The impact of fog on soil moisture dynamics in the Namib Desert

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This is the author's manuscript of the article published in final edited form as:
Li, B., Wang, L., Kaseke, K. F., Vogt, R., Li, L., & Seely, M. (2018). The impact of fog on soil moisture dynamics in the Namib Desert. Advances in Water Resources. https://doi.org/10.1016/j.advwatres.2018.01.004

Abstract

Soil moisture is a critical component supporting vegetation dynamics in drylands. Despite increasing attention on fog in dryland ecosystems, the statistical characterization of fog distribution and how fog affects soil moisture dynamics have not been seen in literature. To this end, daily fog records over two years (Dec 1, 2014 - Nov 1, 2016) from three sites within the Namib Desert were used to characterize fog distribution. Two sites were located within the Gobabeb Research and Training Center vicinity, the gravel plains and the sand dunes. The third site was located at the gravel plains, Kleinberg. A subset of the fog data during rainless period was used to investigate the effect of fog on soil moisture. A stochastic modeling framework was used to simulate the effect of fog on soil moisture dynamics. Our results showed that fog distribution can be characterized by a Poisson process with two parameters (arrival rate λ and average depth α (mm)). Fog and soil moisture observations from eighty (Aug 19, 2015 - Nov 6, 2015) rainless days indicated a moderate positive relationship between soil moisture and fog in the Gobabeb gravel plains, a weaker relationship in the Gobabeb sand dunes while no relationship was observed at the Kleinberg site. The modeling results suggested that mean and major peaks of soil moisture dynamics can be captured by the fog modeling. Our field observations demonstrated the effects of fog on soil moisture dynamics during rainless periods at some locations, which has important implications on soil biogeochemical processes. The statistical characterization and modeling of fog distribution are of great value to predict fog distributions and investigate the effects of potential changes in fog distribution on soil moisture dynamics.

Keywords: drylands, ecohydrology, fog, Gobabeb, soil moisture, stochastic modeling

1. Introduction

Drylands cover 40% of the earth surface, and are characterized by regions where mean annual precipitation is significantly lower than potential evapotranspiration (PET) [1, 2]. Drylands are critical systems inhabited by about 38% of the global population [3, 4], of which 90% of live in developing countries [2]. Drylands are also home to a significant number of flora and fauna, contribute to 40% of the global net primary productivity (NPP) and account for over one third of the global carbon stock in the form of soil carbon [5, 6].

Because of the close linkage between vegetation dynamics and dryland soil moisture, soil moisture is critical in maintaining the functionality of dryland ecosystems [7, 8]. Spatial heterogeneity of root zone soil moisture was reported to be one of the primary contributors to the formation of vegetation patterns in some dryland ecosystems [9-11]. For example in central Kenya, the formation and expansion of a two-phase pattern of *Sansevieria volkensii* is due to “soil moisture halo effect” [12]. While tree-grass coexistence patterns in the Kalahari Desert is primarily induced by differences in soil water balance and plant water stress [13]. Differences in soil moisture were reported as one of the main reasons for low seedling establishment observed under inter-canopy versus canopy environments [14, 15]. In addition, some abiotic factors and physical processes are affected by soil moisture. For instance, a twenty years projection (2080-2099) from multiple modeling results suggests that global surface soil moisture to drop by 5 to 15%, which may indirectly influence soil organic carbon stock and total nitrogen in drylands [16, 17]. Land-surface interactions can also be influenced by soil moisture since the presence of soil moisture darkens surface soil resulting in the changing of surface albedo and air temperature, which may significantly alter near surface climate [18-20].

Defined as suspended water drops in the atmosphere near the Earth's surface, fog is an important supplementary water source for human utilization, sustaining the survival of flora and fauna and maintaining biogeochemical cycling [21, 22]. Previous investigations demonstrated that fog comprised a significant amount of the annual hydrologic input of California redwood forest [23, 24]. A three-year investigation showed that up to 19 % of water used by redwood trees originated from fog during the dry summer season, while up to 66% of water of understory plants was from fog [25]. This phenomenon is much more important in the drylands where water is limiting and fog amount may exceed annual rainfall [26]. The unique leaf structure and physiology of an endemic Namib Desert grass, *Stipagrostis sabulicola*, make it an efficient fog harvester transferring fog water to the plant base by means of stemflow and it is thus heavily reliant on fog water [27]. By means of a spray experiment, researchers concluded that another Namib species, *Trianthema hereorensis*, was able to survive in the southern Namib dune system by distributing leaf-absorbed fog water to the rest part of the plant [28]. Similar results were also found in other drylands. To investigate why dwarf succulents were able to survive in an arid environment of South Africa with poor leaf and stem development, comparisons of atmospheric moisture interception by gravel and two dwarf succulents (*Agyroderma pearsonii* and *Cepphalophyllum spissum*) indicated that fog absorption contributes nearly half of the total water absorbed by those two dwarf succulents [29]. The results indicate that fog is as vital as rainfall in sustaining the growth and survival of dwarf succulents in these arid environments.

