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Comparison of surface foil materials and dew collectors location in an arid area: a one-year field experiment in Kenya

J. Tuure[a*], A. Korpela[b], M. Hautala[a], M. Hakojärvi[a], H. Mikkola[a], M. Räsänen[c], J. Duplissy[c], P. Pellikka[c,d], T. Petäjä[c], M. Kulmala[c] and L. Alakukku[a]

[a] Department of Agricultural Sciences, University of Helsinki, Finland, P.O. Box 28 (Koetilantie 5), FI-00014 University of Helsinki

[b] VTT Technical Research Centre of Finland, Finland, P.O. Box 1000 (Tietotie 4e) FI-02044 VTT, Finland

[c]Institute for Atmospheric and Earth System Research, University of Helsinki, Finland. P.O. Box 64 (Gustaf Hällströmin katu 2a), FI-00014 University of Helsinki

[d]Department of Geosciences and Geography, University of Helsinki, Finland. P.O. Box 64 (Gustaf Hällströmin katu 2a), FI-00014 University of Helsinki

[*]Corresponding author E-mail address: juuso.tuure@helsinki.fi (J. Tuure)

Abstract

This study characterized different polyethylene (PE) and polyvinyl chloride (PVC) plastic foil materials effectiveness for dew collection in arid field-conditions in Kenya. Dew yields were collected daily for one year. Ten dew collectors with four different plastic foils were setup in the experimental field. The cumulated dew yields ranged from 18.9 to 25.3 mm. The greatest cumulated dew yields were 25.3 mm (nightly mean 0.096 mm) and 24.3 mm (nightly mean 0.093) measured with PVC and OPUR coated collectors respectively. The lowest cumulated dew yields 18.9 mm (nightly mean 0.075 mm) and 19.1 mm (nightly mean 0.074 mm) were measured with PVC and PE coated collectors respectively. Dew provided a continuous water source during the dry season. The type of the surface material was not found to be a determining factor for the collected dew yield. The location of the collector at the experimental field had impact on the collected dew yields. We also compared harvested dew yields to measured meteorological parameters and calculated dew yields with the use of a diffusion model using the measured surface temperatures and coefficient of mass diffusion to evaluate the dew collecting potential under the prevailing conditions.

Keywords: Dew, Water harvesting, Drought, Dryland

Symbols:

C_c – Specific heat capacity of the condensing surface

C_w – Specific heat capacity of water

c_c – Water concentration on the surface

c_a – Water concentration in air outside the laminar layer

D – Diffusion coefficient

k – Mass transfer coefficient

L_c – Length of the condensing surface

L_w – Latent heat of vaporization or condensation

m_c – Mass of the condensing surface

m_w – Mass of water

Nu – Nusselt's number

P_{cond} – Conductive heat-exchange energy

P_{conv} – Convective heat-exchange energy

P_{lat} – Latent condensation energy

P_{rad} – Heat radiation energy

Re – Reynold's number

S_c – Condensing surface area

Sh – Sherwood's number

T_c –Temperature of the condensing surface

T_d – Dew point temperature

v – Fluid velocity

x_c – Absolute humidity on the condensing surface

x_a – Absolute humidity of air

p_{sat} – Saturated vapor pressure

p_c – Vapor pressure at the condensing surface

δ – Thickness of the boundary layer

ε – Emissivity

v – Kinematic viscosity of the fluid

ρ_a – Density of air

1. Introduction

Availability of fresh water is one of the most severe global challenges for humankind. It is estimated that 14 percent more freshwater must be used for agricultural purposes in the next 30 years to keep pace with the growing demand for food (UN-Water thematic initiatives, 2006). In theory, the atmosphere could act as a potential fresh water source at locations where access to fresh surface- and ground-water is limited. It has been estimated that the global water content in the atmosphere is 12 700–15 500 km^3 (Chahine 1992; Trenberth and Smith 2005). Many semiarid and arid regions of developing countries that have scarce or only seasonal rainfall events still have large amounts of water in their atmospheres throughout the entire year. Those areas could benefit from dew collection utilizing passive radiative cooling.

Dew occurs when exposed surfaces such as plant leaves, soil, and roofs emit infrared radiation towards the night sky. As the radiation is not balanced by atmospheric radiation, there is a heat deficit, which is compensated by thermal conduction (solid surface contact), convection (sensible heat) and latent heat flux from atmosphere to the surface (dew condensation) on the cooled surface (Monteith 1957; Pedro and Gillespie 1982; Nikolayev et al. 1996; Beysens 2016). The heat radiation towards the night sky is greatly retarded by cloudiness, haze, and dust. In general, high humidity, calm winds, a clear sky, and relatively warm ambient air temperature results in large quantities of dew (Monteith 1957; Beysens 1995; Revankar 2009; Jones 2014). Cooling of the condensing surface can be enhanced by thermal isolation from conductive heat sources, such as the ground.

Several dew collection experiments conducted worldwide have studied dew collection implementing passive radiative cooling (Supplementary material, Table 1). The most commonly used passive dew collection setups have been assembled from a plastic foil, mounted on a Styrofoam sheet (thermal isolation) that is placed in a metallic frame. The metallic frame is tilted around 30° from the horizontal (Nilsson 1996; Berkowicz 2004; Gandhisan and Abualhamayel 2005; Jacobs et al. 2006; Clus et al. 2008; Lekouch et al. 2011; Muselli et al. 2009; Maestre-Valero et al. 2011; OPUR). A horizontal plane could maximize the dew yield, but both numerical simulation and experimental measurements have shown that the 30° angle is a good compromise between weak wind influence, large light-emission solid angle and drop collection (Beysens et al. 2003). Many

of the dew collection experiments have used a specific low density Polyethylene (LDPE) foil (Nilsson et al. 1994; Nilsson 1996; Vargas et al. 1998; Muselli et al. 2002; Beysens et al. 2003; Gandhisan and Abualhamayel 2005; Beysens et al. 2006; Jacobs et al. 2006; Clus et al. 2008; Jacobs et al. 2008; Lekouch et al. 2011; Muselli et al. 2009; Maestre-Valero et al. 2011; Sharan 2011). This LDPE foil (from this on referred as OPUR) initially presented by Nilsson et al. (1994) is recommended as a standard for dew recovery or collection comparisons by the International Organization for Dew Utilization (OPUR). OPUR has titanium dioxide (TiO_2) and barium sulphate ($BaSO_4$) microfillers embedded. These microfillers increase the dew collecting quality by enhancing emissivity in the infrared region of the electromagnetic spectrum, especially in the wave length range of 8−13 µm, contributing to radiative cooling (Nilsson et al. 1994; Maestre-Valero et al. 2011). OPUR has high reflectance in the visible light frequency spectra. This reduces heating of the foil by daylight irradiation in the early morning and the late evening hours, prolonging the effective time for dew formation. OPUR has also a food proof, water insoluble surfactant migrating that provides also hydrophilic properties that lower the nucleation barrier, and thus improves condensation (Nilsson et al. 1994; Maestre-Valero et al. 2011).

The reported dew collecting experiments (Supplementary material, Table 1) have focused on evaluating the dew collecting activities and the dew collecting potential of different locations. A smaller share of dew collecting experiments have actually compared different foils (Nilsson and Niklasson 1995; Nilsson 1996; Beysens et al. 2007; Sharan et al. 2007; Jacobs et al. 2008; Maestre-Valero et. al. 2011; Clus et al. 2013; Arias-Torres and Flores-Prieto 2016). Summing up the previous studies it can be stated that several commercially available and low-cost plastics have seldom been tested simultaneously in same conditions for dew collecting purposes. In addition, the location of dew collectors with same plastic foil at the experimental field needs to be studied. There is therefore a gap in the knowledge regarding plastic surface foil materials that must be addressed.

We addressed these gaps in the previous research by:

Comparing measured dew yields for different commercially available plastic surface foil materials in arid field conditions. Specifically, collected dew yields of the tested foil materials were compared at various locations in the experimental field.

Comparing measured dew yields to yields calculated using Fick's law. We did this to evaluate the upper limit for the dew collecting potential in the conditions using simple meteorological data and to evaluate factors affecting the dew yield.

2. Materials and methods

2.1 Experimental site and weather conditions

A field experiment was conducted in an arid region in Maktau, southeastern Kenya (3° 25'33 S, 38° 8'22 E, 1060 m a.s.l) between April 1st, 2016 to March, 31st 2017. A weather station was installed in the experimental field in August 2014 by CHIESA project (Climate change impacts on ecosystem services and food security in Eastern Africa) and managed by Taita Research Station of the University of Helsinki. The nearest weather station of Kenya Meteorological Department is located in Voi (3° 23' 59 S, 38° 34' 0 E, 579 m a.s.l.), which is located 50 kilometres east of the experimental field site. The climate in the area is characterized by dry seasons in January-February and May-October, and rainy seasons March-April and in November-December (Table 1, Supplementary material Table 2. Supplementary material Fig. 1, Fig. 2). Compared to the long-term rolling means, the mean monthly air temperatures during the experimental period were lower at the experimental site. The total monthly precipitation in the study period was smaller throughout the year than the long-time monthly means except for April, when nearly half of the annual precipitation occurred (Table 1 and Supplementary material Table 2).

Table 1. Weather conditions in Maktau during the study measurement period April 1st, 2016 to March, 31st 2017. Long-term mean values at the nearest official weather station in Voi are presented in Table 2 of Supplementary material.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Mean T Min (°C)	17.9	18.0	18.8	19.1	16.5	15.7	14.0	14.2	14.9	15.6	18.1	18.1	16.7
Mean T (°C)	24.3	24.3	24.9	22.7	21.4	20.9	19.5	19.7	20.2	22.3	23.3	23.3	22.2
Mean T Max (°C)	31.6	32.0	33.0	29.0	28.5	28.3	26.6	27.3	28.0	31.0	31.1	29.9	29.7
Air relative humidity %	63.0	67.0	70.3	87.5	79.2	74.4	73.0	71.9	72.3	67.3	73.1	73.9	72.7
Total precipitation (mm)	7	8	67	154	14	0	1	6	3	1	20	40	27
Sunshine duration (h)	744	673	745	387	409	391	403	402	402	440	720	744	538

2.2 Experimental setup

The dew collectors (Fig. 1) we used were comprised of an aluminium frame supporting a 1x1 m^2 Styrofoam surface tilted at a 30° angle in respect to the ground surface. The Styrofoam backing used was 2.5 cm thick and functioned as thermal insulation, which prevented the absorption of long-wave radiation, emitted by the soil and also convective heat flux in air from warming the dew collecting foil surface. The plastic foil, on which dew condensed, was mounted on top of the Styrofoam. The condensed dew water drains gravitationally from the foil surface into a gutter which directed the water via a small tube into a small collecting tank or vessel (Fig. 1). The water drainage was assisted by manually scraping the remaining water droplets to aggregate them and channel the resulting water into the gutter at sunrise, before the evaporation of the droplets.

