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# Spatial Variation of "Non-Rainfall" Water Input and the Effect of Mechanical Soil Crusts on Input and Evaporation

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*Abstract*—"Non-rainfall" water is important to the soil water balance and ecology of arid ecosystems. A component of this "non-rainfall" water in the Namib Desert, fog, exhibits spatial variation implying variability in composition and significance of each vector (dew, fog, vapour adsorption) to ecology at different locations. The composition of "non -rainfall" water input directly into soil was investigated at two sites in the Central Namib Desert, Kleinberg and Gobabeb. Results showed spatial variation in composition between the sites, although vapour adsorption dominated input at both sites. Fog contributed more to total "non rainfall" atmospheric water closer to the coast (Kleinberg) compared to further inland (Gobabeb) but was lower than expected at both sites. Absolute values of fog input at both sites showed the opposite trend, Kleinberg 0.38 mm per night compared to Gobabeb 8.7 mm per night. This difference was attributed to the development of a mechanical crust on the soil surface at Kleinberg, which resulted in a significant reduction of vapour adsorption compared to Gobabeb. The crust also led to a significant reduction in evaporation from the sample at Kleinberg compared to the one at Gobabeb. Ecological differences between the two sites can be attributed to the development of the soil crust on the sample at Kleinberg and not on the sample at Gobabeb.

**Key words:** "Non-rainfall" water, dew, fog, evaporation, soil crusts, spatial variation.

## 1. Introduction

"Non rainfall" atmospheric water input into soil is supplied via three vectors, namely: fog, dew and vapour adsorption (Agam and Berliner, 2006). In hyper-arid environments, such as the Namib Desert, these atmospheric water sources enable life for the endemic flora and fauna (Henschel and Seely, 2008). Shanyengana *et al.* (2002) reported that advective fog in the Central Namib Desert decreases along a west-east gradient with increasing distance from the coast. The direct influence of fog in this desert is thus restricted or most visible in the fog zone, which extends to about 60 km inland from the Atlantic Ocean. This fog west–east gradient suggests variation in composition of "non-rainfall" water input directly into soil and implies that advective fog would play a more significant role in soil micro-hydrology and ecology closer to the coast than further inland.

According to Olivier (1995), advective fog is the dominant fog process along the west coast of southern Africa and is considered a vital water source for endemic flora and fauna of the Namib Desert (Seely, 1979). Namib fog displays seasonal and spatial variations (Henschel *et al.*, 1998), while Ingraham and Matthews (1995) demonstrated seasonal use of fog input by conifers at Point Reyes Peninsula, California. Advective fog is a major nutrient depositor to natural spruce forest ecosystems and generally ion concentration is influenced by the origin of the air mass (Thalman *et al.*, 2002). Fog ion concentration has also been reported to be higher than in rain water (Dasch, 1988; Collett *et al.*, 1993; Schemenauer *et al.*, 1995) and according to Eckardt and Schemenauer (1998) Namib fog-water has an enrichment factor of 17.3 for calcium, 5.8 for sulphates and 2.3 for potassium relative to sea water. Therefore, apart from supplying moisture to the arid Namib soil system, fog could also be a vital nutrient supplier to the ecosystem. However, there is very little if any direct

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fog deposition onto the soil surface and fog movement inland is limited by the arid nature of the new soil surface resulting in dissipation downwind (Desmet and Cowling, 1999). Thus fog inputs may vary depending on location and could significantly impact and influence soil fertility and productivity resulting in marked ecological differences between sites within the fog zone.

Lange *et al.* (2006) reported that some Namib Desert lichens are photosynthetically activated by high humidity and distribution of these lichens is related to humidity and fog frequency in this desert. Prado and Sancho (2007) reported that *Teloscites lacunosus*, a lichen species in the Tabernas Desert of Spain, was only photosynthetically active when rehydrated by liquid water (dew or rain) and that its distribution appeared linked to dew distribution in this desert. According to Ye *et al.* (2007) dew amounts differ from landscape to landscape while Kidron (2000) suggests that distribution patterns may have important ecological implications.

Direct vapour adsorption is a significant feature of environments characterised by high oscillations in relative humidity (Kosmas *et al.*, 1998). Agam and Berliner (2006) suggest that in arid environments, environmental conditions are more favourable to the occurrence of vapour adsorption than dew, thus the former may be more important to the micro-hydrology and water balance of arid soils. It may positively affect rainfed vegetation, thereby protecting extensive mediterranean hilly areas from desertification (Kosmas *et al.*, 1998). The dissipation of fog inland is governed by the aridity of the soil surface and hastened by surface heating (Desmet and Cowling, 1999). However, fog may still indirectly influence soil micro-hydrology via the resulting high humidity from the thinning fog, resulting in more vapour adsorption than fog input with increasing distance from the coast.