Although some dryland studies have highlighted the role of soil moisture and fog on maintaining plant development and biogeochemical processes, little is known about how the temporal distribution of fog can impact soil moisture dynamics. To our knowledge, only few snapshot observations have been made between fog and soil moisture dynamics. For example, observations in California coastal pine forest showed that fog was an important contributor to the re-wetting of soil during rainless periods [23, 30]. However, no previous studies have investigated how and to what extent the temporal distribution of fog can affect soil moisture dynamics. Moreover, most dryland fog observations concentrate on the effect of fog on vegetation water status than on soil biogeochemical processes. There is still a lack of studies that address the statistical distribution of fog particularly in the Namib Desert where fog frequently occurs [31]. Characterizing the distribution of fog is a crucial step toward quantitatively describing fog dynamics and predicting the changes in fog patterns. Therefore, to address these knowledge gaps, the objectives of this study were to, 1) quantify the statistical distribution of fog; 2) fill in data gaps of fog and soil moisture dynamics in the Namib Desert; 3) modify a stochastic modeling framework to simulate the effects of temporal fog distribution on soil moisture dynamics during rainless periods.

2. Materials and methods

2.1 Site description

The field observations were conducted at three locations (gravel plains at Gobabeb, here after GPG; sand dunes at Gobabeb, here after SDG and gravel plains at Kleinberg, here after GPK) from two sites (Gobabeb and Kleinberg) within the Namib Desert. Gobabeb (lat. -23.55° S, long. 15.04° E, and elv. 405 m a.s.l) is located 60 km from the Atlantic Ocean south-east of Walvis Bay on the banks of the Kuiseb River and at the edge of the Namib Sand

Sea [32] (Fig. 1a & Fig. 1b). The climate is hyper-arid and the frequency of rainfall is extremely low with a mean annual rainfall of 27 mm [33]. Wet season and dry season of Gobabeb are pronounced with December to May being the rainy season and June to November being the dry season. The mean annual temperature of Gobabeb is 21.1℃ (mean monthly temperature ranging from 17.7 to 24.2℃) [34, 35]. The average relative humidity of Gobabeb is around 50% with most of the moisture derived from fog [35]. The mean annual foggy days at Gobabeb is ninety-four days, which is nearly fifty days less than that of Walvis Bay where fog is strongly influenced by the cold Benguela current [36]. The ephemeral Kuiseb River separates the Sand Sea and the gravel plains (gypcrete) north and south of Gobabeb, respectively (Fig. 1a and Fig. 1b) [37]. The dominant plant species in the gravel plains are *Zygophyllum simplex* and *Z. stapffi* while *Stipagrostis sabulicola* and *Trianthema heroensis* are the dominant species in the sand dune area [38].

Kleinberg (lat. -22.98° S, long. 14.73° E and elv. 180 m a.s.l) is located 33 km the Atlantic Ocean and has been a Gobabeb Research and Training Centre (GRTC) field site since 1982 [39]. The mean annual temperature is 22. 5 ℃ at Kleinberg and the average relative humidity is around 35%. Most areas of Kleinberg are dominated by gravel plains (Fig. 1c) with high salinity and low organic matter inhabited by pencil bush (*Arthraerua leubnitziae*) and lichen fields.

2.2 Data collection

Soil moisture was measured at hourly intervals using the CS655 Water Content Reflectometer (Campbell Scientific, Inc. Logan, Utah, USA) from three locations. At GPG a single probe was installed under bare soil at 4 cm depth. At SDG two probes were installed at

4 cm soil depth, one under bare soil and the other under vegetation. At GPK one probe was installed under bare soil at 3 cm depth. The soil moisture probe can detect water content from 0 to 100% (with M4 command) with a high precision (< 0.05%) and they were installed horizontally at the field sites. Fog data was obtained from FogNet stations (Fig. 1d), which are part of the Southern African Science Service Centre from Climate Change and Adaptive Land Management (SASSCAL). Each FogNet station comprised a cylindrical passive fog collector (Juvik fog collector) coupled with regular rainfall gauge and screen mesh to measure fog amount every second. Due to the close proximity of SDG and GPG (approximate 3.5 km apart), data from the same fog collector was used. Eighty rainless days' (August 19, 2015 to November 6, 2015) continuous volumetric soil moisture data and approximately two years' (December 1, 2014 to November 1, 2016) fog data were used for field data analysis and modeling purposes.