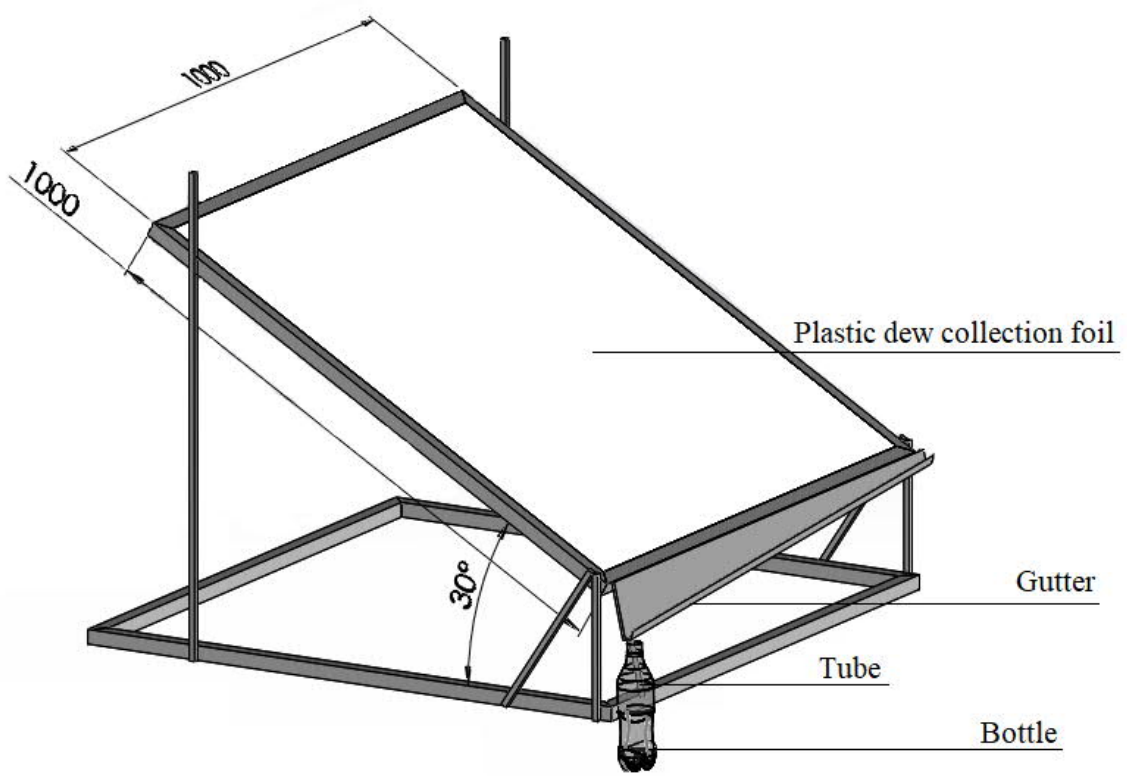


Figure 1. Illustration of a planar dew collector used at the experimental field.

149 The 10 dew collectors were set up randomly at the end of a field with maize (*Zea mays L.*) as the main crop.
150 There were no notable vegetation on the surface of the tilled soil at the end of the field. The natural vegetation
151 next to the field can be characterized as Acacia-Commiphora tree savanna with Acacia tortillis and
152 Commiphora baluensis as typical tree species (Pellikka et al., 2013)

153 The collectors were coated with the four different plastic foils tested, which were white polyvinyl chloride foil
154 (PVC), white polyethylene foil (PEW), black polyethylene foil (PEB) and OPUR (Table 2 and Fig. 2). All 10
155 collectors were positioned facing west in order to lengthen the condensation time in the morning (Fig. 2). The
156 prevailing direction of the nocturnal wind was southeast. The adverse effect of wind on the condensation of
157 dew can be reduced by turning the back surface of the dew collector towards the dominant direction of the
158 nocturnal wind (Beysens et al. 2001). The wind carries humid air to the surface of the condenser, but a wind
159 with too great a velocity can prevent condensation.

160 Table 2. The plastic foils used on the dew collectors. Measured thickness and contact angle with water bearing
161 air.

Plastic foil	Surface color	Thickness (μm)	Contact angle with water (°)	Manufacturer
PVC	White	370	89.5	Köckner Pentaplast GmbH
OPUR	White	340	80.5/51.9*	OPUR
PE	White	50	95.1	Raniplast
PE	Black	50	95.1	Raniplast

162 *For OPUR foil different measurement results were obtained for the contact angle at different measurement
163 points. Values for contact angles between the surface and water were measured using the SMART–CAM 200
164 goniometer (KU Leuven 2017) with an accuracy 0.1° given for contact angles between 5 and 180° and with
165 the image area 5.7 x 5.4 mm^2.

166 The emissivity of the dry plastic surfaces was determined with a FT-IR spectrometer (Perkin-Elmer Spectrum
167 One). The spectral curve was obtained in the mid IR spectrum (2.5 – 25 μm). The spectral curve was a mean
168 of five repetitions. Special attention was paid on the spectral range of 7 – 14 μm (atmospheric window), for
169 which the average emissivity was calculated.

170 The average emissivities measured for the dry plastic foils in the spectral range 7 – 14 μm were $\varepsilon_{OPUR} = 0.967$,
171 $\varepsilon_{PEB} = 0.927$, $\varepsilon_{PEW} = 0.975$, $\varepsilon_{PVC} = 0.965$. Wetting of a plastic condensing surface has been shown to increase
172 the surface emissivity (Maestre-Valero 2011). When dew condenses on the surface, the surface covered by

water is no longer exposed to the sky and the emissivity that matters for the water covered surface is the emissivity of liquid water, being close to 1 (Beysens 2018).

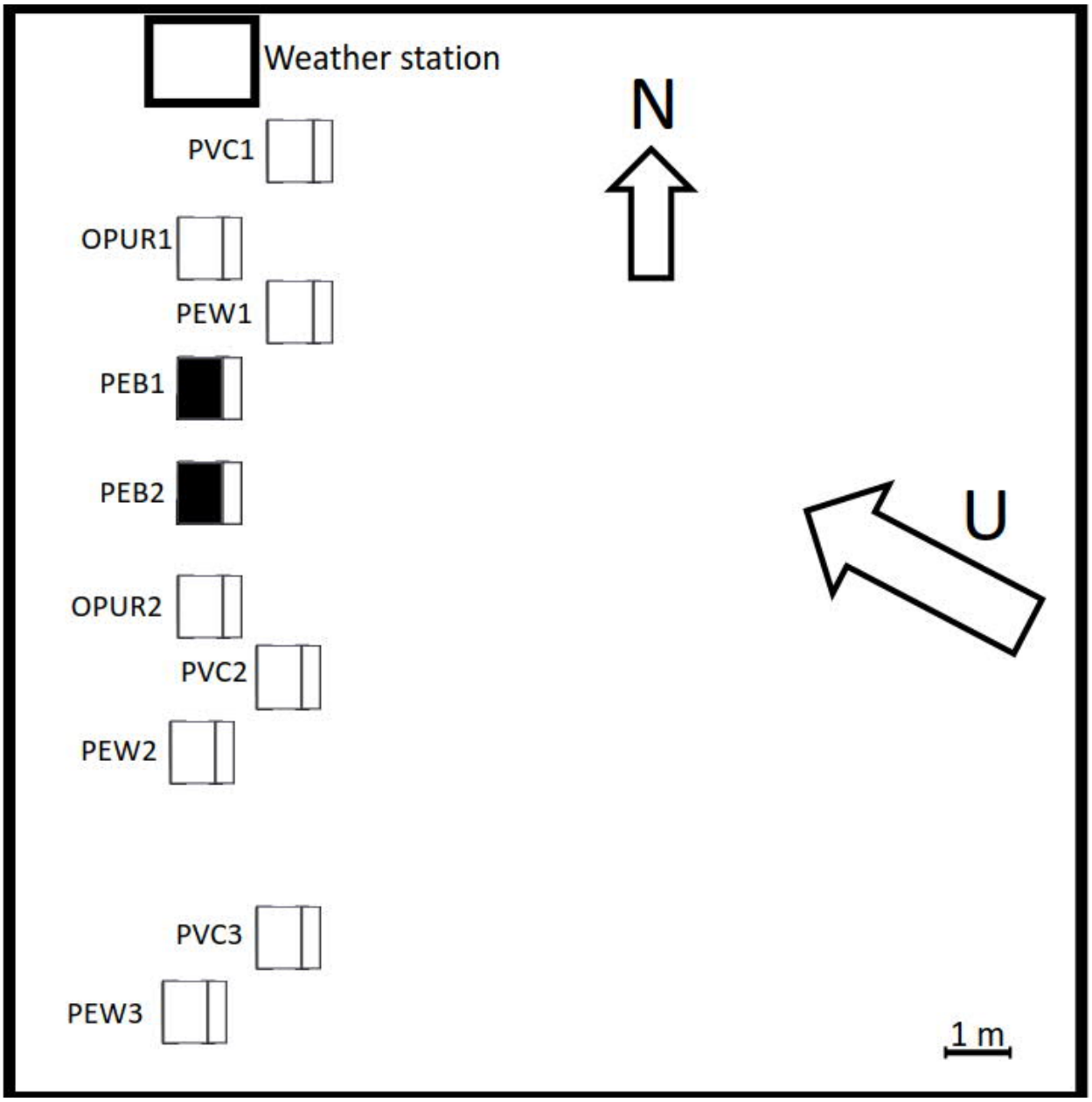


Figure 2. The location of the dew collectors and the weather station at the experimental field. The arrow U displays the dominant direction (southeast, 120°) of the nocturnal wind measured by the weather station.

183 **2.3 Measurements**

184 We measured surface temperature on 8 of the 10 collectors. The surface temperatures were measured with T-
185 type thermocouples (standard limit tolerance of 1°C or ± 0.75%) mounted with aluminium tape, leaving the
186 peeled end of the thermocouple outside the tape on the surface of the plastic condensing foil. The ambient
187 relative humidity was measured by sensors (Honeywell HIH-4000) with a measurement accuracy of 3.5 RH-
188 %, mounted on the rack of the dew collectors 0.5 meters above soil surface. Measurement data was acquired
189 every minute and means were stored in 10-minute intervals on a data logger (CR1000, Campbell Scientific,
190 Logan, Utah).

191 The weather station acquired data minutely and data was stored as 30-minute means using a data logger
192 (CR1000, Campbell Sci.). The sensors of the weather station measured air temperature and air relative
193 humidity (CS215, Campbell Sci.) at the height of 1 meter from the ground. Precipitation was measured by a
194 rain gauge (ARG100, Campbell Sci.) at the height of 1.5 meters above ground. Wind speed and direction were
195 measured with a wind monitor (WMS 05103, Campbell Sci.) at the height of 2 meters.

196 The dew amount was measured every morning at sunrise approximately 06.00 AM, with a graduated cylinder
197 with accuracy of 1 ml. The water remaining on the condensing surface was scraped and the measured and
198 reported water amount was a result of dew water collected by both gravity induced flow and by wiping.

199 **2.4 Calculating dew output**

200 Calculation of dew accumulation can be considered as a combination of heat and mass balances. The heat
201 balance equation presented in several studies (i.e. Pedro and Gillespie 1982; Nikolayev 1996 ; Vuollekoski et
202 al. 2015) for the dew condensing surface is:

$$\frac{dT_c}{dt}(C_c m_c + C_w m_w) = P_{rad} + P_{cond} + P_{conv} + P_{lat} \quad (1)$$

203

204 where T_c is the temperature of the condenser, C_c is the specific heat capacity of the condenser and C_w of water
205 m_c is the mass of the condenser and m_c of water. The right hand side of the equation represent the powers that
206 are involved in the heat exchange. $P_{rad,}$ is the energy gain or loss due to radiation, P_{cond} describes the conductive

heat flow to the surface. We considered the dew condenser perfectly insulated with the Styrofoam and thus excluded P_{cond}. P_{conv} describes the convective heat-exchange term. P_{lat} in Eq. (1) is the energy that is released due to latent condensation: $P_{lat} = L_w\, dm/dt$,

where L_w is the latent heat of vaporization or condensation. These equations are needed for calculating the surface temperature of the condensing surface. We measured the surface temperature and thus exclude these calculations.