According to Agam and Berliner (2006) only a small fraction of the desert landscape is covered by vegetation due to water scarcity—a limiting factor to arid land productivity (Kidron, 2000). To reduce erodibility and erosivity of this vulnerable soil, the desert has replaced vegetation with equally effective erosion control mechanisms: biological soil crusts, desert pavements and mechanical soil crusts. Apart from reducing erosion these mechanisms also play other roles; e.g., Liu *et al.* (2006) suggest that biological soil crusts increase dew input into the soil and Kemper *et al.* (1994) concluded that desert pavements retard evaporative losses from the soil. Apart from acting as soil stabilisers very little is known on the effects of mechanical soil crusts on "non-rainfall" water input, although Jury and Horton (2000) suggested that diffusion is not significantly restricted in dry soil crusts. Therefore, although we know that the surface skin of mechanical soil crusts can significantly reduce water permeability (McIntyre, 1958), we are not aware of any experimental evidence that shows the effect of mechanical crusts on "non-rainfall" water input.

In the absence of coastal advection fog, dew and vapour adsorption might contribute significantly to the soil water balance (Desmet and Cowling, 1999). This study aimed to determine spatial variation and composition of "non-rainfall" water input at two sites in the Central Namib Desert and the effect of location on input (dew, fog, vapour adsorption).

## 2. Materials and Methods

### 2.1. Site Description

Research was conducted at two sites in the fog belt of the Central Namib Desert, Namib Naukluft Park which extends to about 60 km inland from the Atlantic Ocean. The two sites were located on a west–east gradient (decreasing fog, increasing rainfall) and are shown in Fig. 1. Apart from their geographic location, the two sites, Gobabeb and Kleinberg, were selected on the basis that they are existing long term environmental observatories of the Gobabeb Research Centre that roughly typify the west-east fog rainfall gradient characteristic of the Namib, and because the centre has historical climatic data available for these sites and because of the differences in ecology between the sites. According to long term meteorological data from Gobabeb Research Centre, the Namib is classified as a hyper-arid desert. Rainfall is rare, unpredictable and variable in the Namib Desert with the western half of the desert receiving 0–12 mm annually (Henschel and Seely, 2008). The study area is characterised by dry

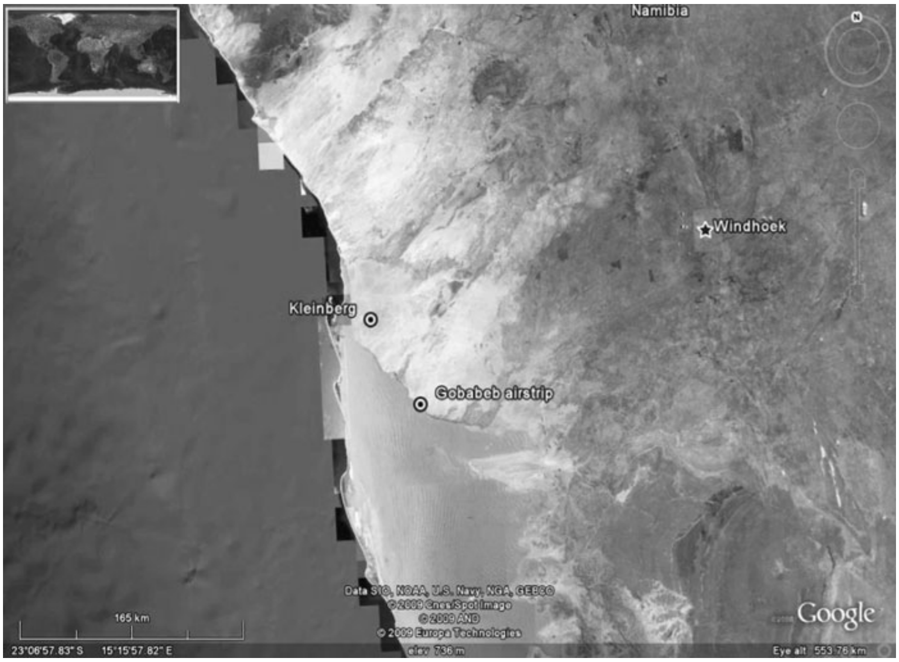


Figure 1
Satellite image of Namibia showing Gobabeb and Kleinberg sites in the Namib Desert

conditions during the day and at night the atmosphere becomes humid due to the SW–NW sea breezes that bring moisture and or fog to the area from the Atlantic Ocean. Therefore, the site experiences high diurnal changes in temperature and humidity.

#### *2.1.1 Kleinberg (S23 01.008 E14 43.439 and Elevation180 m a.s.l)*

The site is located almost in the middle of the fog zone, about 33 km from the Atlantic Ocean. Kleinberg has been a Gobabeb Training and Research Centre long-term environmental monitoring site since 1982 and is dominated by a rich assemblage of lichen fields growing directly on the soil (biological soil crusts), the desert pavement and on branches of the few bushes at the site. Grasses and large mammals are also notably absent from the site. Soils at the site are sandy, strongly saline, calcareous and low in organic matter content, and the profile has a cemented carbonate layer about 15–20 cm from the surface. The lichen encrusted surface is shown in Fig. 2.

#### *2.1.2 Gobabeb (S23 32.311 E15 02.805 and Elevation 412 m a.s.l)*

The site is located in the gravel plains, on the edge of the fog belt, 59.6 km from the Atlantic Ocean. Vegetation comprises a few grasses dominated by the *Stipagrostis* species and the shrub *Zygophyllum simplex*. Soils are sandy, strongly saline, calcareous and low in organic matter content. The soil profile has a cemented carbonate layer 15–20 cm from the surface. The Gobabeb site in the gravel Plains is shown in Fig. 3.

