

The nature of moisture at Gobabeb, in the central Namib Desert

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ABSTRACT

This paper reviews the nature of moisture at Gobabeb, Namibia with emphasis on rainfall, and fog. It introduces the observational record produced by the Gobabeb Training and Research Centre and examines nature and cause of the rainfall record from October 1st 1962 to May 30th 2011. Over this period of 17749 days only 381 rainy days produced a total of 1213 mm of rain with an annual average of 25 mm. 2011 has been the wettest year on record also featuring the two most wettest days (March 12th and May the 6th). 1992 has been the driest year with no rain at all. Over the last 3 decades (1979–2009) the number of decadal rain days has decreased from 77 to 56 to 54 days, while total decadal rain amount has increased from 130 mm to 149 mm up to 300 mm. 193 Individual rain events between 1979 and 2009 were linked to synoptic conditions present in the region including the Zaire Air Boundary (ZAB), Tropical Temperate Troughs (TTT), the Angola Low, temperate cold fronts and cut-off lows (850 hgt geopotential height). Cluster analyses in the form of Self Organising Maps (SOMs), suggests that all synoptic states have the potential to produce rain but that the Angolan low dominates with an increase in TTT activity being evident. Fog collection techniques have evolved through time and suggest a range of possible event types, including advected fog, coastal stratus cloud, high stratus cloud, radiation fog and fog drizzle. While each of these has their own meso- and micro-scale synoptic control and may even vary in their bulk and isotopic chemistry, they collectively make a significant moisture contribution to the flora and fauna of the Namib. Additional sources of moisture are gaining appreciation and include the widespread occurrence of hypersaline springs on the Namib gravel plains as well as micro-scale moisture including vapour in desert soils and regolith.

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1. Introduction

This paper reviews the synoptic climatology of the sporadic Namib Desert rain, it also examines the various types and uses of persistent fog contributions to the hyper-arid environment and provides an overview of groundwater discharge springs on the Central Namib gravel plains. Using climate records collected over the last 49 years (October 1st 1962 and May 6th 2011), this paper examines the nature, cause and trends of rainfall for the Gobabeb Training and Research Centre (Fig. 1, Lat -23.561116° Lon 15.041341°). The paper also introduces recent studies concerned with soil moisture in the Namib, but it does not cover the ephemeral

highland drainage, which has its headwaters in the semi-arid east of the escarpment.

2. Part 1) Rain

2.1. The climatology of the Central Namib

The arid west coast of the southern African subcontinent is rarely disturbed by rain events. Arid regions such as the Namib are the result of dry descending air as part of the Global Hadley Circulation. A strong NE-SW rainfall gradient across southern Africa results in the semi-arid Kalahari and Karoo and ultimately the hyper-arid Namib coast (Fig. 1a). The subsidence associated with the South Atlantic High Pressure (anticyclone), along with the stable air generated by the cold sea surface temperatures, introduces stability which effectively suppresses convection along the

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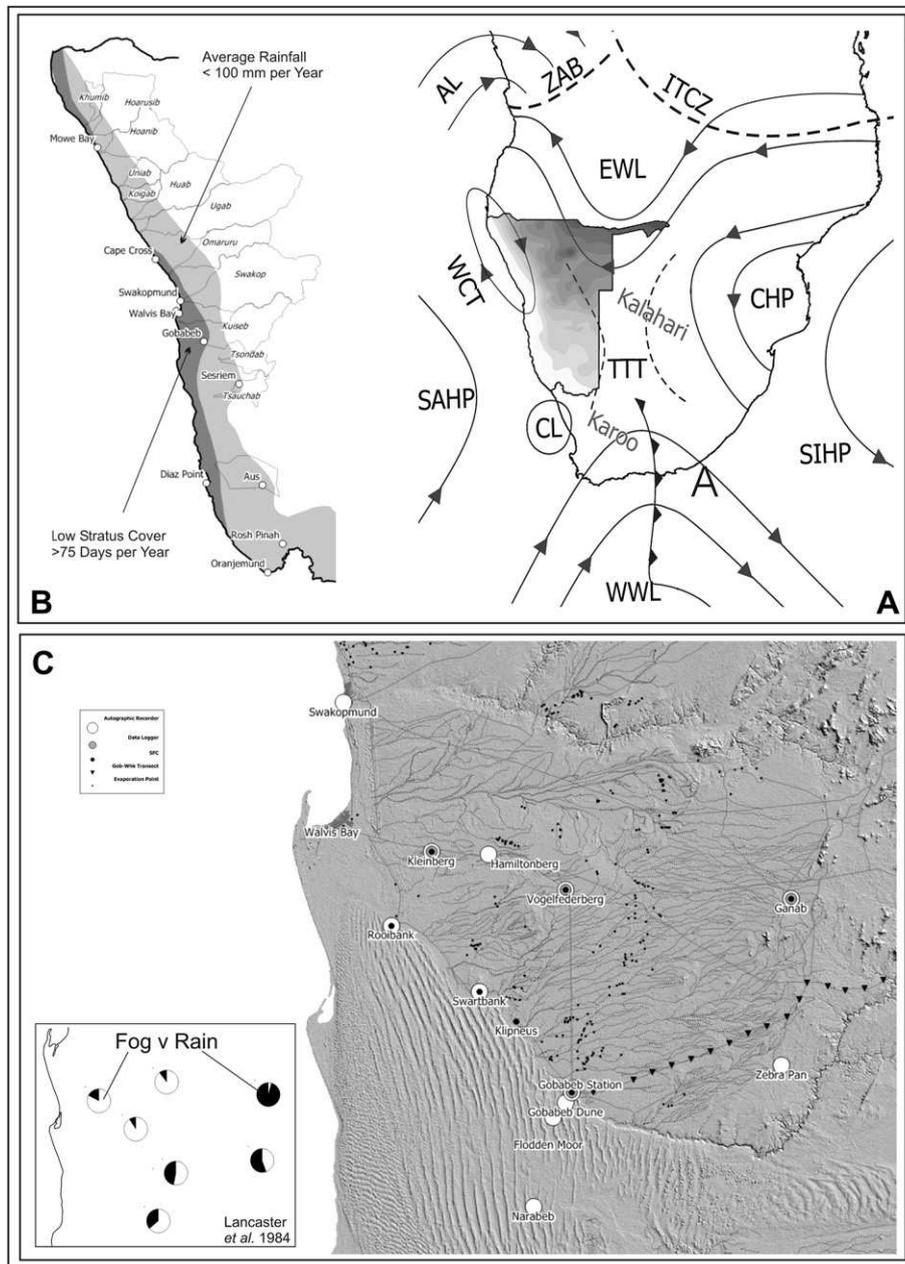


Fig. 1. Top A): Southern African Synoptics and Namibia. Top A) Southern African synoptics which promote Namibian rainfall: Angola Low (AL), Coastal Low (CL), Cold Front (CF), Intertropical Convergence Zone (ITCZ), Tropical Temperate Trough (TTT), West Coast Trough (WCT), Westerly Wave Low (WWL), Zaire Air Boundary (ZAB) and other major pressure system such as the Continental High Pressure (CHP), South Atlantic High Pressure (SAHP), South Indian Ocean High Pressure (SIHP). Modified from Lindesay (1998) and Tyson and Preston-Whyte (2001). (Note rainfall source: Mendelsohn et al., 2003). Top B) Namib Coastline. Coverage of national first order weather stations in the Namib region, location of highland catchments, as well as fog (>75 days) and rain distribution (<100 mm) (Source: Mendelsohn et al., 2003). Bottom C) Central Namib. Map featuring weather stations operated by Gobabeb since 1962, including autographic recorders, data loggers and standard fog collectors (SFC). Saline evaporation points on gravel plain north of the Kuiseb mapped from Landsat imagery using gypsum and halite absorption features. Insert Rain (Solid) v Fog (Clear) from data compiled by Lancaster et al. (1984). (Topography from shaded ASTER GDEM version 1, gravel plain drainage from geological map of Namibia and road pattern modified from Tracks 4 Africa data).

southern African west coast (Logan, 1960; Pietruszka and Seely, 1985) which is further accentuated by a shallow surface temperature inversion.