The condensation rate can be written as the mass equation, i.e. Fick's law, that gives the mass flow i.e. the diffusion of water vapor through the laminar layer at the surface, when temperatures and humidity at the surface and in air as well as the thickness of the laminar layer are known. Water vapor is condensed onto a surface by diffusion through a thin laminar boundary layer δ, thickness of which depends on air velocity. Accordingly,

$$\frac{dm_w}{dt} = S_c k(c_c - c_a) = S_c k \rho_a (x_c - x_a) \quad (2)$$

where m_w is the mass of water, S_c is the surface area, D is diffusion coefficient, c_c is water concentration (kg m^{-3}) on the condensing surface and c_a is water concentration in air outside the laminar layer. If $c_c < c_a$ the mass flux is negative and there is evaporation, this applies only if there is accumulated dew on the condensing surface. x (kg kg^{-1}) is the absolute humidity and ρ is the density of air. On the condensing surface, the relative humidity of air is assumed 100%. This may not always be the case, but we made this assumption as our intention was to calculate the upper limit of condensation. When the surface temperature is measured, then x_c is also known. The x_a term is similarly obtained from the measured air temperature and air relative humidity.

Instead of δ, k (m s^{-1}) is used in dimensional analysis and is obtained from $k = Sh \cdot D/L_c$, where Sh is the Sherwood's number, D is the diffusion coefficient and L_c is the length of the condensing surface. Value of D represents the diffusion of the vapor in air and depends on the temperature, i.e. at 30 °C it is $2.57 \cdot 10^{-5}$ m^2 s^{-1}. The water diffusion coefficient in air at 20°C is $2.49 \cdot 10^{-5}$ m^2 s^{-1} (Monteith and Unsworth 1990). We used this value in our calculations. In this case Sh is unknown. We assumed that the thickness of the laminar layer is

similar for heat transfer and mass transfer and replaced *Sh* with Nusselt's number (*Nu*) accordingly, $k = Nu \cdot D/L_c$. According to Monteith and Unsworth (1990) the *Nu* for flat plates in turbulent flow ($Re > 2 \times 10^4$) is $Nu_{turb} = 0.032Re^{0.8}$ and *Nu* for flat plates in streamline flow ($Re < 2 \times 10^4$) is $Nu_{stream} = 0.60Re^{0.5}$. Reynolds number (*Re*) for the condensing surface (flat plate) can be calculated $Re = vL_c/v$. Where *v* is the fluid velocity, L_c the length of the condensing surface and *v* the kinematic viscosity of the fluid. The kinematic viscosity of air at 27 °C is 1.57×10^{-5} $m^2 s^{-1}$ (Pitts and Sissom 1977).

Surface temperature of the condensing surface, relative humidity of the air, air temperature and wind speed were measured to calculate the potential upper limit of dew accumulation using Eq. (2) and then compare these with actual measured dew yields. The upper limit of potential accumulation comes from the assumption that the whole condensing surface is wet, i.e. relative humidity is 100%. The dew mass flow on the surface was calculated for every 10-minute. For the calculation purpose, the weather station data was interpolated from 30-minute interval to 10-minute interval, utilizing linear interpolation. In practice, the calculations were codified in MATLAB.

When the results for model calculations were inspected, it was determined, that only the results for PEW2 collector would be presented, because it provided the most consistent temperature measurement data series.

2.5 Location of the collector

For field experiment data, a Kruskal-Wallis test (MATLAB 2015) was performed to test the statistical significance of measured dew yields. The test was performed in order to examine if there are differences between the plastic foils or differences between the collectors with the same foil caused by differing placement (or location) at the experimental field. The use of the Kruskall-Wallis test is justified by the fact that the distributions of the groups (mean dew yields obtained with different plastic foils) were non-normally distributed.

3. Results

3.1 Determined dew yields during one year

During the measurement period from the beginning of April 2016 to the end of March 2017 (365 days) rainfall occurred at the experimental field on 76 days producing cumulative precipitation of 322 mm (Table 3). Rainfall occurred only periodically, whereas the condensation of dew occurred continuously throughout both the rainy and the dry seasons (Fig. 3). The difference between the highest mean yield per event at 0.096 mm (PVC2) and lowest yield 0.074 mm (PEW3) was 23%. The difference between mean dew yield per night was highest between the highest yielding 0.069 mm (PVC2) and lowest yielding 0.052 (PVC3) being 25%. The difference between the highest cumulated dew yield 25.3 mm (PVC2) and lowest cumulated dew yield 18.9 mm (PVC3) 25%.

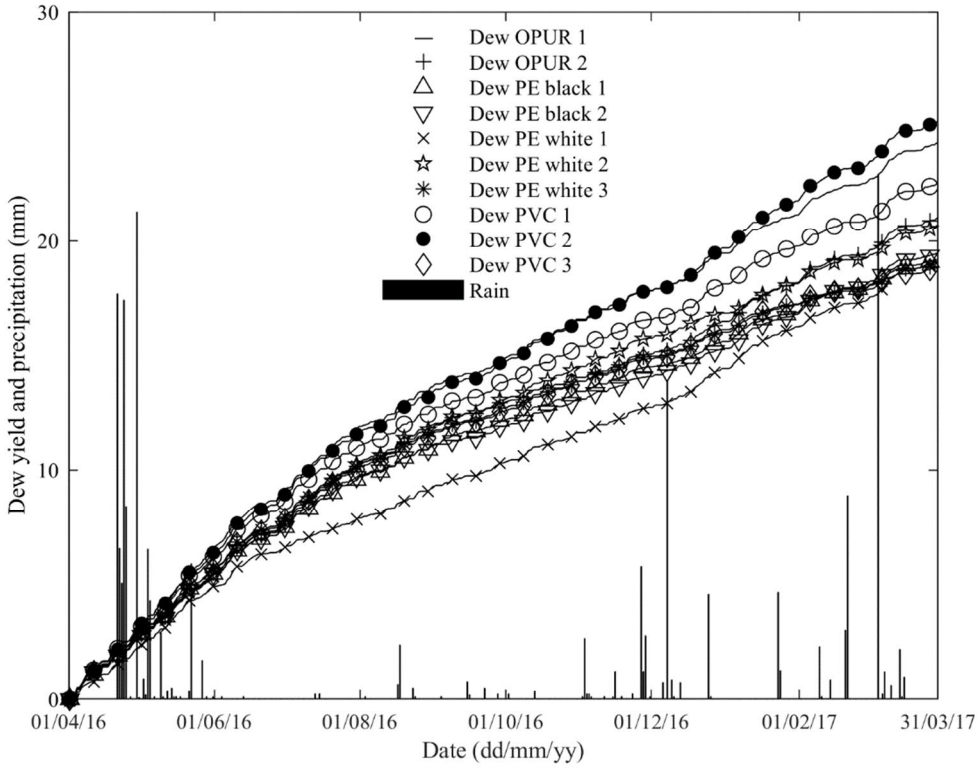


Figure 3. Cumulative daily dew yields during the measurement period. The bars present the rainfall events during the 365-day measurement period. Rain occurred during 76 days. The total rainfall was 322 mm.

Table 3. Number of dew events and cumulative and mean dew yields in mm collected during the 365-day measurement period. The mean "dew/night" nights with no dew harvest are included in the calculation of the mean, whereas in the calculation of the mean for "dew/dew event" the nights with no dew harvest were rejected.

Collector materials	Cumulative dew yield (mm)	Mean dew yield/dew event (mm)	Standard deviation dew/dew event (mm)	Mean dew yield/night (mm)	Standard deviation dew/night (mm)	Dew events/365 nights
OPUR1	24.3	0.093	0.062	0.067	0.067	262
OPUR2	21.1	0.082	0.056	0.058	0.060	258
PEB1	19.2	0.075	0.052	0.053	0.056	255
PEB2	19.5	0.077	0.053	0.053	0.056	255
PEW1	19.1	0.074	0.049	0.052	0.053	260
PEW2	20.7	0.081	0.054	0.057	0.059	256
PEW3	19.1	0.074	0.055	0.052	0.057	256
PVC1	22.6	0.088	0.058	0.062	0.063	257
PVC2	25.3	0.096	0.061	0.069	0.067	263
PVC3	18.9	0.075	0.054	0.052	0.057	250

For all of the tested surfaces the most dew events resulted in a dew yield class of 0.05–0.1 mm. There were some differences between the tested foils. OPUR and PVC collectors had more of the larger scale dew events (>0.15 mm) than PE collectors (Fig 4). Moreover, 11.8% and 7.0% of the dew events on the OPUR collectors gave yields greater than 0.2 mm. The corresponding proportions for PVC collectors were 8.2%, 8.0%, and 5.6%. The percentages for the PE coated collectors were 5.5% and 4.7% for PEB collectors compared with 5.4%, 7.0%, and 5.9% for the PEW collectors.

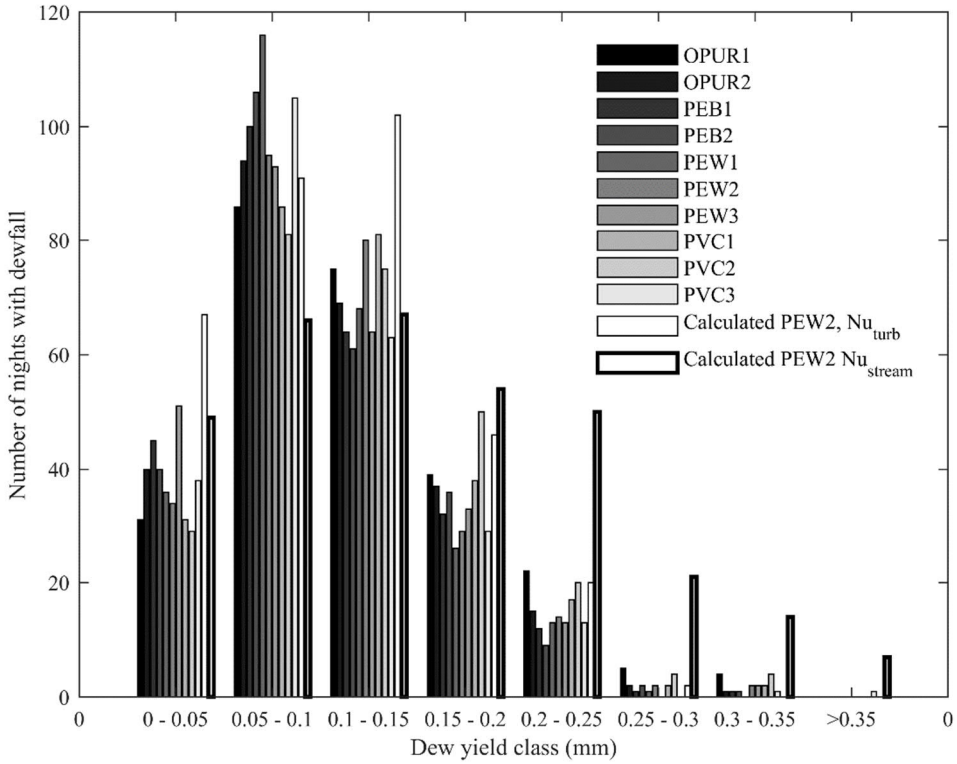


Figure 4. Dew yield frequency for the different surface materials presented in different classes (mm) over the 365-day measurement period. Outlined bars represent calculated dew yield frequencies

3.2 Effect of meteorological parameters and collector location on the harvested dew yield

Regarding the behaviour in the relation to the different measured meteorological parameters the collector PEW2 (Fig. 2) was chosen to be examined as the surface temperature measurement data of this foil was most consistent throughout the measurement period.

It was possible to observe the condensing period when the surface temperature fell below the dew point temperature (Supp. Material Fig. 3–6). We noticed that high water yields were harvested even though the surface temperatures were only slightly below the dew point (Supp. Material Fig. 6). During these kind of nights, the relative humidity was near 100% throughout the night.