### *2.2. Experimental Setup*

The study made use of the automated load cell microlysimeter method—an in situ method that directly measures mass loss or gain (Heusinkveld *et al.*, 2006) and residence time of water derived from "non-rainfall" sources (Brown *et al.*, 2008) in a sample. The instrument, principles and theoretical considerations for this method are described in detail in Kaseke *et al.* (2011a). The current paper, however,

Figure 2
Lichen encrusted soil surface, Kleinberg October 2008

Figure 3
Desert pavements and *Stipagrostis* grasses, Gobabeb Gravel Plains October 2008

only highlights changes specific to the current experimental set-up specific to this study.

Two microlysimeter units were buried, one unit at each site. Each microlysimeter unit comprised of three microlysimeters, three Dallas Semi-Conductor temperature sensors, a Maxi-Control temperature humidity combo sensor and a common logger specially designed for this study. Soil samples were collected from the upper 5 cm of the Gobabeb Gravel Plains, mixed thoroughly and passed through a standard screen sieve for uniformity. This sample was referred to as the reference soil and sub-samples were drawn from this composite sample and loaded into the loading dishes of the automated microlysimeter units at Gobabeb and Kleinberg until flush with the surrounding surface. The use of sub-samples derived from the same composite sample minimised the influence of soil properties on input and it was thus assumed that the differences in input would be related to micro-climatological differences between

Table 1

*Selected properties of the reference soil sample obtained from the Gobabeb Gravel Plains*

| Properties | EC 2.5 (dS/m) | (%) Sand | (%) Clay | (%) Silt | Texture |
|---|---|---|---|---|---|
| Reference | 1.9 | 91 | 0.6 | 8.4 | Sand |

the two sites. Selected analytical properties of the reference soil are displayed in Table 1. A single temperature sensor was placed on the soil surface of one microlysimeter on each unit, another 20 mm above the soil surface to measure air temperature whilst the humidity sensor sampled 15 mm above the soil surface.

### 2.3. Vector Definitions

There is no international standard for measuring "non-rainfall" water input direct into soil (Zangvil, 1996; Brown *et al.*, 2008) and there are disagreements on the very definitions of the vectors (Noffsinger, 1965; Zangvil, 1996). It is, therefore, important to define the vectors and method of differentiation as applied to this study.

#### 2.3.1 Fog

It is a low cloud or a weather phenomenon composed of water droplets suspended in the atmosphere with its base at the Earth's surface (Fu *et al.*, 2006). According to Agam and Berliner (2006), fog formation occurs when atmospheric humidity approaches saturation independent of surface conditions. Observations at Gobabeb Research Centre using the Maxi Control temperature humidity combo sensor at the soil surface showed that fog occurred at over 84 % relative humidity which was taken as the threshold for fog classification at both Gobabeb and Kleinberg sites.

#### 2.3.2 Vapour Adsorption

It is a reversible interfacial physical process resulting from differential forces of attraction and repulsion between vapour molecules and soil particles (Agam and Berliner, 2006). It occurs as a result of vapour movement from the atmosphere into the soil due to the establishment of a vapour gradient between the two. Direct water vapour adsorption is a significant feature of areas characterised by high oscillations in relative humidity (Kosmas *et al.*, 1998). This study makes no attempt to differentiate the osmotic effect as a result of high soil salinity from vapour adsorption; instead, the combined effect of the two will be referred to as vapour adsorption.

#### 2.3.3 Dew

Dew is the natural condensation of water vapour into liquid droplets on a sufficiently cooled substrate surface (Stone, 1963; Beysens, 1995; Malek *et al.*, 1999). It is a phase transition at the soil–plant-atmosphere interface affecting energy balance (Agam and Berliner, 2006). Dew formation is dependent on the receiving substrate surface characteristics which determine nucleation and growth of the droplets (Beysens, 1995).

### 2.4. Theoretical Differentiation of Input Vectors

Theoretically, conditions conducive for one input vector preclude the others from occurring concurrently (Brown *et al.*, 2008). Dew formation occurs when the receiving substrate surface temperature equals or falls below ambient dew point (Beysens, 1995), and vapour adsorption occurs when a vapour gradient is established between the atmosphere and the soil, independent of dew point temperature (Brown *et al.*, 2008). Therefore, the receiving substrate (soil) surface temperature, according to Agam and Berliner (2006) can be used to distinguish between dew and vapour adsorption input. In the present study, input that occurred when soil surface temperature was below ambient dew point temperature was classified as dew and if temperature was above ambient dew point it was classified as vapour adsorption.

Manual observations of fog events at Gobabeb Research Centre showed that fog occurred at over 84 % relative humidity at the soil surface. Therefore, relative humidity at the soil surface above 84 % was classified as fog, while below this, was considered as vapour adsorption. However, dew formation occurs under high humidity (Agam and Berliner, 2006);

thus, if dew point temperature was attained by the soil surface at a relative humidity above 84 % this was considered as dew and not fog. If dew point was not attained by the soil surface the input was then considered as fog input.