Rainfall in the region is spatially and temporally highly variable (Mattes and Mason, 1998; Tyson, 1986). Central southern African and in particular Namib rainfall is subject to both inter- and intra-annual variations (Mason and Jury, 1997; Seely, 1978). In fact the coefficient of variation for Namibian rainfall is the greatest in southern Africa, with extreme variability experienced across the

central and northern Namib (Mendelsohn et al., 2003; Southgate et al., 1996), where rainfall events are not only highly localized but also of low intensity (Gamble, 1980; Hachfeld and Jürgens, 2000; Sharon, 1981). Average precipitation in the Namib ranges from 50 to 100 mm in the far south, 5–18 mm in the central Namib and less than 50 mm along the Angolan coast in the north. Furthermore, there is an increase in rainfall from west (~10 mm at the coast) to east (~60 mm at 100 km inland) (Hachfeld and Jürgens, 2000; Henschel and Seely, 2008; Lancaster et al., 1984;

Pietruszka and Seely, 1985; Seely, 1978; Southgate et al., 1996) producing a steep but variable rainfall gradient from the desert interior to the Namibian highland (Fig. 2).

The Namib only covers the western fifth of Namibia, and thus a small portion of southern Africa, however many of the climatic systems which bring rain to the surrounding regions also have the potential to influence rainfall along the west coast. Atmospheric moisture availability is dependent on sea surface temperature variability in the south east Atlantic beyond the Benguela upwelling, the western Indian Ocean as well as the tropical Pacific in particular El Nino Southern Oscillation (ENSO) (Cook, 2000; Landman and Mason, 1999; Lindsay, 1998; Mason, 1995; Mason and Jury, 1997; Tyson and Preston-Whyte, 2001; Reason, 2002; Reason et al., 2000; Reason et al., 2006; Rouault et al., 2003; Shannon et al., 1986; Todd and Washington, 1999; Walker and Shillington, 1990). Namibian precipitation largely occurs during convective thunderstorms, common throughout the region (Tyson and Preston-Whyte, 2001), including the Namib (Gamble, 1980; Hachfeld and Jürgens, 2000; Lancaster et al., 1984; Sharon, 1981). Lightning density at Gobabeb is low at 0.2 km²/year, compared with 0.3 at Cape Town, 2.3 at Windhoek, 7.5 at Johannesburg and 13.0 at Giants Castle, Drakensberg (Measured using onsite Cigré –10 kHz detector, between 1975 and 1986 (Held, 2008)). The intensity of convection is driven by diurnal heating, meso-scale controls and the prevailing synoptic conditions at the time, including low-level convergence and upper air divergence as well as general atmospheric instability (Tyson and Preston-Whyte, 2001). Gamble (1980) noted that a large proportion of storms in the Namib Desert Park occurred either as afternoon events or early morning showers promoted by nocturnal cooling and associated instability (Gamble, 1980; Taljaard, 1979). Sharon (1981) found evidence of

Benard storm cell patterns which form over the relatively uniformly heated desert surface at preferred distances of 40–50 km and 80–100 km from each other.

Storms may be isolated events at times, but large scale circulation systems may temporarily create wider instability and provide significant moisture input. Various regional precipitation triggers, have been identified by Mattes and Mason (1998), Todd and Washington (1999), Reason et al. (2006), and Muller et al. (2008) (Fig. 1c). These conditions introduced below do not necessarily occur in isolation, but rather tend to form complex composite precipitation systems (Tyson and Preston-Whyte, 2001), some of which directly and indirectly impact upon the Namib.

The first is a tropical convection associated with the **The Zaire Air Boundary (ZAB)**, a convergence of tropical and subtropical circulation over central and southern Africa (Lindsay, 1998) similar to the Intertropical Convergence Zone (ITCZ). Both display pronounced vertical motion, cloud formation and precipitation, and depressions are much deeper than any other easterly wave depressions over tropical Africa (Lindsay, 1998; Tyson and Preston-Whyte, 2001). During the austral summer, these low pressure systems will mostly be located over Zimbabwe and Zambia but they do occasionally migrate westward into the Kalahari including Namibia (>18°S) where they produce significant regional rain events (Lindsay, 1998; Mattes and Mason, 1998). These might not reach the Namib Desert but certainly add to the eastern most catchments of the Swakop and Ugab Rivers which have their headwaters deep in the Namibian highlands including the Otavi Mountains south of Etosha.

Secondly, **Tropical Temperate Troughs (TTTs)** are considered the most significant southern African summer rainfall producing systems (Mason and Jury, 1997; Reason et al., 2006; Todd and

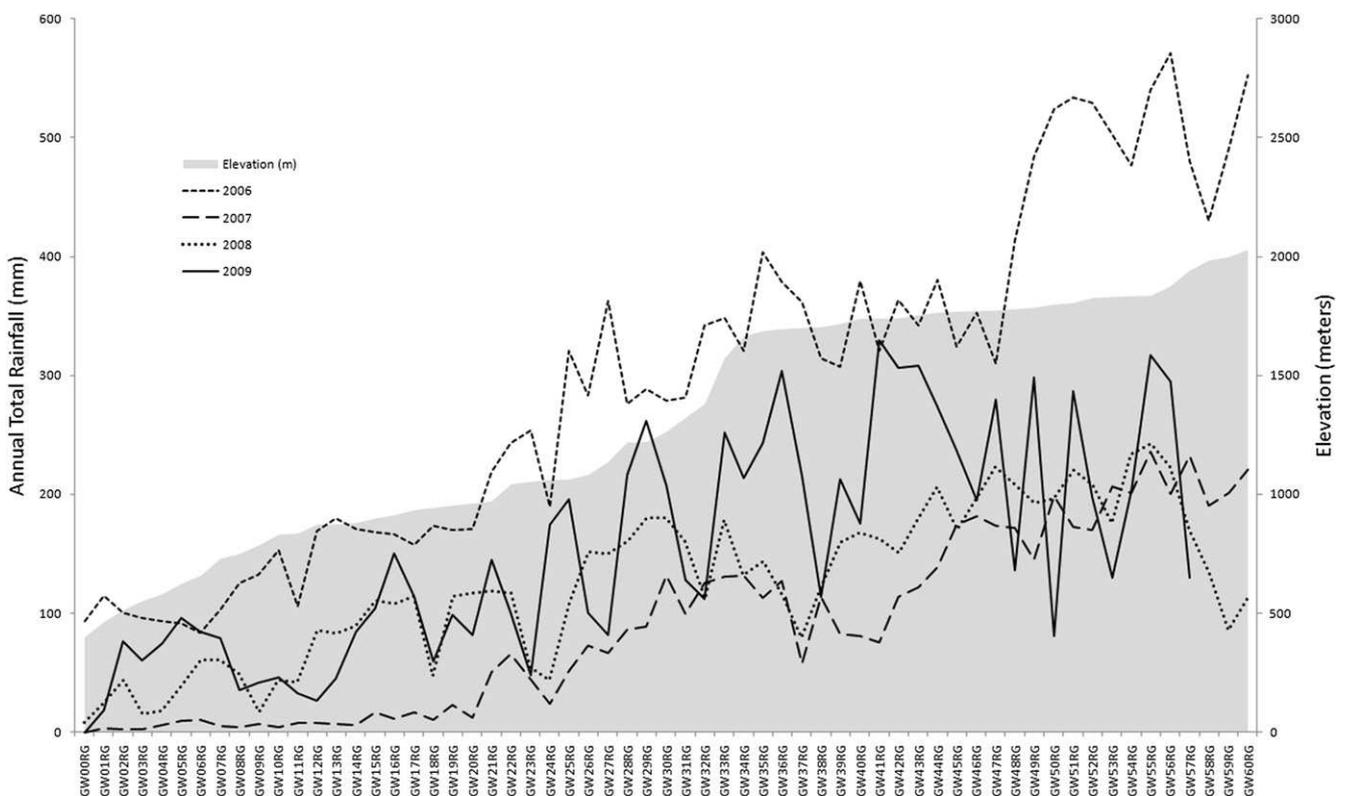


Fig. 2. Total annual rainfall for 2006, 2007, 2008 and 2009, obtained from 60 rain gauges between Gobabeb (GW00RG) and Windhoek (GW60RG) (5 km interval), juxtaposed against topographic profile of gravel plain, escarpment and highlands (source: ASTER GDEM version 1). Note both rainfall gradient and inter annual variation of rain. (Refer to Fig. 1 for locations of rain gauges).