2.3 Analyses of field data

To evaluate the effect of fog on soil moisture dynamics, hourly soil moisture data and fog data were processed to daily scale. Central tendency and variability of fog and soil moisture data were expressed as mean, standard deviation (S.D.) and coefficient of variation (CV). To characterize the distribution of fog, a graphic method was used by visually examining histograms of field fog data and a sequence of data generated by a non-homogeneous Poisson process [40].

2.4 Fog modeling

A process-based modeling framework was used to simulate soil moisture dynamics with fog as the sole water input variable. The model was originally developed to understand how the stochastic rainfall influences soil moisture dynamics in drylands by expressing rainfall as a non-homogeneous Poisson process [41]. In this study, the model was modified by replacing rainfall with fog water input and used a deterministic approach using field fog data to drive the model. A simplified stochastic differential equation for bare soil water balance over the layer of depth Z_r is expressed as follows:

$$\mathrm{n}Z_r \frac{\mathrm{ds}}{\mathrm{dt}} = \mu F - E(s) - T(s) - L(s), \qquad (1)$$

where *n* is soil porosity, Z_r is the active soil depth and was set to 0.34 cm because it is the best fit of the simulation results within our isothermal framework. In reality, soil thermal properties including conductivity and diffusivity are strongly dependent on soil moisture whereby increase of soil moisture increases both (note that thermal diffusivity decreases at high water contents) [42]. Analysis incorporating both soil moisture and temperature dynamics during nonisothermal evaporation requires further work. *s* is relative soil moisture which is defined as the ratio between volumetric soil moisture and soil porosity (*n*), *F* is the amount of fog collected by fog collector, *E*(*s*) and *T*(*s*) are moisture loss through evaporation and transpiration respectively, *L*(*s*) is leakage via the bottom layer, μ is a fog parameter that represents the percentage of fog absorbed by soil surface. The fog factor is an empirical factor and was selected to best fit our simulation. In reality, the factor represents two processes. Firstly, fog was collected from the fog collector above the soil surface, and it is not always the amount of fog that is intercept by the soil. Secondly, not all the intercepted fog could infiltrate into the soil (e.g., soil texture and soil crust will have impact on fog infiltration) which need another factor to characterize it. Our study basically merged these two processes into one parameter. We also understand that soil evaporation is a complex process but evaporation (E(s)) in this modeling framework was simplified and the simplification should be sufficient when applying on dryland ecosystems.[43]. $T(s)$ was set to zero because the modeling was applied to a bare soil ground. The modified model assumes that all fog water deposited on the soil surface is immediately transported into the soil (infiltration) and no leakage or surface runoff is generated (i.e., L(s) = 0).

According to this modified framework, the increase in soil moisture is due to fog infiltration. The loss of soil moisture is only due to soil evaporation. The loss function can be expressed as:

$$E(s) = \begin{cases} 0 & 0 < s \leq s_h \\ E_{\text{vap}} \frac{s - s_h}{s_{ESP} - s_h} & s_h < s \leq s_{ESP}, \\ E_{\text{vap}} & s_{ESP} < s \leq 1 \end{cases} \quad (2)$$

where s is the relative soil moisture, s_{h} is soil moisture at the hygroscopic point, s_{ESP} is soil moisture at evaporation stress point (note: s_{h} and s_{ESP} are relative soil moisture parameters with a range from 0 to 1), E_{vap} is the soil evaporation rate. For $s > s_{ESP}$, evaporation will reach its maximum rate. For $s_{\mathrm{h}} < s \leq s_{ESP}$, soil moisture starts to restrict evaporation and a positive relationship between soil moisture and evaporation is found. For $s \leq s_h$, no evaporation is generated. In our study, the estimation of parameters in equation (1) and equations (2) are based on previous studies (e.g., E_{vap}, s_{h}) and field measurements (e.g., n) [41, 44, 45]. The details of modeling parameters that were used in this study can be found in Table 1.

