ages of the various layers at the site

Pollen from hyrax middens in the same region as Mirabib suggests the vegetation in this period of the late Pleistocene was considerably different than today, with more shrub and woodland pollen compared to the grass that has dominated from the early Holocene to the present. There is also palynological evidence of ferns growing in the region that probably indicate periods of relatively cool and humid conditions (Scott et al. 2004). The sediment matrix of stratum G at Mirabib is made up mostly of red aeolian sand distinct in terms of texture and color from all other layers.The origins and depositional processes of the sand layer are unclear. One possibility is that the sand accumulated as a result of declining vegetation on the landscape immediately surrounding the site that allowed sand to be mobilized by wind. Alternatively, changes in wind regimes could have transported sand from the dune fields of the Namib Sand Sea 20 km to the south of Mirabib. This question requires further investigation: a combination of two or more processes is also possible.

The artifacts from layer G from ca. 18–21 ka BP consist almost entirely of somewhat crude "macrolithic" flakes and debitage. Retouched tools make up less than 3% of the assemblage, with cores making up less than 3% of the assemblage as well (Figure 4, Table 1). At this time period, around 84% of the artifacts were manufactured using clear, glasslike, and very high quality crystal quartz, while much coarser milky vein quartz makes up about 16% of the sample. Both of these raw materials can be found in abundance around

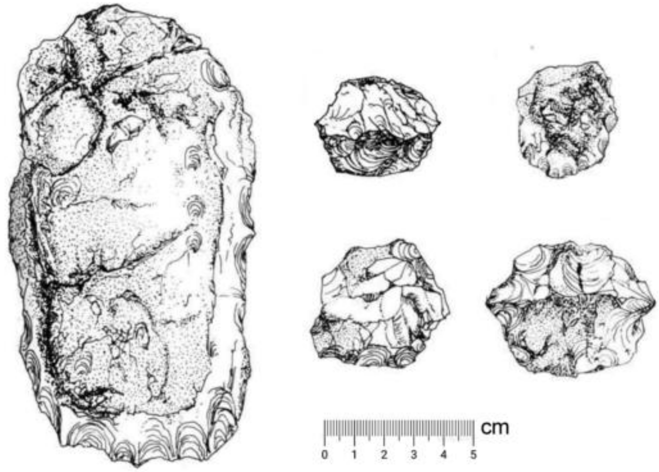

Figure 4: Typical lithics from the late Pleistocene lower levels at Mirabib. Left: scraper. Center/Right: scrapers/discoid cores. Drawings adapted after Sandelowsky (1977)

Mirabib in the form of small pebbles and larger chunks and exposures of hydrothermal quartz veins. Notably, the proportion of milky vein quartz in the lithic assemblage is substantially higher in the late Pleistocene layer than in any other overlying stratum. Knapping techniques were superficially rather crude, with unsystematic multidirectional striking patterns used in order to produce simple 5 to 10 cm flakes from the quartz cores. That said, under virtually any knapping strategy, the proportion of unsystematic multidirectional cores tends to increase in assemblages as the raw material is used to exhaustion. This may point to relatively intensive exploitation of individual pieces of raw material before they were discarded, as well as broader factors related to stone raw material economics that are beyond the scope of this paper (e.g. Andrefsky & Andrefsky 1998).

In comparison to other sites in the region like Erb Tanks Rockshelter (Mccall et al. 2011, Marks 2018) or Apollo 11 (Wendt 1976, Vogelsang et al. 2010), the late Pleistocene

Table 1: Counts of lithic artifacts from the 2013 1x1 meter test pit at Mirabib Rockshelter. Flakes include complete and fragmentary pieces. Cores include unidirectional, multidirectional, centripetal, bipolar, and microblade types. Tools include all retouched and/or utilized pieces.

Stratum	Flakes	Cores	Tools	Grand Total
B	172	4	31	207
C	264	9	3	276
D	4723	163	92	4978
E	1169	39	23	1231
F	1762	62	73	1897
G	202	6	6	214
Grand Total	**8292**	**283**	**228**	**8803**

assemblages recovered from the stratified deposits at Mirabib are sparse and difficult to interpret. No artifacts indicative of specific Middle or Late Stone Age industries such as the Howieson's Poort, Robberg, or Oakhurst industries have been recovered so far from the site. Nevertheless, what has been found indicates at least a limited human occupation of the region and use of the rockshelter by at least 18–21 ka BP. I have previously hypothesized, based on an extensive raw material sourcing study, that during this time populations may have more heavily focused their foraging and mobility patterns into the river valleys themselves as well as in the upland regions to the east of Mirabib. As discussed above, this would be the result of the improved productivity and resource availability of the river valleys around the time of the aggradation of the Homeb silts (Marks 2018). The sparse and low-density late Pleistocene record at Mirabib might therefore be explained by relatively brief and infrequent uses of the site by hunter-gatherers moving around the region. Mirabib at this time may have been located at the edge of groups' annual ranges that tended to be more centered on the riparian corridors and upland regions.

Just outside the rockshelter 100 m to the southeast, there is a large surface accumulation of diagnostically Middle Stone Age tools and flakes. This accumulation has been designated WH-1. As a surface site, the age of WH-1 is not known and it is also unclear whether these artifacts represent a lag deposit or have eroded out of many small rills from a stratified subsurface deposit. Nevertheless WH-1 tentatively suggests that a Middle Stone Age human presence in the area around Mirabib may have been more extensive than is suggested by what has been found in the rockshelter alone. Further investigation of this question is necessary.

The Early to Middle Holocene

In contrast to the late Pleistocene layers, the early to middle Holocene layers (designated strata F, E, and D) at Mirabib dated 5.6 to 12.1 ka BP have produced a dense and diverse assemblage of artifacts that probably signals a very different pattern of intensive residential use of the rockshelter. The total mass of all artifact types rises dramatically in these layers (Table 2) compared to both the underlying and overlying strata. In the series of excavations conducted at the site, well-preserved organic artifacts and debris were recovered along with thousands of lithic flakes, cores, and tools. In the 1x1 m 2013 test pit alone, more than 8000 lithic artifacts, about three kilograms of ostrich eggshell fragments, and more than three hundred grams of tiny bone fragments from small to large sized mammals and birds were found in the early to middle Holocene layers. Seeds from the !nara melon (*Acanthosicyos horridus*) are common in all layers after about 8 ka BP, with isolated examples from as far back as 10–12 ka BP, indicating use of this endemic plant by this early time period. Today !nara plants are semi-domesticated and closely managed as a staple food and source of oil for the Topnaar communities living in the region currently. The presence of !nara at such an early date and its persistence in the record through

Table 2: Total mass of major artifact types from the 2013 1x1 meter test pit at Mirabib Rockshelter. All masses are given in grams.

Stratum	Lithics	Ostrich Eggshell	!Nara Seeds	Fire Cracked Rock	Bone Fragments	Ochre	Total Mass
B	74.5	28.5	1.5	0	19.1	0	**123.6**
C	152.4	51.2	0.3	1.8	9.4	0	**215.1**
D	4669.6	2936.9	2.6	204.7	231.6	0	**8045.4**
E	468.4	77.1	<1	0	50.3	29.2	**625.0**
F	327.2	19.1	<1	2.1	27.6	10.7	**386.7**
G	112.9	0	0	0	18.3	0.1	**131.3**
Grand Total	**5805**	**3112.8**	**4.4**	**208.6**	**356.3**	**40**	**9527.1**

climatic fluctuations in the Holocene suggests a long and complex history of exploitation of this plant which remains poorly understood.

The lithic assemblages in the early to middle Holocene layers at Mirabib are of the typical Wilton type seen across Southern Africa. Tools, as is typical in Wilton assemblages, make up only about 2.3% of the total number of lithic artifacts (Table 1). They consist of backed crescentic microliths, microblades, thumbnail scrapers, drills, and utilized flakes (Figure 5). Cores were struck multidirectionally, bidirectionally, and centripetally, with carefully prepared platforms and ridges set up to produce small bladelets. They are also very tiny, ranging only about 1 to 5 cm in diameter. There are many examples of lithics with heavy coatings of red and yellow ochre. Between 92 and 95% of all of the lithic artifacts in the early to middle Holocene layers are made on very clear and homogenous "crystal" quartz. Pebbles of this material are found in abundance in the immediate vicinity of Mirabib and it is likely that this high-quality stone was an attractive resource exploited by hunter-gatherers in the area. The presence of small amounts of other high-quality lithic raw materials like silcrete, gray chert, and red agate (0.2 to 2% of the total assemblage)

Figure 5: Typical lithic artifacts from the early to late Holocene layers at Mirabib. Top row: crescentic microliths. Bottom row: microblade cores. Drawings adapted after Sandelowsky (1977)

indicate movement and/or trade with more distant regions close to the coast and further to the north (see Marks 2018).

Together with the other non-lithic material from the early to middle Holocene layers, these data suggest that the people who inhabited the area around Mirabib at this time were taking advantage of a wide range of plant and animal resources and were likely using the rockshelter as a primary residential base. Likely climatic conditions at this time were an overall drying trend through the Holocene and a transition to hyper arid conditions similar to today, but punctuated with millennial-scale periods of relatively increased humidity (Chase et al. 2009). Flash floods during dry periods began to erode away the silt deposits in the Kuiseb river (Srivastava et al. 2006), making the long vegetation corridor of the Kuiseb a less attractive and more discontinuous habitat for human groups. At this time across Southern Africa, it is thought that hunter gatherers were probably maintaining more long-term residential base camps at specific points on the landscape where access to water and shelter was more reliable. This is opposed to the typically more mobile pattern of the later Pleistocene wherein people made smaller camps and made frequent moves, but mostly only within relatively restricted landscape zones. This shift to a "hyper-residential" land and site use pattern with a greater degree of logistical foraging (i.e. transporting food and resources back to semi-permanent camps) is typical for many early Holocene sites across Southern Africa. While it is unclear what drove this shift, it does appear to be the context from which the early pastoral communities in this region eventually arose.

The Middle to Later Holocene

The uppermost mid to late Holocene strata, layers C and B, were dated by radiocarbon to ca. 1.5 to 5.2 ka BP. There is a distinct stratigraphic break between layers D and C, transitioning sharply from fine ashy gray sediments in layer D to layer C whose matrix is made up of at least 50% grass and plant material mixed with fine brown silt. In the overlying layer B at or near the modern surface, nearly the entire rockshelter floor is covered by layers of a smooth, hard pavement of dung with intervening layers made up mostly of grass fibers. There are at least two distinct pavements laid on top of each other separated by "subfloor" layers of dry grass. In the pavements, Sandelowsky's analysis tentatively identified sheep hair, suggesting that pastoral communities and likely domesticated stock animals were present in this part of the Namib by at least 1.5 ka BP and possibly earlier. The question of the identification of the sheep hair requires revisiting by a specialist, but if correct it would place Mirabib among other well-known sites suggesting early animal domestication and pastoralism in the wider Namib region, including Leopard Cave, Big Elephant Shelter, and Geduld Rockshelter (Pleurdeau et al. 2012, Wadley 2012, Smith & Jacobson 1995). By this time, the climate had started to steadily deteriorate to dry conditions. This may have impacted the shift in humans' adaptations toward the pastoral economies that have dominated the region ever since, though the process was obviously complex and a great number of ecological and social factors likely played a role (e.g. Kinahan 1986, Kinahan 1989).

It is still unknown whether the dung pavement layers were deliberately laid down by people as a firm and impermeable living surface or whether it perhaps simply accumulated from animals that were being corralled in the rockshelter. The smoothness and layering of the pavements suggests the former interpretation. In either case, the impermeable pavement has served as an excellent seal on the underlying strata that has prevented water, plant roots, and fossorial animals from disturbing the archaeological deposits below. In addition to its preservative function, the dung and grass layers themselves have yielded a truly unique assemblage of late Holocene artifacts (Sandelowsky 1977). These include, among others, a variety of leather pieces, grass cordage, ochre-encrusted human hair, copper beads, stone pendants, and gourd rattles. Bone artifacts include points, beads, and arrow linkshafts, many of them coated in red and yellow ochre. Fragmentary faunal remains, including parts of hoofs and horns from medium and large ungulates were recovered as in the underlying layers. Worked wooden artifacts are particularly well preserved and include beads and weapon hafts with their original cordage wrappings intact. Seeds from the !nara melon are again also very common, continuing the evidence of heavy exploitation of this endemic plant for food. Pottery is present in these layers but rare, and made up only of small fragments of low-fired and coarse sand-tempered fragments from clay probably sourced from the Kuiseb River. Stone artifacts in the late Holocene layers are likewise characteristic of the Wilton microlithic industry as seen in the early to middle Holocene layers. This includes large numbers of backed crescentic bladelets, multidirectional and bipolar microcores, and thumbnail scrapers dominating the tool assemblage. There are likewise large quantities of flaking debris, although in lower density than in underlying layers. As in the early to middle Holocene, fine crystal quartz makes up the overwhelming majority of the raw material, with very small quantities of silcrete, gray chert, and agate. Strong similarities across various aspects of the lithic technology at Mirabib indicates its persistence through thousands of years, multiple climatic fluctuations, and the shift towards pastoral economies in the region.

Conclusions

In summary, Mirabib represents one of the most important archaeological records presently known from the Central Namib gravel plains region. At Mirabib, we see evidence for human adaptations shifting between strategies focused on hunting and gathering in rich riparian corridors, to more dispersed and intensive occupation of the open gravel plains, and finally towards pastoralism. Nevertheless, this area of Southern Africa has been sparsely researched over the recent decades, and a great deal more work needs to be done. This includes further excavation of the large unexplored area of the site and high resolution dating to better link occupational events and regional climate conditions. The unique environmental conditions presented significant challenges to human life in the region over the past 20,000 years, but the superb preservation and high resolution record at Mirabib offers archaeologists an excellent test case for evaluating hypotheses about human adaptive flexibility in the late Pleistocene and Holocene.

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References

ANDREFSKY, W., & ANDREFSKY JR, W. 1998. *Lithics.* Cambridge University Press.

CHASE, B.M., MEADOWS, M.E., SCOTT, L., THOMAS, D.S.G., MARAIS, E., SEALY, J., & REIMER, P.J. 2009. A record of rapid Holocene climate change preserved in hyrax middens from southwestern Africa. *Geology,* 37(8), 703–706.

KINAHAN, J. 1986. The archaeological structure of pastoral production in the central Namib Desert. Goodwin Series, 69–82.

KINAHAN, J. 1989. *Pastoral nomads of the central Namib Desert.* Doctoral dissertation, University of the Witwatersrand.

MARKS, T.P. 2018. *Bedtime for the Middle Stone Age: land use, strategic foraging, and lithic technology at the end of the Pleistocene in the Namib Desert, Namibia*. Doctoral dissertation, University of Iowa.

MIYAMOTO, S. 2010. Late Pleistocene Sedimentary Environment of the “Homeb Silts” Deposits, along the Middle Kuiseb River in the Namib Desert, Namibia. *African study monographs,* 40, 51–66.

PLEURDEAU, D., IMALWA, E., DÉTROIT, F., LESUR, J., VELDMAN, A., BAHAIN, J.J., & MARAIS, E. 2012. “Of sheep and men”: earliest direct evidence of caprine domestication in southern Africa at Leopard Cave (Erongo, Namibia). *PloS one,* 7(7), e40340.