Washington, 1999; Todd et al., 2004). Harrison (1984) states that TTTs account for 39% of the mean annual rainfall over this region and 35% of all rain days. TTTs essentially link an easterly wave or low in the tropics to a westerly wave in the south (temperate region) through a trough (Lindesay, 1998), an event which is associated with a cloud band and precipitation (Todd et al., 2004). Todd and Washington (1999) suggest that in early summer (Nov–Dec) the TTTs and associated cloud bands alternate between the South West Indian Ocean (SWIO) and the South East Atlantic (SEA), forming west coast troughs due to the north westward displacement of the South Atlantic anticyclone. In late summer (Jan–Feb) the TTTs in general lie over the SWIO, due to the eastward displacement of the South Indian Ocean anticyclone (SIHP). Todd and Washington (1999) suggest low-level transport across the equatorial Indian Ocean as one of the main moisture sources of TTTs. Rainfall occurs as a result of both a strong low-level easterly flux from the SWIO and a low-level westerly flux from equatorial Africa, which converge at the ITCZ and ZAB to produce rain (Todd and Washington, 1999). Thus, the total rainfall volume from any such TTT event depends on moisture availability, atmospheric stability, strength of divergence in the upper atmosphere, and the speed with which the trough moves (Mason and Jury, 1997). The Namib region in particular will benefit when additional moisture is added from the eastern tropical Atlantic Ocean which feeds moisture towards Angola and the Skeleton Coast.

The third system, the **Angola Low**, a shallow heat low, receives low-level westerly moisture flux from the tropical east Atlantic (Reason et al., 2006), which produces a west coast trough and rainfall south of 15°S. In general, the Angolan low develops in October then strengthens through to January and February (Reason et al., 2006), and commonly acts as the source region for the TTTs discussed above (Mason and Jury, 1997; Reason et al., 2006).

Finally, **temperate cold fronts or cut-off low**, disturbances occur in the form of westerly waves and lows, west-coast troughs or smaller scale coastal lows (Tyson and Preston-Whyte, 2001). The westerly waves or mid-latitude cyclones are baroclinic in structure and travel eastward in the mean westerly flow and can be displaced towards the equator out of the basic westerly current (Lindesay, 1998; Tyson and Preston-Whyte, 2001). Cut-off lows are generally associated with some of the heaviest rainfalls and are responsible for many of South Africa's severe flooding events (Singleton and Reason, 2006; Taljaard, 1985). Over subtropical southern Africa and the neighbouring oceans (20–40°S, 10–40°E), cut-off lows have a relatively low rate of occurrence (about 1–2 events each April), while next to the north western coast of South Africa and the southern Namibian coast the rate of occurrence is even lower (Singleton and Reason, 2007). Muller et al. (2008) identified an anomalous cut-off low, which in combination with other factors resulted in a very extreme rain event at Lüderitz (16–23 April 2006/102 mm). This cell reached 20°S. Such events occur in winter and are not convective in nature.

2.2. Introducing and analyzing the Gobabeb rainfall record

The frequency and intensity of rainfall at Gobabeb is remarkably low (Fig. 3a–d, Fig. 5a). Between October 1st 1962 and May 6th 2011 a total of only 1213 mm of rain was collected at Gobabeb (annual average of 25 mm). The 49 year long precipitation record (17749 days, includes 12 missing days) produced 381 days (2% of the observation period) with discrete rain events and 312 days of rain with more than 0.2 mm of rainfall. The annual total rainfall varies between zero (1992) to just over 100 mm for 1976 and 164 mm for 2011 (Note: rainfall recorded for 2011 only covers the first half of the rainy season). April tends to be the wettest month and March home to most of the extreme rain events. Summer rain

before January appears very uncommon while winter rain in August on the other hand is more common. September appears to be the driest month in the 49-year record (Fig. 4). No visible long-term trends are discernible in the data (Fig. 3a–c) and rainfall statistics are very much effected by a skewed and fat tailed distribution generated by series of extreme events (Fig. 3d).

In this paper we further examined the regional synoptic, conditions (represented by 850 hPa geopotential heights) responsible for all rain events covering the window of 1979–2009 and using the NCEP II (National Centers for Environmental Prediction) Re-analysis data. Satellite data was introduced into the NCEP II re-analysis post 1979, markedly increasing its quality in the southern hemisphere which informed the selection of this period of analysis. We use Self Organising Maps (SOMs) (Hewitson and Crane, 2002, 2006), which is a form of objective cluster analysis, depicting the range of synoptic states present for each of the rain producing days. For the purpose of this study, 30 synoptic nodes in a 5 by 6 array were populated with 193 days of rain. At first glance it is evident that almost all synoptic archetypes outlined above have the potential to produce rain. However, many events at Gobabeb can be attributed to the Angolan low, which given its location, is not surprising. Over the last 3 decades (1979–2009), the number of decadal rain days has decreased from 77 to 56 to 54 days, while total decadal rain amount has increased from 130 mm to 149 mm up to 300 mm. Over this period we also witness a distinct shift from winter rain dominance in the 80's to a distinct return of late summer rains in March and April (Fig. 4b). The SOMs analysis suggests intensification in Tropical Temperate Trough activity over eastern Namibia which could have the potential to effect Central Namib rainfall. The SOMs also showed that isolated winter rain events are produced by westerly waves. Such conditions have the tendency to promote cloud cover but seldom produce measurable rain. Virga rain (Fig. 5e), which evaporates before it reaches the ground may be visible during the winter period. While such events play a role in moistening the lower atmosphere they have so far not be quantified.

The most recent heavy rain events listed in Table 1, are convective in nature and in addition to a moisture source, require a mid/upper level instability. On February 25th 2009, the region was subjected to a low-level moisture influx from the Angola low, coupled with instability from a cut-off low over the south coast of South Africa. Remarkably for March 12th 2011, the wettest day on record (49 mm), we see no evidence of strong synoptic forcing. A continental heat low was present and rain would have been evident throughout the Central Namib. On May the 6th 2011, moisture was fed from the northwest as part of a coastal trough and rain was triggered by a ridging anticyclone to the south. Extreme rains events are rare but memorable. The remarkable rains of early 2011, which features the wettest two days on record, transformed the gravel plains into a grass land, and on May the 5th and 6th along with the access roads to Gobabeb, flooded parts of Walvis Bay, Swakopmund and Henties Bay, (<http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50573>) (Fig. 6). It is however quite likely those extreme rain events elsewhere may exceed the amounts measured at Gobabeb to date. For example, the Uniab River flash floods in 2000, triggered by unknown amounts of rain along the Skeleton Coast, were able to cut through 15 km of dunes (Svendsen et al., 2003). Such local, but formative downpours are yet to be recorded at Gobabeb.

Additional rain records, not reported here, are available for the region through various gauges operated by the Namibian Meteorological Services, as part of the global 1st order network, (Table 2, Fig. 1a). A second and denser network has been implemented by the Gobabeb Training and Research Centre (Table 2) as early as October 1962 with focus on the Central Namib gravel plains and the

