Meteorologische Zeitschrift, Vol. **13**, No. 5, 405-412 (October 2004)

Article

Dewfall measurements on Lanzarote, Canary Islands

ALEXANDER GRAF[1]*, WILHELM KUTTLER[1] and JULIUS WERNER[2]

[1]University of Duisburg-Essen, Institute of Geography, Essen, Germany
[2]University of Münster, Institute of Landscape Ecology, Münster, Germany

(Manuscript received January 17, 2004; in revised form March 26, 2004; accepted March 29, 2004)

Abstract

At Lanzarote, Canary Islands, condensation is considered to play a significant role in the water budget of fields mulched with porous volcanic products ("Picón"). Here, 68 nights of gravimetric condensation measurements with mulched and bare surfaces, along with meteorological measurements were carried out. Results presented here indicate two major findings of interest with respect to general assumption: Firstly, nocturnal condensation on the mulch surface is lower than on a dry bare (loam) soil surface. A slightly higher nocturnal cooling of the mulched surface, and resulting higher dewfall in the strict sense, is overcompensated by the stronger hygroscopic properties of the soil. Secondly, dewfall, though otherwise consistent in magnitude and meteorological dependency with empirical and theoretical knowledge in literature, can still be observed at high wind speeds ($\overline{u} \approx 10$ m s^{-1} at 10 m a.g.l.) in northern to north-eastern trade winds that carry moist air from the sea. Dewfall to the mulched surface was observed in 39 of the measurement nights with a mean nocturnal sum of 0.07 mm.

Zusammenfassung

Eine auf der Kanarischen Insel Lanzarote weitverbreitete Feldbaumethode nutzt poröses vulkanisches Auswurfmaterial ("Picón") als Mulchdecke; dabei wird unter anderem eine bedeutende Rolle der nächtlichen Kondensation für den Wasserhaushalt angenommen. Erste Ergebnisse gravimetrischer vergleichender Kondensationsmessungen an unbedecktem und gemulchtem Boden während 68 Nächten zeigen: Zum einen bleibt die Kondensation in der vulkanischen Mulchdecke hinter derjenigen an unbedecktem Boden (Lehm) zurück, obwohl sich erstere nachts geringfügig stärker abkühlt, woraus ein höherer Tauabsatz folgen müsste. Die stärkere Hygroskopizität der trockenen unbedeckten Bodenoberfläche überkompensiert jedoch diesen Einfluss. Zum anderen konnte der ansonsten in Höhe und Wetterabhängigkeit dem allgemeinen theoretischen und empirischen Kenntnisstand entsprechende Tauabsatz auch in windstarken Nächten ($\overline{u} \approx 10$ m s^{-1} in 10 m Messhöhe) nachgewiesen werden. Insgesamt wurde in 39 Nächten Tauabsatz auf der picónbedeckten Oberfläche festgestellt, in denen sich eine mittlere Nachtsumme von 0,07 mm ergab.

1 Introduction

Agriculture on the Canary Islands has developed a method to cope with drought that has been thought, besides reducing evaporation losses, to exploit atmospheric water vapour content by enhancing dewfall. Porous volcanic material abundantly available on the island, mostly in the form of grain size class Lapilli (0.002 to 0.064 m), has been used as a mulch layer above the soil surface for approximately 250 years. In places where the mulch layer has been provided about 1 m thick directly by volcanic eruptions, perennial plants like vines are cultivated in a technique called "Enarenado natural". Even more widespread is the artificial application of an approximately 0.1 m thick layer on top of the originally uncovered surface, called "Enarenado artificial", that allows the cultivation of cereals and vegetables. Local terms referring to the Lapilli include "Arena", "Rofe" or "Picón".

The mulching technique is known to reduce evaporation. A strong long-term saving effect has been shown by FERNANDEZ CALDAS and TEJEDOR SALGUERO (1987) and TEJEDOR SALGUERO et al. (2002, 2003) by comparing soil samples taken from mulched and bare fields throughout the year. An additional raising effect on dewfall has neither been proven nor disproven so far. Nonetheless, such an effect is supposed firmly in popular literature, e.g. travel guides, as well as in various scientific publications of more descriptive nature (MATZNETTER, 1958; ACOSTA BALADÓN, 1973; LAUSCHER, 1976; ACOSTA BALADÓN, 1996). Properties favourable for condensation that are attributed to Picón include a high longwave emissivity and a low thermal conductivity, both enhancing nighttime cooling of the surface, and hygroscopic behaviour.

Some authors have measured nocturnal condensation sums for a limited number of nights on artificial surfaces (HANLE, 1961) or directly in the Picón layer.