## 3. Results and Discussion

Fieldwork was conducted from mid-February to end of March 2009 and a total of 34 days' worth of analysable data was obtained. ANOVA showed no significant difference in input among the three microlysimeters of each unit and these were averaged to give a single output representative of the sample. The effects of soil type on "non-rainfall" atmospheric water input, vectors and evaporation were tested analysed by repeated measures ANOVA ($\alpha = 0.05$) over the test period.

### 3.1. Net and Total "Non-Rainfall" Water Input

According to Kaseke *et al.* (2011a), there are two methods of calculating "non-rainfall" input into soil using the microlysimeter approach: net and total input. The difference between the two is that,, total input does not take evaporation from the input phase into account while net input takes this into account, resulting in higher total input figures. Total input is therefore a summation of all input during the input phase and is the basis for vector differentiation in this study.

Because Namib fog frequency and intensity decreases in a west–east gradient, it was expected that "non-rainfall" water input into soil would reflect this trend, decreasing from Kleinberg to Gobabeb. However, contrary to expectations both mean daily net and total "non -rainfall" water input into the reference sample at Gobabeb was significantly ($F_{(4.14)} = 1{,}879$, $p < 0.01$; $F_{(4.14)} = 1{,}202$, $p < 0.01$, respectively) higher, 30 and 23 times more than that experienced at Kleinberg (Fig. 4). This was based on the assumption that Kleinberg would experience more frequent and intense fogs or humidity compared to Gobabeb which is located further inland (Fig. 1). Repeated measures ANOVA confirmed that ground level humidity at the Kleinberg site was significantly more humid compared to that at Gobabeb ($F_{(3.843)} = 4{,}916$, $p < 0.01$), with average ambient humidity at the former site about 12.5 % higher than at the latter site (Fig. 5). Figure 5 also shows that humidity at Gobabeb lagged behind that at Kleinberg and this could be because as the fog (advective) drifts inland from the ocean it reaches Kleinberg first due to its close proximity to the ocean before it reaches Gobabeb (Fig. 1), illustrating the west–east fog gradient established for advective fog in the Central Namib Desert. Therefore, a plausible explanation for the difference in input between the sites could be the close proximity of the Atlantic Ocean to Kleinberg which might have had a mitigating effect on humidity (Fig. 5) and temperature (Fig. 6) at this site, reducing steepness of the vapour gradients established between soil and

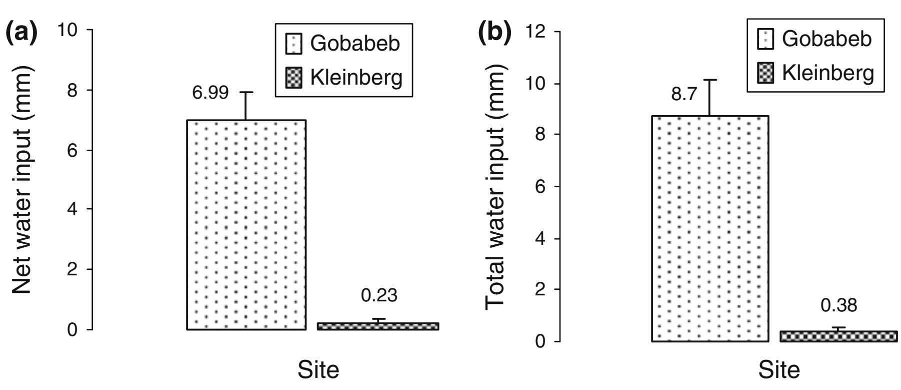


Figure 4
Daily mean "non-rainfall'" atmospheric water input into reference soil at Gobabeb and Kleinberg sites expressed as **a** net input and **b** total input, Feb–Mar 2009

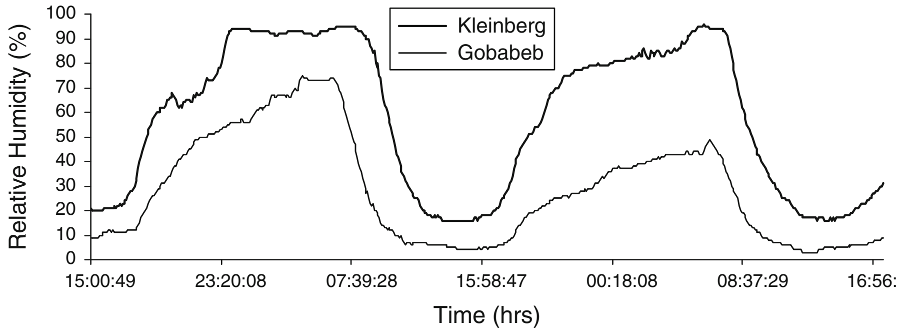


Figure 5
Typical ambient humidity at ground level at Gobabeb and Kleinberg sites, Feb–Mar 2009