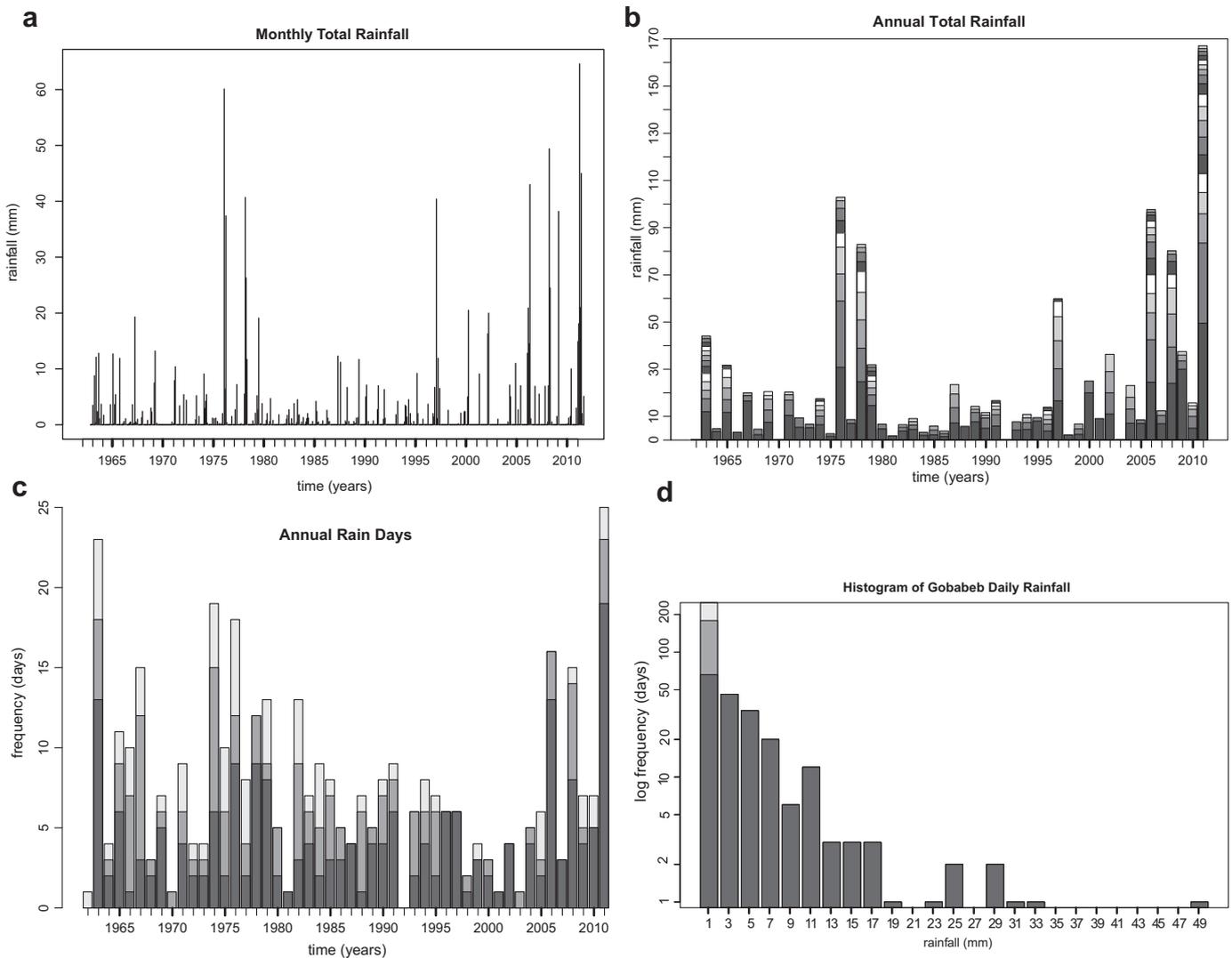


Fig. 3. Gobabeb rainfall data spanning the period from October 1st 1962 to May 6th 2011. a) Total monthly rainfall (ppt >0.2 mm). b) Annual total rainfall (ppt >1 mm). Bars have been shaded to depict total rainfall accumulation per rain day (e.g. 2011 has 19 rain days, while 2000 has 2 rain days). Rain days are stacked from largest at the bottom to smallest at the top. c) Annual total number of rain days. Bars have been shaded to depict intensity. Light bar shows all rain events where ppt >0.1 mm, the mid-grey shows those with ppt >0.2 mm and the dark grey shows those days with ppt >1.0 mm. d) Histogram of daily rainfall amount. The first bar also depicts rainfall intensity. Light grey ppt >0.1, mid-grey ppt >0.2, dark grey ppt >1 mm.

banks of the Kuiseb (Fig. 1b). Data from the earlier autographic drum recorders has been summarized in Lancaster et al. (1984, Table 3). By April 1994 some of these stations had been replaced with automatic Data Loggers (Mike Cotton Systems) which produces hourly data (Henschel and Seely, 2008). The most consistent observation points have been Ganab, Gobabeb, Kleinberg, and Vogelfederberg. Earlier stations featured in Lancaster et al. (1984) such as Flooden Moor, Narabeb Rooibank, Swartbank, Swakopmund and Zebra Pan have been deactivated. Considerable records are also available for Hamilton Berg and Welwitschia Flats. Additional brief weather observations were collected by Gobabeb and are available for the following site: Conception Highway, Delta Channel, Double Three, Dune 7, Dune 8, Dune Substation, Gamsberg, Garnet Hill, Gobabeb Airstrip, Haalenberg, Homeb, Koichab Pan, Kolmanskop, KP25 Station, Lüderitz Airport, Mirabib, Mniszechis Vlei, Möwe Bay, Nara Valley, Nisbet's Nook, Sleepy Hollow, The Midden, Ugab, Uniab, Visitors Dune, Walvis Bay, Weissenhorn, Welwitschia Flats, Welwitschia Wash and Wolwedans.

Approximately a hundred research projects have made use of these records (Seely *pers comm*) in one form or another. Some

studies also produced additional transects and precipitation records such as Hachfeld and Jürgens (2000), Soderberg (2010). A recent transect even features 60 gauges, with a 5 km interval between Windhoek to Gobabeb, showing not only the overall trend of rainfall from west to east, but also considerable variability over short distances (Figs. 1b and 2).

Rain is clearly an unreliable addition of moisture which is dependent on remote sea surface temperature conditions and as far as the Namib Desert is concerned, anomalous synoptic configurations. Fog is of local origin and mechanisms which are needed for its production are much more readily met.

3. Part 2) Fog

3.1. The climatology of Namib Desert Fog

While quasi-stationary cold upwelling cells in the Atlantic and associated inversion layers prevent local convective rain, they are very efficient and consistent in sustaining coastal fog, a relatively high humidity and associated dew. The Namib Desert along with