---

*Corresponding author: Alexander Graf, University of Duisburg-Essen, Campus Essen Fb 9, Institute of Geography, Dept. of Applied Climatology and Landscape Ecology, Universitätsstraße 5, 45141 Essen, Germany, e-mail: alexander.graf@uni-essen.de

0941-2948/04/0013-0405 $ 3.60

DOI: 10.1127/0941-2948/2004/0013-0405

Table 1: Climate data of the airport of Arrecife (28°57'08" N 13°36'01" W, 9 m a.s.l.) based on measurements from 1972 to 2000. t is mean air temperature, t_{min} and t_{max} mean minimum and maximum air temperature, respectively, P precipitation and rH relative humidity. Differences between sum of all months and year result from rounding.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
t / °C	17.0	17.5	18.5	19.0	20.2	21.9	23.8	24.7	24.4	22.5	20.3	18.1	20.7
t_{min} / °C	13.7	13.9	14.6	15.0	16.3	18.1	19.9	20.7	20.4	18.7	16.8	14.8	16.9
t_{max} / °C	20.4	21.2	22.5	23.0	24.2	25.7	27.8	28.8	28.4	26.3	23.9	21.4	24.5
P / mm	24	14	15	6	2	0	0	0	2	7	12	27	110
rH / %	71	71	69	69	69	69	70	71	73	73	72	73	71
days w. fog	0	0	0	0	0	0	0	0	0	0	0	0	1

This was done either by sampling the surface in the evening and morning (HÖLLERMANN and ZEPP, 1991) or by positioning simple predecessors of microlysimeters, i.e. small substrate-filled containers, in the mulch layer overnight and weighing them in the evening and morning (GONZALES BERNALDEZ et al., 1964). The maxima found cover a range from < 0.01 mm up to 0.59 mm water with the most extensive measurements taken directly in the Picón, covering 24 nights, showing a mean of 0.06 mm per night and a maximum of 0.2 mm per night (HÖLLERMANN and ZEPP, 1991). All authors concluded that the benefit of condensation would at most be indirect by modifying the morning Bowen ratio. However, as pointed out by ACOSTA BALADÓN (1996), only a few tens of mm of dew per year might be of importance where annual rainfall does not exceed 100 mm as is the case in great parts of the eastern Canary Islands.

As these measurements were not carried out simultaneously on mulched and bare surfaces, the effect of the Picón surface on nocturnal condensation has remained an object of speculation. The main focus of this study is to quantify both, condensation occurring simultaneously on mulched and bare surfaces, and their physical properties governing the meteorological conditions of condensation. Moreover, the frequent occurrence and supposed importance of condensation on Lanzarote as an arid island calls for a site-specific empirical study of the influence of meteorological and climatological factors, known from theory and from other sites, on condensation. First results concerning both topics are presented in the following paper.

2 Study area

Lanzarote (study area at 29° N, 13°30' W, maximum elevation of the island 670 m a.s.l.) belongs to the volcanic Canaries archipelago in the eastern north Atlantic, 100 km off the Moroccan coast. Most of the year and especially in summer, the archipelago is subject to the north-north-easterly trade winds and the associated temperature inversion between 1000 and 2000 m a.s.l. suppressing the development of rich rainfalls. However, trade winds are accompanied by a high relative humidity (Tab. 1). Most islands of the archipelago feature a variability of humid and arid climates including frequent fog dependent on altitude and exposition. However, Lanzarote and its neighbour Fuerteventura as the easternmost and flattest islands receive only 50 to 260 mm, depending on location, of mean annual precipitation. Nearly all of it is subject to winterly disturbances of low pressure and frontal systems as known from the mid-latitudes. Alongside the trades and disturbances, the third major weather type according to a simple classification by HUETZ DE LEMPS (1969), is an easterly wind carrying dry, dusty air from the Sahara desert.

The main study site was a plant-free Enarenado artificial field adjacent to the agrometeorological station of the island administration, located at 110 m a.s.l. (28° 59'59" N 13°33'30" W), 4.5 km north-westerly from the south-eastern coast. The upper 0.5 m of the soil is loam, applied artificially to the original rocky ground. It is covered by a Picón layer of 0.06 to 0.2 m thickness. Additional data is provided by the meteorological station of the islands' airport, located on the south-eastern coast (see Tab. 1). Additional mobile measurements conducted to assess spatial variance of dewfall will not be discussed in this paper. Local standard time in winter is UTC, true local time is one hour behind.

3 Methods

3.1 Condensation measurement

At the main study site, two adjacent squares of 4 m x 4 m were defined. One of the squares was denuded of its Picón layer. On these two squares, a temporary station was set up during three measurement periods. These

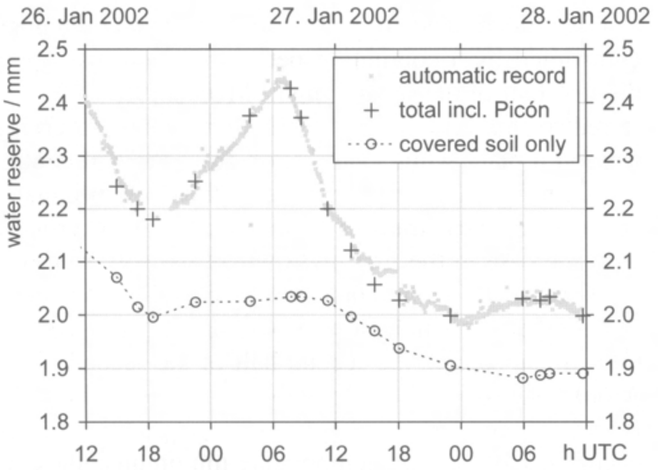

Figure 1: Gravimetrically measured condensation and evaporation in a soil sample covered with Picón, 26 to 28 January 2002. Automatic record: water reserve derived from recorded weight of the whole sample. Total incl. Picón: the same for calibrated, wind-shielded manual readouts. Covered soil only: water reserve derived from the weight of soil sample only without its mulch cover for manual readouts. Meteorological conditions see chapter 4.

periods, June 2001, January/February 2002 and October 2002, were chosen to account for annual variability.