The distribution between the dew yield and nocturnal wind speed (measured at 2 m height) is displayed in Fig. 5. Practically all dew events occurred when nocturnal wind speed means were 0–2.4 ms^{-1} The figure shows an envelope that decreases with wind speed starting at 2.4 ms^{-1}. The dominant wind direction of the nocturnal wind was south east (Fig. 5).

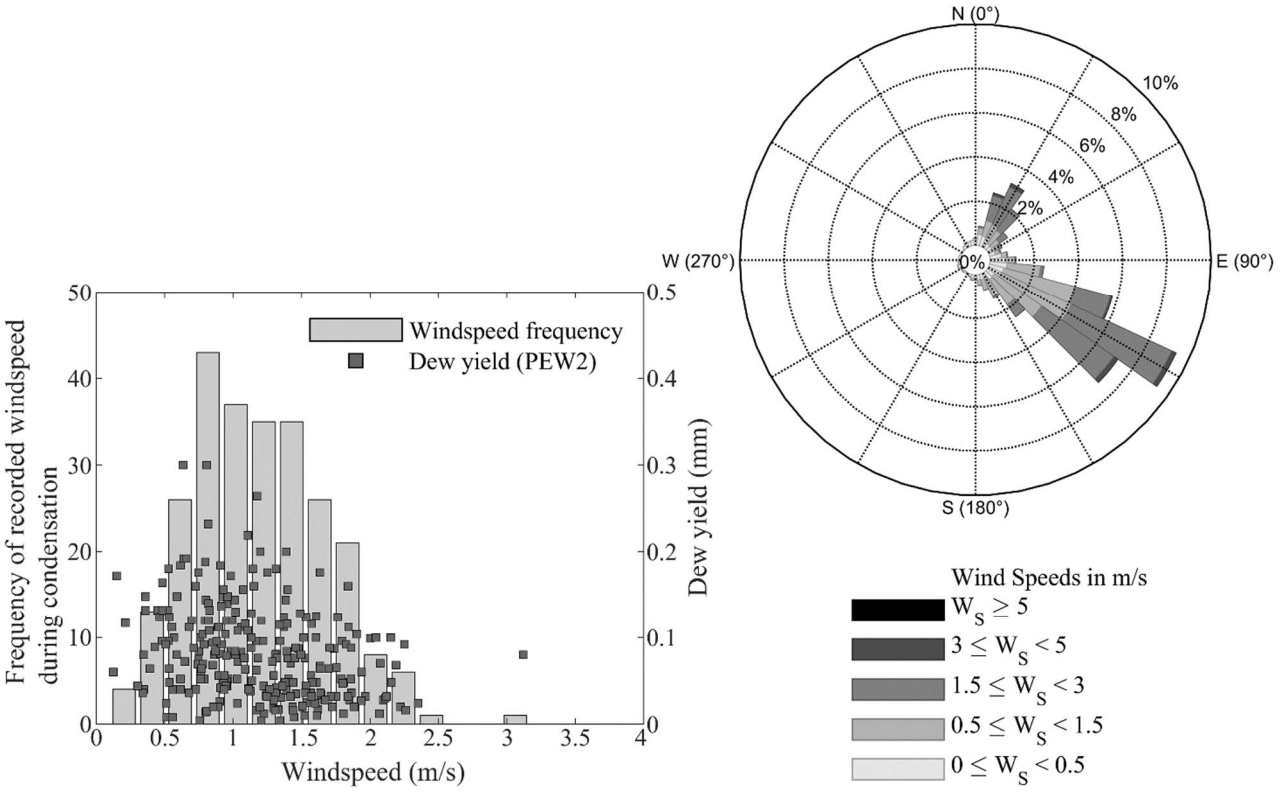


Figure 5. Relationship between mean nightly wind speed and the mean nightly dew yields (PE-White 2) over the 365-day measurement period. The bars stand for the wind speed frequency presented in wind speed classes. The wind rose displays the distribution of the nocturnal winds (speed and direction) over the measurement period. Each concentric circle represents a different frequency at which winds occur.

A key factor for the formation of dew is that the dew condensing surface temperature falls and stays at temperatures below the dew point temperature. The relationship between the temperature differences (dew point–surface temperature) and the harvested dew yield is displayed in Fig. 6. The dew point was derived from the air temperature and relative humidity values. Modest correlation was found between both the nighty dew

yield and the temperature differences dew point-to-surface temperature (Fig. 6) and dew point-to-air difference related to relative humidity (Fig. 7).

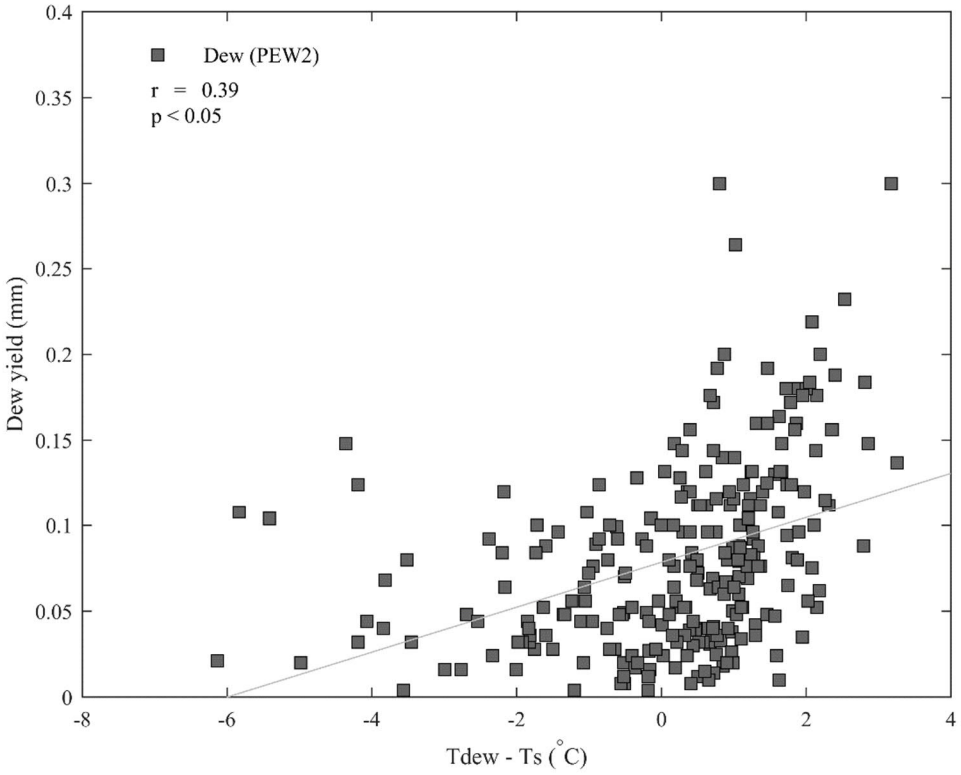


Figure 6. Correlation between the mean nightly temperature differences (dew point temperature, T_{dew} – foil surface temperature, T_s) and the nightly dew yields (PE-White 2) harvested during the 365-day measurement period of April 1st, 2016 to March, 31st 2017. Pearson's correlation coefficient r = 0.39, p < 0.050

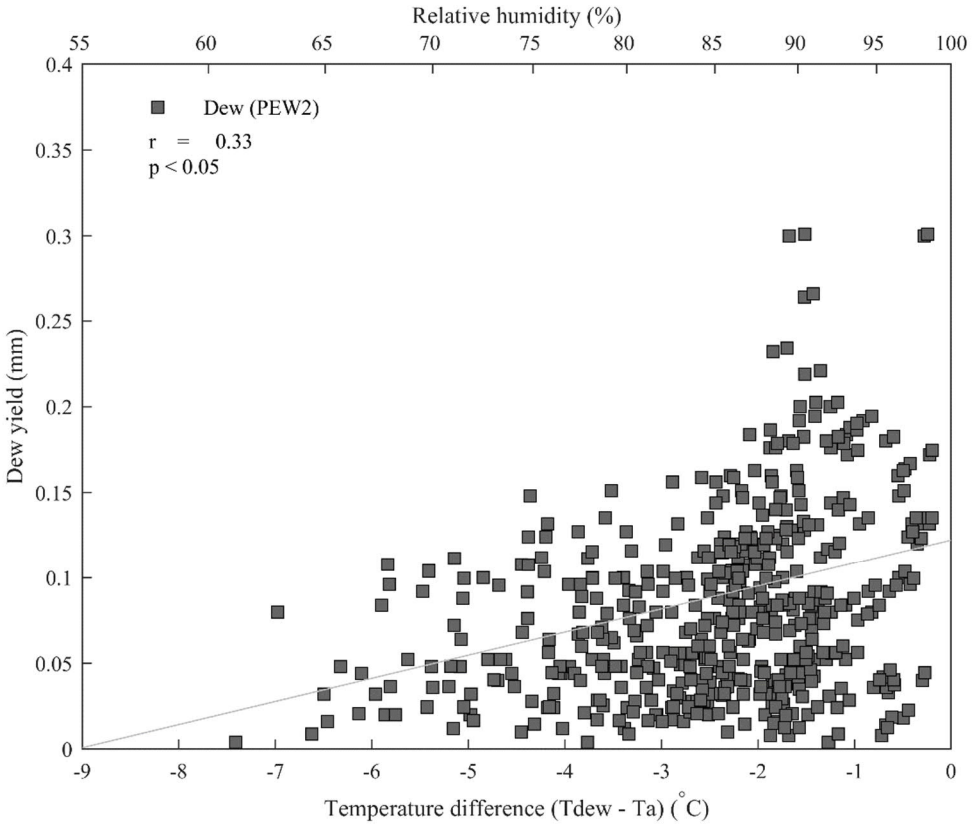
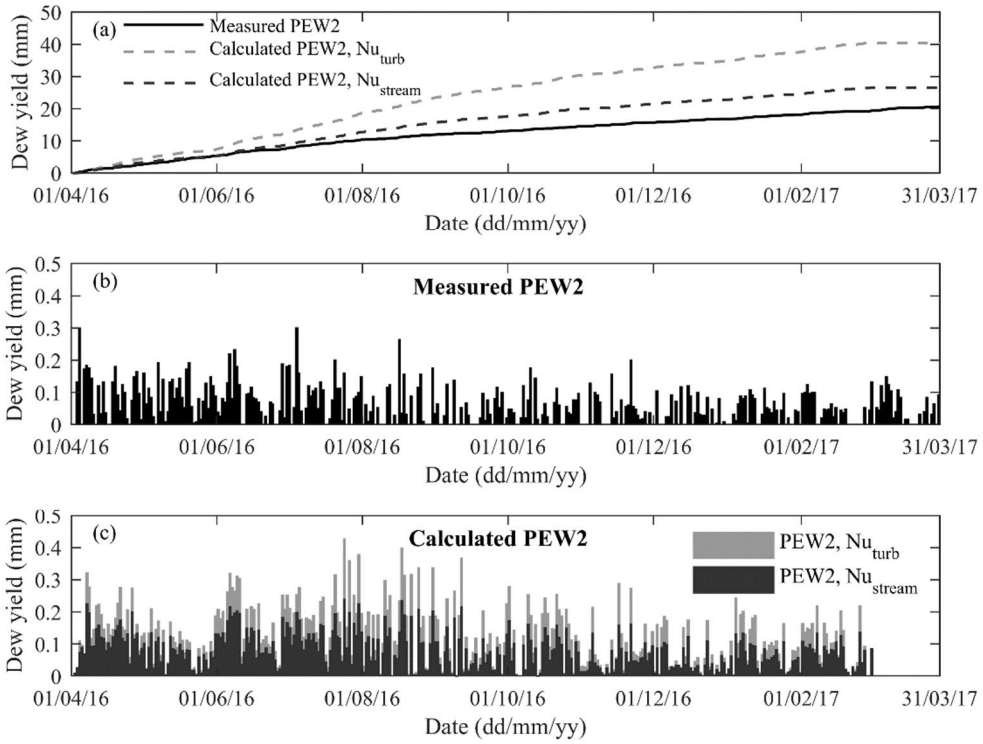


Figure 7. Correlation between mean nightly temperature difference ($T_{dew} - T_a$) (°C, lower scale), relative humidity (upper scale) and the nightly harvested dew yield (PE-White 2) during the 365-day measurement period of April 1st, 2016 to March, 31st 2017. Pearson's correlation coefficient r = 0.33, p < 0.050

3.3 Comparison of measured and calculated dew yields

We calculated the dew that condenses according to the measured meteorological parameters.We assumed that the wind direction was mostly not along the surface as the equations assume, thus calculations using two different *Nu*-numbers are presented (Fig. 8). The correlation between the daily measured and the daily calculated dew yield was only moderate or modest depending on the used *Nu*-number (Fig. 9). When comparing the cumulative sums of dew yields (Fig. 10) instead of daily dew events, a strong relationship found between the calculated and measured dew yields. It is also possible to observe the systematic deviation between the calculated and measured dew yields that continuously increases the difference.