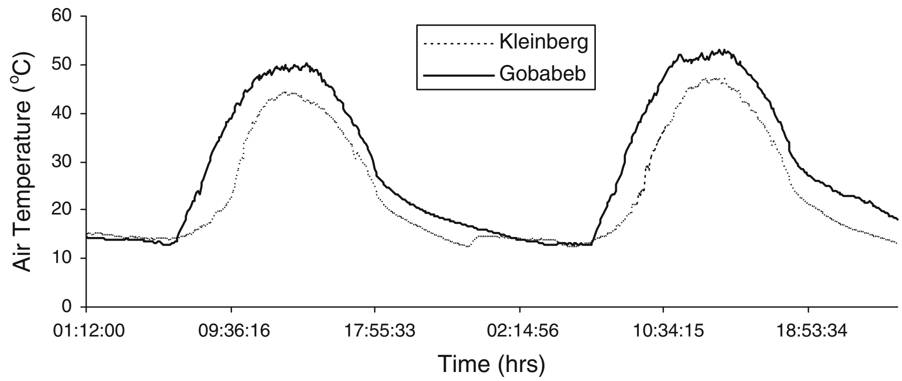


Figure 6
Air temperature 20 mm above ground level at Kleinberg and Gobabeb sites, Feb–Mar 2009

atmosphere for vapour movement into soil at Kleinberg compared to Gobabeb.

### 3.2. *Volumetric Composition of "Non Rainfall" Atmospheric Water Input*

To understand and fully appreciate the complexity of the dynamics of "non-rainfall" water supply into the soil and the water balance of arid soils, it is essential that we differentiate input from each of the three vectors: fog, vapour adsorption and dew.

#### 3.2.1 *Fog*

Fog deposition is a function of droplet settling and interception by foreign objects; however, direct deposition on the soil surface is rare (Desmet and Cowling, 1999), especially in desert areas with little or no vegetation to aid interception and fog drip. Repeated measures with ANOVA without replication revealed that fog input into the reference soil sample at Gobabeb was significantly higher ($F_{(4.14)} = 4.69$, $p = 0.04$) than that into the sample at Kleinberg (Table 2). However, this is in contrast to our fog frequency observations which indicate that Kleinberg (53 %) experienced a higher fog frequency, 21 % more during the test period, compared to Gobabeb (32 %), and in theory was expected to receive higher fog input. Because there was no fog interception at both sites to aid fog drip, fog droplet settling was the only avenue for deposition onto the reference soil sample surface at both sites. Because we expected higher fog input into the sample at Kleinberg due to the higher fog frequencies at the site compared to Gobabeb, we partially attribute the abnormally high fog input into the sample at Gobabeb to a misclassification of fog input. We acknowledge that the theoretical basis for vector differentiation as applied to this study, although useful in giving a rough idea on the composition of "non-rainfall" water input is nevertheless overly simplistic (Kaseke *et al.*, 2011b). It is therefore very much possible that input classified as fog was not strictly fog as per definition and likely included vapour adsorption. Thus, fog input in this study should be taken as an indication of the effect of fog episodes on total "non-rainfall" water input and not the effects of deposition alone.

According to Desmet and Cowling (1999), the movement of advective fog inland is limited by the arid nature of the new soil surface resulting in dissipation of the fog downwind; therefore, by the time fog reaches Gobabeb from the coast (Fig. 1) it would have thinned out due to distance travelled inland, an additional 26.6 km compared to Kleinberg. This explains the lower fog frequency observed at Gobabeb compared to Kleinberg and why fog and humidity levels at the former site lagged behind those at the latter. As a result, despite the differences in absolute amounts (Table 2): fog contributed 5.5 times more to the total water balance of the reference soil samples at Kleinberg (22 %) compared to Gobabeb (4 %) during the test period.

### 3.2.2 Water Vapour Adsorption

Repeated measures with ANOVA showed that vapour adsorption into the reference soil sample at Gobabeb was significantly more ($F_{(4.14)} = 985$, $p < 0.01$) than that into the sample at the Kleinberg site, 28 times more (Table 2). Since the soil samples used at both sites were derived from the same composite parent sample, material influences on input were eliminated; thus, differences in vector input were attributed to differences in microclimatology between the sites. According to Adamson (1990), it is possible to calculate the average soil water potential ($\Psi_w$) at both sites during both the night and day using the equation below:

$$\Psi_w = (RT/M)\, ln\, (RH/100)$$

where $R$ is the gas constant (8.31 $\mathrm{Jmol^{-1}K^{-1}}$), $T$ the temperature (K), $M$ the partial molar mass of water (0.018 kg $\mathrm{mol^{-1}}$) and $RH$ the relative humidity.

Table 3 displays the mean night-time and day-time temperatures and humidity at the soil surface at both sites. Table 3 shows that mean night-time conditions at Gobabeb during the evaluated period were at equilibrium with soil at a water potential of 84 bars and at Kleinberg, 72 bars. Mean daytime conditions at Gobabeb were at equilibrium with soil water potential at 268 bars while at Kleinberg, 221 bars. We can therefore calculate theoretical water potential gradients for the samples at both sites, typifying diurnal fluctuations in soil water potential. Both samples resulted in the establishment of steep water gradients due to changes in matric suction at night: 184 bars at Gobabeb site and 172 bars at Kleinberg. Daytime soil water potentials show unsaturated pore air and at night are vapour saturated at both sites. A change in matric suction 0–100 bars is accompanied by a vapour pressure change of only 1.6 mbar (Hillel, 1982). Therefore, the difference between vapour pressure gradients generated between Gobabeb and Kleinberg, 12 bars, cannot fully account for the 96.3 % drop in vapour adsorption at Kleinberg compared to Gobabeb (Table 2).