3. Results and discussion

3.1 Fog distribution

In the recent stochastic soil moisture modeling framework, rainfall was assumed to be a Poisson process with a rate parameter λ and each event carried a random amount of rainfall α, which follow an exponential distribution [40, 44]. This is in coordinate with the occurrence of fog because the occurrence of each fog event is independent and each fog event carries a random amount of water. This suggests that fog and rainfall potentially share a similar distribution. We derived λ and α parameters using two-year fog field observations from the Gobabeb and Kleinberg FogNet stations (Table 2). A sequence of data was generated from a Poisson process using the two derived parameters. By plotting field observed fog data against derived data set at Gobabeb and Kleinberg, the results showed that histograms between field observed fog and derived fog in these two locations generally showed a similar pattern suggesting that the two groups of data can be generated from the distribution (Fig. 2a and Fig. 2b). This suggests that we can characterize fog distribution using a Poisson process. Unveiling fog distribution particularly in arid regions is of great value. For example, fog waters in some drylands were reported to include a substantial amount of elements and were clean enough for human drinking and production purposes [46, 47]. A better understanding of distribution of fog deposition may enhance the rationality of when and where to install the fog harvesting systems, which could dramatically improve the efficiency of fog harvest. Vegetation patterns were also found to have close links with fog deposition because vegetation not only benefits from fog water (moisture) but also the various essential nutrients from fog water for growth [48, 49]. By characterizing fog distribution and incorporating this into ecohydrological models, it becomes feasible to project changes in vegetation dynamics induced by fog pattern changes under the context of global climate change.

3.2 Field observations of fog and soil moisture dynamics

Table 2 shows fog parameters based on eighty day field observations (August 19, 2015 to November 6, 2015) recorded from the three locations. Total fog amount for GPK was 89.8 mm (Table 2), which was significantly higher than that of GPG and SDG (36.2 mm, Table 2). The frequency (λ) and average depth (α) of fog exhibited different patterns at these two locations, with a larger average fog depth and more foggy days occurring at GPK. The differences between the fog total amount and fog parameters at Gobabeb and Kleinberg may be affected by the elevation, topography and location (e.g., distance to the ocean) of fog gauges.

Fig. 3 shows soil moisture dynamics and its relationships with fog events at three study sites. The mean soil moisture at GPG was 1.55%, which is approximately three times higher than that at SDG (0.51% under bare soil, 0.53% under vegetated soil, respectively, Table 2) regardless of vegetation cover. The CV at GPG was smaller than the CVs at SDG. The CV under bare soil at SDG was the largest (19.6%, Table 2), which is nearly six times more than that of GPG. The differences between mean soil moisture among three study sites might be explained by their differences in soil texture [45]. The soil moisture observations at SDG suggests that the mean soil moisture for vegetated soil (0.53%, Table 1) were slightly higher than that of bare soil (0.51%, Table 2).

During the rainless period, fog was observed to have moderate impacts on soil moisture dynamics with rising soil moisture corresponding to a series of fog events at GPG (Fig. 3a). Considering no additional liquid water inputs (e.g., from groundwater) to the surface soil water and evaporation is the only source of soil water loses at GPG, the water content dynamics in Fig. 3a supports the effect of fog in supplying soil water in dry regions. At SDG, the relationship between soil moisture and fog tended to be weaker though some soil moisture peaks matched with fog events (Fig. 3b). We also noticed that there was a clear rising trend both in the vegetated and bare patches (Fig. 3b) during the study period. The rising trend was suspected due to water vapor transportation. However, we are not able to prove this proposed explanation at this moment due to a lack of robust evidence. A clear discrepancy in soil moisture dynamics between SDG and GPG (Fig. 3a, Fig. 3b) existed under the same fog regimes. The discrepancy might be due to the differences in soil texture since gravel plain has a stronger water hold capacity than sand dune when given the same water input. At GPK, no soil moisture dynamics (Fig. 3c) were observed to be related to fog occurrences, which may be attributed to the presence of soil crusts on the soil surface at GPK. They might act as an impermeable layer impeding water infiltration, particularly preventing small amounts of water (e.g., fog, water vapor adsorption and dew) to be absorbed by the soil surface [39]. In summary, soil moisture dynamics was observed to have moderate correlation with fog events at GPG. A weak relationship between fog and soil moisture were found at SDG and there was no relationship when moving further west to GPK during the rainless period. During the course of wet periods (e.g., during rainy reason), no soil moisture and fog relationships were found at any of those three sites (data not shown). This is because the occurrences of rainfall events were mainly concentrated in the summer season. Even a small amount of rainfall may affect soil moisture dynamics for a long time and might mask the effect of fog on soil moisture dynamics.