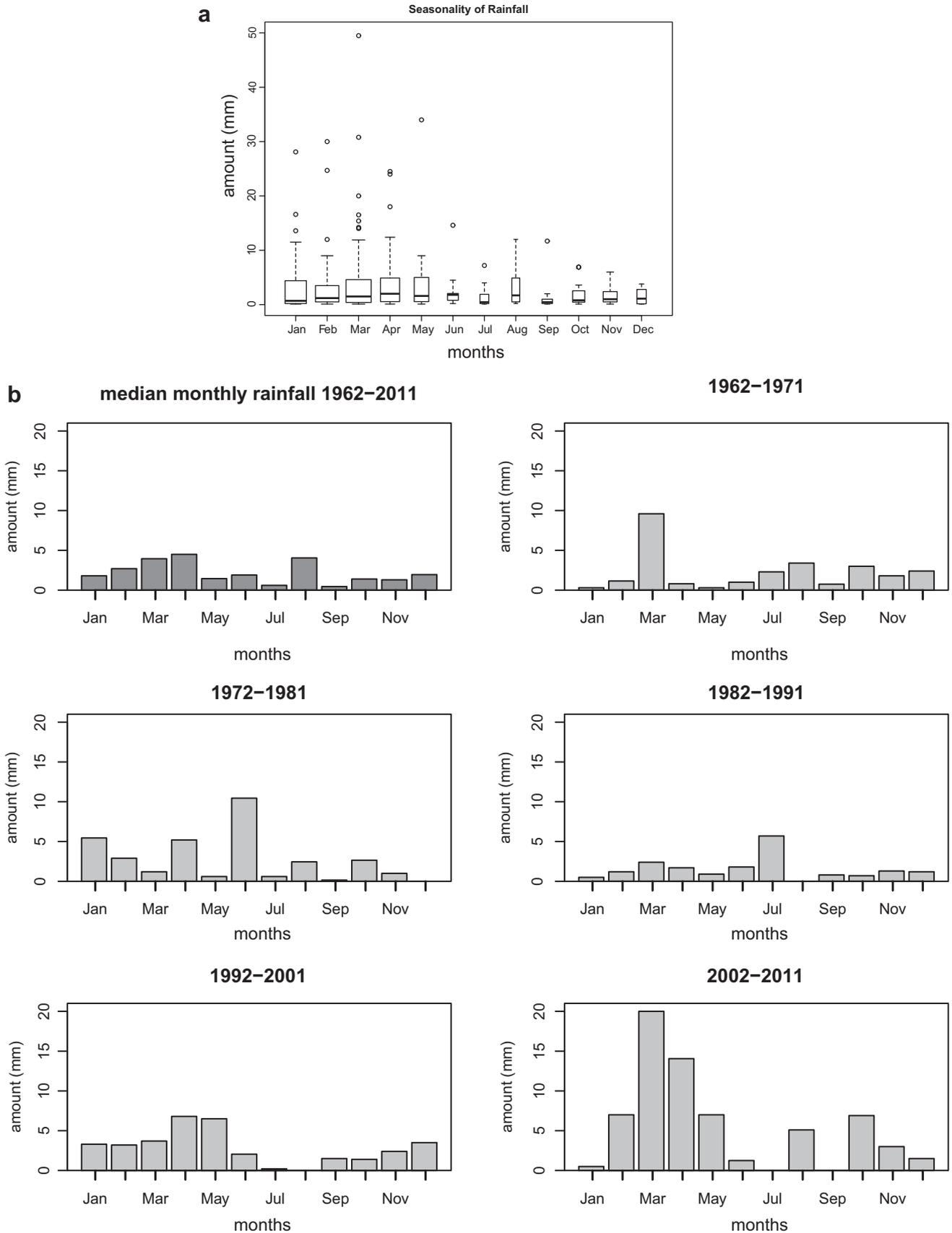


Fig. 4. a) Seasonality of rainfall (ppt >0.1) October 1st 1962 to May 6th 2011. Median represented by dark solid line, box represents the 1st and 3rd quartile range. The boxes are drawn with widths proportional to the square-roots of the number of observations in the groups. The whiskers extend to the most extreme data point which is no more than 2 times the inter quartile range from the box. Circles represent outliers. Number of observations per month: Jan – 58, Feb – 70, Mar – 81, Apr – 47, May – 27, Jun – 15, Jul – 10, Aug – 8, Sep – 14, Oct – 19, Nov – 25, Dec – 11. b) Median rainfall distribution for overall record and temporal decadal subsets.

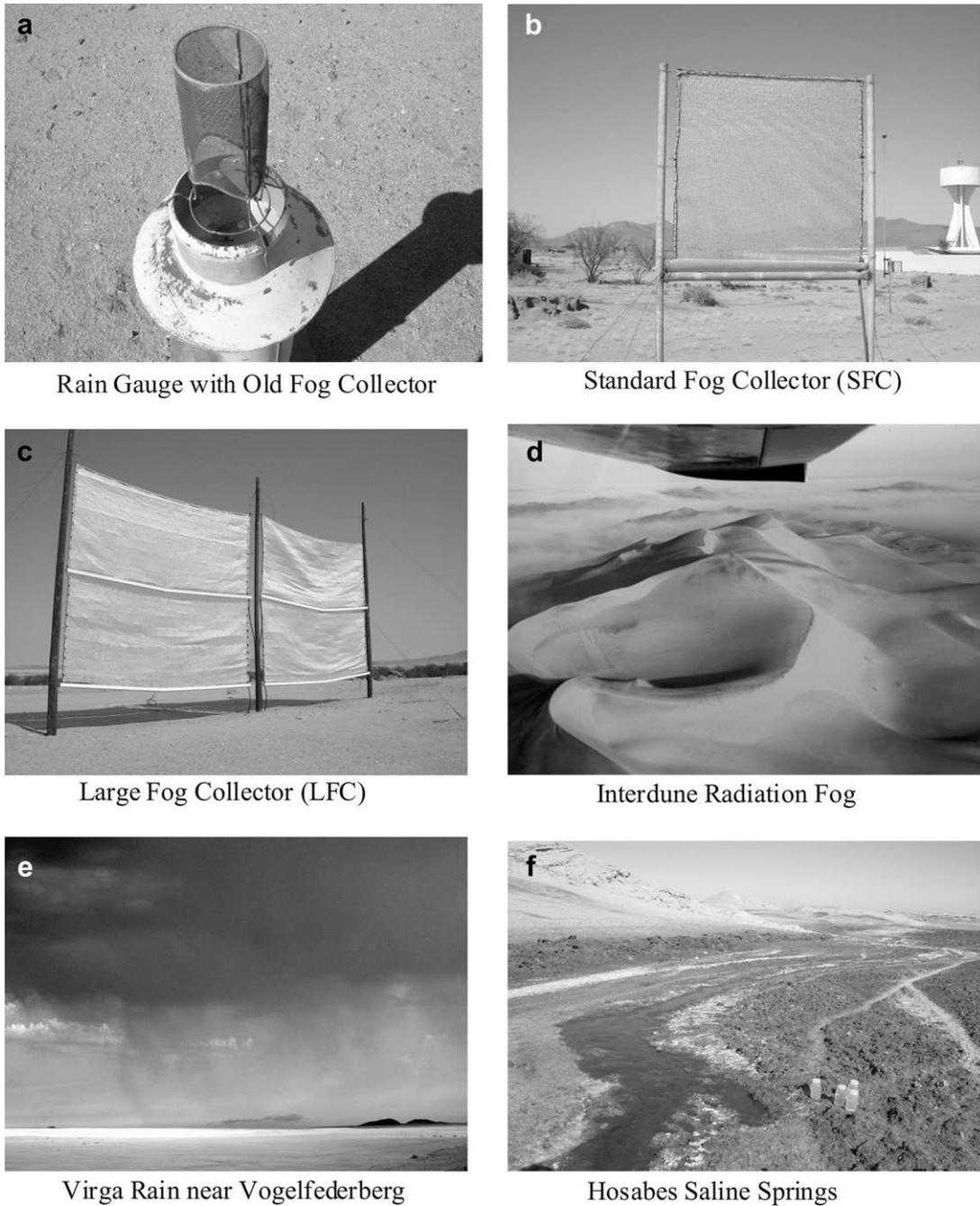


Fig. 5. a) Standard Rain Gauge with Old Fog Collector b) Standard Fog Collector (SFC) c) Large Fog Collector (LFC) designed for fog water harvesting. d) Interdune Radiation Fog south of Gobabeb (October 1995) e) Virga Rain near Vogelfederberg (September 1995) f) Hosabes Saline Springs near Gobabeb (All Photos: Frank Eckardt).

the Atacama Desert, Baja California and Omani and Yemeni arid coastlines are home to sporadic desert rains which are augmented by significant coastal fog precipitation. Low stratus clouds are closely associated with cold Benguela upwelling waters, which may

determine the occurrence and extent of the low stratus clouds (Olivier and Stockton, 1989). Once these clouds reduce visibility at sea or ground level to less than 1 km, they would be classified as fog. During the day, low stratus clouds hug the coastline; however

Table 1
Top 5 wettest years, months and days for Gobabeb.

Ranking	Wettest Years	Wettest Months	Wettest Day
1	2011 (Jan–May only) – 163.5 mm – 23 days	Mar 2011 – 64.5 mm – 3 days	12/03/2011 – 49.5 mm
2	1976 – 105.8 mm – 12 days	May 2011 45 mm – 3 days	06/05/2011 – 34 mm
3	2006 – 99.2 mm – 16 days	Jan 1976 – 60.1 mm – 6 days	30/03/1976 – 30.8 mm
4	1978 – 84.9 mm – 12 days	Mar 2008 – 49.4 mm – 6 days	15/02/2009 – 30 mm
5	2008 – 83.4 mm – 14 days	Apr 2006 – 43 mm – 3 days	21/01/1976 – 28.1 mm

All these stats above use the 0.2 mm as the threshold for rain.



Fig. 6. May 5th 2011, late afternoon, rain cloud and associated downdraft near Rooikop. Total observed accumulated rainfall at Gobabeb on May 6th was 34 mm. The second wettest day on record. Also refer to links below. (<http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50573>). (http://www.youtube.com/watch?v=220BFp_j1e4). (Photo and Video: Frank Eckardt).

during the afternoon they are advected into the desert interior. Satellite imagery has shown that such stratus clouds are most prevalent in the central section of the coastal Namib Desert (Olivier, 1995). Low cloud and fog are very common at the coast and on occasion may reach the foot of the escarpment (<10 days per annum). One has to remember that stratus clouds do not always produce fog or precipitate since they do not always intersect the terrain. In particular higher stratus clouds or “high fog” at 100–600 m above sea level may have to travel between 20 km and 60 km from the coast, to intersect terrain. High fog, the most common type of fog at Gobabeb, arrives during early morning hours and dissipates quickly with sunrise.