Closer inspection of the soil sample surface at Kleinberg revealed the development of a mechanical soil crust that was absent from the sample at Gobabeb. The surface skin of mechanical soil crusts can reduce water permeability by as much as 2,000 times that of a crust free surface (McIntyre, 1958). Jury and Horton (2000) suggested that diffusion was not significantly restricted in dry soil crusts, but there is no experimental evidence to support this to the best of our knowledge. Net and total "non-rainfall" water

Table 2

*Mean daily vector input into reference soil (±SE) in the Namib Desert, Feb–Mar 2009*

| Site | Fog (mm) | Adsorption (mm) | Dew (mm) |
|---|---|---|---|
| Gobabeb | 0.35 ± 0.13 | 8.32 ± 0.26 | 0.03 ± 0.02 |
| Kleinberg | 0.08 ± 0.02 | 0.30 ± 0.02 | 0.00 ± 0.00 |

Table 3

*Mean meteorological conditions at Gobabeb and Kleinberg sites, Feb–Mar 2009*

| Site | Time of day | |
|---|---|---|
| | Night | Day |
| Gobabeb | 295.91 K, 54.01 % RH | 322.21 K, 16.44 % RH |
| Kleinberg | 293.29 K, 69.94 % RH | 319.19 K, 22.30 % RH |

input into the reference soil samples showed that input into Kleinberg was 30 and 23 times less than that into the sample at Gobabeb (Fig. 5), and that vapour adsorption into the sample at Kleinberg was 28 times less than that at Gobabeb (Table 2). Because the differences in micro-climatology between the sites cannot account for the significant difference in vapour adsorption input between the sites, we attribute this difference to the effect of the soil mechanical crust on the sample at Kleinberg. Contrary to the suggestion by JURY and HORTON (2000), we believe our results indicate a significant reduction in vapour adsorption (diffusion) at Kleinberg compared to Gobabeb due to the mechanical soil crust and resulted in less "non-rainfall" water input at the former site compared to the latter. We theorize that the crust blocked vapour adsorption deeper into the sample and restricted input to the crust itself (KASEKE 2009), and this explains the low input classified as fog input into the sample at Kleinberg (Table 2) despite the dominance of fog at the site. The mechanical crust must have blocked vapour adsorption during the frequent fog episodes at Kleinberg and because it was not present on the sample at Gobabeb—resulted in the higher input classified as fog despite lower frequency at the site. Because material influences were minimised by using the samples from the same parent material, the question that remains unanswered is how and why the crust formed so fast at Kleinberg and not at Gobabeb although we believe that this could be related to the higher humidity at Kleinberg (KASEKE, 2009).

### 3.2.3 Dew

The natural deposition of dew is a function of meteorological conditions and of the physical properties of the underlying surface (LI, 2002). The critical factor governing dew formation or input is the receiving substrate surface nocturnal temperature (BEYSENS, 1995). Since the same soil type was used in this study, the underlying soil properties were assumed to be similar, eliminating the influence of soil physical properties on dew input.

Large diurnal fluctuations in temperature and clear skies favour dew formation (PRADO and SANCHO, 2007). Diurnal fluctuations in air temperature (20 mm above ground level) at Gobabeb could be over 36 °C while at Kleinberg this was usually about 4 °C lower (Fig. 6) and this was attributed to higher humidity at Kleinberg (Fig. 5) which had a mitigating effect on air temperatures. This resulted in faster temperature increases and attainment of higher maximum temperatures at Gobabeb compared to Kleinberg (Fig. 6). This may have also resulted in the difference between air and soil surface night temperatures at Kleinberg being about 1 °C while at Gobabeb this was about 3 °C (Fig. 7). Therefore, although the dew point temperature at Gobabeb was lower than at Kleinberg, the dew point temperature at the former site was attainable due to lower soil surface temperatures at the site (Figs. 6, 7), resulting in more dew formation and input into the soil at Gobabeb (Table 2). Repeated measures with ANOVA confirmed that dew input into the reference soil sample at Gobabeb was significantly ($F_{(4.14)} = 4.00$, $p = 0.05$) more than that into the sample at Kleinberg (Table 2); although, dew contribution to the soil water balance at both sites was insignificant.

KIDRON (1999) reported an approximately 0.015 mm increase in dew input per 100 m gain in altitude in the Negev Desert despite increasing distance from the sea. There is a difference of approximately 232 m in altitude between Kleinberg and Gobabeb with the latter being at a higher elevation. The average difference in dew input between the two sites was 0.03 mm (Table 2), which translates to roughly a 0.013 mm increase in dew input per 100 m increase in elevation between the sites in the Central Namib. Although the data suggests that topography could be an important factor governing dew formation in the Central Namib Desert and despite the fact that it compares well with the work by KIDRON (1999), more data is required to evaluate this in the Namib Desert.