Our field observations filled the data gaps in concurrent fog and soil moisture observations in the Namib Desert and provided data support for studying vegetation and animal adaptions in the fog dependent systems. In addition, predictions in this already arid desert indicated that there would be less rainfall or larger rainfall variability in the future [50]. Knowledge of the soil moisture-fog relationship during the rainless periods suggested that stochastic modeling frameworks coupled with fog parameters can be used for future soil moisture predictions.

3.3 Soil moisture modeling with fog as the sole water input

Soil moisture dynamics at GPG during rainless periods was selected and simulated by a modified stochastic modeling framework driven by field fog observations. In order to fully take the advantages of the stochastic modeling, besides modeling soil moisture dynamics using a deterministic mode (i.e., using fog observations from the field as input to drive the model), soil moisture dynamics at GPG were also simulated by using Poisson process to generate fog input. In general, overall soil moisture patterns can be captured using this modified modeling framework (Fig. 4). Simulated mean relative soil moisture values using both deterministic and stochastic modeling were close to that observed in the field (Fig. 4a and Fig. 4b). Most of the simulated soil moisture peaks and observed soil moisture peaks matched (Fig. 4a and Fig. 4b). Comparing the soil moisture dynamics between using deterministic approach and stochastic approach (Fig. 4c), mean soil moisture was consistent and most of the soil moisture peaks agreed well between the two approaches. All these findings implied the feasibility of the modified modeling framework for future projections. Such a modeling framework would be particularly useful for drylands such as the Namib Desert where rainfall is rare, but fog is frequent.

Although the overall soil moisture dynamics can be simulated, some modeled moisture peaks did not match the field observations (Fig. 4a). The mismatch between field soil moisture peaks and simulated peaks may be affected by how the amount of fog is estimated. Fog is suspended water droplets and it forms only when the atmosphere water vapor reaches saturation [21]. At the field sites, fog collectors are installed above the ground [46]. Because of this arrangement, fog water collected by fog collectors is not necessarily the actual fog that deposited on the soil surface, which might one of the reasons why there are mismatch between simulated soil moisture peaks and observed peaks. In addition, the infiltration mechanism of fog water is still poorly understood. For example, a heavy fog event doesn't mean more fog infiltration to the soil profile and in turn a small fog event unnecessarily indicates less fog infiltration. In addition, moisture input into soil may start earlier as water vapor adsorption, which the modified framework failed to take into consideration. These three uncertainties may be responsible for the mismatch of soil moisture peaks. Moreover, although soil moisture dynamics can be simulated using fog as a sole water input during rainless periods, wet season soil moisture dynamics may not be fully revealed by the modeling framework, which requires further improvements toward a better understanding of fog characterization, fog infiltration and fog-soil moisture relationships.

Further work could be focusing on a better characterization of fog parameter (μ) which influences how much fog can infiltrate into the soil. In addition, the depth of fog infiltration would also be a valuable topic for further research. Other water resources (e.g., dew, water vapor adsorption) in the Namib Desert could also be potential factors that can be incorporated into our fog modeling framework to fully understand soil moisture dynamics during the rainless period.

4 Conclusions

In this study, we demonstrated that fog can be well-characterized by a non-homogeneous Poisson process with two parameters (fog arrival rate and average depth). Our fog distribution investigation provided new insights and modeling support for future ecohydrological studies. For example, fog influenced vegetation dynamics in drylands can be predicted by coupling ecohydrological models with fog parameters. Soil moisture and fog analyses from three field sites within the Namib Desert suggested that soil moisture dynamics were affected by fog occurrence at GPG, while the relationship became less pronounced at SDG and there was no relationship at GPK. The field results and analyses filled the concurrent fog and soil moisture observation data gap in the Namib Desert and shed light on using ecohydrological models to couple fog parameter with soil moisture dynamics. Informed by field observations, a stochastic modeling framework was used to simulate the impact of temporal distribution of fog on soil moisture dynamics. The modeling results showed that most of soil moisture peaks and mean relative soil moisture were well captured by the modeling framework. This suggests the feasibility of using this modified framework to predict future soil moisture changes under changing fog conditions. However, the fog impact on soil moisture during the rainy season cannot be captured due to residual effect of rainfall that may mask the impact of fog on soil moisture dynamics, which might require future work.

ACKNOWLEDGMENTS

We would like to acknowledge Gobabeb Research and Training Centre for access to the FogNet weather stations and for the logistical support and fieldwork assistance. Funding for this work was made available from the U.S. National Science Foundation (IIA-1427642 and EAR-1554894).

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Table 1 Soil and fog parameters for gravel plain (Gobabeb).