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344 Figure 8. Cumulative dew yields of measured and calculated dew yields as a function of time (a) for the 365-
345 day measurement period of April 1st, 2016 to March, 31st 2017. Corresponding daily measured dew events (b)
346 and daily calculated dew events (c) using different Nu- numbers (turbulent and streamline flow) presented as
347 a function of time).

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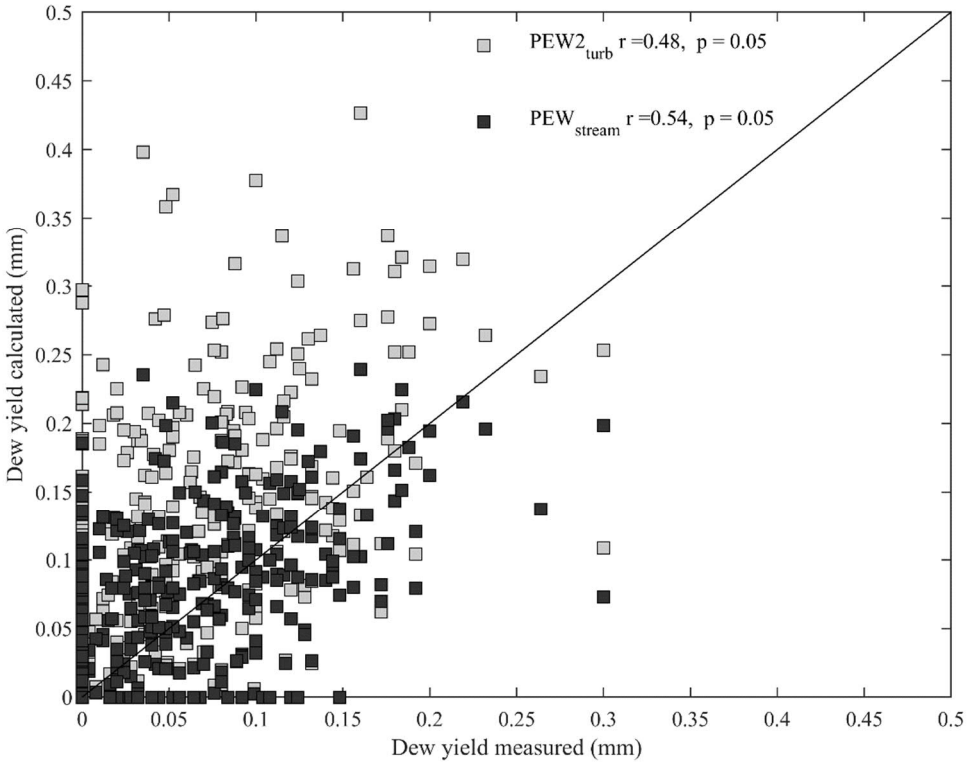

Figure 9. Correlation between measured (PE-white 2) and the calculated dew yields (Nu_{stream} and Nu_{turb}) during the 365-day measurement period. Pearson's correlation coefficient for streamline flow $r = 0.54$, $p < 0.05$ and turbulent flow $r = 0.49$, $p < 0.05$. If the dry nights from the both calculated and measured data are rejected the corresponding Pearson's correlation coefficient would be $r = 0.47$, $p < 0.050$ and for turbulent flow $r = 0.39$, $p < 0.05$. The line is the 1:1 relationship.

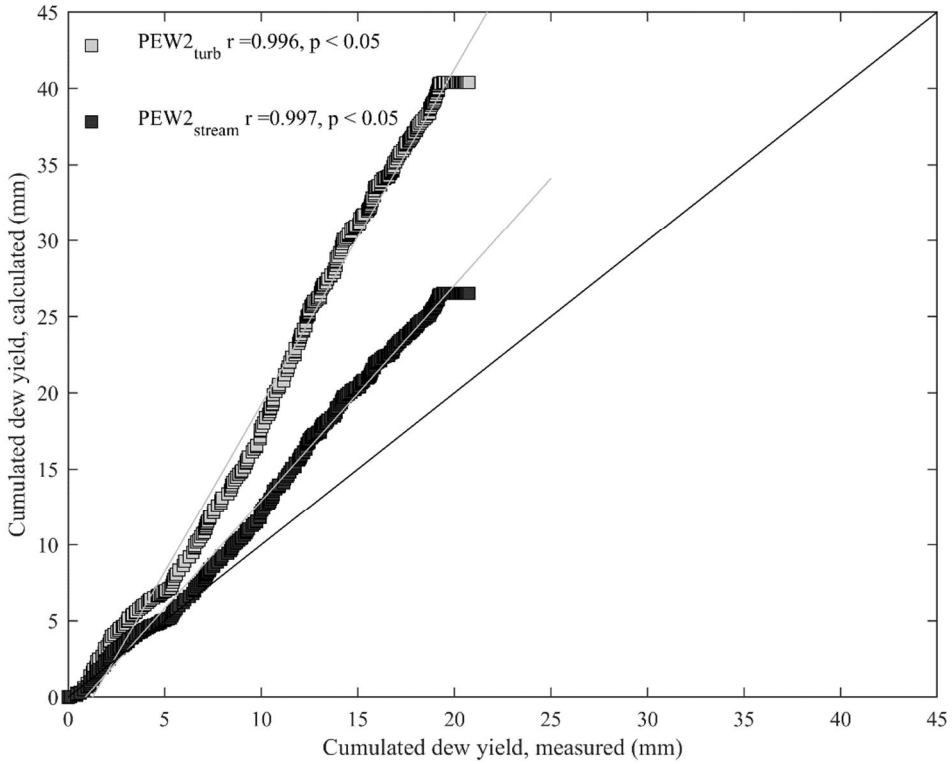

Figure 10. Correlation between cumulative sum of the measured (PE-white 2) and the calculated dew yields (Nu_{turb} and Nu_{strean}) during the 365-day measurement period. Pearson's correlation coefficient for turbulent flow r = 0.996, p < 0.05 and streamline flow r = 0.997, p < 0.05. The black line is the 1:1 relationship. The grey lines are the best linear fits.

3.4 Impact of the location of the collectors

The distribution of the population of the samples (nightly dew yields) of PVC2 differed significantly (p = 0.0048, 95 % confidence interval) from both PEW3 and PVC3 (Figure 2). The differing distributions were found between the collectors PEW3 and PVC3, which gave smallest total dew yields and PVC2 which gave the greatest total dew yield. There were no significant difference found between other measured dew yields (Fig. 11).

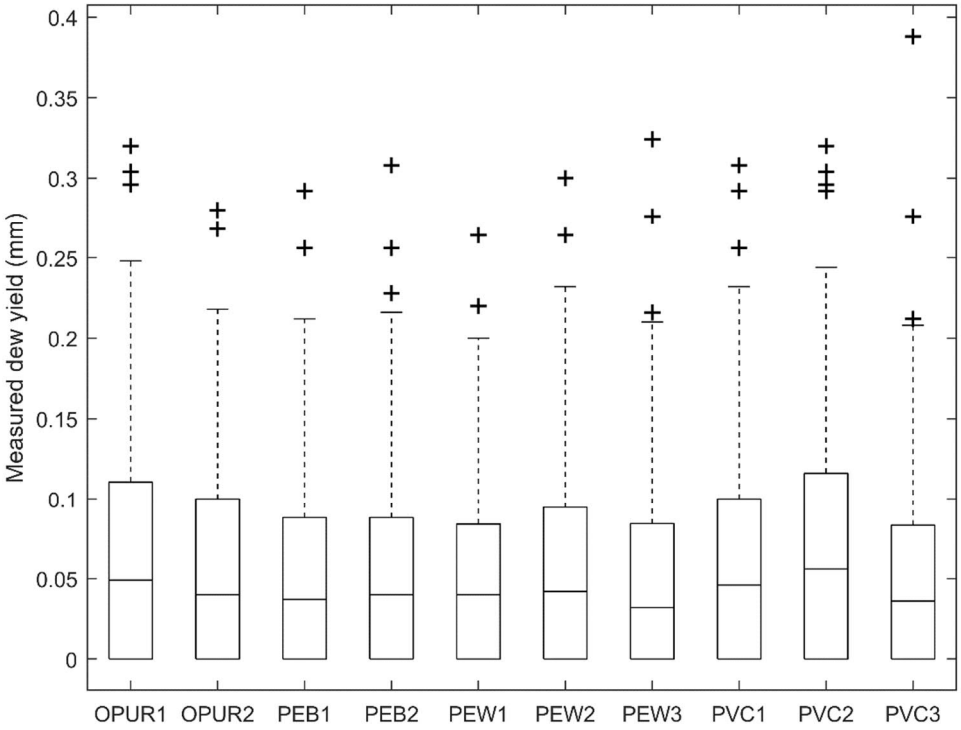

Figure 11. Distributions of the daily dew yields of the different plastic foils. The horizontal lines within the box represent the medians (50% quantiles), while the 25% quantiles are shown by the lower ends of the central boxes and the 75% quantiles by the upper ends of the central boxes. The maximum whisker length is 1.0 times the interquartile range. Data points beyond the range of the whiskers are displayed using "+".

4. Discussion

The nightly dew yields we harvested were in line with the dew yields reported in previous studies (supplementary material: Table 1). The amount of dew we collected was a result of both gravity-induced flow and scraping of the residual dew. According to Muselli et al. (2002) the scraped dew amount contributed on average one third of the collected dew yield. The presented dew yield distributions would have been different

384 if we would have presented the distributions for dew yields collected by gravity induced flow. However, the
385 magnitude of the decrease in the dew yield can vary considerably according to the foil material and its aging
386 as it is dependent on the wetting properties of the surface material. This matter should be studied more closely
387 for further discussion. In addition, the emissivity of the surface, specially in the atmospheric window (7 – 14
388 μm) has an impact on the cooling of the surface and thus the dew yield. The measured emissivities of the dry
389 condensing surfaces were measured they were all near unity (εOPUR = 0.967, εPEB = 0.927, εPEW = 0.975,
390 εPVC = 0.965). However, when condensation has started, liquid water emissivity matters much, as a large
391 fraction of the condensing surface is wet, more than 55% (Beysens 2018).