## 3.3. Net and Total Evaporation

Evaporation is the reverse process of "non-rainfall" water input and is dependent on wind speed, air and surface temperatures. It is the loss of water in gaseous form from a sample, and according to KASEKE *et al.* (2011a), there are two methods of calculating evaporation from the automated microlysimeter

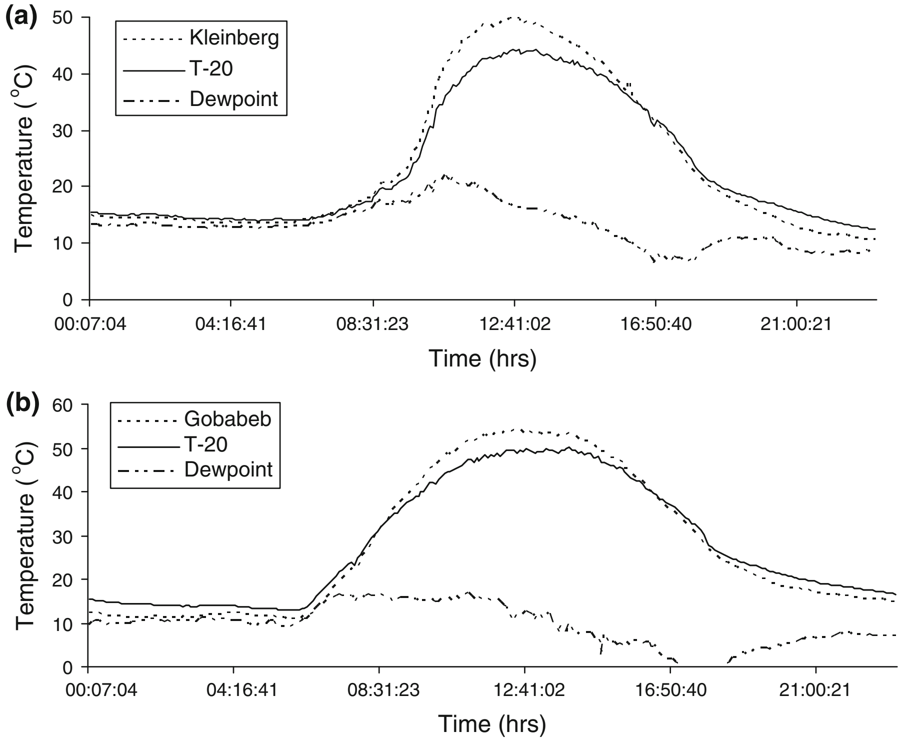


Figure 7
Soil surface temperature at Kleinberg and Gobabeb sites, air temperature 20 mm above ground level (T-20) and dew point temperature at each site, 22–23 March 2009

method: net and total evaporation. Repeated measures with ANOVA showed significantly more net and total ($F_{(4.14)} = 1{,}557$, $p < 0.01$; $F_{(4.14)} = 864$, $p < 0.01$, respectively) evaporation from the reference sample at Gobabeb compared to that at Kleinberg (Fig. 6). An analysis of air and soil surface temperatures at both sites showed that Gobabeb was significantly warmer ($F_{(3.843)} = 7{,}046$, $p < 0.01$; $F_{(3.843)} = 4{,}315$, $p < 0.01$, respectively) than Kleinberg (Fig. 6) and drier (Fig. 5). The mean air temperature 20 mm above the soil surface was 3.4 °C warmer t at Gobabeb compared to Kleinberg while the soil surface was 3 °C warmer at Gobabeb compared to Kleinberg (Figs. 6, 7). Higher temperatures coupled with lower humidity at the soil surface at Gobabeb could have generated steeper vapour gradients from soil to air (evaporation), resulting in greater evaporative losses observed from this site compared to Kleinberg. Mean net and total evaporation from the samples at Gobabeb were 27 times and 18 times more than that experienced at Kleinberg. However, inasmuch as differences in humidity and temperatures between the sites exist, the differences in vapour pressure gradients between the two sites are too low to fully account for such a large difference in evaporation; at best they can only partially explain it. According to Webb and Wilshire (1983), inorganic soil stabilisers (desert pavements, silt–clay crusts and chemical crusts) retard evaporative losses. Salt crusts impede water vapour transport into the atmosphere (Fujimaki *et al.*, 2006) and can reduce evaporation to only a few percentage points of the of the potential evaporation rate, even when underlying soil is moist (Chen, 1992). The soil crust on the sample at Kleinberg could have therefore, blocked evaporation from the sample resulting in a 96.3 and 94.4 % drop in net and total evaporation compared to the crust free surface at Gobabeb (Fig. 8).