In the middle of each square, a recording electronic balance (Ohaus DP6, New Jersey/Giessen, USA/Germany, max. load 6 kg, resolution 0.2 g) was put into a container in the ground such that the surface of its load was level with the surrounding surface. The load consisted of a container 0.06 m high and 0.29 m in diameter, filled with soil from the surrounding surface and, in the mulched case, an additional upper container with a wire mesh bottom (width 1 mm), containing a 0.07 m Picón layer. From the weight changes of the balance loads, condensation and evaporation were derived with an accuracy of 0.01 mm. Water content measurements of samples taken from the loads at the beginning and end of each experiment were used for calculating the absolute (mm) and relative (% dry mass) water content. It also verified that the measurements were not affected by solid particle losses or gains caused by wind. However, wind forces and diurnal balance temperature changes affected the reliability of the automatically recorded weight changes (see Fig. 1). Thus quantitative analyses are based on calibrated, wind-shielded readouts that were conducted several times a day. These also allowed for the weighing of the soil part of the load without its mulch layer (circles in Fig. 1). On these occasions, surface temperature of the weighed samples and their surrounding were measured with an infrared thermometer (Novasens i-tec 2003, Lüneburg, Germany; accuracy 0.8 K) with automatic emissivity correction for emissivities between 0.8 and 1, a range expected to apply to both substrates.

Simple methods for determining nocturnal condensation sums, similar to those adopted by former measurements on Lanzarote (see. chapter 1), have been applied also. They were used for method comparison and mobile measurements, not subject to this article as well as the testing of alternative mulch substrates. (see GRAF, 2004).

3.2 Meteorological measurements

Six combined thermistor/capacity sensors (Hygrotec 1310, Titisee-Neustadt, Germany; accuracy 0.2 K, 2 % rH) with steel sinter shields measured temperature and humidity of the air near the ground as well as in soil and mulch substrate pores in varying heights between –0.3 and +0.3 m, at 0.5 m distance from the balances. When measuring inside the soil, the values were also used for the calculation of soil water potential with Eq. 3.1 (OR and WRAITH, 2000). By comparing the soil water potential thus measured outside the balances to the soil water content of the samples on the balances, a reference for the validity of balance-derived water budget data for their undisturbed surrounding was given.

$$\begin{aligned}\Psi_W &= \mathrm{R\,T}\,\rho_W\,\mathrm{M}_W^{-1}\ln(\mathrm{rH}) \\ &= 4620\,\mathrm{hPa\,K^{-1}\,T}\ln(\mathrm{rH})\end{aligned} \tag{3.1}$$

Here Ψ_W is water potential with $[\Psi_W] = \mathrm{Pa}$, R the ideal Gas constant of 8.31 J $\mathrm{K^{-1}\,mol^{-1}}$, T the air temperature with [T] = K, ρ_W the density of liquid water (1.000 kg $\mathrm{m^{-3}}$ at 20° C), M_W the molar mass of water (0.018 kg $\mathrm{mol^{-1}}$) and rH the relative humidity with [rH] = 1.

In the second and third measurement period, two more combined sensors with additional heat anemometers (Testo 452, Lenzkirch, Germany) were used in heights between +0.05 m and +1.00 m. A net pyrradiometer (Thies 8111, Göttingen, Germany, 300 to 30000 nm) and an albedometer (Kipp & Zonen CM7B, Delft, the Netherlands, 305 to 2800 nm) were used to measure incoming and outgoing long- and shortwave radiation. A heat flux plate (Hukseflux HFP01, Delft, The Netherlands) was inserted into the soil and, on some occasions, the mulch layer. It was used in combination with soil temperature profile measurement for determining substrate heat conductivity and the subsequent calculation of soil heat flux density at the surface. In the case of Picón, too, effective heat conductivity was controlled in laboratory. All measured data was stored in intervals of 5 minutes (first measurement period: 30 minutes).

3.3 Laboratory work

Picón is supposed (see chapter 1), and dry bare soil quite well known (MONTEITH, 1963; KOSMAS et al., 2001), to be hygroscopic. This means that it will take up water from unsaturated air even at surface temperatures above the air's dewpoint, up to an equilibrium with air humidity. This property was measured in a simple laboratory set-up. It was conducted in a windowless laboratory and consisted of exposing oven-dry samples of the substrates inside an exsiccator to air of different humidities that were controlled by silica gel (≈ 2 % rH), pure water (≈ 100 % rH) and various salt solutions (intermediate humidities). The exact air temperature and humidity inside the exsiccator was measured with one of the combined sensors mentioned above (Hygrotec 1310). The water potential of atmospheric humidity inside the exsiccator, controlling hygroscopic water uptake and loss, was calculated with Eq. 3.1. The samples' water content was measured by weighing the samples and re-exposing them to the same salt solution until mass remained constant. The resultant empiric relationship between water potential and water content is the part of the substrate's water potential curve responsible for its hygroscopic behaviour. Out of this relationship, hygroscopicity as a single value roughly representing this behaviour under natural air humidity and temperature conditions is extracted as indicated by Eq. 3.2.