SANDELOWSKY, B.H. 1974. Archaeological investigations at Mirabib Hill rock shelter. *Goodwin Series,* 2, 65–72.

SANDELOWSKY, B.H. 1977. Mirabib-an archaeological study in the Namib. *Madoqua,* 10(4), 221–253.

SCOTT, L., MARAIS, E., & BROOK, G.A. 2004. Fossil hyrax dung and evidence of Late Pleistocene and Holocene vegetation types in the Namib Desert. *Journal of Quaternary Science,* 19(8), 829–832.

SRIVASTAVA, P., BROOK, G.A., MARAIS, E., MORTHEKAI, P., & SINGHVI, A.K. 2006. Depositional environment and OSL chronology of the Homeb silt deposits, Kuiseb River, Namibia. *Quaternary Research,* 65(3), 478–491.

VOGELSANG, R., RICHTER, J., JACOBS, Z., EICHHORN, B., LINSEELE, V., & ROBERTS, R.G. 2010. New excavations of Middle Stone Age deposits at Apollo 11 Rockshelter, Namibia: stratigraphy, archaeology, chronology and past environments. *Journal of African Archaeology,* 8(2), 185–218.

WADLEY, L. 2012. Revisiting later stone age collections from big elephant shelter, Namibia. *South African Archaeological Bulletin,* 67(195), 101.

WENDT, W. E. 1976. 'Art Mobilier' from the Apollo 11 Cave, South West Africa: Africa's Oldest Dated Works of Art. *The South African Archaeological Bulletin,* 5–11.

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Dr Ted Marks is an American archaeologist who has conducted research in the Namib Desert since 2008. He earned his Ph.D. in 2018, with his dissertation focused on examining Late Pleistocene and Early Holocene human land use patterns through sourcing of lithic artifacts from two sites in the Central Namib, Erb Tanks and Mirabib Rockshelter. He is currently involved in a project working to establish chronologies and understand technological organization at Early and Middle Stone Age sites in the Namib Sand Sea. He lives in New Orleans with his wife and two children.

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!Nara Harvesters of the Northern Namib: a Cultural History through Three Photographed Encounters

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Key words: northern Namib, on-site oral history, cultural landscapes, Indigenous histories, Khoekhoegowab, *!nara* (*Acanthosicyos horridus*), Skeleton Coast National Park, Namibia.

Abstracts

English

We report on Indigenous cultural heritage and histories associated with the northern Namib desert, designated since 1971 as the Skeleton Coast National Park. Review of historical documents and oral histories from elderly people with direct and familial memories of accessing and living in the northern Namib show how places and resources were used here by Khoekhoegowab-speaking peoples in the past. A focus of this use was the availability of valued foods, especially melons of the *!nara* (*Acanthosicyos horridus*). Three photographed encounters provide focus for a narrative connecting memories about the northern Namib that stretch back to the first European colonial journeys into this remote area of north-west Namibia. In 'repeopling' the northern Namib, we aim to also 'rehumanise' documented colonial encounters that objectified and diminished the peoples who knew, accessed and dwelled in this now protected area.

Khoekhoegowab

Nēba ta ge !hūǁî khoen di !hao!nabe ǁnaedigu tsî ǀuǀarus ǀawasǀkhab Namib ǀGowas dib hîna ge 1971 ǁî gurib !nâ !ûihesa !khaib ase ǂanheb xara !nuri. ǀUǀarusi xoa-ain tsî kai khoen hîna ǀaokhoesi !gaeǁarede Namib !nâ ge ǁgan hâ-î khoen ǀkha ge uhâ in di ǁgaeǂhoân ge ra ǁgau Khoekhoegowaba ra !hoa khoen ge ǀawas Namib disa !haru ge ǁaeb !nâ ge re sîsen u !khaisa. Nē sîsen-us ge lo-aisase !garob ǂûn, !gosasa *!naran* (*Acanthosicyos horridus*) di hâs tsî hohes ai ge !gao!gaosa i. !Nona !hoǁnahege a ai-isigu ge ra ǁapoǁapo tsî ra ǀhaoǀhao ǁnâ ǂâihodi tamas gara io mûnanaidi ǀawas Namib disa !oa hâde hîna ǂguro !urikhoen Europapa xu hân gere nē kaise a !nū ǀawas-hurib ǀkhab Namibiab dis !na !narima ǁaeba !oa. Sida di ditsâs khoena ǀawas Namib dis ǀkha !gaeǁares !nâ da ge ra si!nâ ǂgao, nē lkharib xa a xoasa ǀuǀarus !urikhoenxas hîna ǁnāba ge hâ tsî ǁnabara hohe huisen-uxuna gere sîsen u khoena xoaǁauǁau tsî ǂkhari!gôasa di unusa.

This article is dedicated to the late Michael |Amigu Ganaseb, who shared his memories of the northern Namib with us. |Amigu passed away on 30 April 2022.

Portrait of Michael |Amigu Ganaseb, by Oliver Halsey, Sesfontein/!Nani|aus, 25 May 2019

"The !Narenin people are the people of Sarusas and down there in Hoanib, but the ǁUbun people are the people who are coming from Walvis Bay. Now along the ocean there are the huts of the ǁUbun people they built with ribs of the whale. So the !Narenin are this side—Purros side. … The ǁUbun, they move from the !Uniab to the Hoanib, and the !Narenin are also moving from Sarusas [north of the Hoarusib] where they are, to the Hoanib."
(Christophine Daumû Tauros and Michael |Amigu Ganaseb (ǂNū!arus), 7 April 2014)

Introduction

The quote above is from a recorded conversation about the diversity of Khoekhoegowab-speaking peoples now concentrated in the Sesfontein area of north-west Namibia, who were once associated with the northern Namib, and with *!nara* melons from the near-endemic cucurbit *Acanthosicyos horridus* Welw. ex Hook.f. Their histories have tended to be overlooked in the better known links between *!nara* and the peoples of the !Khuiseb further south (Budack 1977; Henschel et al. 2004). Perceptions of the northern Namib as an uninhabited and desolate place, consolidated now by restrictions on access afforded by its protected status as the Skeleton Coast National Park (SCNP), also works against awareness of its use and habitation up to the recent past. The many archaeological sites found in the SCNP, however, reveal that the northern Namib desert was important to people in the past (J. Kinahan and J.H.A. Kinahan 1984; Blümel *et al.* 2009; Vogelsang and Eichhorn 2011). Rather than being historically unpopulated, the landscape has instead been emptied of human presence through historical processes and events.

The paper draws on oral history, heritage mapping and ethnographic research to clarify the meanings of our opening quote, which speaks of diverse groupings of Khoekhoegowab-speaking peoples moving through and utilising areas of north-west Namibia now uninhabited by local people. Such peoples have often been portrayed in almost mythical terms as 'strandlopers' seen emerging through the Namib fog by various European travellers along Namibia's Atlantic Coast. For example:

> "[s]hips travelling to India in the sixteenth century via the Cape were so fearful of the coastline that they travelled 250 miles offshore to avoid its hidden rocks and treacherous currents. The Dutch, the master navigators of their age, dared to come closer, as they headed to their empire in the East Indies. Their sailors reported that, when peering through the fog, they could on occasion spot black figures on the shores staring back at their ships. The Dutch called these unknown people *strandloopers*—beach runners. From the fifteenth to the end of the eighteenth century this was the limit of human contact between the peoples of south-western Africa and Europe"
> (Olusoga and Erichsen, 2010:18)[1].

To distil a much larger story (see Sullivan 2021), we use three photographed encounters—from the late 1800s, the mid-20th century and the present—to open up complex cultural histories that 'repeople' the northern Namib, and 'rehumanise' otherwise objectified accounts of their presence.

[1] Following the sixteenth century there was in fact rather more interaction between the coastal peoples of Namibia and explorers and traders from afar than indicated in this quote.

Methods and Sources

The material shared below comes from three main threads of research:

1. Iterative review of historical literatures and archive sources regarding *!nara* harvesting and harvesting peoples connected with Namibian coastal areas, collated in the following timelines:
   - *Archaeological and historical records that mention* !nara *use in Namibia,* linked at https://www.futurepasts.net/nara-in-archaeology-and-history, plus map of references to *!nara* use, online at https://www.futurepasts.net/archaeological-historical-nara-refs;
   - *Historical references to habitation of the !Khuiseb delta,* linked at https://www.futurepasts.net/khuiseb-historical-habitation.
2. Oral histories and interviews with primarily Khoekhoegowab-speaking individuals now living in the Sesfontein area, carried out intermittently since initial fieldwork was undertaken in 1992 on plant-use in Kowareb settlement on the Hoanib River (Sullivan 1998).
3. On-site oral histories and heritage mapping journeys with elderly individuals who remember living in, moving through, and harvesting from a wide area of north-west Namibia connecting the Palmwag Concession, Sesfontein, Anabeb and Purros Conservancies, and adjacent areas of the northern Namib (Sullivan and Ganuses 2021). Journeys within the SCNP were undertaken as part of a project led by Dr Gillian Maggs-Kölling, Gobabeb Namib Research Institute, on *The significance of the Namib Desert endemic* !nara *(*Acanthosicyos horridus*) as a keystone species in ecology, phenology, culture and horticultural potential.*

All interviews from field research were carried out by both authors. Interview transcriptions in Khoekhoegowab and translations from Khoekhoegowab to English were led by Ganuses. We worked on interpretations of this material together, as well as iteratively with our local research collaborators. Sullivan carried out the literature review and drafting of this article, with Ganuses checking the work. All field research journeys were guided by Mr Filemon |Nuab, a 'Rhino Ranger' based in Sesfontein whose knowledge of the north-west Namibian landscape is renowned. Field research benefitted from oversight by the Nami-Daman Traditional Authority and the Sesfontein Conservancy.

Findings: A History of *!Nara* Use in the Northern Namib, Through Three Photographed Encounters

As mentioned above and shown in Figure 1, *!nara* is not restricted to the !Khuiseb valley where its use and cultural significance are well documented. Given its utility as a significant—even staple—food source in a challenging environment, it is unsurprising to find that archaeological and historical literatures report the use of *!nara* in the Namib desert south and north of the !Khuiseb River, as shown in Figure 2.

A map published in 1852 of the cartographic work undertaken by British explorer Francis Galton during his travels in 1850–51, clearly positions a grouping of people denoted as 'Nareneen' to the west of 'Kaoko' mountains west of Outjo and Etosha (Galton 1852)—see Figure 3. This ethnonym is suggestive of *!nara*-harvesting '!Narenin-Dama/ ǂNūkhoen', as mentioned in the quote that opens in this paper:

> "[t]he !Narenin people are the people of Sarusas and down there in Hoanib …"

Also,

> "[t]he !Narenin were staying to the north of the Hoanib, and the ǁUbun people were staying in !Uniab in the south. And they knew that when the *!naras* get ripe then we come together—!Narenin and ǁUbun—and we collect together." (Franz |Haen ǁHoëb, (ǂŌs, near Sesfontein), 6 April 2014)

This presence of *!nara* harvesters in the northern Namib is elaborated further through three photographed historical and contemporary encounters.

1 'Seebuschmänner', Hoanib and Hoarusib Rivers, 1895–96

In the midst of broader colonial carving up of the territory as sources of exploitable resources, a large area of the north-west, including the northern Namib, was claimed for the Kaoko Land and Mining Company (Kaoko-Land- und Minen-Gesellschaft—KLMG). The KLMG was represented in Deutsch-Südwestafrika by German geographer and surveyor Georg Hartmann[2] in strategic alliance with the German colonial governor Leutwein (Rizzo 2012: 63-64). It was in service to the KLMG that the first systematic surveys of the northern Namib—in 1894 and 1895–96—were financed and attempted.

The second of these surveys includes a startling photograph—see Figure 4. It is labelled as of a 'Group of sea-bushmen ["Seebuschmänner", named "Hottentotten"[3] in Hartmann (1902/03: 413)] at Hoanib mouth; captain with a woman in the foreground' (Hartmann 1897: 129[4]). This image conveys a group of people whose body language in facing up to

[2] It is this Hartmann that both the 'Hartmann's Valley' in Kaokoveld, and the Hartmann's mountain zebra (*Equus zebra hartmannae*) of north-west Namibia and south-west Angola are named after.

[3] This term is today considered derogatory (Elphick 1977: xv). No offence is meant by its occasional inclusion when quoting directly from historical texts, in which the term denotes a specific ethnic and cultural identity for Khoekhoegowab-speaking peoples, usually pastoralists known today as Nama or Khoe/Khoikhoi. It is included in this text *only* when quoting directly from historical material, with the intention of drawing into focus the past presence of Khoekhoegowab-speaking peoples who are often marginalised in work concerning north-west Namibia.

[4] All German to English translations by Sullivan with the help of the DeepL Translator app.

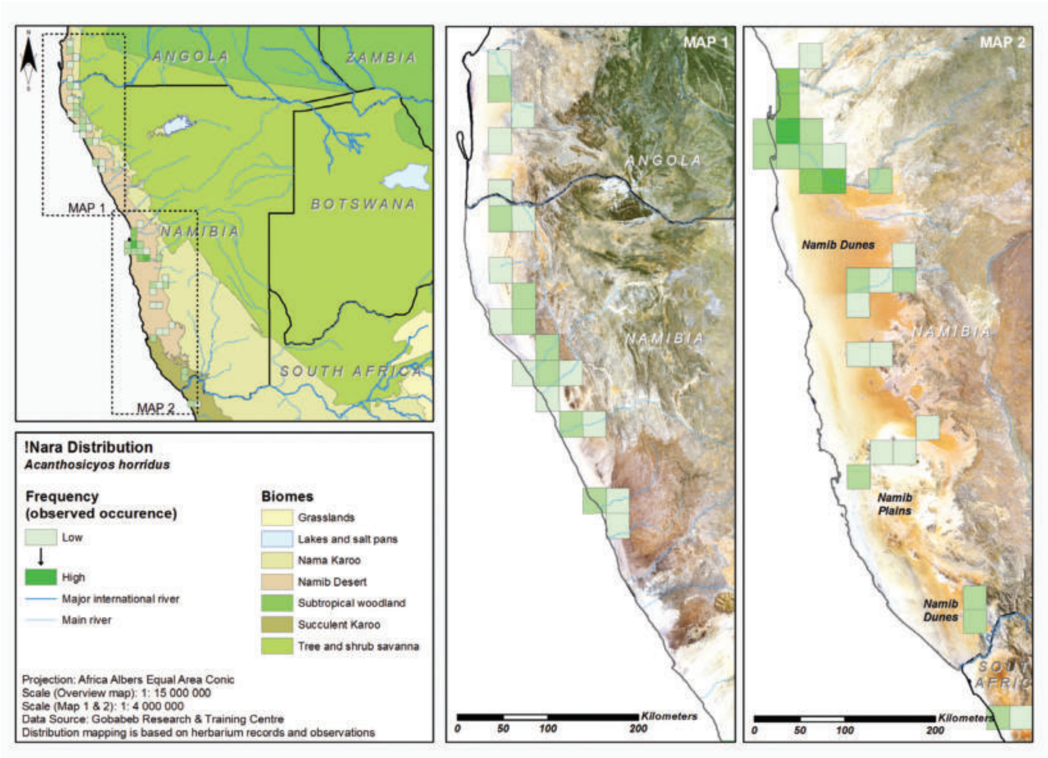

Figure 1: Distribution of Acanthosicyos horridus *Welw. ex Hook.f. or* '!nara' *in south-western Africa. Source: Created by Sylvia Thompson of the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL - http://www.sasscal.org), based on data provided by Dr Gillian Maggs-Kölling and used with permission.*

Hartmann's photographer appears proud and defiant. Their attire is a combination of what look like springbok and seal skins, as well as a hat worn by their 'captain' that seems to be of European design. Knives used perhaps for scooping out *!nara* melon flesh, amongst other things, are worn around their necks. Hartmann's text speaks of this group of photographed people as a 'decimated tribe', described in rather derogatory and objectifying terms as 'the apparently bastardized Hottentot or crossbreeds between Hottentotten and Berg-Damara', living 'at the mouths of the |Uni!ab-river [!Uniab] up to the Hoarusib and sleep[ing] where in the dunes the ǂNaras [*!naras*] fruit is to be found' (Hartmann 1897: 138).[5] In a second image (Figure 5), 'Seebuschmänner' huts assumed to be abandoned are photographed at 'Rietgrasfontein' close to the mouth of the Hoarusib (Hartmann 1897: 127). It is tempting

[5] Bollig and Heinemann-Bollig (2005: 271-272) reproduce an image of only the man and woman at the forefront of the photograph, but omit additional qualifying information.