	Gravel plain (Gobabeb)
Vegetation coverage	Bare soil
Soil parameters	
Porosity[†], n (unitless)	0.34
Hydroscopic point[*], s_h (unitless)	0.04
Soil depth[*], Z_r (m)	0.34
Evaporation[*], E_{vap} (mm day^{-1})	0.65
Evaporation stress point[*], s_{ESP} (unitless)	0.085
Fog parameter	
Fog arrival rate[*], λ (day^{-1})	0.3
Average fog depth[*], α (mm)	1.51
Fog absorption factor[*], μ (unitless)	0.13

[†]Li et al. (2016)

[*]This study

Table 2 Soil vegetation coverage, soil depth, means soil moisture, standard deviation of soil moisture, coefficient of variation (CV), total fog amount (mm), fog arrival rate (λ), and average fog depth α (mm) at three field sites spanning from August 19, 2015 to November 6, 2015. Note: No soil moisture dynamics were observed in GPK during the study period.

<table>
<tr><th>Field sites</th><th>Depth (cm)</th><th>Mean soil moisture (% m^3/m^3)</th><th>CV (%)</th><th>Total fog (mm)</th><th>λ (day^{-1})</th><th>α (mm)</th></tr>
<tr><td>Gravel plain (Gobabeb) Bare soil</td><td>4</td><td>1.55±0.05</td><td>3.3</td><td rowspan="3">36.2</td><td rowspan="3">0.3</td><td rowspan="3">1.51</td></tr>
<tr><td>Sand dune (Gobabeb) Bare soil</td><td>4</td><td>0.51±0.1</td><td>19.6</td></tr>
<tr><td>Sand dune (Gobabeb) Vegetated</td><td>4</td><td>0.53±0.1</td><td>18.8</td></tr>
<tr><td>Gravel plain (Kleinberg) Bare soil</td><td>5</td><td>0</td><td>0</td><td>89.8</td><td>0.55</td><td>2.04</td></tr>
</table>

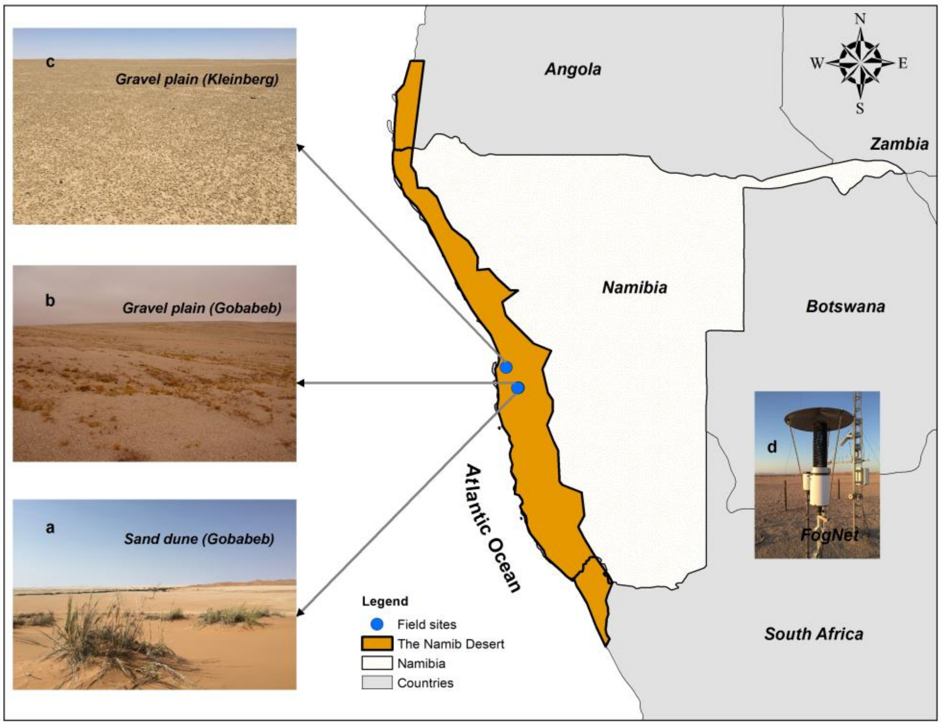

Figure 1 Geographic location of study sites (sand dune site at Gobabeb (a), gravel plain site at Gobabeb (b), gravel plain site at Kleinberg (c)) and a schematic photo of fog collector (d). The map was generated using ArcGIS for Desktop 10. 3. 1 1 (http://www.arcgis.com).