$$\mathrm{Hy} = (\mathrm{m}_W - \mathrm{m}_d)/\mathrm{m}_d \qquad (3.2)$$

Here Hy is hygroscopicity with [Hy] = 1 or % dry mass, m_W is sample mass at $\Psi_W = -8$ MPa, corresponding to rH = 94.3 % at T = 293.15 K (see Eq. 3.1), with $[\mathrm{m}_W]$ = kg, and m_d is "dry" sample mass at the lowest water potential that could be established ($\Psi_W = -530$ MPa, corresponding to rH = 2 % at T = 293.15 K), with $[\mathrm{m}_d]$ = kg. Therefore, a substrate with a high Hy value will take up more water during nocturnal increase of relative humidity than a substrate with a low Hy value.

4 General results

A short time series of measured cumulative condensation and evaporation on the Picón-mulched balance is given in Fig. 1. It depicts two nights with different meteorological conditions. Namely, the first night was almost clear (0/8 to 2/8) with radiation balance values ranging from – 80 W m^{-2} at the beginning to – 60 W m^{-2} at the end of the night while the second night was cloudy (4/8 to 8/8) with a maximum hourly mean of – 60 W m^{-2}. Relative humidity (2 m) at the agrometeorological station was around 95 % in the first and around 75 % in the second night. Note that dew, defined most commonly as the condensation on an object near the ground the temperature of which has fallen below the dewpoint of ambient air due to radiational cooling (AMS 2000), is represented best by the increase of the difference between the "total" and "soil only" datasets, i.e. the water reserve of the mulch layer. However, this condensed water can be redistributed from the soil underneath, being accompanied by a continuing net evaporation loss, as in the first half of the second night. MONTEITH (1957) referred to this process as "distillation" when observing dew on a plant while evaporation from the soil continues. A net gain is only generated when dew originates in the latent heat transfer from atmosphere to ground, as is the case in the first night where the soil even participates in the gain. This process is called "dewfall". A mixed dew composition of both dewfall and distillation can be seen in the second half of the second night. Around sunrise, a small part of the condensation gain is redistributed from mulch layer to soil due to retarded occurrence of the daily temperature minimum at the covered soil surface. The difference between morning maximum and evening minimum of water reserve is the nocturnal sum of condensation, in the case of the first night 0.25 mm.

Out of 68 nights when such measurements were conducted, 39 featured dewfall, 20 continued evaporation or stagnation and 9 nights included light rain that prohibited determining dew from weight gains. Fog was not observed, nor were hourly means of relative humidity above 96 %, measured at the lowest atmospheric measurement level of 0.002 m. Mean dewfall of all rain-free nights, including evaporation nights as 0, was 0.07 mm. Highest mean (0.17 mm) and maximum (0.33 mm) was found in the June measuring period, where no rain-free night without dew occurred.

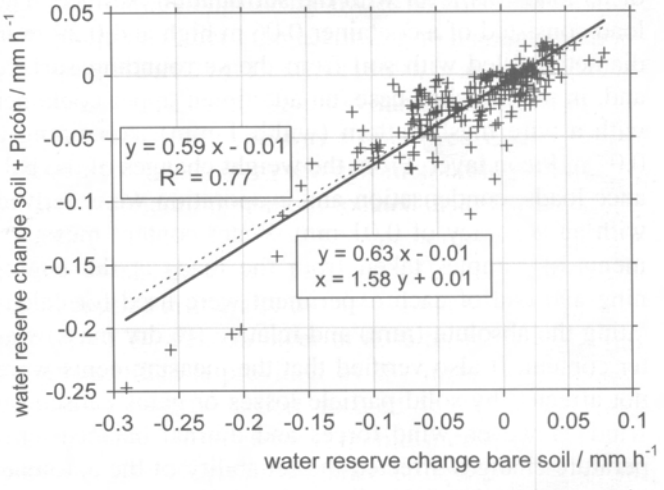

Figure 2: Gravimetrically measured condensation and evaporation to and from a bare soil surface compared to a surface mulched with 0.07 m Picón. Dotted and solid line: regression and principal major axis, respectively. Further explanations see text.

5 Comparison to a bare surface

5.1 Results

A scatterplot comparing hourly water content changes, in units of precipitation, of bare soil with those of the

Table 2: Properties of Picón lapilli and the loam soil. Heat conductivity for mean wetness of both substrates was estimated as described in chapter 3.2. Longwave emissivity was estimated from surface temperature and outgoing longwave radiation in the field. Hygroscopicity was measured in laboratory as described in chapter 3.3.