Figure 2: Archaeological and historical records of !nara *use. Placemarks from north and south of the !Khuiseb are: 1. Sechomib River 1988 (Jacobsohn 1995: 117–118); 2. Sesfontein 1953 (Knobel in Dart 1955: 175); 3. Sesfontein 1977 (Dentlinger 1977: 28; du Pisani 1983: 5); 4. !Uniab mouth, 1896 (Von Estorff in Jacobson and Noli 1987: 174); 5. Brandberg West, early 1950s (Haythornthwaite 1956: 101); 6. Natas Mine, 1850s (Kinahan and Vogel 1982: 45); 7. 'Mount Murray' near 'Ababis' on 'Chuntop-Rivier' (i.e. Tsondab-River), 1837 (Alexander 2006[1838] vol. 2, pp. 18–19); 8. Sossusvlei, 1909 (Gondwana Collection Namibia 2011: 30–31); 9. Awasib-Gorrasis Basin, ca. 700BP (J. Kinahan and J.H.A. Kinahan 2006); 10. Angra Pequeña, 1829 (Morrell 2014[1832]: 315); 11. Skorpion Cave, 1340±60BP & 180±15BP (J. Kinahan and J.H.A. Kinahan 2003); Rosh Pinar shelter, 5,000BP (Sievers 1984: 36–37)*

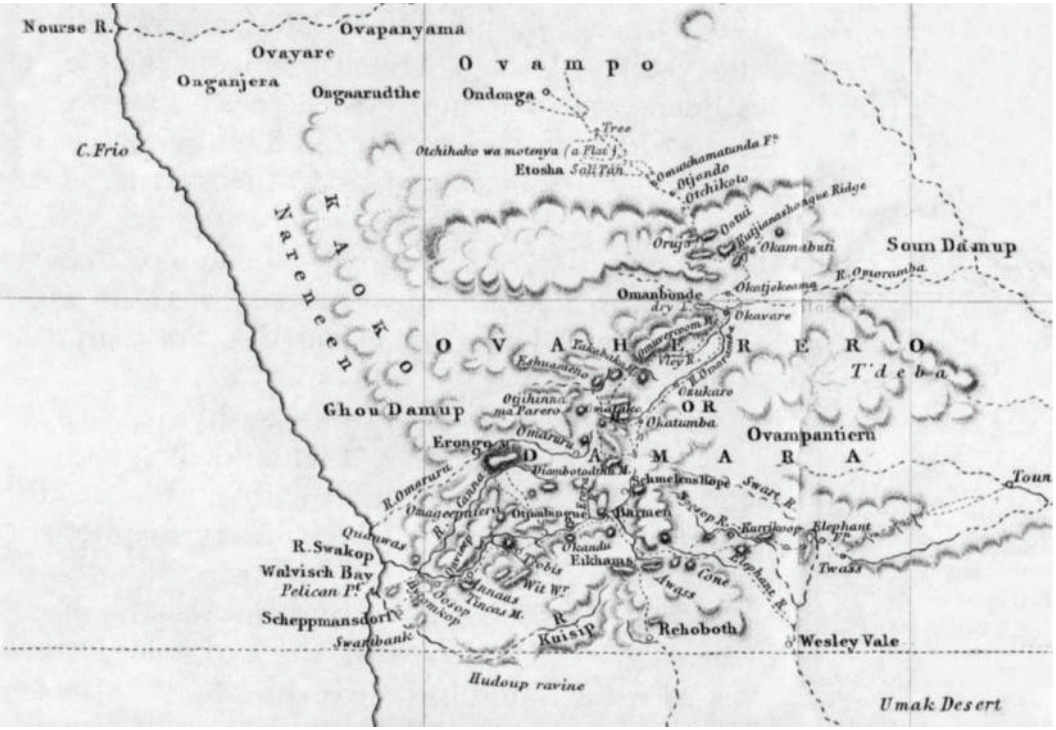

Figure 3: Detail from Francis Galton's map of Africa between 10 and 30 degrees South latitude, positioning 'Nareneen' west of 'Kaoko' mountains. Source: Galton 1852: 141 (out of copyright)

to wonder if perhaps the inhabitants of these shelters had absented themselves so as to avoid Hartmann's expedition.

Several additional observations from this period report people using, moving through and inhabiting the northern Namib. As part of Hartmann's 1895–96 expedition, Schutztruppe officer Ludwig von Estorff observed 'deserted, circular reed huts at the Uniab River mouth', and on return a month later finds here 'a band of 30 "Bushmen" who had just arrived from the Hoanib River' and who 'were living off narra for the most part', with one 'narra knife' reportedly 'made from elephant rib at the Hoarusib River' (Jacobson and Noli 1987: 174 and references therein). Ten years later, on a 1906 expedition to seek northern deposits of guano, George Elers built a road north of the Koigab and Huab rivers to enable travel northwards towards Sesfontein, doing this with 'a large number of Berg-Damaras who live in this [*sic*] Velds' who showed him where water may be found (Elers' 1907 report quoted in Jacobson and Noli 1987: 173). At Sesfontein, by now a German military post with a brick fort under the command of a Lieut. Schmidt, Elers was informed that travel further north is ill-advised because of drought. Nonetheless, and with local guides, he proceeded westwards down the Hoanib, finding in between the Hoanib and the Hoarusib, 'some Berg-Damaras and Bushman who live close to the sea' who were

Figure 4: 'Group of sea-bushmen at Hoanib mouth; captain with a woman in the foreground'. Source: Hartmann 1897: 129 (out of copyright)

Figure 5: 'Rietgrasfontein close to the mouth of the Hoarusib, on the north side of the spring, protected from the southwest wind, abandoned huts of the Seebuschmanner; two servants of Dr Hartmann with horses'. Source: Hartmann 1897: 127 (out of copyright)

> "constantly walking up and down the coast in search for whales that come ashore, *you will find their Kraals all the way to Khumib and also a long way south to the Hoanib*"
> (Elers' 1907 report quoted in Jacobson and Noli 1987: 173, emphasis added).

In 1910, geologist Kuntz similarly meets 'Bergdamaras' upstream on the !Uniab returning from the !Uniab mouth, where presumably they had been harvesting *!nara*[6].

The northern Namib explored by these colonial actors in the late 1800s and early 1900s was clearly inhabited and utilised by Khoekhoegowab-speaking peoples who moved both between the different westward-flowing ephemeral rivers of the north-west, and between the resources of both the coast and areas inland.

2 'Strandlopers', Sesfontein, 1953

Continuity with Hartmann's images is indicated in several sources from the 1950s—a time when Namibia as 'South West Africa' was administered essentially as a 5th province of South Africa. Bernhard Carp, a businessman who financed a 1951 scientific collecting expedition to Kaokoveld (Macdonald and Hall 1957), thus writes to the Administrator of South West Africa of encountering 'foragers' at the Hoanib River mouth, comprising:

> "3 bushmen, 2 bushwomen, 3 Damas and 3 Dama-women and … called Sandloopers [*sic*?] as they lived in the sand and also part of the year on the beaches of the coast, where they ate dead fish etc. Inland their diet consisted of grass veldkos and anything they could catch. They lived in scherms, no proper huts and had a very primitive life"
> (quoted in Bollig 2020: 22[7]).

A government ethnologist for the former Dept. of Bantu Administration based in Pretoria states in the early 1950s that '[t]his group of Bushmen calls itself Kubun (with click ǁ ubun)'—i.e. 'ǁUbun'—and that 'the informant said they originally came from a place called !kuiseb which is south of Walvis Bay, near the sea', with himself (called !Hu-!gaob) and his nephew |Nanimab 'born where the !Uniab flows into the sea, about seven days walk from Sesfontein' (Van Warmelo 1962[1951]: 45). At Brandberg West mine near the Ugab River in the early 1950s, the Anglican Rector for Walvis Bay and Northern Areas observed 'Berg Dama' living there with some goats and working at the mine, who 'use the naras where they can find it' (Haythornthwaite 1956: 61).

[6] NAN.A.327 Krause and Kuntz, Kuntz 25/8/1910, report to KLMG.
[7] Referencing NAN SWAA Kaokoveld A522.

In May 1953 a Mr Louis Knobel from Pretoria, in the company of Dr P.J. Schoeman—'the Game Warden of South West Africa'—photographed a group of people in Sesfontein later described by archaeologist Raymond Dart in a dated and (again) somewhat derogatory text as:

> "a small group of coastal Bush-Hottentot folk consisting of three males and an ancient doddering female, said to be their mother, who were reported by the Topnaar Hottentot elders, their overlords, to be the last remnants of what was once a large body of Strandlopers. It was the custom of the Hottentots to allow these Strandloper retainers to go down to the coast each year when the *narra* fruit was ripe. … On the coast this Strandloper group still subsists for several months on these fruit and the sea food found along the coast …, especially on the rocks about the mouth of such rivers as the Kumib and Hoarusib. This group, however, were not being allowed by the Hottentots to go to the coast for the past three or four years because of the bad seasons"
> (Dart 1955: 175).

Knobel's photographs (Figure 6), form the basis of Raymond Dart's 1955 hierarchised account of this encounter. Schoeman additionally reports that,

> "according to these Strandlopers' own story, their stock had branched off from a Name [*sic*] Hottentot tribe, somewhere near the Brandberg … in the Kaokoveld, but their predecessors had lived along the Skeleton Coast and up towards Rocky Point for hundreds of years"
> (Dart 1955: 175).

The three 'Strandloper' men photographed in Sesfontein stand before a circular hut made of 'pieces of wood, branches and palm fronds' and are described as

> "clad in front and back aprons of buck-skin suspended from a girdle string, ear-rings and in one case a necklet of the type usually encountered amongst Bush peoples [perhaps of ostrich egg-shell beads?] as well as rude sandals tied about their ankles with leather thongs"
> (Dart 1955: 175-177).

Dart's paper proceeds with a very objectifying account of the physical characteristics of the photographed men.

In May 2019, and again in March 2022, these images were discussed with Sesfontein resident Franz |Haen ǁHoëb, born *ca.* 1935 at Auses in the lower Hoanib and who grew-up as a *!nara* harvester of the northern Namib. Franz recognised one of the men photographed here as called |Gabenaeb, known to be an enthusiastic dancer of |*gais* praise songs. In

Figure 6: (L) 'Three Strandlopers of Sesfontein S.W.A., standing in front of their rude hut built of wood, bark, palm fronds and grass'; (R) 'The same three Strandlopers seated or squatting, the tall one on the right side of the previous picture having changed over to the left side in this picture'. Source: Dart 1955: 176 (out of copyright)

Figure 6, this man is seated on the right, and also standing in the centre of the image on the left. His full name is Werner |Gabenaeb ǁHoëb, and he is an uncle of Franz: Franz's father David |Gero ǁHoëb is the brother of |Gabenaeb—indicated in the genealogy shared in Figure 7.

What is extraordinary is that |Gabenaeb, pictured in these images from the 1950s, and recognised in field research some 60 years later, was also recorded in Sesfontein in 1999 as an elderly man playing multiple 'bow-songs' *(goma-khās),* a musical genre formerly commonly played, often simply for 'self-delectation' (Mans and Olivier 2005: 30-31): i.e. for pleasure, delight, amusement and meditation (Figure 8). These recordings, made by ethnomusicologists Emmanuelle Olivier and Minette Mans have ended up being deposited in the British Library Sound Archive as part of Emmanuelle Olivier's broader Namibia archive of research recordings (http://cadensa.bl.uk/ C1709). In March 2022 we managed to return the full-set of Sesfontein recordings, including 15 recordings of |Gabenaeb playing the *goma-khās,* to Sesfontein for safe-keeping by the Nami-Daman Traditional Authority. The image in Figure 8 is of |Gabenaeb, photographed in the early 1950s as an unnamed 'strandloper', playing *goma-khās* in Sesfontein in 1999. In the notes accompanying the Olivier/Mans recordings from 1999, the late Werner |Gabenaeb ǁHoëb plays songs whose names are suggestive of his preoccupations at this time: 'Should I stay alone?', 'The camp has moved', 'Homesick', 'Who will cry', 'We move towards Namib', 'Springbok', 'I was left alone in the bush at Tceǁami', 'We will meet during the rainy season', 'Waterhole', …

When pursuing this conversation with Franz in March 2022 more information about these men came to light. The images are not in fact of exactly the same men, as conveyed

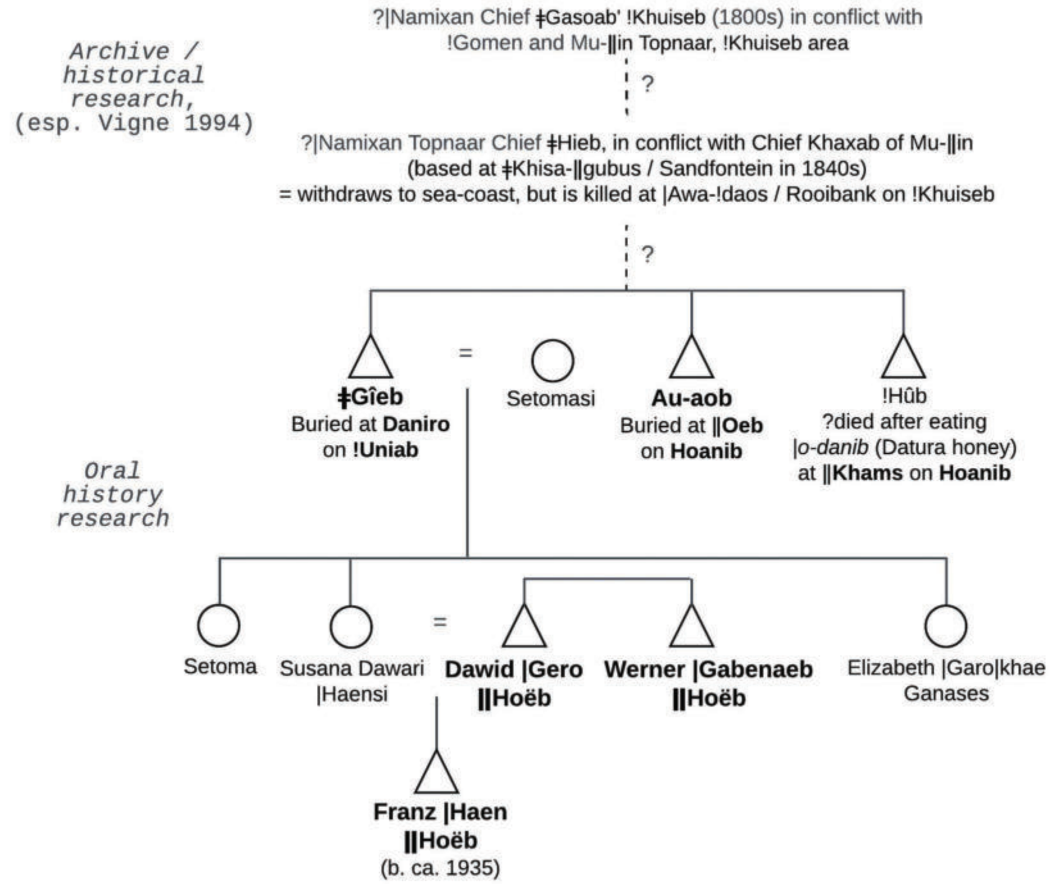

Figure 7: Reconstructed genealogy of remembered ‖Ubun leader ǂGîeb, drawing on oral histories with especially Franz |Haen ‖Hoëb, now resident in Sesfontein, and historical material in Vigne (1994: 8)

in Dart's 1955 paper. The man standing to the left in Figure 6 is Alfred |Nabunab, recalled—like |Gabenaeb—as someone who loved to dance |gais praise songs: but he is not photographed in the image on the right. |Nabunab is described by Franz as mostly staying with |Namimab (Huiseb) Xam-khaob, !Hûnib and Au-aob, the third of these men being a brother of ǂGîeb, who we will meet again below. All these men referred to ǂGîeb as their elder: as *da kai.* It is tempting to speculate that '|Namimab' named here may have been the man referred to by Van Warmelo above as '|Nanimab', 'born where the !Uniab flows into the sea, about seven days walk from Sesfontein'.