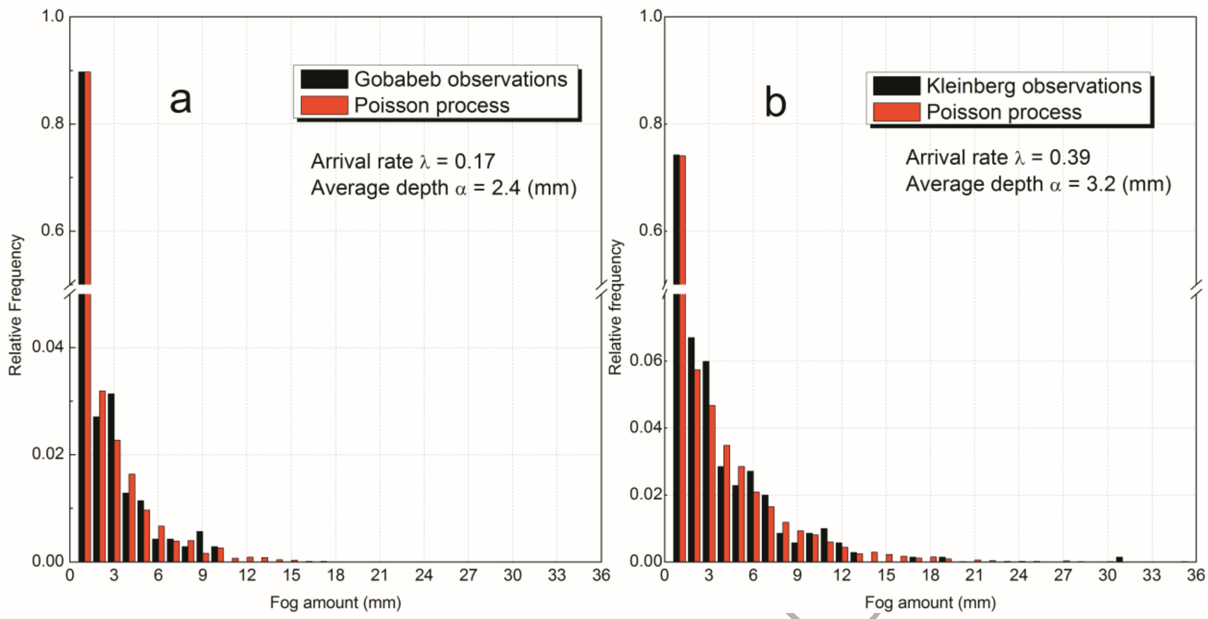

Figure 2 Comparison of histograms between field observed fog and Poisson simulated fog at Gobabeb (a) and Kleinberg (b).