There are four types of fog: advected coastal stratus, high stratus cloud, radiation fog (Fig. 5d) and fog drizzle. Advected coastal stratus or fog enters the desert with the prevailing south westerly breeze but remains at elevations of less than 200 m and is thereby restricted to the immediate coastal belt and is common at Walvis Bay and Swakopmund. Secondly, higher stratus cloud or fog, more common in the desert interior between September and March, is

capped by the Namib inversion layer. It enters the desert mostly from the NW in the form of cloud, then tends to mix with the lower easterly airflow from the interior which results in a surprising SSW to S vector for resulting fog events as observed at Gobabeb (Seely and Henschel, 1998). Observers often assume that fog sitting solely in river valleys was advected inland. This however appears to be radiation fog which most likely is the third type of fog. Radiation fog forms in situ and tends to be more localized and restricted to topographic lows such as dry river valleys, interdune corridors, as well as Tumas and Tinkas flats. Radiation fog is fed by clear moist air rather than low stratus cloud. A fourth but rare type consisting of fog drizzle has been associated with the passing of winter cold fronts (Seely and Henschel, 1998).

3.2. Measuring fog precipitation

Measuring rainfall accurately is limited by the number of rain gauges one deploys. There are some additional considerations required when sampling fog, which does not simply settle out of

Table 2
Major weather stations operated by the Gobabeb from 1962 until present. Note transition and focus shift from autographic recorders to data loggers as well as introduction of dedicated small fog collectors (SFC).

Weather Stations	Lat	Lon	Autographic Recorder	Data Logger	SFC
Flodden Moor	–23.617	15.000	Feb'79–Nov'82		
Ganab	–23.123	15.538	Jan'68–Aug'93	Nov'90–present	Feb'97–pre
Gobabeb Dune	–23.584	15.028	May'80–1983		
Gobabeb Station	–23.561	15.042	Oct'62– unknown	Dec'93–present	Jul'96–pre
Hamiltonberg	–23.023	14.853	Jun'82–May'93		
Kleinberg	–23.016	14.724	Jun'82–Apr'93	Jul'94–present	Dec'96–pre
Klipneus	–23.400	14.917			Sep'96–'01
Narabeb	–23.783	14.783	Nov'72–Mar'87		
Rooibank	–23.183	14.633	Jun'66–Apr'83		Sep'96–'01
Swakopmund	–22.679	14.525	Feb'67–Jan'76		
Swartbank	–23.333	14.833	Jul'69–Apr'83		Oct'96–'01
Vogelfederberg	–23.103	15.028	Aug'78–Apr'93	Jul'90–present	Dec'96–pre
Zebra Pan	–23.500	15.517	Nov'89–Nov'93		

Table 3

Monthly rainfall in mm from autographic recorders covering period from 1962 to 1981 (Source: Lancaster et al., 1984).

Location	Jan	Feb	Mar	Apr	Mar	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Flooden Moore	0.0	0.4	0.0	0.7	0.9	0.9	0.0	0.0	0.0	0.4	0.0	0.1	3.3
Ganab	21.6	15.5	32.0	9.0	1.2	0.8	0.0	0.8	0.0	0.2	2.7	3.2	86.9
Gobabeb	5.5	4.6	6.7	3.3	0.3	1.6	1.1	1.7	1.1	0.5	0.6	0.4	27.2
Narabeb	1.5	2.5	4.7	4.6	0.0	5.0	0.3	1.1	0.2	0.2	0.2	0.0	20.4
Pelican Point	1.8	2.6	7.0	0.5	0.3	1.2	0.0	0.3	0.1	0.2	1.2	0.1	15.2
Rooibank	1.9	1.5	8.1	1.6	0.1	2.0	0.7	0.8	0.1	0.1	0.1	0.0	17.0
Swartbank	2.7	4.6	3.7	2.0	0.1	2.2	0.0	1.7	0.0	0.5	0.8	0.5	18.8
Vogelfederberg	0.4	0.5	1.4	0.6	0.0	15.5	0.0	3.1	0.0	0.0	0.0	0.0	21.5
Zebra Pan	1.6	0.0	0.1	1.6	0.2	10.1	0.0	4.0	0.1	0.4	0.1	0.8	18.9

the atmosphere under the influence of gravity, instead suspended fog droplets coalesce on surfaces. Fog may on occasion produce drizzle and also promote the onset of dew as relative humidity increases during such an event. The net effect for the flora and fauna may be the same, however, the amount of precipitation measured depends on the density of the fog, the direction and speed at which it moves and the type of surface it interacts with.

Between 1962 and 1996, Gobabeb monitored fog using a cylindrical metal screen (10 cm diameter, 22 cm tall) to direct fog into typical rain gauges attached to an autographic recorder (Fig. 5a). In 1996 these were replaced by the Standard Fog Collector (SFC) (Fig. 5b). This uses a double layer of mesh in a 1 m² frame mounted 2 m above ground (Schemenauer and Cereceda, 1992b) (Table 2). These two instruments correlated relatively well ($r^2 = 0.62$, Henschel et al., 1998) but the differences underline the fact that fog measurements are very much instrument dependant. Fog precipitation records are either taken manually by the Topnaar Communities along the Kuiseb River at Klipneus, Rooibank and Swartbank or the collectors are connected to a Davis Rain-o-Matic tipping bucket fog-water gauge as part of current Gobabeb Centre's weather stations at Ganab, Gobabeb, and Kleinberg, Vogelfederberg. The properties of the mesh (polyethylene net with a 35% shade coefficient), the fog frequency and density, the wind speed and the orientation of the SFC with respect to fog movement, will determine the final fog yield. A detailed analysis of the fog record remains to be undertaken, but would require a different approach and consideration compared to the rain record analysis and results outlined above. Dew has been recognized as equally important: hence a standard dew collector (SDC), an inclined metal plate with a trough, is now operational at Gobabeb.

A short-term study by Hachfeld and Jürgens (2000), on the vegetation-climate relationship saw the implementation of two 120 km transects between Swakopmund and Usakos and Henties Bay and Uis. In addition to the use of five automatic weather stations, numerous rain and fog collectors were deployed. These consisted of 1 L plastic bottles with a 15 cm diameter funnel to collect rain, or 45 stainless steel wires 35 cm in length to collect fog. Both had an addition of oil to prevent any precipitation from evaporating. The study showed that fog usually did not extend beyond 50 km from the coastline and only rarely penetrated to about 70–75 km distance. Fog within the first 30 km can largely be attributed to the advective type which also produces fog drizzle; while high fog dominates 25–50 km. Maximum total annual fog precipitation of around 65 mm is observed 35 km from the coast. At 55 km distance precipitation drops significantly to 30 mm. Rain only gradually increases to reach around 60 mm at a distance of 110 km from the coast. Resulting trends for number of species per area and total % canopy cover in the above mentioned transects are slightly higher near the coast, then decrease between 50 and 80 km from the coast to then increase steadily towards the foot of the escarpment. While the two moisture gradients have the potential

to overlap, they each produce distinct vegetation zones. Near the coast lichens and leaf succulents dominate due to fog input, this is followed by a “minimum” zone featuring ephemeral species (including grasses) which respond to sporadic rain events, after which a gradual transition from desert to savanna vegetation dominates as rainfall becomes a more reliable source of moisture (Hachfeld and Jürgens, 2000).