It seems clear that in the 1950s it was not uncommon for a network of individuals connected with the nodal settlement of Sesfontein to move between the coast and inland, in part so as to harvest *!nara* in the lower reaches of several rivers traversing the Northern

Figure 8: Werner |Gabenaeb ǁHoëb (d.) plays goma-khās *in Sesfontein. Photo: Emmanuelle Olivier 1999 (no. 37), digitised by Sian Sullivan March 2018, identification of musician made by W.S. Ganuses and S. Sullivan May 2018. Used with permission.*

Namib: the Khumib, Hoarusib, Hoanib, !Uniab and Ugab are all mentioned, spanning a north-south distance of more than 200kms. Nonetheless, less than two decades later in a report commissioned by the Wildlife Society of South Africa about shifts to the then boundaries of Game Reserve no. 2 and Etosha Game Park, Etosha ecologist Ken Tinley (1971: 4) was able to speak of ‘recently extinct Strandlopers along the coast’.

Tinley (1971: 4–5) describes the previous distribution of these ‘Strandlopers’ as ‘discontinuous as they were governed by the occurrence of freshwater in the mouths of the seasonal rivers crossing the Namib Desert’: although ‘they also extended up some of the rivers traversing the desert’, writing that they ‘are extinct today except for one or two very old individuals living in Sesfontein’. He overlooks the role played in their ‘extinction’ by the establishment of mining concessions for diamond and semi-precious stones through the northern Namib from the 1950s onwards: at Sarusas in the Khumib River, Möwe Bay, Terrace Bay and Toscanini (Mansfield 2006). In creating the northern Namib as an area restricted for mining, peoples using coastal resources were increasingly advised that they could no longer access these areas and must become more permanently settled in the formal settlement area of Sesfontein. These circumstances are invoked in a short film in which Sesfontein resident Hildegaart |Nuas tells of how Nama headmen from Sesfontein came to those living in the Hoanib west of Sesfontein saying, 'you cannot stay here alone, you have to move to Sesfontein so that the government can recognise you' (Figure 9: full video online at https://vimeo.com/380044842). Hildegaart's parents, and also her husband, the late Manasse |Nuab, continued to go to the Hoanib *!naras* at the time of the year when they became ripe, bringing *!nara* cakes back to Sesfontein (see Sullivan 2019). At least some of those removed from the northern Namib found their way back there as labourers for the mines, including Franz ǁHoëb mentioned above.

Iterative clearances of people and livestock from landscapes west and also south of Sesfontein acted to facilitate shifts in the boundaries of 'Game Reserve no. 2'. Under the German colonial regime from 1907, this Game Reserve connected Etosha Pan in the east with 'Kaokoveld' in the north-west—an area incorporating the northern Namib from the Hoarusib to the Kunene rivers (Figure 10)—creating a landscape wherein access to what is called 'game' was restricted locally, and access to the area overall was restricted from the outside. With Ordinance 18 of 1958, a radical shift in the boundaries of Game Reserve no. 2 took place. It now included the area south of Sesfontein towards the Ugab River westwards to the coast, and north of the 1955 Police Zone boundary (see Figure 10). The protected area thereby incorporated the northern Namib from the Ugab to the Hoanib rivers, with the area around Etosha Pan in the east proclaimed as 'Etosha Game Park'[8]. The

Figure 9: Screenshot for short film from 2019 of Hildegaart |Nuas describing harvesting !nara *in the dune fields of the Hoanib: see https://vimeo.com/380044842*

[8] The southern boundary of Game Reserve no. 2 was shifted again in 1967, moving slightly northwards to lie between the Koigab and !Uniab Rivers.

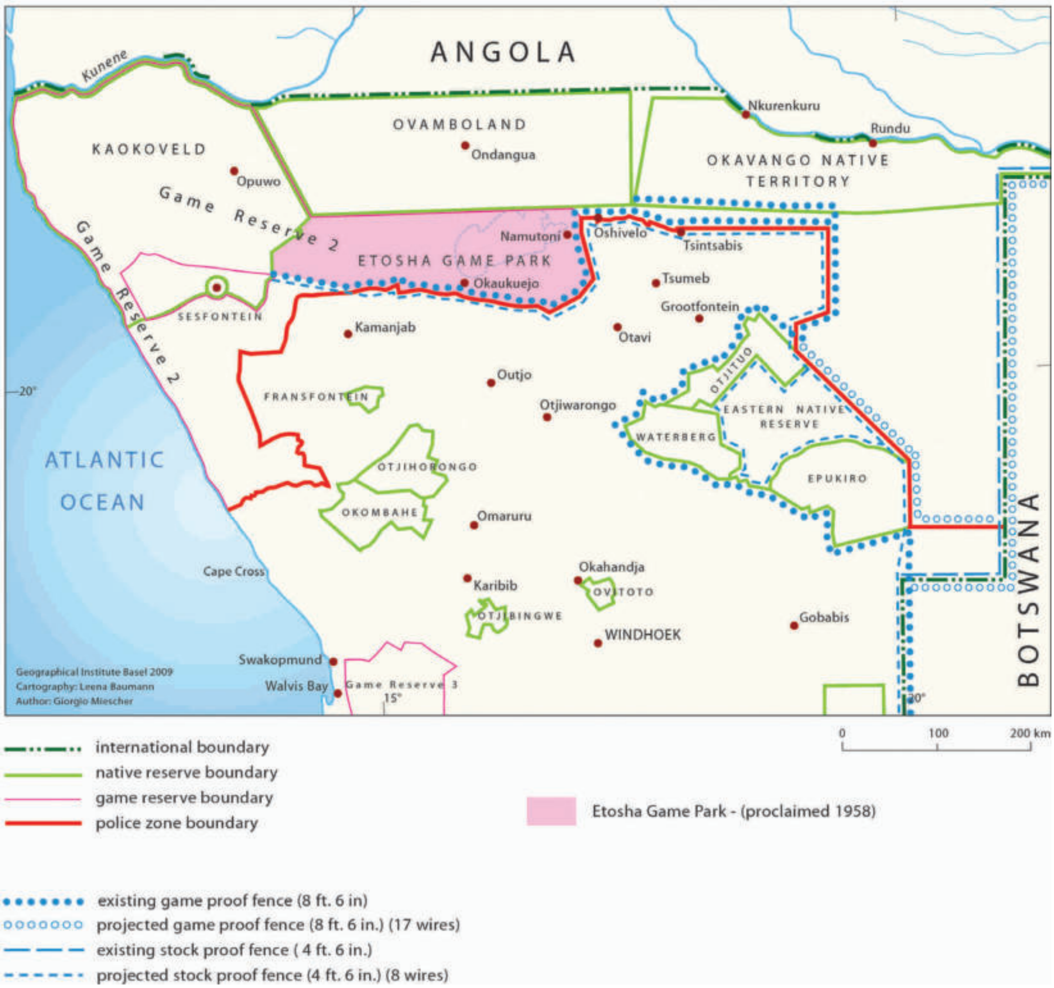

Figure 10: Boundaries in 1965, showing the extent of Game Reserve no. 2 which then surrounded an area of 'Native use' around Sesfontein, stretching north-west towards the Kunene, south-west to the former Police Zone boundary and along the Namib coast; plus existing and projected game and livestock fences. Source: Miescher 2012: 170, colour version received from Miescher and used with permission

'Kaokoveld Native Reserve' in the north-west remained part of Game Reserve no. 2 until the 'Kaokoland Homeland' was established after 1970, at which point all western areas stretching to the coast were removed from the new boundaries of 'Etosha National Park', established as a protected area (with some adjustments) along the lines of the 1958 'Etosha Game Park'.

Enacted in connection with the recommendations of the Odendaal Commission (Odendaal Report 1964), these boundary changes were perceived by conservationists to have 'sacrificed' the protected area of Game Reserve no. 2 'to the land needs of Owambo, Kaokoland and Damaraland' (De la Bat 1982: 20): even though the area west of Etosha had only been incorporated as part of Game Reserve no. 2 for 12 years. Various proposals were made at this time to further remove people from areas of north-west Namibia in which they had long histories. Tinley (1971: 5, 14), for example, lumps together 'the Nama people at Sesfontein and Warmquella, the extinct Strandlopers, and the Heiqum "Bushmen"' as 'all of the Hottentot or Nama stock and shar[ing] the same language': stating that '[o]ne homeland should suffice, as they are a single language group', and advocating that '[t]he Nama people at Sesfontein and in the adjacent country should be moved to the same homeland area as the Fransfontein people'. Inexplicably, Tinley omits mention of the presence of Damara / ǂNūkhoen, despite their being documented as the most populous of Khoekhoegowab-speaking peoples of the Sesfontein Native Reserve and surrounding area in these decades[9].

These boundary changes and reorganisations of people and livestock eventually cleared the way for proclamation of what was already a restricted area: in 1971 the Skeleton Coast National Park was established, encompassing the northern Namib from the Ugab (!Uǂgāb) to the Kunene rivers, from which people were banned from entering without a permit.

3 Re-locating ǂGîeb's grave in the Skeleton Coast National Park, 2019

As noted above, Franz |Haen ǁHoëb, who identifies as of ǁUbun descent, connects celebrated |*gais* dancer Alfred |Nabunab, standing to the left of the image in Figure 6, as mostly staying with several men, one of whom is ǂGîeb, denoted as *da kai,* i.e. as their elder. In the quote that opens this paper, Khoekhoegowab-speaking ǁUbun are identified as those who built huts with ribs of the whale. Whalebone huts and shell middens have been well documented for a settlement located south of the Ugab River mouth, made from the ribs and mandibles of the Southern Right Whale (*Eubalaena australis*) with ceramics from this site dated between 600BP and 200BP (J Kinahan and JHA Kinahan 1984: 70; J. Kinahan 2020: 318-319). Whale bone material is also reported in association with hut circles north of the Munutum in the northern Namib (Vogelsang and Eichhorn 2011: 172–173). It is possible that northern Namib settlements constructed in part of whalebones may have looked something like an image linked with surveyor Carel Brink. He accompanied a 1761–62 expedition north of the Orange River from the Cape Colony led by Hendrik Hop. A map from this journey includes a sketch of a 'Strand Bosjemans' ('Beach Bushmen') village constructed of whale bones, on the coast north of the Orange (then !Garieb) River (Figure 11). In the image, the huts are placed very close to each other, the family grouping

[9] See population figures in Van Warmelo (1962[1951]: 40), UN Special Committee for South West Africa (1962: 13) and National Planning Commission (1991); also summary in Sullivan 1998: 46.

Figure 11: Detail of 'Strand Bosjmans' village from 'Historical map, Orange River to Karas Mts., SWA', apparently created as a composite of multiple sources of information from different expeditions, including that led by Hendrik Hop in 1761–62 accompanied by surveyor Carel Brink. Adapted from Mossop 1947: opp. p. 50

is accompanied by several dogs, a beached whale is being butchered to the left of the huts, and a human figure in the centre is carrying on their back a bag filled with ostrich eggs used for storing potable water.

ǁ*Ubun* are Khoekhoegowab-speakers sometimes referred to as 'Nama' and at other times as 'Bushmen', living on the ocean side of the Namib north of the !Khuiseb, reportedly for generations[10]. They are likely to be amongst those coastal peoples associated with the term 'Strandloper' in historical texts. Their presence in the northern Namib is inscribed on an 1893 *Deutscher Kolonial Atlas* map in which the name 'Hubun' appears across the vicinity of the Hoarusib and Hoanib rivers near the coast. In recent generations, ǁUbun moved between *!nara* fields in the !Uniab and Hoanib river mouths via Kai-as and Hûnkab springs, now in the Palmwag Tourism Concession.[11] They also stayed at Dumita in the lower Hoarusib where there is a spring[12]. It seems possible that contemporary ǁUbun are connected with a 'Topnaar group' called |Namixan, who in the 1800s under their 'Chief ǂGasoab, lived in the !Khuiseb', coming into conflict with Topnaar groups called !Gomen and Mu-ǁin, which continued 'between ǂGasoab's successor, *Chief ǂHieb,* and Chief Khaxab of the Mu-ǁin' (Vigne 1994: 8, emphasis added[13]; also Hoernlé (1985[1925]: 47).

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[10] Franz |Haen ǁHoëb (Kai-as), 25 November 2015.

[11] Documented through journeys with Franz ǁHoëb and Noag Ganaseb, 20–26 November 2015, and Franz |Haen ǁHoëb 5–9 May 2019.

[12] Hildegaart |Gugowa |Nuas (*née* Ganuses) |Nuas, (Sesfontein), 6 April 2014.

[13] Vigne (1994) draws on an archived late 1800s statement by "Piet !Haibeb", son of Mu-ǁin "Topnaar" leader Frederick Khaxab, to an agent of German colonial settler Adolf Lüderitz.

The |Namixan reportedly withdrew 'to the sea-coast' from where 'Chief ǂHieb and two companions travelled secretly to Rooibank [in the lower !Khuiseb] to look for any of his people left there', being 'surprised at a Mu-ǁin werf [settlement] by a commando which attacked from the dunes rather than approaching them along the river, killing Chief ǂHieb and his companions' (Vigne 1994: 8). The |Namixan were again driven away *'under Chief ǂHieb's son'* (Vigne 1994: 8, emphasis added).