	Picón lapilli	*Loam soil*
Heat conductivity / W m^{-1} K^{-1}	0.14	0.37
Longwave emissivity / 1	0.98	0.99
Hygroscopicity / % dry mass	0.3	9.3

soil and mulch system is given in Fig. 2. It shows that mulching, though reducing evaporational losses, reduces rather than raises condensation. Note that axis and factor of the roughly linear relation describing the simultaneous behaviour of both surfaces are given more precisely by the principal major axis than by regression (WEBSTER 1997). They indicate that vapour transfer to the bare surface already begins when evaporation from the mulched surface is still continuing and is about 1.6 times stronger. However, the water uptake of bare soil is often not accompanied by a surface temperature drop below the dewpoint of the adjacent air. An example is given in Fig. 3. In the night shown, cloudiness was 1/8 to 2/8, net radiation – 50 W m^{-2} to – 70 W m^{-2} and relative humidity (2 m) around 80 %. Condensation in the Picón layer roughly begins when its surface temperature falls below the dewpoint of the ambient air. In this night, condensation is very weak, corresponding to the small amount of cooling below the dewpoint observed. Bare soil, in contrast, shows pronounced condensation though its surface temperature is too high to enable dewfall in terms of the definition given in chapter 4. Properties governing nocturnal surface cooling and condensation are given in Tab. 2. It shows that the stronger cooling of the Picón surface is due to the substrate's low heat conductivity rather than differences in longwave emissivity. Hygroscopicity, governing additional water uptake independent from surface cooling as described in chapter 3.3, is much higher for the soil.

5.2 Discussion

Though hygroscopic condensation is sometimes included as "hidden" part into the term dew for practical reasons (MONTEITH 1963, ACOSTA BALADON, 1996; JACOBS et al., 2000), an important practical difference besides the thermodynamical one is given by the potential plant-availaibility of "real" dew water (MONTEITH 1963). Water drawn from the air by a hygroscopic substrate cannot be extracted by the roots of most agricultural plants if the relative humidity of that air was below approximately 99 %, dependent on air temperature, as this humidity corresponds to the "permanent wilting point" at $\Psi_W = 15000$ hPa (see Eq. 3.1). Thus the hygroscopic properties wrongly assigned to Picón in literature would not be of direct use for agriculture, a problem that has already been anticipated by JAHN (1988). However, hygroscopic water could enhance the water-saving effects of the mulch layer by modifying the morning Bowen ration or eventually become activated by thermally induced redistribution inside the soil. Here, the same is true for "real" dew formed on the Picón surface as it is transferred to the soil via the gas phase. Liquid water dripping out of a 0.07 m thick Picón layer only begins, when precipitation overcomes its interception capacity of about 1.9 mm, as could be shown on the light rain occasions mentioned in chapter 4. As this amount was never reached by dewfall, condensation gains of bare and mulched surfaces both are mainly of indirect use, though they originate mostly from hygroscopic uptake in the case of bare soil and from dewfall in the case of the Picón surface. The answer to the question of dew enhancement by Picón mulching is twofold: Nocturnal surface cooling responsible for "real" dewfall is slightly stronger, but overall condensation is lower than in bare soil due to the weak hygroscopic properties of Picón. A reduction of condensation by gravel mulches has also been reported by LI (2002) from the semiarid region of China.

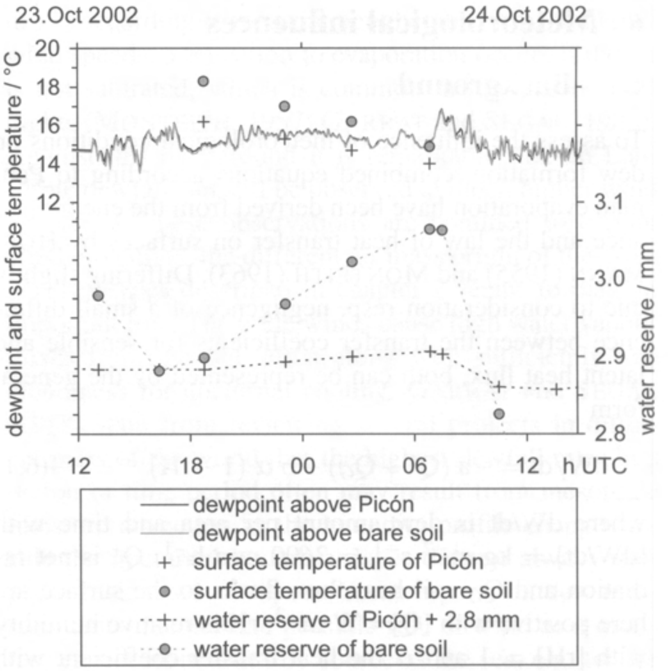

Figure 3: Air dewpoint temperature 0.02 m above the surface, surface temperature and gravimetrically measured condensation and evaporation comparing a bare soil surface to a Picón mulch layer, from 23 to 24 October 2002. Meteorological conditions see text.