3.3. Namib fog water chemistry

Previous measurements on fog water chemistry reported high dissolved loads (Besler, 1972; Boss, 1941; Goudie, 1972), which supported the notion that fog was a significant vector of marine sulphates, in particular H₂S towards the paedogenic gypsum crust formation in the Namib (Martin, 1963). The Canadian Atmospheric Environment Service collector (AES) (Falconer and Falconer, 1980), designed to sample for chemical analyses, in particular for quantifying acid deposition in industrial regions, has also been deployed in the coastal and foggy deserts of Oman (Schemenauer and Cereceda, 1992a), Chile (Schemenauer and Cereceda, 1992b) and Namibia (Eckardt and Schemenauer, 1998). The AES collector consisted of 370 ultra clean, Teflon Fluorocarbon Monofilaments (0.5 mm) vertically mounted between two polypropylene plates (48.5 cm), which feed water into a clean funnel and collection bottle. Average total ion concentration for 7 collections was only 14.5 ppm. Three 24 h dry aerosol collections with the AES on the other hand, produced average rinse loads of 151.3 ppm. The Namibian AES samples were among the cleanest ever obtained (Schemenauer *pers. comm.*), which suggests that previous findings were the result of dry aerosol contamination on collection surfaces leading up to the fog water sampling. Later work by Eckardt and Spiro (1999) also showed that dry marine aerosol deposition in the form of CH₃SCH₃ (Dimethyl sulphide DMS) and aeolian reworking from evaporation points on the plains was a more likely source for gypsum crusts (Eckardt et al., 2001). Two rain events collected with AES were even cleaner and produced an average total concentration of 8.11 ppm (Table 4). While fog is important in maintaining coastal vegetation, its role in shaping paedogenic processes and accumulations appears less significant.

Two AES water samples were also analysed for their isotopic signature (Eckardt, 1996). An advective fog sample, originating from a SW direction and collected close to the coast produced $\delta^{18}\text{O}$ (−0.86, −0.39‰) and δH (+0.8, +3.3‰) values comparable to coastal fog from Chile (mean $\delta^{18}\text{O}$ −1.8‰ and mean δH −3.2‰, (Aravena et al., 1989)). The proximity of these values to Standard Mean Ocean Water (SMOW) values stresses their direct marine atmospheric origin. A second fog water sample originating from a northerly direction and sampled at Gobabeb, which could be described as a “high fog” event, produced heavier $\delta^{18}\text{O}$ (−6.06‰) and δD (−40.5‰) values, surprisingly in line with Namibian ground and rainwater. Isotopic variability beyond anticipated SMOW

Table 4
Atmospheric Environment Service (AES) samples for fog and rainwater chemistry. A comparison between Namibia, Chile, Oman.

	Namib	Namib	Namib	El Tofo, Chile	Jebel Al Qara, Oman
Sample Type	Fog	Dry	Rain	Fog	Fog
Distance to Ocean	20–40 km	50 km	50 km	5 km	15 km
Altitude	200–430 m	200–430 m	430 m	780 m	900 m
n	7	3	2	7	7
pH	6.24	6.35	5.82	4.65	7.44
TDS	14.52	151.3	8.11	31.31	103.76
SO ₄	3.19	18.68	1.9	12.34	3.39
NO ₃	0.4	3.01	1.14	1.62	4.66
Cl	4.83	67.29	1.3	8.71	44.11
Na	2.87	41.25	0.79	5.37	24.09
K	0.23	1.77	0.34	0.34	1.09
Ca	1.19	12.85	0.84	0.97	12.97
Mg	0.39	4.09	0.34	0.73	2.5
HCO ₃	0.65	2.09	0.22	0	10.75
NH ₄	0.91	0.27	0.94	1.24	0.22

values for fog was also observed by Soderberg (2010), who sampled a total 35 fog events. The source of such ‘heavier’ moisture is not clear but would suggest that the simple classification of advected fog, high fog and radiation fog, may in fact require a more gradual continuum, which not only takes into account stratus clouds and local winds but also a mixing of various moisture sources including micro meteorological dynamics.

3.4. The importance of fog to the Namib Desert environment

Fog plays an integral part in the Namibs hydrological cycle (Hamilton and Seely, 1976; Seely and Hamilton, 1976). In addition to the lichens, common perennial grass species of the Namib dunes – the *Stipagrostis sabulicola* and the leaf succulent shrub *Trianthema hereroensis* – have been shown to take up fog deposited on the sand surface and leaves, respectively (Ebner et al., 2011; Louw and Seely, 1980; Seely et al., 1977). The gravel plains shrub *Arthroa leubnitziae*, common within about 50 km of the coast, has also been shown to take up fog and dew water through ecophysiological measurements of individual plants (Ebert, 2000; Loris, 2004).

Recent stable isotope data ($\delta^2\text{H}$, $\delta^{18}\text{O}$) has further confirmed fog/dew water uptake by other plant species (Soderberg, 2010). Plants of various sizes and at distances from the coast (10–50 km) showed contributions of fog/dew to stem water of $41 \pm 30\%$ (*S. sabulicola*), $37 \pm 11\%$ (*T. hereroensis*) and $18 \pm 26\%$ (*A. leubnitziae*). Of the other six species investigated – three tree species from the Kuiseb River (*Acacia erioloba*, *Faidherbia albida*, *Tamarix usneoides*), a shrub from the gravel plains (*Zygophyllum stapfii*), and the well known Namib endemics *Welwitschia mirabilis* and *Acanthosicyos horridus* (Inara melon) – only *Z. stapfii* showed any fog/dew contribution ($5 \pm 24\%$), which was statistically similar to *A. leubnitziae* ($p < 0.05$). The lack of an isotopic fog/dew signal in the *Welwitschia mirabilis* stem samples ($n = 13$) (Soderberg, 2010) is consistent with the long-term observations linking the growth and health of this plant to rainfall rather than fog deposition (Henschel and Seely, 2000). Fog and dew are important sources of water for certain vegetation of the Namib, however rainfall and groundwater availability are often the primary determinants of species distribution (Schachtschneider and February, 2010).

Concomitant measurements of $\delta^{34}\text{S}$, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ in the plant material indicate some effects of fog on nutrient cycling (Soderberg, 2010). The $\delta^{34}\text{S}$ values indicated increased delivery of marine sulphur with fog uptake, and the $\delta^{15}\text{N}$ of C3 plants decreased

towards the coast in an apparent reversal of the negative correlation with precipitation found in the Kalahari (Swap et al., 2004). Interestingly, the $\delta^{13}\text{C}$ of *W. mirabilis* increases towards the coast (-24.2% to -17.4%), indicating an increase in CAM-cycling due to water stress even in areas which receive frequent fog (Schulze, 1969; Schulze et al., 1976; Soderberg, 2010; von Willert et al., 2005). Non-vascular plants also benefit from fog/dew deposition. For example, this regular water source more than doubles the dry mass of lichens, allowing them to be photosynthetically active for a brief period in the morning after a fog or dew event (Lange et al., 2007). The lichens and biological soil crusts also play an important role in stabilizing desert soils as well as in primary production and nutrient cycling (Lalley and Viles, 2005).

3.5. Harvesting fog water

Fog mesh collectors have also been scaled up to collect fog water successfully in the coastal deserts of Peru, Yemen and Chile (www.fogquest.org). Currently there are fog collection projects in countries as widely separated as Nepal, Guatemala and South Africa. One of the first operational arrays at El Tofo in Chile featured 100 Large Fog Collectors (LFCs) (Fig. 5c) with a total area of 4800 m² of mesh and is able to produce an average of 15000 L of water per day. At Klipneus, on the banks of the Kuiseb, the mean annual quantity of water collected by an SFC is approximately 1 L/m²/per day, which is a low, but useful water production rate. Scaling this up to 1200 m² (30 LFC \times 40 m²) would in theory meet the minimum total daily requirement of 1200 L, sustaining a village including 13 People, 50 Goats, 20 Donkeys, 16 Cattle, 7 Dogs and 30 Chickens (Henschel et al., 1998; Shanyengana et al., 2002). The higher yields in Chile can be attributed to the steep coastal mountain barrier which channels advective fog into narrow canyons where subsequent fog deposition is more efficient than in the Namib. In addition fierce easterly Bergwind storms, common in the Namib, can stretch and tear the mesh and ultimately even break 15 cm thick wooden poles that support the LFC. Either lowering the mesh in times of high winds or the construction of smaller LFCs could mitigate these problems. The latest fog collection initiative considers the use of artificial dune grass hummocks, since its stemflow (*S. sabulicola*) has proven to be very effective at channelling fog droplets into the sand. A medium sized mound of grass appears to collect as much as 4 L of fog water per event (Roth-Nebelsick et al., 2010).