Given known naming practices in which sons of lineage leaders may be named after their fathers, the possibility exists that 'Chief ǂHieb's son' mentioned above is the maternal grand-father ǂ*Gîeb* remembered by the elderly ǁUbun man Franz ǁHoëb, born at the *!nara* fields near Auses/!Uiǁgams in the lower Hoanib river and now living in the vicinity of Sesfontein / !Nani|aus: see reconstructed genealogy in Figure 7.

In May 2019, Franz led us to this grave of his grand-father ǂGîeb in the lower !Uniab river, located exactly as mentioned in prior interactions, in the present-day Skeleton Coast National Park on the south side of the !Uniab, inland of the coastal dunes (see Figure 12). ǂGîeb's grave is next to the former dwelling site called Daniro (the place of honey, *danib*). Here ǂGîeb and others first encountered German men travelling down the !Uniab, described to Franz as being the first occasion when these ǁUbun had seen white men and encountered food in tins. This encounter was perhaps the 1896 journey by L. von Estorff mentioned above, which found 'deserted, circular reed huts at the Uniab River mouth' and on return a month later encounters here 'a band of 30 "Bushmen" who had just arrived from the

*Figure 12: Franz |Haen ǁHoëb stands at the grave of his grand-father ǂGîeb, having told us repeatedly about this grave in previous interviews. The footsteps from a recent sports run across the desert are clearly visible around the grave. The dwelling place of Daniro (the place of honey/*danib*), where ǁUbun lived in the past, is close to the !Uniab River on the right of the image.*

Hoanib River. They were living off narra for the most part …' (in Jacobson and Noli 1987: 174).

When we located this grave spoken of in previous interviews, there were imprints of footsteps all around it which we later learned were from a running event of around 40(?) people across the park, held in April 2019. It would mean a lot to descendants of ǂGîeb living in the Sesfontein area today for this grave to be marked and protected from human and animal disturbance into the future.

Concluding Remarks

For the duration of written accounts about the northern Namib, overlapping into the pasts recorded in archaeological research, diverse Khoekhoegowab-speaking peoples accessed, used and inhabited the northern Namib. The historical influences and boundary changes ushered in by European colonial venture, acted increasingly to fix new, bounded conceptions of the landscapes of the northern Namib that restricted and contained prior mobilities, whilst creating new regimes of access, governance and use. We have attempted to bring into focus ways that the northern Namib was once accessed and utilised by contemporary Indigenous Namibians, drawing on their own accounts of who they are and why the coastal resources were important to them. In juxtaposing these accounts with the rather objectifying and often derogatory narratives of encounter left by various colonial European actors, the gulf between both sets of accounts seems stark. We can only imagine how different the information bequeathed in the historical texts might have been had the peoples of the northern Namib been met and engaged with as complex persons with names, histories and agency. What rich stories they might have shared about why living in the northern Namib was important to them, and how they managed to thrive in such an extreme environment.

Intersecting archaeology research and historical documentation with contemporary oral history and ethnographic voice(s) demonstrates Namibian pasts to be resistant to, and refractory of, typologies of peoples, key resources and places that have become reified in archaeology, historical and ethnographic analyses. This generative methodology may assist with recovering complexity in Namibian pasts, so as to support diverse perspectives on environmental and cultural concerns into the future.

Acknowledgements

We are grateful to all the contemporary residents of the Sesfontein area who consented to share their memories and experiences (as named in the text), as well as the Nami-Daman Traditional Authority, the Hoanib Cultural Group of Sesfontein, and the Sesfontein Conservancy for supporting this research. Numerous colleagues, librarians and archivists have shared sources and other materials: thank you to Kenneth |Uiseb (especially for the Khoekhoegowab translation of the abstract), Esther Moombolah-|Gôagoses, Gillian Maggs-Kölling, Eugène Marais, Scott Turner, Selma Lendelvo, Pat Craven, John Kinahan, Jill Kinahan, Trudi Stols, Michael Bollig, Ute Dieckmann, Werner Hillebrecht, Wolfram Hartmann, Giorgio Miescher (apologies if we have inadvertently missed anyone from this list). Our research has been made possible through the support of Gobabeb Namib Research Institute, Save the Rhino Trust, Bath Spa University, the UK's Arts and Humanities Research Council through *Etosha-Kunene Histories* (www.etosha-kunene-histories.net, AH/T013230/1) and *Future Pasts* (www.futurepasts.net, AH/K005871/2), a National Commission for Research, Science and Technology Research Permit (AN202101038), and Ministry of Environment and Tourism research permits 2023/2015; 2190/2016; 2311/2017.

References

ALEXANDER, J.E. 2006[1838]. *An Expedition of Discovery into the Interior of Africa: Through the Hitherto Undescribed Countries of the Great Namaquas, Boschmans, and Hill Damaras, Vol. 2.* Elibron Classics Series, orig. published by London: Henry Colburn.

BLÜMEL, W.D., EBERLE, J., HÜSER, K. and EITAL, B. 2009. Holozäne Klima- und Landschaftswandel in der Namib? *Acta Nova Leopoldina* NF 108(373): 125–149.

BOLLIG, M. 2020. *Shaping the African Savannah: From Capitalist Frontier to Arid Eden in Namibia.* Cambridge: Cambridge University Press.

BOLLIG, M. and HEINEMANN-BOLLIG, H. 2005. Visual presentations of the people and land of north-western Namibia in German colonial times, pp. 259–278 *in* Hartmann, W. (ed.) *Hues Between Black and White: Historical Photography from Colonial Namibia 1860s to 1915.* Windhoek: Out of Africa.

BUDACK, K.F.R. 1977. The ǂAonin or Topnaar of the lower !Kuiseb Valley, and the sea. pp. 1–42 *in* A. Traill (ed.) *Khoisan Linguistic Studies 3, A.S.I. Communication no. 6.* Johannesburg: University of the Witswatersrand.

DART, R.A. 1955. Three strandlopers from the Kaokoveld coast. *Suid-Afrikaanse Joernaal van Wetenskap* January: 175–179.

DE LA BAT, B. 1982. Etosha. 75 Years. In *S.W.A. Annual:* 11–26.

DENTLINGER, U. 1977. The !Nara plant in the Topnaar Hottentot culture of Namibia: ethnobotanical clues to an 8,000 year-old tradition. *Munger Africana Library Notes.* 38: 3-39. California: Institute of Technology.

DU PISANI, E. 1983. Past and present plant utilization in Namaland and the lower Kuiseb River valley, South West Africa (Namibia). A preliminary report. *Khoisis.*4: 1–19.

ELPHICK, R. 1977. *Kraal and Castle: Khoikhoi and the Founding of White South Africa.* London: Yale University Press.

GALTON, F. 1852. Recent expedition into the interior of South-Western Africa. *Journal of the Royal Geographical Society* 22: 140–63.

GONDWANA COLLECTION NAMIBIA 2011. *Gondwana History: Memorable Moments from Namibia's Past.* Windhoek: Gondwana Publishers.

HARTMANN, G. 1897. Das Kaoko-Gebiet in Deutsch-Südwest Afrika auf Grund eigener Reisen und Beobachtungen. *Verhandlungen der Gesellschaft für Erdkunde zu Berlin* 24: 113–141.

HARTMANN, G. 1902/03. Meine Expedition 1900 ins nördliche Kaokofeld und 1901 durch das Amboland. *Beiträge zur Kolonialpolitik und Kolonialwirtschaft* IV: 399–430.

HAYTHORNTHWAITE, F. 1956. *All the Way to Abenab.* London: Faber & Faber Ltd.

HENSCHEL, J., DAUSAB, R., MOSER, P. and FALLEN, J. (eds.). 2004. *!Nara—Fruit for development of the !Khuiseb Topnaar.* Windhoek: Namibia Scientific Society.

HOERNLÉ, W.A. 1985[1925]. The social organisation of the Nama Hottentots of south-west Africa, pp. 39–56 *in* Carstens, P. (ed.) *The Social Organisation of the Nama and Other Essays by Winifred Hoernlé.* Johannesburg: Witswatersrand University Press.

JACOBSOHN, M. 1995. *Negotiating Meaning and Change in Space and Material Culture: An Ethno-Archaeological Study Among Semi-Nomadic Himba and Herero Herders in North-western Namibia.* Ph.D. Thesis, University of Cape Town.

JACOBSON, L. and NOLI, D. 1987. An eye witness account of coastal settlement and subsistence along the northern Namibian coast. *South African Archaeological Bulletin* 42: 173–174.

KINAHAN, J. 2020. *Namib: The Archaeology of an African desert.* Windhoek: University of Namibia Press.

KINAHAN, J. and KINAHAN, J.H.A. 1984. Holocene subsistence and settlement on the Namib coast: the example of the Ugab River Mouth. *Cimbebasia* (B) 4 (6): 59–72.

KINAHAN, J. and KINAHAN, J.H.A. 2003. Excavation of a late Holocene cave deposit in the southern Namib Desert, Namibia. *Cimbebasia* 18: 1–10.

KINAHAN, J. and KINAHAN, J.H.A. 2006. Preliminary report on the late Holocene archaeology of the Awasib-Gorrasis basin complex in the southern Namib desert. *Studies in the African Past* 5: 1–14.

KINAHAN, J. and VOGEL, J.C. 1982. Recent copper-working sites in the Khuiseb drainage, Namibia. *The South African Archaeological Bulletin* 37(135): 44–45.

MACDONALD, J.D. and HALL, B.P. 1957. Ornithological results of the Bernard Carp/ Transvaal Museum Expedition to the Kaokoveld, 1951. *Annals of the Transvaal Museum* 23: 1–39.

MANS, M. AND OLIVIER, E. 2005. *Scientific Report: The Living Musics & Dance of Namibia: Exploration, Publication & Education, Volume One – Instruments.* Unpublished report.

MANSFIELD, C. 2006. *Environmental Impacts of Prospecting and Mining in Namibian National Parks: Implications for Legislative Compliance.* Unpub. Masters Dissertation, Univ. Stellenbosch.

MIESCHER, G. 2012. *Namibia's Red Line: The History of a Veterinary and Settlement Border.* Basingstoke: Palgrave Macmillan.

MORRELL, B. 2014[1832]. *A Narrative of Four Voyages to the South Sea, North and South Pacific Ocean, Chinese Sea, Ethiopic and Southern Atlantic Ocean, Indian and Antarctic Ocean.* Cambridge: Cambridge University Press.

MOSSOP, E.E. (ed.) 1947. *The Journals of Brink and Rhenius, being The Journal of Carel Frederik Brink of the Journey into Great Namaqualand, (1761-62), made by Captain Hendrik Hop, and The Journal of Ensign Johannes Tobias Rhenius (1724).* Cape Town: The Van Riebeeck Society.

NATIONAL PLANNING COMMISSION 1991. *Population and Housing Census, Preliminary Report.* Windhoek: Central Statistics Office.

OLUSOGA, D. and ERICHSEN, C.W. 2010. *The Kaiser's Holocaust: Germany's Forgotten Genocide and the Colonial Roots of Nazism.* London: Faber and Faber.

RIZZO, L. 2012. *Gender and Colonialism: A History of Kaoko in north-western Namibia.* Basel: Basler Afrika Bibliographien.

SIEVERS, C. 1984. Test excavations at Rosh Pinah Shelter, southern Namibia. *Cimbebasia* (B) 4: 29–40.

SULLIVAN, S. 1998. *People, Plants and Practice in Drylands: Sociopolitical and Ecological Dynamics of Resource Use by Damara Farmers in Arid North-west Namibia.* Ph.D. Anthropology, University College London.

SULLIVAN, S. 2019. Celebrating Hildegaart |Nuas of Sesfontein—90 years still dancing, *Future Pasts Blog* 19 December 2019, https://www.futurepasts.net/post/celebrating-hildegaart-nuas-of-sesfontein.

SULLIVAN, S. 2021. Cultural heritage and histories of the Northern Namib: historical and oral history observations for the Draft Management Plan, Skeleton Coast National Park 2021/2022-2030/2031 *Future Pasts Working Paper Series* 12 https://www.futurepasts.net/fpwp12-sullivan-2021.

SULLIVAN, S. and GANUSES, W.S. 2021. Densities of meaning in west Namibian landscapes: genealogies, ancestral agencies, and healing, pp. 139–190 *in* Dieckmann, U. (ed.) *Mapping the Unmappable? Cartographic Explorations with Indigenous Peoples in Africa.* Bielefeld: Transcript.

TINLEY, K.L. 1971. Etosha and the Kaokoveld. Supplement to *African Wild Life* 25(1): 3–16.

UN SPECIAL COMMITTEE FOR SOUTH WEST AFRICA 1962. *Report of the Special Committee for South West Africa. Annex X1.* Geneva: United Nations, A/5212/Add.1.

VAN WARMELO, N.J. 1962[1951]. *Notes on the Kaokoveld (South West Africa) and its People.* Pretoria: Dept. of Bantu Administration, Ethnological Publications 26.

VIGNE, R. 1994. "The first, the highest", identifying Topnaar of Walvis bay and the Lower !Khuiseb river. Symposium, May 1994: Writing history, identity, society. Hanover, Univ. of Hanover.

VOGELSANG, R. and EICHHORN, B. 2011. *Under the Mopane Tree: Holocene Settlement in Northern Namibia.* Köln: Heinrich Bath Institut.

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A Decade of Solar and Terrestrial Radiation Monitoring at Gobabeb for BSRN

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Abstract

The Gobabeb Baseline Surface Radiation Network (BSRN) location was established a decade ago as part of a global network to provide standardised, high quality surface observations of radiation fluxes under the auspices of the World Meteorological Organisation. The Gobabeb BSRN measures the incoming and outgoing shortwave and longwave radiation at two locations in the Central Namib Desert. With a suite of instruments, radiative fluxes of shortwave downward radiation (*SWD*), direct solar radiation (*DIR*), diffuse radiation (*DIF*), longwave downward radiation (*LWD*), shortwave upward radiation (*SWU*) and longwave upward radiation (*LWU*) are recorded at 1-min intervals, together with relevant meteorological variables directly at the locations. As logistical issues prevent frequent calibration of instruments against World Radiometric standards, the measurements of *DIR*, *SWD* and *LWD* are duplicated to replicate radiation measurements as primary and redundant datasets. The two datasets are compared to each other to identify and exclude questionable data before being deposited in an open-access repository. The Gobabeb BSRN dataset is of very high quality, with less than 1% data missing for downward radiation. The upward radiation dataset has more missing data due to its becoming operational at a later date. As expected, climatic variables have the greatest influences on radiation fluxes at Gobabeb. Due to its location in a hyperarid desert, radiation is generally high throughout the year. Reflected radiation from rare cloud walls during the austral summer may, however, result in very high downward fluxes. The frequent incidence of fog due to onshore advection of stratus cloud banks over the nearby South Atlantic Ocean from August to February is distinctly visible in the dataset. Variation in the radiative fluxes of the different elements provides more detailed information on seasonal and daily incidence of fog, as well as seasonal changes in atmospheric aerosols. We briefly illustrate how high-quality BSRN data are used globally for validating solar energy resource assessments and evaluating differences between modelled predictions and actual surface performance.