6 Meteorological influences

6.1 Background

To assess the influence of meteorological conditions on dew formation, combined equations according to Penman evaporation have been derived from the energy balance and the law of heat transfer on surfaces by HOFMANN (1955) and MONTEITH (1963). Differing slightly due to consideration resp. negligence of a small difference between the transfer coefficients for sensible and latent heat flux, both can be represented by the general form

$$\mathrm{dW/dt} = -\mathrm{a}\,(\mathrm{Q}^* + \mathrm{Q}_G) - \mathrm{b}\,\alpha\,(1 - \mathrm{rH}) \tag{6.1}$$

where dW/dt is dew amount per area and time with [dW/dt] = kg m^{-2} s^{-1} = 3600 mm h^{-1}, Q* is net radiation and Q_G soil heat flux; fluxes to the surface are here positive with [Q] = W m^{-2}, rH is relative humidity with [rH] = 1 and α the heat transfer coefficient with [α] = W m^{-2} K^{-1}, dependent on surface and increasing with wind speed. The coefficients a ([α] = kg J^{-1}) and b ([b] = kg K J^{-1}) subsume the evaporation heat as well as magnitude and slope of the saturation vapour pressure in dependence on temperature, both rise with temperature. These equations are strictly valid only if rH and all coefficients can be represented by a value independent of height above or below the condensing surface. This is normally not the case with high humidities and low transfer coefficients inside soil responsible for distillation and higher transfer coefficient and different humidity above the surface responsible for dewfall. Furthermore gradients of temperature, humidity and turbulent diffusion coefficients in both directions, govern the replacement of vapour near the surface and make it difficult to decide up to which distance from the surface rH may be measured. The use of such equations has therefore somewhat been limited to theoretical considerations about maximum potential dewfall or what happens when a meteorological factor is changed. However, the present study in an arid environment with low distillation, a surface with weak hygroscopic properties such as Picón, and humidity measurement at a low height as 0.02 m seems favourable for a comparison of empirically found relations between meteorological factors and gravimetrically measured dewfall to the relations predicted by Equation (6.1).

6.2 Results

A summary of such empirically found relations for all rain-free hours of the measurements is given in Tab. 3. Correlation coefficients have been computed as well as partial correlation coefficients, excluding the strongest parameter in steps. The first two steps reveal some hidden relations to the remaining parameters.

Table 3: Correlation coefficients r between dW/dt (dewfall/negative evaporation) on the Picón surface and parameters Q* (net radiation), rH (relative humidity 0.02 m above the Picón surface), Q_G (soil heat flux), t (air temperature 0.02 m above the Picón surface) and u (Wind speed 10 m a.g.l. at airport station). Data: All rain-free hourly means of the measurement periods (June 2001, January/February and October 2002). Bracketed: Not significant at error probability 0.05.

Parameter	*r bivariate*	*r partial*	*excluded*
Q*	- 0.60	-	none
rH	+ 0.58	+ 0.37	Q*
Q_G	+ 0.48	- 0.40	Q*, rH
t	- 0.60	(- 0.08)	Q*, rH
u	(- 0.04)	(+ 0.002)	Q*, rH

As one would expect by Eq. (6.1), wherein saturation of the air reduces the evaporative term to 0, high relative humidity enhances dewfall and hinders its evaporation. Strong net radiation towards the surface provides energy for evaporation while strong net radiation from the surface provides the discharge of condensation heat, necessary for continued dew formation. Both parameters correlate to each other due to their diurnal cycle, dependent on changing global radiation. The same applies to temperature near the surface which shows an only slightly smaller bivariate r than net radiation due to the essential role of cooling, but no significance if the former parameters are excluded. In Eq. (6.1), an increase of temperature increases both a and b, resulting in a weak influence of temperature on dew formation which changes in direction and strength dependent on the other parameters (HOFMANN 1955; MONTEITH, 1963). Also due to the daily cycle dependency, soil heat flux reveals the expected influence only in the partial correlation, showing that for outgoing net radiation (neg. Q*), weak energy replacement from soil depth is favourable for dew as expected from Eq.6.1. Wind speed shows no significant correlation as long as both dewfall and evaporation are considered. However, a small yet significant correlation of r = 0.12 exists if only hours with positive dewfall are analysed. Relatively high dewfall rates > 0.02 mm h^{-1} could be observed throughout the spectrum of observed wind speeds (10 m a.g.l., airport station) up to 13 m s^{-1}. The month of June, which showed the most abundant and richest dewfall nights of the three measurement periods, was also the one where trade winds were steadiest and strongest. A plot that shows the influence of wind speed and direction on dewfall is given in Fig. 4. While westerly wind directions show maxima at low wind speeds and no dewfall at higher wind speeds, the trade winds show highest dewfall rates and a maximum at high wind speed at northern direction, medium dewfall rates and only weak speed dependence at their typical north-easterly directions and lowest dewfall rates with a negative speed influence when turning to the easterly wind of continental origin mentioned in chapter 2.