4. Part 3) Gravel plain springs

About 7 km north of Gobabeb, lies Hosabes; a spring which was first described by Day and Seely (1988) (Fig. 5f) and is generally rather saline with a dissolved load of 200 g/l. It manifests perennial flow between 0.22 and 0.75 L/s (0.012–0.023 m/s). Permanent water pools and fresh water springs are found within the riparian oasis of the ephemeral highland drainage (Day, 1990). Saline springs such as Hosabes, can be found in between the highland drainage systems, in particular the gravel plains. A survey on the aquatic fauna of the Namib demonstrated that the saline springs support the least number of taxa, many of which are arthropods (Day, 1990). A wider, southern and west African survey on saline waters, which consisted of 67 Namibian water samples, including: boreholes, river springs and pools, demonstrated that Namib saline springs, were amongst the most saline systems in sub-Saharan Africa (Day, 1990, 1993). A follow up survey of saline sites north of the Kuiseb in 1993 and 1994 by Eckardt (1996) clearly underlined the perennial nature of these systems; if one also considers some of the archaeological evidence, these sites may have been in place for a considerable period of time (Kinahan pers. comm.) and may have

been less saline in the past. These saline springs are not chemically different from the coastal pans, many of which are barely above sea level (Schneider and Genis, 1992). In fact, the strontium and sulphur isotopic composition for saline water in the Namib, including the coastal pans, showed no marine water signal but considerable bedrock and marine aerosol contributions (Eckardt, 1996; Eckardt and Spiro, 1999).

The ephemeral rivers on the other hand, traverse the Namib and generally have their headwaters to the wetter east of the escarpment. Surface flow is short lived; the resulting groundwater flow occurs at depth, recharging many of the coastal aquifers in particular the Kuiseb and Omaruru alluvium and associated fans which are crucial for coastal water demand. Groundwater derived recharge at Sossusvlei and Tsondabvlei also traverses much of the sand sea at depth (Hellwig, 1968), presumably taking advantage of buried palaeochannels and the porous nature of the Tsondab sand stone. It is therefore not surprising that fresh water springs have been described along the sand sea coast.

This is in stark contrast to the gravel plains, where shallow and low volume groundwater follows the 1% gradient of the plains, accompanied by evaporation rates of a hyper-arid environment. The plains north of the sand sea have a thin Tertiary cover and are crossed by dolerite dykes as well as the NE-SW trending Damara Orogen which traverse the drainage pattern. Hence these geological obstructions cause gravel plain groundwater to pond (Eckardt et al., 2001; Eckardt and Drake, 2011), and at locations such as Hosabes (Fig. 5f), even sustain surface flow. A dedicated remotely sensed survey, making use of the absorption characteristics of salts in the mid infrared waveband region, revealed several hundred saline accumulations points between the Kuiseb and Ugab Rivers. The historic name, Poachers Fountain, for one of these locations is not incidental and it is indeed not uncommon to find gemsbok, springbok or ostrich upon approaching some of these gravel plain springs. Fresh water may be stratified above the brine (Day and Seely, 1988) or have had little time to evaporate and little contact with pre-existing salts.

However water quickly becomes saline and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and halite (NaCl) precipitates are common. Such accumulations have on occasion been prospected, such as Eisfeld pan and mined at Ehrhorn pan, north east of Swakopmund (Schneider and Genis, 1992). Traces of sylvite (KCl) and nitrates including the rare humberstonite ($\text{Na}_7\text{K}_3\text{Mg}_2(\text{SO}_4)_6(\text{NO}_3) \cdot 6\text{H}_2\text{O}$) have also been found (Eckardt et al., 2001). The concentrated near surface flow of groundwater over geological timescales has also promoted the accumulation of secondary paedogenic uranium deposits in the Namib (Carlisle, 1978). Namib uranium is currently extensively prospected and mined with focus on the primary ore deposits, as well as the secondary paedogenic accumulations associated with the calcrete and gypcrete of the gravel plains.

Recent sampling efforts have also identified perchlorate (ClO_4^-) as a minor constituent in Namibian saline waters and associated crusts (Rao et al., 2010). Interest in this inorganic anion stems from its role as an agricultural and industrial groundwater pollutant. The application of nitrate fertilizers from the Atacama Desert and the production and decommissioning of explosives and solid rocket motor fuels has led to relatively high perchlorate levels in surface and groundwaters; (Dasgupta et al., 2006) and to a lesser extent, the use of nitrate fertilizers from the Atacama Desert which contain natural (ClO_4^-) as a minor component (Böhlke et al., 2009). Indigenous natural (ClO_4^-) has been identified across North America (Rao et al., 2007; Rajagopalan et al., 2009), and in soils of Antarctica as well as the Phoenix Lander site on Mars. Efforts of placing Namibian (ClO_4^-) into this wider context are currently underway, with dedicated sampling of soils and water having been completed (Jackson *pers. comm.*).

5. Part 4) Vapour and micro-scale moisture

Despite, or because of the hyper-arid environment, understanding the spatial and temporal occurrence of water is essential if one is to account for floral and faunal ecological adaptations and population dynamics. Measuring rainfall and its variability accurately is hampered by the number and length of time that rain gauges are deployed. Collecting rain itself is relatively straight forward since drops simply settle out under the influence of gravity. Estimating fog precipitation on the other hand is much more dependent on the design of the fog collecting device, its surface characteristics and the nature of the fog. Adequately distinguishing fog from dew is also challenging and not yet systematically done. Techniques to measure the net delivery of moisture at the micro-scale are however improving using leaf wetness moisture sensing kits (Soderberg, 2010) and miniature ibutton relative humidity data loggers (Cowan *pers comm.*).

Interesting results from such instrumentation have come out of the Atacama Desert, where the topographic fog barrier to the west (2500 m high) and rain barriers to the east (>4000 m) has created areas with extremely limited moisture availability. Yungay, situated within a basin at an elevation of 1050 m, ~60 km from the coast, receives less than 2 mm of rain per annum (Warren-Rhodes et al., 2006). The occasional humid sea breeze appears to offer the only reliable source of moisture. Hence, rock dwelling hypoliths are virtually absent and the only significant forms of life documented are endolithic cyanobacteria existing in hydrated salt crusts (Davila et al., 2008; Wierzchos et al., 2006).

In April 2010, the spaceward bound initiative ([www://quest.nasa.gov/projects/spacewardbound/](http://www.nasa.gov/projects/spacewardbound/)) applied micro sensors to the study of hypoliths living under the translucent quartz gravels of the Namib plains. Possibly due to the overlapping rain and fog gradients, hypoliths are widespread with uniformly high populations. Detailed surveys and species distribution analyses have yet to be undertaken (Warren-Rhodes and McKay *pers. comm.*). Multiple 'non-rainfall' sources of moisture to hypolithic communities are being investigated, including: fog, dew, atmospheric water vapour and high soil humidity derived from evaporated ground water transported to the surface (Cowan *pers. comm.*). Recent short-term monitoring of sub-surface soil humidities in the Namib Desert suggests an ample supply of water, at least in the gaseous form (Kaseke, 2009; Warren Rhodes *pers. comm.*). Although condensation under rock surfaces occurs, it is not clear how often this moisture is available to biological systems. Some organisms, most notably lichens, are capable of directly absorbing gaseous H_2O .

The label hyper-arid is applied to both the Namib and Atacama Deserts and as this article has demonstrated, there are indeed some parallels between the two. However, the passive tectonic margin environment of the Namib has produced gentle topography and relatively moderate climatic conditions, which is in stark contrast to the Atacama Desert, where focus has been on global extremes. Research at Gobabeb on the other hand, has established the existence of an intricate water based economy (Henschel and Seely, 2008), largely maintained by fog and dew collection on surfaces, including living surfaces, consumption of moist food and the absorption of water vapour. We can conclude that rainfall variability at Gobabeb is determined by regional synoptic switches, in particular the Tropical Temperate Trough; secondly, fog may not only depend on Atlantic moisture; and thirdly, ambient sub-surface humidity on the plains may not be as low as one would have anticipated. A possible link between the last two observations cannot be discounted.

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