1 Introduction

The sun is practically the only source of energy for the Earth system and is the basis of life on Earth. The energy comes as solar radiation, which, converted into different forms and redistributed by the rotating planet, drives the ocean currents and the general circulation of the atmosphere resulting in weather and climate. Of the 70% of the solar radiation absorbed by the planet, approximately two thirds reaches the Earth's surface (Wild et al. 2015) where net radiation is a crucial component of the surface energy balance both on ocean and land surfaces. Here, small changes in irradiance can "cause a profound change in climate" (BSRN 2021). While the solar input at top of the atmosphere is known with sufficient accuracy, knowledge about the irradiance at the Earth's surface, especially its spatial distribution—horizontally and vertically—is not sufficient to understand the present climate. As existing radiometric networks were not accurate enough for climate research, a new Baseline Surface Radiation Network (BSRN) was initiated more than 30 years ago by the World Climate Research Programme Radiative Fluxes Working Group to resolve this top-bottom discrepancy.

The BSRN stood out from existing measurements by special features such as: a commitment for the long-term operation of the stations under the guidance of radiation experts; measurements of basic radiation components in 1-min resolution; and traceable calibrations of the radiation instruments to the World Radiometric Reference, which is maintained at the World Radiation Center in Davos, Switzerland. For more details see McArthur (2005) or Driemel et al. (2018). Apart from monitoring the background shortwave and longwave radiative components[1] with the best methods available, BSRN also provides data for verification of satellite-based estimates of the surface radiation budget.

Although nowadays solar resource assessment is based mostly on satellite-based gridded solar radiation products, ground-based measurements from the BSRN continue to be essential and serve as benchmarks and anchor points.

Esterhuyze (2004) nicely summarizes how the BSRN radiometric network evolved in the 1990s. It is interesting to note that as early as 1989 Namibia was identified as the initial candidate country to represent southern Africa in the new radiometric network, called GBSRN at that time, that intended to reach global coverage (Esterhuyze 2004).

In the global distribution of BSRN stations, ocean areas and the southern hemisphere were and still are underrepresented (Figure 1). When the measurements in Gobabeb started in 2012 it was the only station in Africa south of the Equator. With its decade of measurements, it has now the longest continuous record for that area (the South African station in De Aar restarted in 2014). Another special feature of BSRN at Gobabeb is that south of the Equator, apart from stations in the Antarctic, it is one of only two stations measuring upward radiation fluxes, which allows the estimate of net surface radiation (Driemel et al. 2018) and the evaluation of ground surface reflectance models, for which Gobabeb BSRN data were used (Tuomiranta et al. 2021, 2022).

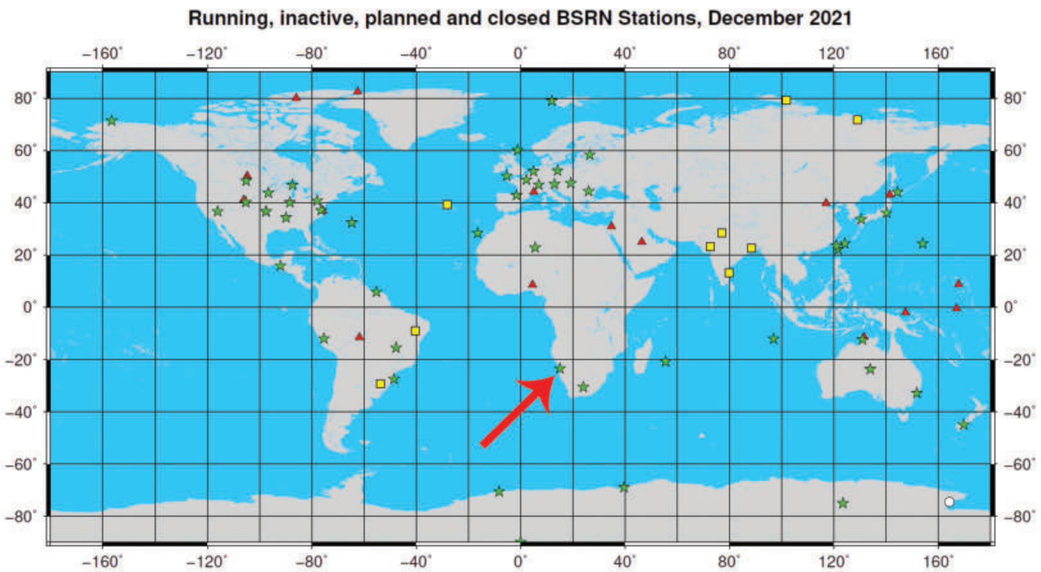

Figure 1: Overview map of BSRN stations. The arrow marks the station in Gobabeb.

[1] In the context of meteorology, shortwave and longwave are used synonymously for solar and terrestrial radiation as there is only a small overlap (≈1%) around 4 µm due to the Sun-Earth distance.

Direct surface observations provide an important input for estimating the global annual mean energy balance, for which the latest estimates are summarized in Figure 2 arranged in energy budgets for top of the atmosphere (TOA), atmosphere and surface (Forster et al. 2021, Wild et al. 2015). *Incoming solar* corresponds to a quarter of total solar irradiance (also referred to as solar constant), which reaches on average the Earth's orbit at TOA and is distributed over the spherical surface. *Reflected solar* consists of solar radiation reflected back to space from the atmosphere (mainly from clouds) and the Earth's surface without being energetically relevant, while *thermal outgoing* is the longwave emission of the Earth. Upward and downward fluxes for each level sum up to zero (e.g. for the atmosphere: +80+82+21+398-342-239 = 0). The slight imbalances at TOA and surface are discussed in detail in Wild et al. (2015) and are not relevant in this context.

The BSRN measurements are therefore important to quantify the energy balance at the Earth's surface. In addition to the components of the surface radiation budget (Figure 2), the direct solar radiation plus the diffuse solar radiation are also measured and provide a relevant input for evaluating radiative transfer models.

The BSRN measurements at Gobabeb are presented in the following sections, together with selected initial results from the first decade.

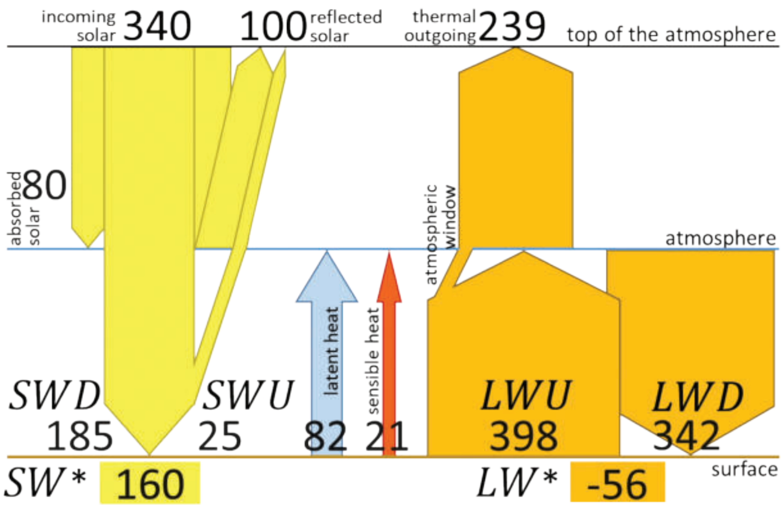

Figure 2: Schematic of global annual mean energy balance estimate based on figures from Wild et al. (2015). All energy fluxes in W m^{-2}. Variables indicate fluxes measured at BSRN stations. For abbreviations see Table 1 and text.

2 Description

2.1 The Gobabeb BSRN station

The station is a joint effort of the Gobabeb Namib Research Institute, the Karlsruhe Institute of Technology (KIT) and the University of Basel (UBAS). The latter provides the station manager.

Gobabeb meets the minimum requirements for BSRN stations with basic measurements of the downward radiation fluxes (Driemel et al. 2018). The downward radiation fluxes are measured 60 m north-east of the Gobabeb water tower on a 2.5 m high rock with the tracker base at 2.8 m height above ground (23.5614S, 15.042E 407 m a.s.l.). Power for the operation of the station comes from Gobabeb. Since the environment close to Gobabeb is not representative for a larger area, the upward fluxes are measured 6 km north-east at a homogeneous area on the gravel plains (23.5195S, 15.0832E, 460 m a.s.l.) at a site called Plains station where the downward oriented instruments are mounted at 5 m above ground.

2.2 Radiation flux measurement

Shortwave downward radiation *SWD* is also called global radiation and represents the incoming solar radiation incident on a horizontal surface. *SWD* is the sum of direct and diffuse solar radiation and is measured with a pyranometer, an instrument sensitive to solar radiation from the hemisphere that it is pointing to.

Direct solar radiation *DIR* is the radiation on a surface orthogonal to the sun's beam, therefore also called direct normal incidence, and the portion incident on a horizontal surface DIR_h contributes to *SWD*. *DIR* is measured with a pyrheliometer, a tube-like instrument pointed by a sun tracker towards the sun so that only the direct solar radiation from the disk of the sun is measured.

Diffuse radiation *DIF* is the part of *SWD*, which comes from the radiation scattered by the atmosphere. A ball positioned by a sun tracker at a distance in front of the disk of the sun (Figure 3a) shadows the pyranometer to block *DIR* for measuring *DIF*.

LWD is the thermal emission of the atmosphere incident on a horizontal surface and is measured with a pyrgeometer, an instrument sensitive only to longwave radiation by means of a longwave filter. The longwave component of direct solar radiation is also blocked by balls positioned by the tracker to measure only *LWD* from the atmosphere. Shadowing also prevents solar leakage through the filter and reduces thermal load on the filter.

The upward fluxes that are measured are *SWU*, the reflected part of global radiation, and *LWU*, the thermal emission of the surface. *SWU* and *LWU* are measured using an upside-down mounted pyranometer and pyrgeometer.

With these measurements of radiation components the net shortwave, net longwave and net radiation are calculated as $SW^* = SWD\text{-}SWU$, $LW^* = LWD\text{-}LWU$, and $Q^* = SWD\text{-}SWU\text{+}LWD\text{-}LWU$.

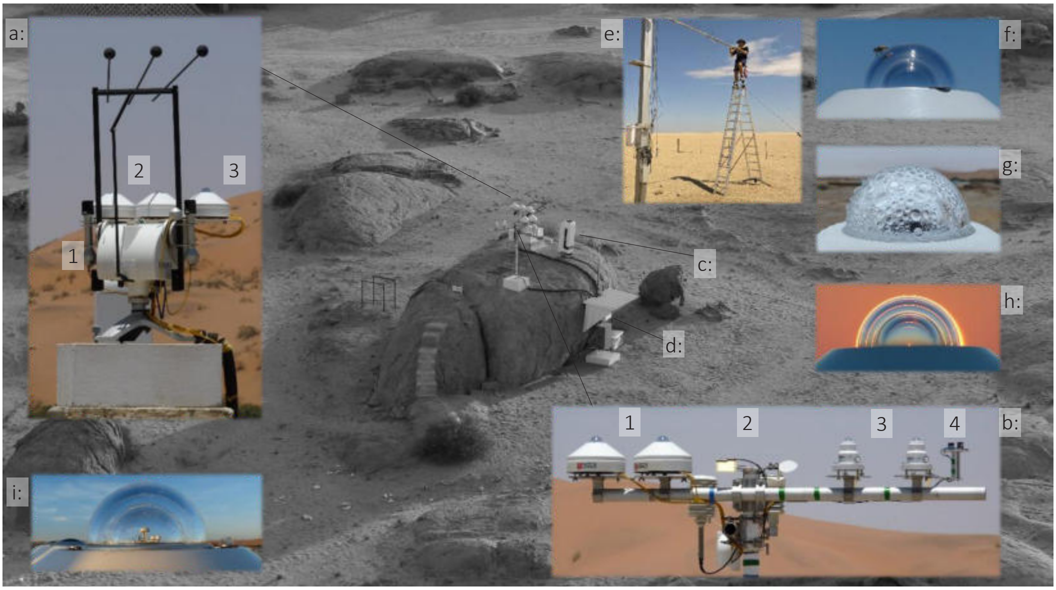

Figure 3: Grey background: View to the BSRN station on the rock with the downwelling flux measurements. a: Tracker positioning two pyrheliometers (1) and shadow balls for two pyrgeometers (2) and one pyranometer (3) with sun close to zenith. b: Boom holding two pyranometers (1), meteorological instruments (2), one UV-B pyranometer and one UV-A pyranometer (3) and two PAR sensors (4). c: Ceilometer. d: Data acquisition and power supply. e: upwelling flux measurements. f: a fly casting a shadow for qualiflying uncertainty. g: fog deposition on a dome. h: sunset in a pyranometer. i: Gobabeb water tower seen through the dome of the pyranometer for diffuse radiation.

The downward (upward) fluxes are sampled at 2s (3s) and stored as 1-min averages. More information on the measured quantities and instrument details are listed in Table 1. Figure 3 presents views of the setup and instrumentation.

2.3 Quality control and data management

For logistic reasons frequent calibrations, as recommended by BSRN, cannot be carried out. Therefore, to have a quality control measure, redundant *DIR*, *SWD* and *LWD* measurements are duplicated by instruments of the same type. In the strict sense, redundancy does not provide information on the accuracy of the measurement, but it is a good indication of long-term stability and helps to identify incorrect measurements. As an example, Figure 4 illustrates the differences of *DIR* values between the main and the redundant measurements for two sets of instruments. The difference is ±1%, which also applies to *SWD* and *LWD* (not shown). The differences were within the accuracy range claimed by the manufacturer, which is 1% of daily totals.

Table 1: Overview on instruments at the Gobabeb BSRN station. Upper part: radiation instruments and the corresponding measured variables/abbreviations. All instrument types are from Kipp and Zonen. Redundant instruments were exchanged in July 2013 (SWD, LWD) and November 2013 (DIR). Lower part: additional meteorological measurements.

Abbreviation/Variable (radiation)		Instrument/Type		Data base
SWD	shortwave downward	Pyranometer	CMP22	BSRN
SWD	redundant	Pyranometer	CMP22	
SWD	shortwave upward	Pyranometer	CMP22	BSRN
LWD	longwave downward	Shaded pyrgeometer	CGR4, T	BSRN
LWD	redundant	Shaded pyrgeometer	CGR4, T	
LWD	longwave upward	Pyrgeometer	CGR4	BSRN
DIF	shortwave diffuse	Shaded pyranometer	CMP22, T	BSRN
DIR	direct solar	Pyrheliometer	CHP1, T	BSRN
DIR	redundant	Pyrheliometer	CHP1, T	

T= instruments mounted on sun tracker SOLYS2, Kipp and Zonen
Data logger downward fluxes: CR3000, Campbell Sci.; upward fluxes: CR1000, Campbell Sci.

Variable	Instrument/Type
Air temperature	Aspirated Thermocouple. Campbell Sci.
Air temperature, relative humidity	HMP45AC, Vaisala
Weather Transmitter: Air temperature, relative humidity, wind speed, wind direction, air pressure, precipitation	WXT520, Vaisala
Leaf wetness sensor	Model 237, Campbell Sci.
UV-B global radiation	UV-S-B-T radiometer, Kipp and Zonen
UV-A global radiation	UV-S-A-T radiometer, Kipp and Zonen
Photosynthetic active radiation	LI-190R quantum sensor LI-COR Biosciences
Cloud base, aerosol backscatter	Ceilometer CS135, Campbell Sci.