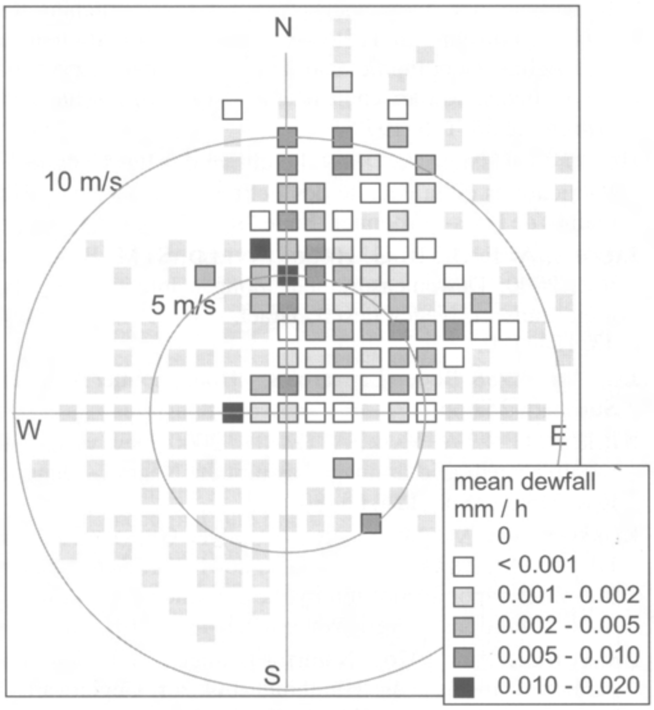

Figure 4: Mean hourly dewfall on the Picón-mulched surface in dependence on wind speed and direction (10 m above ground, airport station) as given by north and east vectors. Wind vectors were calculated from hourly wind speed and direction and rounded to 0 decimal places. For each of the resulting speed/direction classes, hourly dewfall was averaged, considering condensation and rain as zero dewfall. Data from all measurement periods (June 2001, January/February and October 2002).

6.3 Discussion

While for most parameters observation conforms to theoretical expectations, wind dependency cannot be detected by the simple means of correlation confined to linear relations. In Eq. (6.1), high wind speed increases the heat transfer coefficient and thus the evaporational term, diminishing dew. This reflects the common expectance of a calm night to be favourable for dew formation. This, however, applies to the wind influence for a given relative humidity near the surface. This humidity has to be maintained either by evaporation from a sufficiently moist soil and thus a high fraction of distillation in dew, or by turbulent transfer from the atmosphere to enhance dewfall (for the definition of dew, dewfall and distillation see chapter 4). Therefore, measurements and calculations of dewfall rather than dew show the need for ventilation. Typically, maximum dewfall is observed at wind speeds roughly between 1 and 4 m s^{-1} according to measurement height 10 m. At higher wind speeds, a transition to evaporation occurs if the air is not saturated, which is common in fog-free dewfall nights (MONTEITH, 1957; GARRAT and SEGAL, 1988). Against this background it is remarkable that on Lanzarote dewfall can still be observed at much higher wind speeds. As these observations are confined to certain wind directions, the different air mass origin of the three weather types described in chapter 2 seems to play an important role. The trade winds cause high water vapour fluxes from the sea, often along with sufficiently low cloudiness for nocturnal cooling. GARRAT and SEGAL (1988) state from reviewing several projects in different parts of the world that the highest dewfall rates in a region or time period often may result from mesoscale moisture advection as the humidity profile changes inside the nocturnal boundary layer did not always supply sufficient water vapour. Some reports on dew measurements mention the possible role of wind as a moisture carrier from a nearby source as the sea, e.g. for the Negev (KIDRON et al., 2000, here however dewfall not beginning before wind weakens) or the southern baltic sea coast (GELBKE, 1956). Lanzarote seems to be an extreme case of such mesoscale advection. Similar examples may be found in arid regions where local moisture supply by land surface evaporation is weak but strong winds from a nearby water source provide high humidity, yet insufficient for fog.

7 Implications

The properties of Picón lapilli mulch supplying its role as a measure of evaporation reduction rather than of dew exploitation suggest that further applications, such as the search for similar mulch materials and their adoption in other arid areas, should mainly consider two properties: Quick removal of precipitation water from the surface to the covered soil and poor transmittance of daily radiation energy, either by conduction, turbulent transfer through pore space, or radiation transmittance, to that place. A porous substrate of high pore space as well as pore size, but small enough to constrict turbulent exchange of water vapour and sensible heat between atmosphere and soil surface, would be favourable for both. As every mulch layer has a significant interception capacity (here $\approx$ 2 mm), few medium rain events would be preferable to many small ones if the mulch is to be adopted beneficially. This would have to be considered when assessing the suitability of other regions, or when combining the mulching technique with overground irrigation, as it can be observed increasingly on Lanzarote. The highly interesting role of wind for dewfall that could be observed here raises a number of questions for future micrometeorological studies on Lanzarote and elsewhere. E.g., the weak positive influence of wind speed on dewfall under certain circumstances on the nocturnal and hourly basis calls for a study of the small time scale wind speed dependency. The question of water vapour origin and related vertical gradients and horizontal advection as approached by Garrat and Segal (1988) should be further examined for the case of dewfall at high wind speeds. The physical properties of the mulch layer seem to be somewhat intermediate between those described for closed plant canopies and those described for soils, making the adaptation of micrometeorological models from both fields an interesting task. While some of such questions may be assessed using the measurement data partially presented here, many call for more extensive measurements.

Acknowledgements

The authors like to thank the staff of the Granja Agricola Experimental, Cabildo de Lanzarote, where most of the measurements were carried out, for providing accomodation, space and practical help, particularly Ana Garrido, Fernando Delgado, Manuel Perez and Nicolas Gonzales; the Förderverein of the University of Münster for sponsorship and the University of Düsseldorf, particulary Prof. Dr. K. Weber and Alexander Ropertz, for borrowing a part of the measurement equipment.