392 The annual harvested dew amounts per area were less than 8% of the rainfall (highest cumulated dew yield:
393 25.3 mm, total precipitation: 322 mm). We found, however, that dew could provide a continuous water source
394 even during the dry season.

395 Our study on the dew yield frequency revealed that for all tested plastic materials, most dew events that
396 occurred yielded a dew amount ≤ 0.1 mm per night. The OPUR foil and PVC foils gave more and greater dew
397 yields in the magnitude scale (> 0.2 mm) compared to the black and white PE foils. The results of this study
398 differed from the data obtained by Maestre-Valero et al. (2011) who reported that PEB foil was less sensitive
399 to dew and fewer small dew events (≤ 0.05 mm) compared to OPUR foil. On the other hand, Maestre-Valero
400 et al. (2011) reported that the PEB foil was found to give more dew events in the dew yield classes of 0.15,
401 0.20, 0.25, 0.30 and 0.35 mm. The results of our study suggested that PVC and OPUR performed better in
402 collecting greater dew yields than PE plastics.

403 The condensing period can be observed from the measurement data as the period when the surface temperature
404 is below the dew point temperature. However, the measured dew yields did not grow with the temperature
405 difference between the surface and the dew point temperature and neither did the coldest surface foil always
406 condense greatest dew yields. This is in agreement with the fact that low super saturation values (Tdew - Tair)
407 favour condensation of water, rather than cooling the condensing surface (Beysens 2016). We found modest
408 and moderate correlations between different measured meteorological parameters and the harvested dew
409 yields. The wind speed pattern was similar as has been reported in earlier studies. Dew rarely forms during

410 calm nights at wind speeds close to 0 ms^{-1} and there is sharp transition between dew events and no dew events
411 (Muselli et al. 2002; Maestre-Valero et al. 2011). We observed a similar sharp transition at 2.4 ms^{-1} (Fig. 9).
412 Both the dependence between surface temperature and dew point (Fig. 10) and dew point and ambient air
413 shows a large dispersion, but with a tendency to favor dew events at low super saturation values. This is in
414 agreement to the fact that low values (Tdew - Tair) minimizes heat losses (Beysens 2016). The low super
415 saturation values are also highlighted in the correlation with RH proportional to Tdew-Tair (Fig. 11). At these
416 highlighted points, the cooling power is used to condense water by compensating for the latent heat of
417 condensation (Beysens 2016). Similar trend of highlighted values have also been reported earlier (i.e. Muselli
418 et al. 2009, Maestre-Valero et al. 2011). High differences (Tdew-Tair) result in maximum temperature
419 difference between condenser and the ambient (Beysens 2016) and thus, condensation is canceled when all
420 cooling power is used to cool the condenser.

421 The accumulated calculated dew yield was in line with the measured dew yield in the beginning of the
422 measurement period. The model calculations were able to estimate dew yield accumulation for approximately
423 the first 90 days of the 365-day period, but was more or less incapable of estimating daily dew harvests
424 accurately thereafter. For the later part of the measurement period the model calculations gave greater dew
425 yields than the actual harvested dew yields. There was moderate or modest correlation found between the
426 nightly calculated and the actual measured dew amounts. The values of coefficients *Nu*, etc. matter very much
427 and varies with the details of air flow and thus condenser location (Beysens et al. 2005). Comparison of the
428 cumulative sums of measured and calculated dew quantities (Fig. 10), smooths down the daily variation and
429 giving a better view of strong correlation between the measured and calculated dew yields.

430 According to our study, the measured meteorological conditions or more precisely the difference between the
431 calculated water concentration in air and the concentration at the condensing surface could not act as an
432 explanatory factor for the harvested dew yields. A precise prediction of dew occurrence and dew yield was
433 found to be a challenge when only simple meteorological data was available. More specific, dew collector
434 scale meteorological measurements and further on computational fluid dynamics (CFD)-modelling can be a
435 useful tool, for optimizing the location and settings for dew collectors in specific environmental conditions as
436 Clus et al. (2009) and Sharan et al. (2017) have done in deciding the location of collectors. Conditions vary

437 within the nocturnal condensing period. Continuous monitoring of dew accumulation would have enabled
438 more precise evaluation of the relationship between continuously dew and counutnuous meteorological data,
439 rather than averaged values. In addition, the surface temperatures and wind speeds at the surface of each
440 collector would be useful. More sensors than were available would also have been needed for more elaborate
441 measurement results.

442 The wetting properties of the condensing surface have an impact on the harvested dew yields. The wetting
443 properties of the condensing surface vary greatly in field conditions due to dust and fatty contaminants, which
444 are present in any human related activity. A monolayer of fat can even change the contact angle of water on
445 glass from 0° to 100° (Beysens 1995). Plastics can also degrade under intense UV-radiation (Gijsman et al.
446 1999; Scoponi et al. 2000; Bertoldo et al. 2003; Zhaoa et al. 2007) and wear-out by daily wiping of the water
447 droplets condensed on the surface. Wiping may result scratches on the plastic surface that have a weakening
448 effect on the dew collecting attributes. Further research into impact of these factors in field conditions would
449 be needed.

450 The placement of the collector at the field (Fig. 2) can have an impact on the dew yield. According to our
451 results, poor placement can have a reducing effect on the dew yield. The effect was significantly apparent only
452 when we compared two collectors with the lowest cumulated dew yield (PEW3 and PVC3) to the collector
453 that collected the highest yield (PVC2) (Fig. 3 and Fig. 11). Collector PVC3 can be considered poorly placed
454 compared to PVC2. The difference in the amounts of measured dew yield is due to difference in air flow at the
455 surface of the collectors that affects the thickness of the boundary layer and thus the condensation of dew. To
456 find out more about the differences and the reasons for the on sites differences in the dew yields, more specific
457 air flow measurements should be conducted in the vicinity of the individual dew collectors.

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4. Conclusions

All four tested surface materials were found to be suitable for collecting amounts of dew in arid conditions (nightly mean 0.052 − 0.069 mm). The quantities of dew we collected were in line with those reported by earlier dew collection studies. The type of the foil was not found to be a determining factor regarding the amount of dew.

The measured emissivities of all the dry plastic foils were close to unity. As dew forms, a larger part of the foil gets wet and the emissivity of liquid water matters more and reduces differences between the foils. The emissivity and wetting properties of plastic foil may change with time as the plastic wears out and gets contaminated.

Location or placement of the dew collector may be important, due to the airflows at the collector surface affecting the condensation and can have an impact on the dew yield.

We found modest and moderate correlation between the different measured meteorological variables and the measured dew yield. Despite that, the dependences between the measured dew yield and the temperature differences showed large dispersion, there was a tendency to favor dew events at low super saturation, or low temperature difference values. This is also in agreement with earlier findings. It is suggested that at low super saturation values the cooling power is used to condense water rather than cool the dew condenser.

The model for calculating dew output was capable of estimating cumulative dew yields, especially in the beginning of the measurement period. More specific measurement data of airflows and thus the mass transfer at the condensing surface would be needed for more accurate model calculations of the nightly dew yields. In addition, data on cloud cover, which would be helpful when implementing different models for calculating radiative cooling.

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646 **SUPPLEMENTARY MATERIAL**

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648 Table 1. Previously reported dew collecting experiments, locations and yields presented in chronological order
649 of publication

Reported by	Reported amount (mm)	Reporting for	Time frame	Location	Surface material
Wagner et al. 1992	0.15	Mean dew/night	134 dew events/365 days	Fayetteville, AR, USA	PTFE coated aluminum
Wagner et al. 1992	>0.2 mm	Maximum dew yield			PTFE coated aluminum
Nilsson 1994	0.0396	Mean dew/night	30 nights	Dodoma, Tanzania	LDPE with TiO2 & BaSO4
Nilsson 1994	0.12	Maximum dew yield		Dodoma, Tanzania	LDPE with TiO2 & BaSO4
Nilsson 1996	0.145	Mean dew/dew event	14 dew events/19 days	Kungsbacka, Sweden	LDPE with TiO2 & BaSO4
Nilsson 1996	0.207	Maximum dew yield		Kungsbacka, Sweden	LDPE with TiO2 & BaSO4
Nilsson 1996	0.28	Maximum dew yield		Kungsbacka, Sweden	Insulated glass plate collector
Vargas et al. 1998	0.048	Monthly mean dew/night	147 non rainy nights/165 days	Dodoma, Tanzania	LDPE with TiO2 & BaSO4
Vargas et al. 1998	0.24	Maximum dew yield		Dodoma, Tanzania	LDPE with TiO2 & BaSO4
Kidron 1999	0.09	Mean dew/dew event	36 dew events	Nitzana, Israel	Cloth plate method
Kidron 1999	0.18	Mean dew/dew event	34 dew events	Sde Boqer, Israel	Cloth plate method
Kidron 1999	0.22	Mean dew/dew event	21 dew events	Har Harif, Israel	Cloth plate method
Khare et al. 2000	0.592	Mean dew/dew event		Dayalbagh, India	Polyethylene
Khare et al. 2000	1.38	Maximum dew yield		Dayalbagh, India	Polyethylene
Muselli et al. 2002	0.38	Maximum dew yield		Ajaccio, Corsica, France	LDPE with TiO2 & BaSO4
Muselli et al. 2002	0.12	Mean dew/dew event	214 dew events/478 days	Ajaccio, Corsica, France	LDPE with TiO2 & BaSO4
Beysens et al. 2003	0.036	Mean dew/dew event	109 dew events/365 days	Grenonle, France	PMMA
Takenaka et al. 2003	0.133	Mean dew/dew event	No info	Sakai City, Japan	Aluminum painted with car paint
Takenaka et al. 2003	0.139	Mean dew/dew event	No info	Sakai City, Japan	Glass
Takenaka et al. 2003	0.092	Mean dew/dew event	No info	Sakai City, Japan	PTFE coated stainless steel vat
Takenaka et al. 2003	0.034	Mean dew/dew event	No info	Sakai City, Japan	PTFE coated aluminum wall
Beysens et al. 2005	0.046	Mean dew/dew event	211 dew events/365 days	Bordeaux , France	PMMA
Gandhisan and Abualhamayel 2005	0.22	Mean dew/dew event		Dhahran, Saudii Arabia	LDPE with TiO2 & BaSO4
Beysens et al. 2006	0.12	Mean dew/dew event	214 dew events/478 days	Ajaccio, Corsica, France	LDPE with TiO2 & BaSO4
Beysens et al. 2006	0.38	Maximum dew yield		Ajaccio, Corsica, France	LDPE with TiO2 & BaSO4
Beysens et al. 2006	0.073	Mean dew/dew event	one year	Ajaccio, Corsica, France	PMMA plate
Beysens et al. 2006	0.084	Mean dew/dew event	one year	Ajaccio, Corsica, France	PMMA plate
Beysens et al. 2006	0.11	Mean dew/dew event	one year	Ajaccio, Corsica, France	LDPE with TiO2 & BaSO4
Beysens et al. 2006	0.11	Mean dew/dew event	one year	Ajaccio, Corsica, France	LDPE with TiO2 & BaSO4
Beysens et al. 2006	0.115	Mean dew/dew event	one year	Brive-la-Gaillarde	LDPE with TiO2 & BaSO4
Berkowicz et al. 2007	0.6	Mean dew/dew event	554 dew events/1096 days	Jerusalem, Israel	LDPE with TiO2 & BaSO4
Berkowicz et al. 2007	0.199	Maximum dew yield		Jerusalem, Israel	LDPE with TiO2 & BaSO4
Beysens et al. 2007	0.08	Mean dew/night	184 nights	Biševo, Croatia	Commercial polycarbonate sheet thicker than
Sharan et al. 2007	0.18	Maximum dew yield		Kothara, India	Uninsulated galvanized roof
Sharan et al. 2007	0.24	Maximum dew yield		Kothara, India	Uninsulated galvanized roof
Sharan et al. 2007	0.098	Mean dew/night	243 nights	Kothara, India	Uninsulated galvanized roof
Sharan et al. 2007	0.075	Mean dew/night	243 nights	Kothara, India	Uninsulated galvanized roof