The instruments on the rock are maintained daily early in the morning. This includes checking i) the soiling conditions of the domes and filters, ii) the levelling of the instruments, iii) the orientation of the tracker, and iv) the functioning of the ventilations. The status is protocolled, and cleaning and relevelling are carried out if necessary. This type of regular maintenance is crucial to ensure a continuous quality level. For technical reasons the maintenance of the upward fluxes cannot be done as frequently.

Data from the Plains station (*SWU*, *LWU*) are transmitted via a radio link and the ones from the rock via the Gobabeb WiFi to a laptop computer where the 1-min averages and statistics are stored. From there the data are copied to a server at University of Basel and

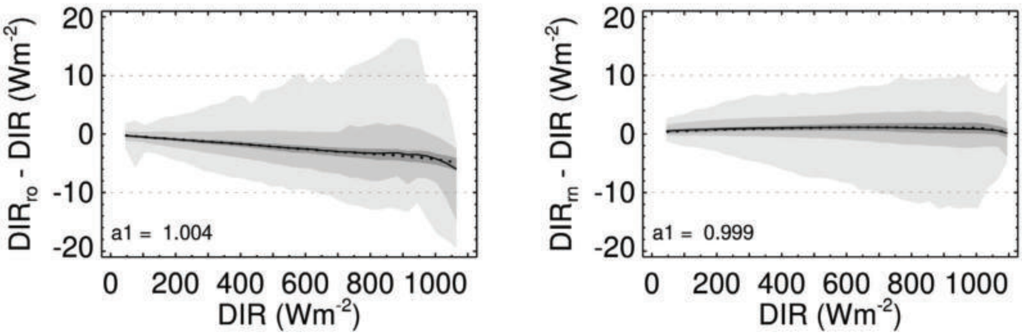

Figure 4: Differences in direct normal incidence between redundant measurements versus the BSRN instrument DIR, which operated continuously since June 2012. Left: for DIR_{ro} (redundant, old) from June 2012 to October 2013. Right: for DIR_{rn} (redundant, new) from November 2013 to March 2020. 1-min averages, class width is 30 W m^{-2}, average/median = solid/dotted line, grey areas contain 50, 90 and 99% of differences. a1 *indicates the regression factor.*

transferred to a MySQL database for further analysis. A visual inspection of data quality is carried out before submitting the data to the BSRN Pangaea database on a monthly basis. Visual inspection means that diurnal courses of all radiation components are plotted together with the differences relative to the redundant measurements. The dynamics of the undisturbed differences show a regular pattern, which makes it easy to identify obvious deviations such as those caused by cleaning of the domes/filters and/or shadows cast during maintenance. These erroneous values are flagged and are reported as missing values. Other causes of errors are insects/birds sitting on the instruments, wetting of the domes/ filters from fog deposition (frequent), rainfall (less frequent) or dew (rare), and strong wind that prevents the tracker from maintaining its exact positioning. The redundant measurements are not reported to the BSRN database, but a summary of the visual inspection is included in the monthly data files. Finally, before submitting, the data are processed with the so-called BSRN Toolbox (Driemel et al. 2018), which provides a format check on the station-to-archive files and performs quality checks as outlined in Long and Dutton (2002). Less than 1% of data are missing for the downwelling fluxes, while the gaps for the upwelling are larger due to the later start at the end of October 2012 (see Table 2). The BSRN data are freely available from bsrn.awi.de.

2.4 Foggy climate

The Gobabeb BSRN site is located in the hyperarid Central Namib close to the Tropic of Capricorn, 56km from the coast and next to the Kuiseb River, the natural boundary between the Namib Sand Sea to the south and the Namib Gravel Plains to the north. The Namib is a coastal desert, with climate influenced by the cold upwelling water of the Benguela Current, accounting for its distinct fog/stratus climatology. Over the eastern

Table 2: Overview on the frequency of gaps in the Gobabeb BSRN data during the 10 years (3652 days). The measurements of the upward fluxes started only November 2012.

	% missing	in days	% ≤10min	% >10min ∧ ≤1h	% >1h	max. gap (days)
SWD	0.85	31.2	0.04	0.09	0.72	4.1
LWD	0.92	33.7	0.14	0.06	0.72	4.1
DIR	0.80	29.3	0.05	0.02	0.73	4.1
DIF	0.73	26.7	0.02	0.01	0.71	4.1
SWU, *LWU*	6.19	226.1	0.003	0.002	6.19	121.4

parts of the southern Atlantic Ocean, a quasi-permanent stratus deck forms that influences the coastal areas. The stratus deck is regularly transported inland by onshore winds, and depending on its cloud base height and thickness, occurs as fog where it intercepts the terrain ascending towards the Great Escarpment in the east. The seasonal changes in stratus height create a west-east gradient in the frequency of fog/stratus occurrence. At Gobabeb that means minimum values from April to July and a broad maximum from September to February. The fog/stratus events at Gobabeb typically start around midnight and dissolve in the morning hours, around three hours after sunrise (Olivier 1992, Seely and Henschel 1998, Spirig et al. 2019, Vogt et al. 2019).

The general climate is well described due to the long-term observations at the Gobabeb Namib Research Institute (Lancaster et al. 1984, Mendelsohn et al. 2009, Eckardt et al. 2013). During the decade of BSRN measurements the mean monthly air temperature for the period 2013 to 2022 can be compared to those in Lancaster et al. (1984) and Mendelsohn et al. (2009). It is interesting to note that summer values seem to have shifted one month later as the maximum now occurs in April instead of March with May the third-highest before a sharp decrease to June. The minimum monthly temperature in August, however, stays the same (Table 3).

Table 3: Mean monthly air temperatures for 06/2012 to 05/2022 for the BSRN station at Gobabeb and for 07/1976 to 06/1981 for Gobabeb according to Lancaster et al. (1984) (= LLS) in °C.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BSRN	22.2	22.7	23.8	24.4	23.4	19.8	19.1	17.5	18.1	19.9	21.2	22.2
LLS	22.8	23.3	24.8	24.3	21.6	19.9	18.6	17.6	18.0	19.2	21.5	21.9

3 Results and Discussion

"Namibia is a country of sunshine" state Mendelsohn et al. (2009) in the Atlas of Namibia. The decade of global radiation measurements supports this statement very well. From Figure 5 it is obvious how regular and frequent clear sky days occur in Gobabeb. The more frequent deviations from clear sky days in the mornings as a consequence of fog/stratus events, which dissolve in the morning hours, are noticeable when comparing the two hours after sunrise with those before sunset. Even the seasonality in the occurrence of fog/stratus, with a minimum from April to July, is apparent in the global radiation values in Gobabeb (Figure 5).

Peak values of global radiation during clear sky days can reach up to 1200 W m^{-2} (max. 1224 W m^{-2}). Larger 1-min averages can occur during days with tall convective clouds when forward reflection from the cloud walls enhances solar irradiance. Rarely but regularly occurring values above 1200 W m^{-2} (4200 times) were observed, exceeding more than 500 times the TOA extra-terrestrial levels around 1360 W m^{-2}, with the absolute maximum value of 1651 W m^{-2}.

Gobabeb's geographical location in the celestial context sets boundary conditions for the radiation components. As an example, clear sky days around solstices and equinoxes illustrate the intra-annual variation (Figure 6). The lower (higher) values in June (December) are expected but the influence of atmospheric turbidity can mask such seasonality. Particularly, direct radiation is strongly affected by aerosol content: peak values of *DIR* can be around 100 W m^{-2} lower at the summer solstice than at equinoxes. Net radiation, which summarizes incoming and outgoing shortwave and longwave radiation

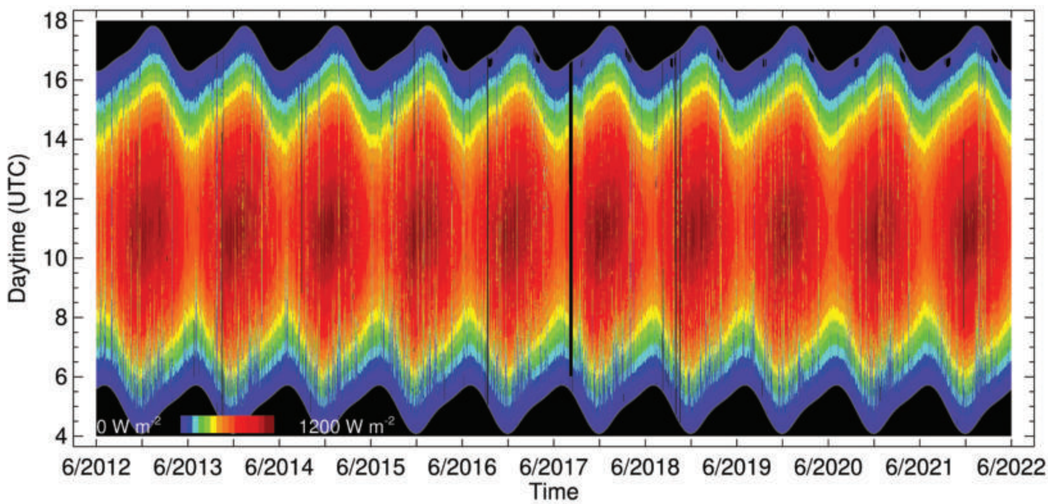

Figure 5: Shortwave downward radiation at the BSRN station Gobabeb based on 1-min averages. Diurnal courses plotted in color code on y-axis. Grey lines indicate times of sunrise and sunset.

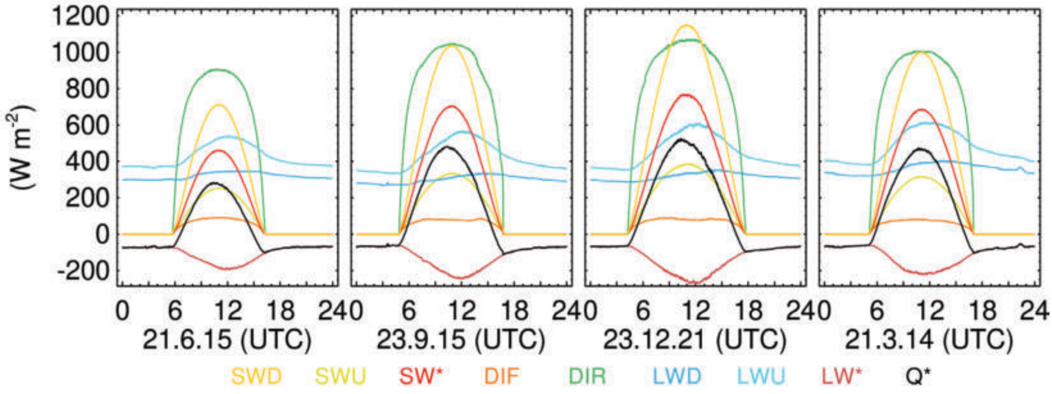

Figure 6: Example clear sky days around solstices and equinoxes for 1-min values of all measured components of radiation at the Gobabeb BSRN station.

fluxes, remains moderate especially in summer compared to mid-latitude values. Despite the strong solar input, peak values range only from a little below 300 to slightly above 500 W m^2. The causes for this are the high albedo and the strong loss in longwave radiation due to the high surface temperatures combined with clear skies above.

An overview on all radiation components derived from the BSRN measurements at Gobabeb is illustrated as monthly averages (Figure 7). All the radiation variables show regular annual courses except the jagged course of direct radiation that fluctuates from month to month. Cloudiness and atmospheric turbidity have a direct influence on *DIR*, but the increase in diffuse radiation compensates partly the reduction in *DIR* for *SWD* values. The monthly averages of net longwave radiation indicate a relatively constant loss of around -100 W m^{-2}, without any pronounced seasonality. When examining the data, the average annual course reveals the highest loss occurs in November (-112 W m^{-2}) and the lowest loss in January (-97 W m^{-2}). This can be explained by the relative lower occurrence of fog and low clouds in November, when surface temperatures are already high, while in January the highest frequency of stratus and low cloud occurrences reduces longwave loss (Vogt et al. 2019). There appears to be a weak decreasing trend in *Q**, which corresponds to slight increases in the outgoing radiation fluxes, especially in *SWU*. A possible explanation could be a reduction in the sparse vegetation since 2012, which decreased and actually disappeared during the last three years. This would cause an increase in albedo and surface temperature. However, further investigation is needed to ascertain that there are no instrument-related errors and by including satellite remote sensing (e.g. time series of surface reflectance from Sentinel-2).

The fog climatology, i.e. the regular occurrence of fog and stratus clouds, is a special feature of the Central Namib and can be tracked throughout the Gobabeb BSRN data. The presence of fog/stratus typically results in an increase of longwave downward radiation. The diurnal and seasonal influence on *LWD* is illustrated in Figure 8. In the absence of fog/

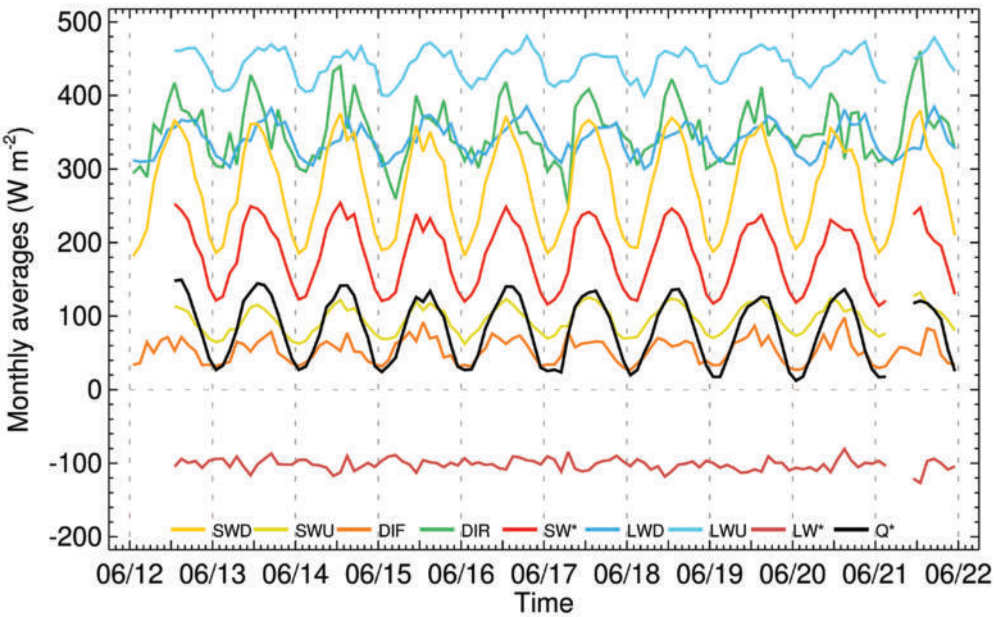

Figure 7: Monthly averages of all components of radiation measured at the BSRN station in Gobabeb from June 2012 to May 2022.