References

Acosta Baladón, A. N., 1973: Cultivos Enarenados. Ministerio del Aire, Servicio Meteorológico Nacional, Madrid. – Publicaciones **A 55**, 224 pp.

—, 1996: Las precititaciones ocultas y sus aplicaciones a la agricultura. – Ornex, 149 pp.

AMS, 2000: Glossary of Meteorology. – Allen Press, Boston, 855 pp.

Fernandez Caldas, E., M. K. Tejedor Salguero, 1987: Mulch farming in the canary islands. – In: Wachira, J. K., A. J. G. Notholt (Eds.): Agroecology in Africa. Seminar Proceedings. CSC technical publication series **226**, 242–256.

Garrat, J. R., M. Segal, 1988: On the contribution of atmospheric moisture to dew formation. – Bound.-Layer Meteor. **45**, 209–236.

Gelbke, W., 1956: Ergebnisse dreijähriger Taumessungen. – Ann. Meteor. **1/2**, 79–86.

Gonzáles Bernáldez, F., M. Kress Foltz, J. García Vicente, A. Higueras Arnal, 1964: El "Mulch" en los Cultivos Enarenados de Canarias. – Instituto de Hídrología, Centro de Estudios Hídrográfico, Comité Espanol de Riegos y Drenajes, 22 pp.

Graf, A., 2004: Kondensation und Verdunstung im Wasserhaushalt vulkanischer Mulchdecken auf Lanzarote (Kanarische Inseln). – Essener ökologische Schriften **22**, 140 pp.

Hanle, A., 1961: Agrarklimatologische Beobachtungen auf der Kanareninsel Lanzarote. – Mainzer geographische Studien **1**, 157–162.

Hofmann, G., 1955: Die Thermodynamik der Taubildung.– Berichte des Deutschen Wetterdienstes **18**, 45 pp.

Höllermann, P., H. Zepp, 1991: Zur Abschätzung und Bedeutung der Taukondensation auf den östlichen Kanarischen Inseln. - In: Höllermann, P. (Ed.): Studien zur Physischen Geographie und zum Landnutzungspotential der östlichen Kanarischen Inseln. – Erdwissenschaftliche Forschung **25**, 175–197.

Huetz de Lemps, A., 1969: Le climat des Iles Canaries. – Publications de la Faculté des Lettres et des Sciences Humaines de Paris-Sorbonnen, Série "Recherches" **54**, 224 pp.

Jacobs, A. F. G., B. G. Heuskinveld, S. M. Berkowicz, 2000: Dew measurement along a longitudinal sand dune transect, Negev desert, Israel. – Int. J. Biometeorol. **43**, 184–190.

Jahn, R., 1988: Böden Lanzarotes. – Hohenheimer Arbeiten. Stuttgart, 257 pp.

Kidron, G. J., A. Yair, A. Danin, 2000: Dew variability within a small arid drainage basin in the Negev. – Quart. J. Roy. Meteor. Soc. **126**, 63–80.

Kosmas, C., M. Marathianou, St. Geronditis, V. Detsis, M. Tsara, J. Poesen, 2001: Parameters affecting water vapor adsorption by the soil under semi-arid climatic conditions. – Agri. Water Man. **48** (1), 61–78.

Lauscher, F., 1976: Naturforschungen auf den Kanarischen Inseln von Humboldt bis zur Gegenwart. – In: Sonnblick-Verein (Ed.): Jahresbericht des Sonnblick-Vereins (1974–1975), Wien, 61–75.

Li, X., 2002: Effects of gravel and sand mulches on dew deposition in the semiarid region of China. – J. Hydrol. **260**, 151–160.

Marzol Jaen, M.V., 1988: La lluvia: un recurso natural para Canarias. – Servicio de Publicaciones de la Caja General de Ahorros de Canarias **130**, 220 pp.

Matznetter, J., 1958: Die Kanarischen Inseln. – Petermanns Geographische Mitteilungen Ergzg. **266**, 192 pp.

Monteith, J. L., 1957: Dew. – Quart. J. Roy. Meteor. Soc. **83**, 322–41.

—, 1963: Dew: facts and fallacies. – In: Rutter, A. J., F. H. Whitehead (Eds.): The water relations of plants. – Blackwell Scientific Publications, London, 37–56.

Or, D., J. M. Wraith, 2000: Soil Water Content and Water Potential Relationships. – In: Sumner, M. E. (Ed.): Handbook of Soil Science. – CRC Press, Boca Raton, 53–85.

Tejedor Salguero, M., C. C. Jiménez, F. Díaz Pena, 2002: Use of volcanic mulch to rehabilitate saline-sodic soils. – Soil Sci. Soc. Amer. J. **67**, 1856–1861.

—, —, —, 2003: Soil Moisture Regime Changes in Tephra-Mulched Soils: Implications for Soil Taxonomy. – Soil Sci. Soc. Amer. J. **66**, 202–206.

Webster, R., 1997: Regression and functional relations. – Euro. J. Soil Sci. **48**, 557–566.