Clus et al. 2008	0.102	Mean dew/dew event	26 dew events/109 days	Tikehau, French Polynesia	LDPE with TiO2 & BaSO4
Clus et al. 2008	0.069	Mean dew/dew event	81 dew events/ 151 days	Tahiti, French Polynesia	LDPE with TiO2 & BaSO4
Clus et al. 2008	0.23	Maximum dew yield		Tikehau, French Polynesia	LDPE with TiO2 & BaSO4
Clus et al. 2008	0.22	Maximum dew yield		Tahiti, French Polynesia	LDPE with TiO2 & BaSO4
Jacobs et al. 2008	0.10 ± 0.06	Mean dew/night	18 months	Wageningen, The Netherlands	LDPE with TiO2 & BaSO4 & PVC*
Jacobs et al. 2008	0.15 ± 0.05	Mean dew/night	12 months	Wageningen, The Netherlands	LDPE with TiO2 & BaSO4
Muselli et al. 2009	0.406	Maximum dew yield		Zadar, Croatia	LDPE with TiO2 & BaSO4
Muselli et al. 2009	0.592	Maximum dew yield		Komiža Croatia	LDPE with TiO2 & BaSO4
Muselli et al. 2009	0.138	Mean dew/dew event	484 dew events/1219 nights	Zadar, Croatia	LDPE with TiO2 & BaSO4
Muselli et al. 2009	0.108	Mean dew/dew event	263 events/1219 nights	Komiža Croatia	LDPE with TiO2 & BaSO4
Maestre-Valero et al. 2011	0.105	Mean dew/dew event	175 dew events/365 days	Cartagena, Spain	LDPE with TiO2 & BaSO4
Maestre-Valero et al. 2011	0.128	Mean dew/dew event	163 dew events/365 days	Cartagena, Spain	Commercial low cost Black PE
Maestre-Valero et al. 2011	0.314	Maximum dew yield		Cartagena, Spain	LDPE with TiO2 & BaSO4
Maestre-Valero et al. 2011	0.316	Maximum dew yield		Cartagena, Spain	Commercial low cost Black PE
Lekouch et al. 2011	0.106**	Mean dew/dew event	178 dew events/365 days	Mirleft, Morocco	LDPE with TiO2 & BaSO4
Sharan et al. 2011	0.189	Mean dew/dew event	69 dew events/192 days	Panandhro, India	LDPE with TiO2 & BaSO4
Sharan et al. 2011	0.566	Maximum dew yield		Panandhro, India	LDPE with TiO2 & BaSO4
Lekouch et al. 2012	0.202	Mean dew/dew event	187 dew events/321 days	Id Ouasskssou, Morocco	LDPE with TiO2 & BaSO4
Lekouch et al. 2012	0.5	Maximum dew yield		Id Ouasskssou, Morocco	LDPE with TiO2 & BaSO4
Galek et al. 2012	0.179	Mean dew/dew event	19 dew events/31 nights	Wroclaw, Poland	Polyethylene
Galek et al. 2012	0.389	Maximum dew yield			Polyethylene
Kidron & Starinsky 2012	0.15	Mean dew/dew event	12 dew envets	Nitzana, Israel	Glass
Kidron & Starinsky 2012	0.21	Mean dew/dew event	29 dew events	Sde Boqer, Israel	Glass
Clus et al. 2013	0.158***	Mean dew/dew event	137 dew events during 229 nights	Idouasskssou, Morocco	OPUR paint on iron sheet and commercially avai
Guan et al. 2014	0.225	Mean dew&dew event	14 dew events during 30 nights	Adelaide Hills, Australia	PTFE
Guan et al. 2014	0.373	Maximum dew yield			
Arias-Torres & Flores-Prieto 2015	0.0317	Mean dew/night	91 nights	Mexico City, Mexico	White painted aluminium sheet
Arias-Torres & Flores-Prieto 2015	0.0327	Mean dew/night	91 nights	Mexico City, Mexico	4.0 mm thick glass
Muskala et al. 2015	0.11	Mean dew/dew event	79 dew events / 183 nights	Krakow, Poland	Polyethylene
Muskala et al. 2015	0.36	Maximum dew yield		Krakow, Poland	Polyethylene
Muskala et al. 2015	0.19	Mean dew/dew event	80 dew events /183 nights	Gaik-Brzezowa, Poland	Polyethylene
Muskala et al. 2015	0.41	Maximum dew yield		Gaik-Brzezowa, Poland	Polyethylene
Beysens et al. 2017	0.055	Mean dew/dew event	63 dew events/365 nights	Paris, France	Steel painted with paint containing hydrophilic additives
Beysens et al. 2017	0.19	Maximum dew yield	63 dew events/365 nights	Paris, France	Steel painted with paint containing hydrophilic additives
Tomaszkiewicz et al. 2017	Beiteddine, Lebanon	Mean dew/dew event	123 dew events /263 nights	0.13	LDPE with TiO2 & BaSO4
Tomaszkiewicz et al. 2017	Beiteddine, Lebanon	Maximum dew yield		0.46	LDPE with TiO2 & BaSO4

*Foil replaced after ten months to commercial PVC

**Yield given for four separate 1x1 m2 condensers

***The vessel was saturated and the value could have been greater

****Total area of four separate condensers

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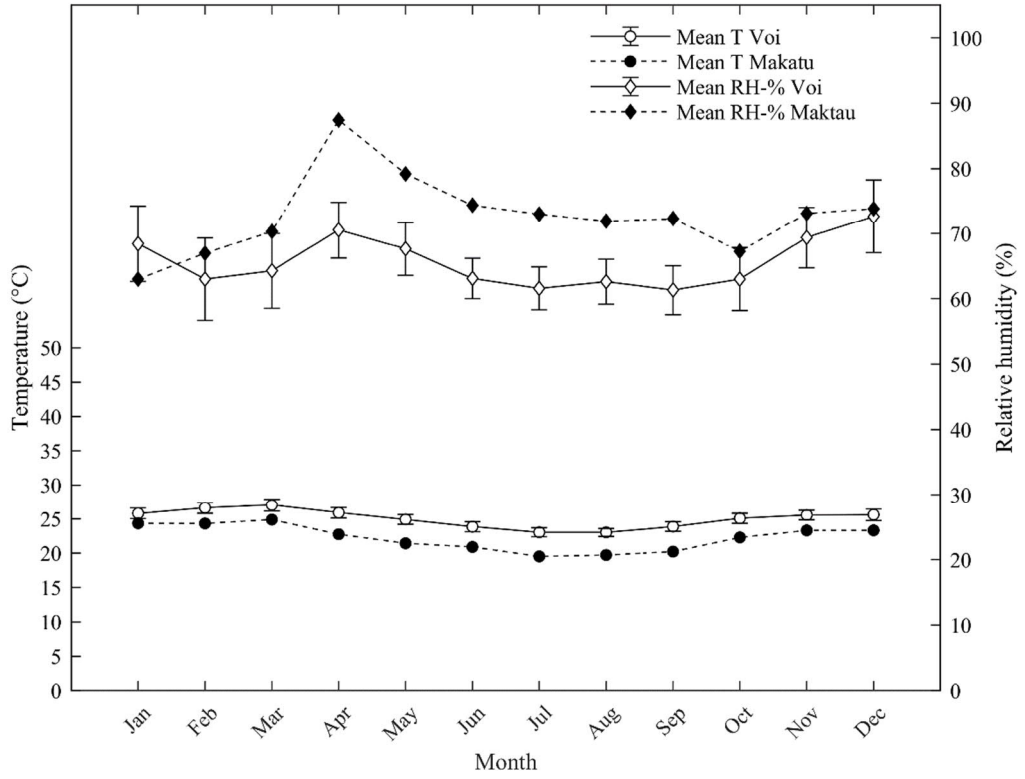


Figure 1. Air temperatures and relative humidity at the measurement field in Maktau and in Voi measurement station. The whiskers present the standard deviation of the 30-year means

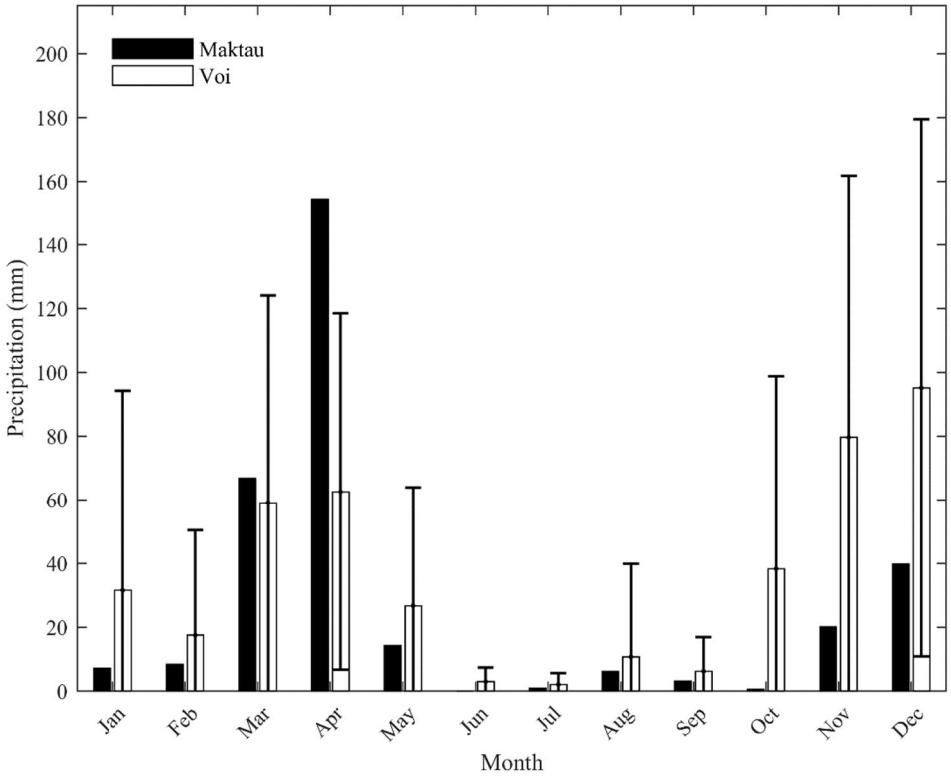


Figure 2. Precipitation at the measurement field in Maktau and in Voi measurement station. The whiskers present the standard deviation of the 30-year means

Table 2. Weather conditions in Voi, the nearest official weather station, located 50 km from Maktau. Mean 30-year rolling monthly values of the period of January 1st, 1986 to December 31st 2016. Data source: NOAA 2017 (National Oceanic and Atmospheric Administration 2017).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Mean T min (°C)	21.8	22.0	22.5	22.6	21.5	20.1	18.8	18.9	19.6	24.8	21.3	21.8	21.3
Mean T (°C)	26.7	27.5	27.9	26.8	25.7	24.6	23.8	23.8	24.7	26.7	26.4	26.5	25.9
Mean T max (°C)	33.4	34.6	35.3	33.7	31.6	30.3	29.5	29.6	31.0	32.8	33.2	34.2	32.4
Air relative humidity-%	70.7	65.1	66.4	72.9	69.9	65.2	63.6	64.7	63.4	62.1	71.7	75.1	67.6
Mean monthly precipitation (mm)	26	18	61	65	28	3	2	11	6	36	82	98	36