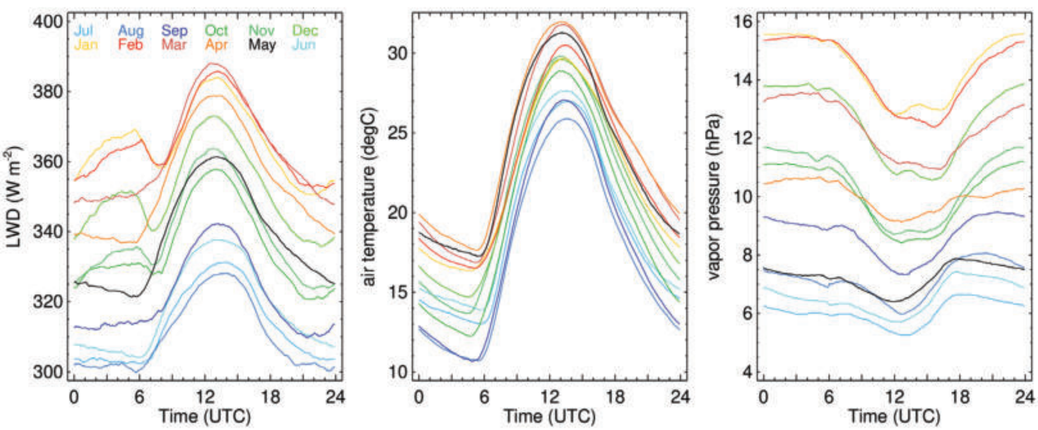

Figure 8: a: monthly average diurnal courses of longwave downward radiation measured at the BSRN station in Gobabeb based on the period June 2012 to April 2022. b: and c: same as a: but for air temperature and water vapor pressure.

stratus, the average diurnal courses of *LWD* are similar to those of air temperature, with a minimum around sunrise and a maximum during the afternoon before monotonously decreasing again towards the minimum. The courses when fog/stratus occurrence is rare, are good examples for that similarity. The nocturnal decrease towards sunrise during the transition July and August months is reduced. From September to February, the decrease of *LWD* after the afternoon maximum ceases during the first half of the night. *LWD* then increases until a sharp drop in *LWD* marks when the fog/stratus disappears. Daytime *LWD* in March is highest, although *LWD* during the second half of the night is much lower than during February. This indicates that the advected fog/stratus is on average much cooler then. The diurnal course of *LWD* during May is roughly in the medium range, while the air temperature is in the top three. This is likely related to the much lower water vapor partial pressure, which contributes to *LWD* during clear sky conditions.

As global interest increased in greater use of renewable energy, the application of BSRN data have proved to be valuable to solar energy engineers. Knowledge about solar radiation is essential to evaluate the potential of particular sites for generating renewable energy, whether by using photovoltaics, concentrated solar power, or both (Salmon et al. 2021). Accurate measurements provide the base for such an evaluation, which should ideally cover at least 10 years or more to capture year-to-year variability. Although models, based on satellite observations combined with climate reanalysis data, can generate solar radiation data at high spatial and temporal resolution (Salmon et al. 2021), surface measurements data provide crucial input to validate model data (Yang and Bright 2020). To illustrate such application, the Gobabeb BSRN data are compared to *SWD* and *DIR* values extracted from the PVGIS database (PVGIS 2022).

In that comparison (Figure 9) the overall agreement for the average daily *SWD* is very good with a measured value of 6.7 kWh m^{-2} compared to the PVGIS value of 6.6 kWh m^{-2} (-1.7%). For *DIR* the deviation is larger with a measured daily average of 8.4 kWh m^{-2} compared to the PVGIS value of 7.8 kWh m^{-2} (-7.4%). The absolute differences ΔSWD show no correlation with the magnitude of *SWD* (Figure 9a) but there is a slight dependence on time of the year (Figure 9b) with a minimum in March/April and a maximum in August/September. However, ΔDIR increases with the magnitude of *DIR* (becomes more negative) and it shows a similar seasonal course to that of *SWD* but with a larger amplitude. This variation in *DIR* is likely linked to the seasonal change in atmospheric turbidity (Salmon et al. 2021) over southern Africa, which is apparently not properly represented in models (Di Napoli et al. 2020). The aerosol load is high during austral spring due to biomass burning (Formenti et al. 2019) and relatively low in autumn. The values above 5% in Figure 9b are all from August/September 2017 when clear sky *DIF* was particularly high due to high atmospheric turbidity.

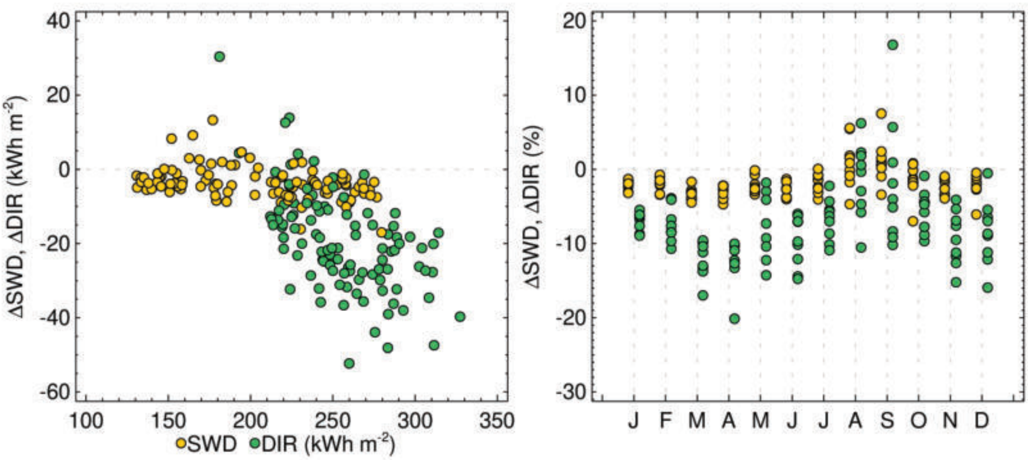

Figure 9: Absolute (a) and relative (b) differences between modelled (PVGIS) and measured monthly averages (BSRN) for SWD and DIR. Measured values are subtracted. Modelled "Global horizontal irradiation" (=SWD) and "Direct Normal Irradiation" (DIR) were downloaded from PVGIS (2022) for coordinates of Gobabeb.

4 Summary and Conclusions

The Baseline Surface Radiation Network (BSRN) is the largest research-grade solar radiation monitoring network world-wide and has been operational since 1992. The Gobabeb BSRN location has been operational since 2012, with two sites in the Central Namib to measure downward and upward radiation fluxes respectively. It is operated jointly by the University of Basel, Gobabeb - Namib Research Institute, and the Karlsruhe Institute of Technology. The Gobabeb BSRN is exceptional as it has provided the longest continuous dataset in sub-Saharan Africa south of the Equator. Excluding Antarctica, it is also one of only two Southern Hemisphere locations to provide both downward and upward radiation data. Although logistical issues do not allow the recommended frequent calibration of instruments, data collection and verification protocols include replication and comparison of measurements to detect and exclude unreliable data. A central repository provides open access to BSRN data at bsrn.awi.de.

The Gobabeb BSRN data is of exceptional quality, hence variations in the various elements of radiation reveal the effects of the nearby cold South Atlantic Ocean and its associated stratus clouds, as well as seasonal fluctuations in atmospheric aerosols transported from the interior of southern Africa over the ocean. Stratus clouds advected inland intersect the rising topography, resulting in fog during the night and early morning, which affects the BSRN radiation measurements. Seasonal and daily patterns in fog incidence is clearly detectible in the BSRN data. Similarly, analysis of the different data elements shows the seasonal effects of high-altitude aerosols on solar radiation, which has its greatest effect on the radiation data at Gobabeb BSRN during August and September. The BSRN data not only helps in the understanding of Earth's energy budget, the high-quality data are also valuable for solar resource assessments to estimate potential energy production and economic feasibility of solar energy investments.

Beyond its global purpose, the Gobabeb BSRN data also can help understand variability and processes in Namibia's climate, as well as Namibia's potential for solar energy production. Frequent and continued use of Gobabeb BSRN data has already proved its international value. In Namibia, however, this resource is still not being used as it might, even a decade later. We can only hope that after ten years of operations, the future will bring greater local interest and involvement in a rich and outstanding resource.

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We are grateful for the longstanding reliable maintenance of the Gobabeb BSRN station by the students, interns and technicians at the Gobabeb Namib Research Institute. Many thanks go to students from the University of Basel for their assistance in the field and at home. Dedicated to the memory of Walter F. Holch, whose technical expertise gave the project the best start ever.

References

BSRN 2021. URL: https://bsrn.awi.de/project/background/ visited 31.05.2021.

DI NAPOLI, C., HOGAN, R.J., PAPPENBERGER, F. 2020. Mean radiant temperature from global-scale numerical weather prediction models. *International Journal of Biometeorology* (2020), doi.org/10.1007/s00484-020-01900-5.

DRIEMEL, A. and 37 co-authors 2018. Baseline Surface Radiation Network (BSRN): structure and data description (1992–2017). *Earth System Science Data.* 10, 1491–1501, doi.org/10.5194/essd-10-1491-2018.

ECKARDT, F.D., SODERBERG, K., COOP, L.J., MULLER, A.A., VICKERY, K.J., GRANDIN, R.D., JACK, C., KAPALANGA, T.S., HENSCHEL, J. 2013. The nature of moisture at Gobabeb, in the central Namib Desert. *Journal of Arid Environments,* 93, 7–19, doi.org/10.1016/j.jaridenv.2012.01.011.

ESTERHUYSE, D.J. 2004. Establishment of the South African baseline surface radiation network station at De Aar. M.Sc. thesis, Faculty of Natural and Agricultural Sciences, University of Pretoria, Pretoria.

FORMENTI, P. and 29 co-authors 2019. The aerosols, radiation and clouds in southern Africa field campaign in Namibia: overview, illustrative observations, and way forward. *Bulletin of the American Meteorological Society,* 100, 1277–1298, doi.org/10.1175/BAMS-D-17-0278.1.

FORSTER, P., STORELVMO, T., ARMOUR, K., COLLINS, W., DUFRESNE, J.-L., FRAME, D., LUNT, D.J., MAURITSEN, T., PALMER, M.D., WATANABE, M., WILD, M., ZHANG, H. 2021. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [MASSON-DELMOTTE, V. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi:10.1017/9781009157896.009.

LANCASTER, J., LANCASTER, N., SEELY, M.K. 1984. Climate of the central Namib Desert. *Madoqua,* 14, 5–61.

LONG, C.N., DUTTON, E.G. 2002. BSRN Global Network recommended QC tests, V2.0, BSRN. Technical Report, hdl:10013/epic.38770.d001.

MCARTHUR, L.J.B. 2005. Baseline Surface Radiation Network (BSRN). WMO/TD-No. 879, WCRP/WMO, hdl:10013/epic.52032.d001.

MENDELSOHN, J., JARVIS, A., ROBERTS, C., ROBERTSON, T. 2009. Atlas of Namibia: A Portrait of the Land and Its People. Sunbird Publishers, Cape Town, 200 pp.

OLIVIER, J. 1992. Some spatial and temporal distribution of fog in the Namib. *South African Geographer,* 119 (1/2), 107–127.

PVGIS 2022. Photovoltaic Geographical Information System. URL: https://re.jrc.ec.europa.eu/pvg_tools/en/.

SALMON, A., QUIÑONES, G., SOTO, G., POLO, J., GUEYMARD, C., IBARRA, M., CARDEMIl, J., ESCOBAR, R., MARZO, A. 2021. Advances in aerosol optical depth evaluation from broadband direct normal irradiance measurements. *Solar Energy,* 221, 206–217, doi.org/10.1016/j.solener.2021.04.039.

SEELY, M.K., HENSCHEL, J. 1998: The climatology of Namib fog. Proc. First Int. Conf. on Fog and Fog Collection, Vancouver, Canada, International Fog and Dew Association, 353–356.

SPIRIG, R., VOGT, R., LARSEN, J.A., FEIGENWINTER, C., WICKI, A., FRANCESCHI, J., PARLOW, E., ADLER, B., KALTHOFF, N., CERMAK, J., ANDERSEN, H., FUCHS, J., BOTT, A., HACKER, M., WAGNER, N., MAGGS-KÖLLING, G., WASSENAAR, T., SEELY, M. 2019. Probing the Fog Life-Cycles in the Namib desert. *Bulletin of the American Meteorological Society,* 100(12), 2491–2507, doi.org/10.1175/bamsd-18-0142.1.

TUOMIRANTA, A., ALET, P.-J., BALLIF, C., GHEDIRA, H. 2022. Calibration of ground surface albedo models, *Solar Energy,* 237, 239-252, doi:10.1016/j.solener.2022.03.047.

TUOMIRANTA, A., ALET, P.-J., BALLIF, C., GHEDIRA, H. 2021, Worldwide performance evaluation of ground surface reflectance models, *Solar Energy,* 224, 1063-1078. doi:10.1016/j.solener.2021.06.023.

VOGT, R., MAGGS-KÖLLING, G., SEELY, M. 2019. Lifting the fog in the central Namib—where did it come from? 8th International Conference on Fog, Fog Collection and Dew, Taipei, Taiwan. URL: https://mcr.unibas.ch/posters/vogt_ifda_2019.pdf.

WILD, M., FOLINI, D., HAKUBA, M.Z., SCHÄR, C., SENEVIRATNE, S.I., KATO, S., RUTAN, D., AMMANN, C., WOOD, E. F., KÖNIG-LANGLO, G. 2015. The energy balance over land and oceans: an assessment based on direct observations and CMIP5 climate models. *Climate Dynamics,* 44(11–12), 3393–3429, doi:10.1007/s00382-014-2430-z.

YANG, D., BRIGHT, J.M. 2020. Worldwide validation of 8 satellite-derived and reanalysis solar radiation products: A preliminary evaluation and overall metrics for hourly data over 27 years. *Solar Energy,* 210, 3-19, doi.org/10.1016/j.solener.2020.04.016.

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Dr Roland Vogt is senior researcher at the University of Basel in the Atmospheric Sciences group of the Department Environmental Sciences. He got his Diploma in hydrology from University of Freiburg, Germany, and received his Ph.D. in meteorology from University of Basel, Switzerland. He has been working in climatology, experimental micrometeorology and turbulence research and has contributed to numerous field experiments (e.g. HartX, EBEX, BUBBLE, MICROPOEM, METCRAX2), investigating the turbulent exchange of natural and urban surfaces. In the city of Basel he started in the mid nineties tower based energy balance measurements, and in 2004 began CO_2 flux monitoring using the eddy covariance method. In 2009, he came to Gobabeb to do surface energy balance measurements, initially planned for one year. What followed were: the installation and operation of the BSRN station; substantial support of FogNet; the Namib Fog Life Cycle Analysis project (NaFoLiCA 2017–2020); the NamTEX field campaign 2020; and 8 field courses with 80 students. He still enjoys being on top of a mast in the Namib.

Eugene Marais

Eugene Marais has been the Research Manager at Gobabeb since 2017 after 31 years as a Curator at the National Museum of Namibia. He first got close and personal with Namib Desert research during a 1983 student research visit by the University of Pretoria, led by the entomologist Prof. Erik Holm. Eugene's fascination with the Namib is reflected by an eclectic body of research on the evolutionary history and ecological drivers of Namibia's biogeography and arid ecosystems. One still finds him most often exploring new ideas, sharing knowledge about environmental processes in southern Africa, assisting the many researchers visiting Gobabeb from all over the world and encouraging young researchers to engage with the fascination of scientific discovery in the Namib Desert.

Gillian Maggs-Kölling

See page 18.

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See page 62.

Jan Cermak

See page 62.

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