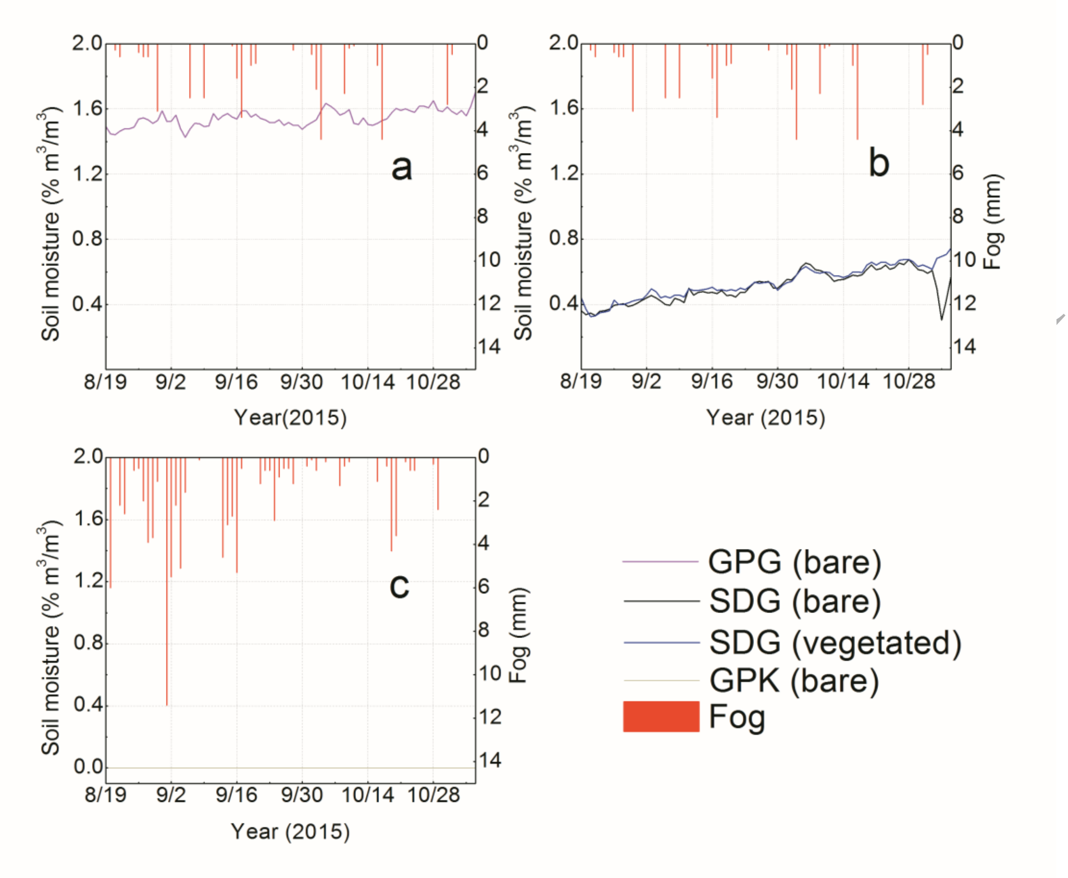

Figure 3 Fog events and soil moisture dynamics at gravel plain Gobabeb (a, GPG), sand dune Gobabeb (b, SDG), gravel plain Kleinberg (c, GPK).

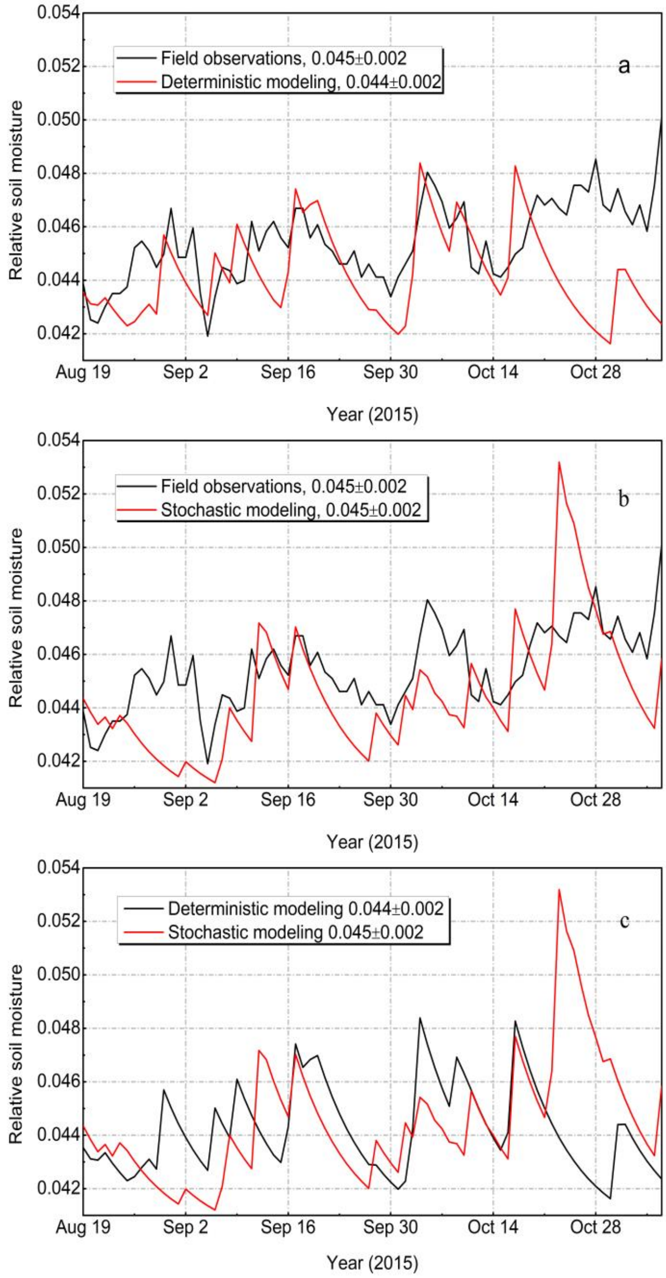

Figure 4 Comparisons between field observed soil moisture dynamics versus simulated soil moisture dynamics using deterministic approach (a), field observed soil moisture dynamics versus stochastically modeled soil moisture dynamics (b), and simulated soil moisture dynamics using deterministic approach versus using a stochastic approach (c) at gravel plain (Gobabeb, GPG) at the depth of 4 cm.