### *3.4. Ecological Significance of "Non-Rainfall" Atmospheric Water*

Fog frequency alone cannot account for the existence and extensive distribution of Namib lichen

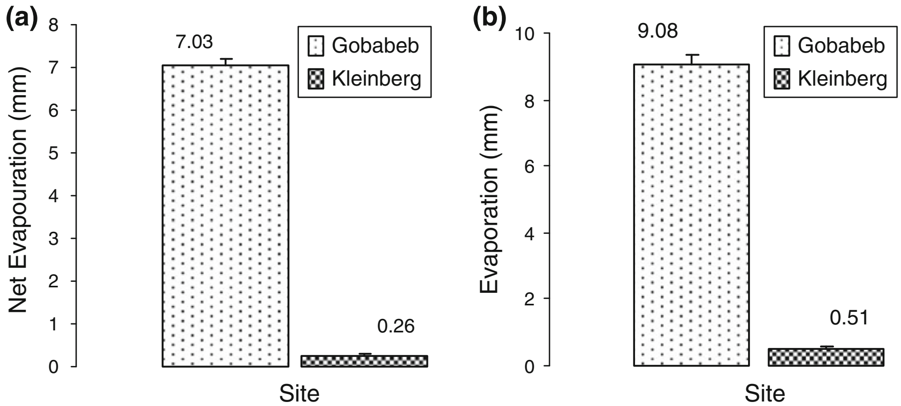


Figure 8
Mean daily evaporation from reference soil at Gobabeb and Kleinberg sites expressed as **a** net evaporation and **b** total evaporation, Feb–Mar 2009

Table 4

*Days when humidity was high enough to activate photosynthesis in lichens in the Namib Desert and the number of fog days during the 34 day test period*

| Site | Fog days | Days Humidity > 81 % |
|---|---|---|
| Gobabeb | 11 | 13 |
| Kleinberg | 18 | 22 |

fields (Lange *et al.*, 2006). According to Lange *et al.* (2006), some Namib lichens experience net photosynthesis at 82 % ambient humidity as they are able to directly utilise water vapour for photosynthesis. Table 4 shows that during the 34 day test period ambient humidity at Kleinberg was sufficient to activate lichen photosynthesis on 64.7 % of the time, however, if fog days alone were considered, this would drop to 52.9 % of the time. At Gobabeb ambient humidity capable of activating lichen photosynthesis was experienced on 38.2 % of the days and fog on a mere 32.4 % of the time. The data presented here was for the low fog season but the conditions at Kleinberg enabled net productivity for brief periods on 64.7 % of the days during the driest period. This could explain the existence of the extensive lichen fields at Kleinberg and the absence of such fields at Gobabeb. The Kleinberg site is, however, devoid of any grass; this is possibly related to a critical shortage of liquid water for germination, and secondly, the biological and mechanical soil crusts at the site could impede germination (Hillel, 1982).

## 4. Conclusion

The difference between the calculated soil water potentials and gradients between Gobabeb and Kleinberg could not account for the 95–97 % drop in "non rainfall" atmospheric water input into soil at the latter site. This difference was attributed and most likely related to the development of a mechanical soil crust on the sample at Kleinberg. Mechanical soil crusts can significantly reduce permeability of a soil by as much as 2,000 times compared to an uncrusted surface (McIntyre, 1958), and in this case vapour movement by between 23 and 30 times that of the uncrusted sample at Gobabeb. This was in direct contrast to the suggestion by Jury and Horton (2000), that diffusion in a crusted soil would not be significantly reduced.

The composition of "non rainfall" atmospheric water input directly into soil at both sites was different with fog contributing less than expected to total "non rainfall" atmospheric water input. This was attributed to the season in which the study was conducted. It is, however, important to acknowledge that fog contributed significantly more input to total input during other months at both sites (Kaseke, 2009). Fog contribution to total input was higher at Kleinberg compared to Gobabeb and this was attributed to the lower fog frequency due to limited movement of advective fog inland, resulting in its dissipation before it reached Gobabeb in agreement with Desmet and Cowling (1999). The dissipating fog nonetheless, indirectly influenced "non rainfall" atmospheric water input into soil at Gobabeb by generating a vapour gradient between the atmosphere and soil that facilitated vapour adsorption into the soil at the site, the dominant vector.

The formation of dew appeared to increase further inland with more dew input at Gobabeb compared to Kleinberg. Dew input in the Central Namib Desert suggested that altitude was an important factor governing dew formation similar to the Negev Highlands, Israel (Kidron, 1999). However, given that dew contribution to total "non rainfall" atmospheric water was insignificant at both sites we conclude that significance of dew to arid soil ecology in the Namib Desert is questionable, at least at the two sites and during the observed period.

The development of the mechanical soil crusts at Kleinberg could have important ecological significance to the site as soil crusts can impede germination (Hillel, 1982). Apart from insufficient water for germination at Kleinberg, mechanical crusts could contribute to ecosystem structure by physically restricting germination of grasses at the site. The high fog frequency and or humidity at Kleinberg supports the lichen fields which are geared towards obtaining atmospheric water (Henschel and Seely, 2008), resulting in the lichens as ecosystem engineers at the site. This helps explain the vegetation differences between Gobabeb and Kleinberg.

Evaporation was significantly lower at Kleinberg compared to Gobabeb and this was attributed to the mechanical soil crusts. Soil crusts can retard evaporation to a fraction of the potential evaporation from an uncrusted soil (Chen, 1992) and according to this data; evaporation was reduced by about 95 %. Therefore, although mechanical soil crusts negatively influence non rainfall atmospheric water input into soil they are, however, important for soil moisture conservation because they shield the underlying soil from excessive radiation and wind.

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