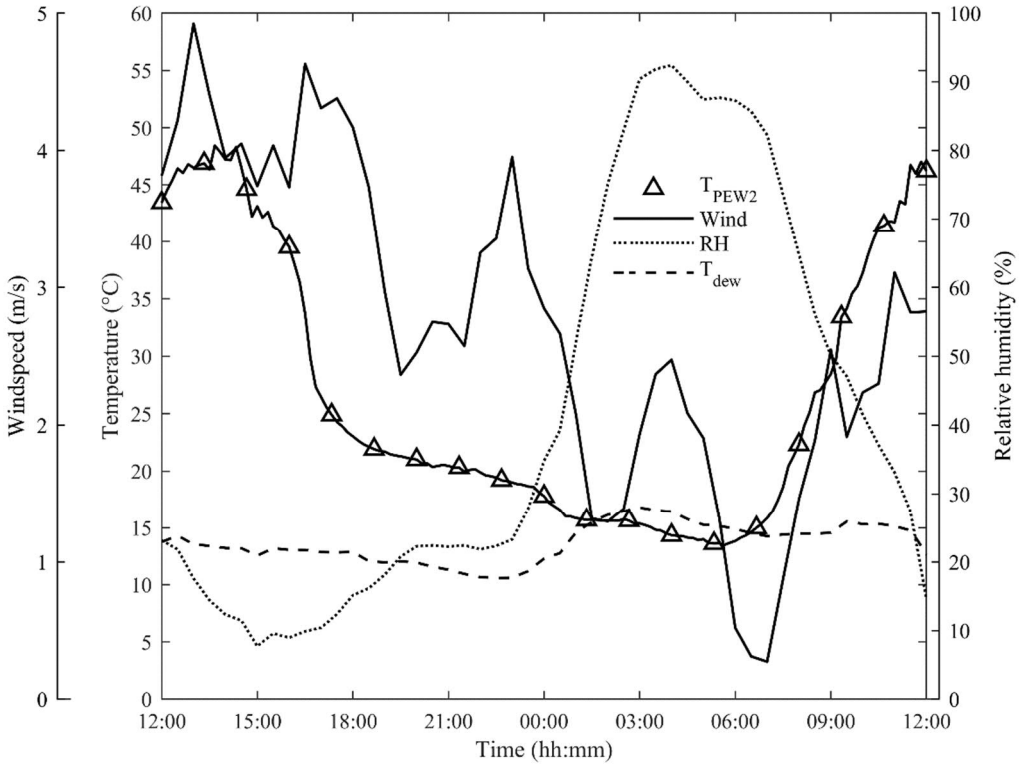
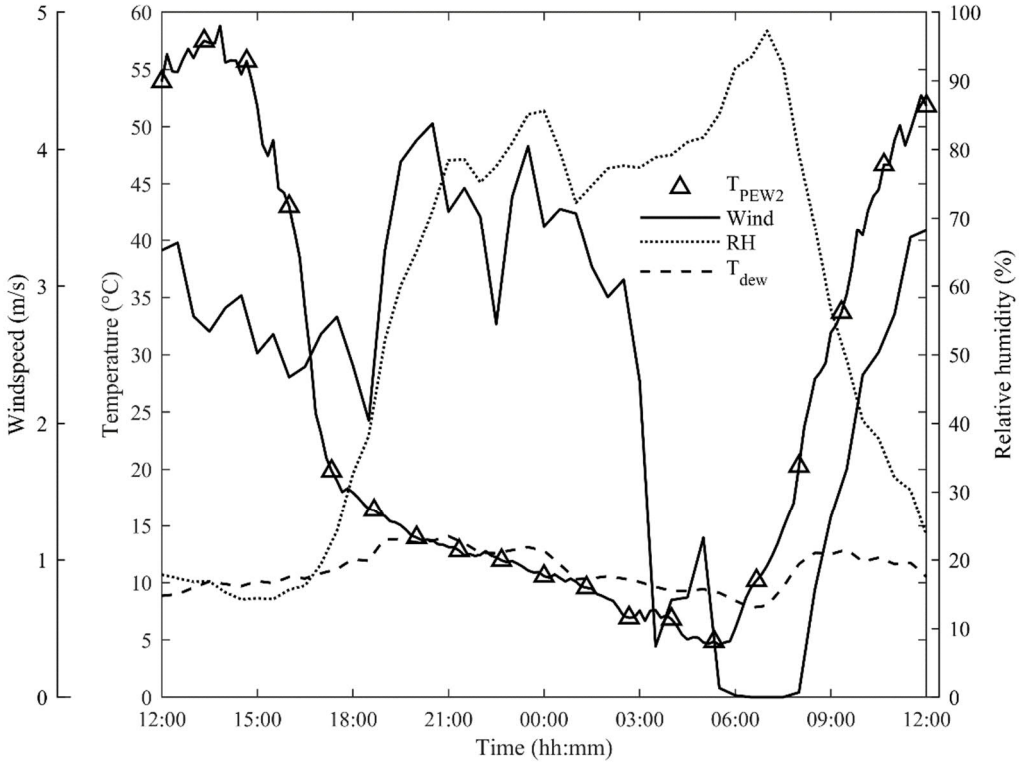


Figure 3. Windiest night 11-12.1.2017. Surface temperatures of the dew collectors (TPEW2), dew point temperature, ambient temperature and air wind speed displayed as a function of time. Dew yield during the night for PEW2: 0.08 mm. RH stands for relative humidity of air and Tdew for the dew point temperature.



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674 Figure 4. One of the coldest nights 2-3.8.2016. Surface temperatures of the dew collector (TPEW2), dew point
675 temperature, ambient temperature and wind speed displayed as a function of time. Dew yield PEW2: 0.014
676 mm. RH stands for relative humidity of air and Tdew for the dew point temperature.

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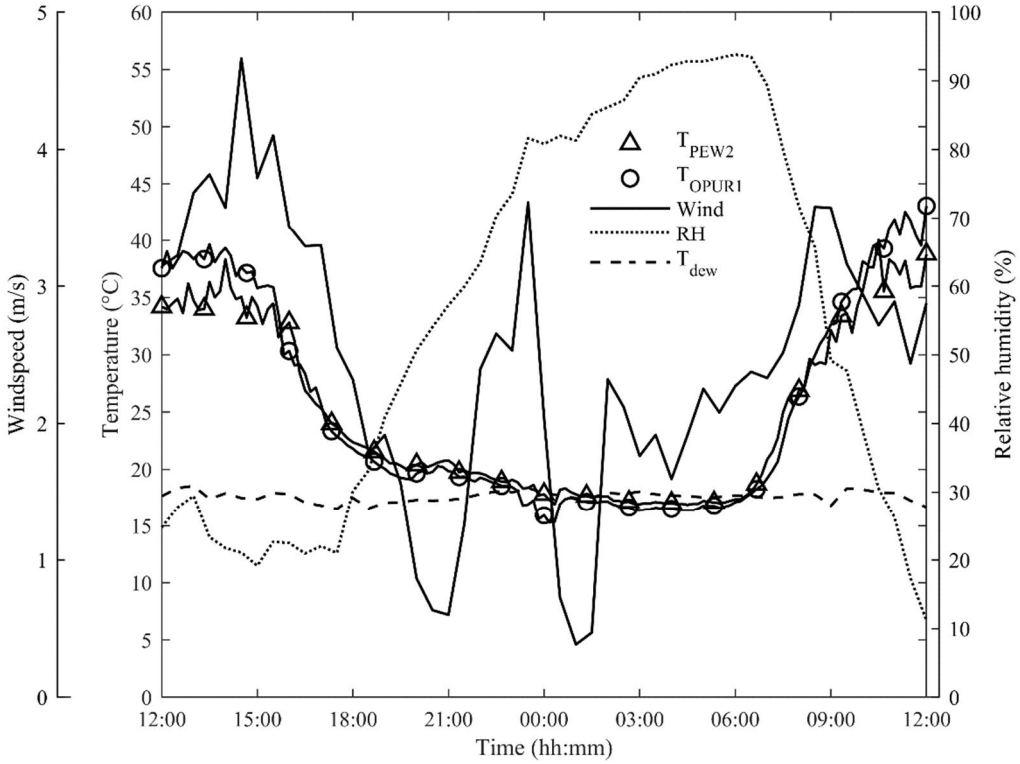

Figure 5. Large dew yield differences between the foils during the night 24-25.12.2016. Surface temperatures of the dew collectors (TPEW2 and TOPUR1), dew point temperature, ambient temperature and wind speed displayed as a function of time. Dew yields: PEW2: 0.048 mm, OPUR 1 2: 0.136 mm. RH stands for relative humidity of air and Tdew for the dew point temperature.

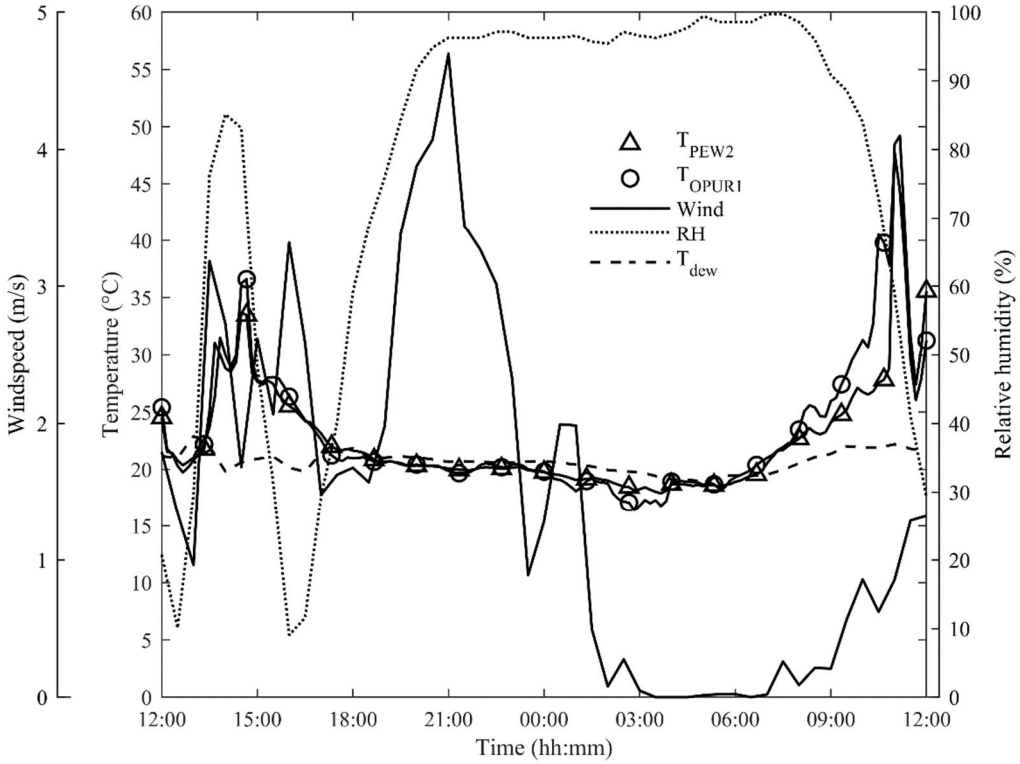

Figure 6. Large dew yields measured with all foils during the night 3-4.4.2016. Surface temperatures of the dew collectors (TPEW2 and TOPUR1), dew point temperature, ambient temperature and wind speed displayed as a function of time. Dew yields: PEW2: 0.320 mm, OPUR1: 0.308 mm. RH stands for relative humidity of air and Tdew for the dew point temperature.

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