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Angle and aspect dependent dew and fog precipitation in the Negev desert

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Abstract

Knowledge regarding dew and fog precipitation in relation to angle and aspect may be of great importance to plant photosynthesis and to rock dwelling microorganisms, especially in arid land where water is highly limited. Measurements of dew and fog were carried out periodically during the fall of two years (1989, 1992) at a hilltop in the Negev Desert Highlands, Israel. Measurements were carried out using velvet-like cloths ($6\times6\times0.15$ cm) attached to the center of different angle sides of 5 pairs of wooden boxes ($50\times50\times10$ cm) and to the top of an additional pair ($10\times10\times5$ cm) that served as a control (horizontal surface). The sides of each pair of boxes had angles of 30, 45, 60, 75 and 90° facing north, east, south and west.

Whereas fog showed an advective pattern of precipitation, with windward aspects receiving higher amounts, that was not the case with dew. When the dew values received in the different aspects within each angle were grouped together, surfaces at 30, 45, 60, 75 and 90° received 99.8 (SE$\pm$11.9), 78.2 (SE$\pm$17.9), 42.0 (SE$\pm$18.3), 33.8 (SE$\pm$10.8), and 25.6 (SE$\pm$9.7) percent of the amounts condensed on the horizontal surface, respectively. A positive linear relationship characterized the dew amounts with cos (θ). The data also showed an increase in dew duration with west > north > south > east. The data thus imply that aspect and angle may play an important role in controlling dew and fog availability.

Keywords: Dew; Fog; Angle; Aspect; Negev Desert

1. Introduction

Water is the most important limiting factor in arid lands. Any additional source of water may have a positive impact upon crop yield and upon plants and other organisms within the ecosystem. Although supplying relatively low amounts, dew and fog precipitation are a constant and stable water source and thus may be of great importance in arid and semiarid zones (Wallin, 1967; Evenari et al., 1971; Noy-Meir, 1974; Seely, 1976). Dew and fog duration, which may be largely controlled by aspect (Duvdevani, 1964), may affect plant stomata opening (Schulze et al., 1972), photosynthesis and transpiration (Stone, 1957a; Kappen et al., 1972). Dew may

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assist in plant recovery from wilting (Duvdevani, 1964), in plant growth (Duvdevani, 1964), flowering (Wallin, 1967), crop yield (Duvdevani, 1964; Rotem and Reichert, 1964; Wallin, 1967) and seedling survival (Stone, 1957b) but may also cause fungal infection (Duvdevani et al., 1946; Wallin, 1967). Condensation, which is largely affected by longwave radiational cooling, may largely depend upon surface angle (Angus, 1958). Any information regarding dew and fog precipitation and duration in relation to angle and aspect may thus be of great importance.

Dew and fog abound in the Negev Desert (Evenari et al., 1971; Zangvil, 1996), exhibiting an increase in precipitation with altitude (Kidron, 1999). An average of 195 dewy days with 33 mm of dew were recorded over 17 years of measurements in Avdat, at the heart of the Negev Desert Highlands, Israel (Evenari, 1981). In addition to their importance to plants, dew and fog were also found to play a major role in the water budget of microorganisms and insects (Friedmann and Galun, 1974; Broza, 1979), providing the main source of water for lichens in the Negev Desert (Lange et al., 1970).

Although important, little is known regarding the conditions that may control dew and fog condensation. While angle and aspect were previously reported to control dew precipitation (Angus, 1958; Duvdevani, 1964), quantitative data are scarce. Kappen et al. (1980) performed dew measurements around a hill in the Negev Highlands and concluded that the higher amounts received at the west- and north-facing slope in comparison to the east-facing slope stem from advective precipitation. Accordingly, vapor carried by wind from the Mediterranean Sea would preferentially condense at the windward northern and western aspects (in agreement with the north-westerly direction of the prevailing wind; Kidron et al., 2000), whereas lower amounts will be received at the eastern and southern aspects, i.e. the leeward aspects. Kappen et al. (1980) hypothesis was not supported when dew values obtained at different slope sections within a drainage basin were analyzed (Kidron, 2000). However, the validity of the aforementioned hypothesis within a single habitat, such as a hilltop, exposed to the prevailing winds, was yet to be checked. Examination of the possible effect of aspect and angle upon dew and fog precipitation was thus called for.

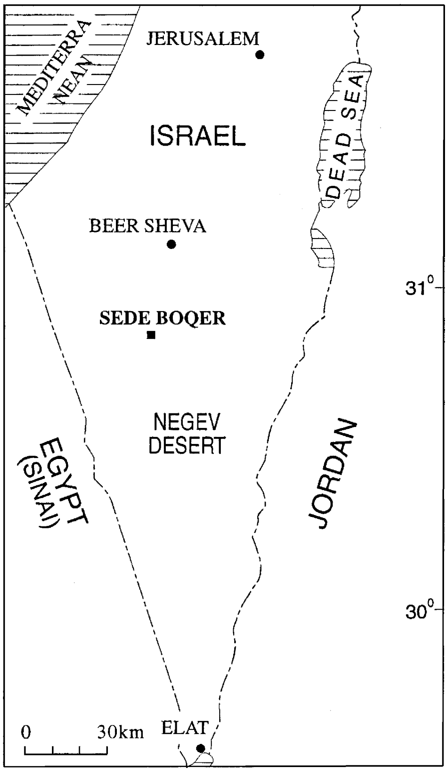

Fig. 1. Location of research site.

2. The research site and methodology

A hilltop, 550 m above m.s.l., located near Sede Boqer in the Negev Highlands, was chosen for dew and fog measurements (Fig. 1). The rocky hilltop consists of limestone, having limited soil cover (<20%) and low vegetal cover (10–20%). Abundant cobbles, all covered with endolithic and epilithic lichens (the former predominating) are scattered on the surface (Danin and Garty, 1983). Average annual precipitation is 95 mm (Rosenan and Gilad, 1985). Dew is frequent, being most abundant during the fall (Evenari et al., 1971; Zangvil, 1996).

Six pairs of wooden boxes were placed on the flat hilltop ground during the falls of 1989 and 1992. The shrubs at the vicinity of the boxes were removed. Five of the pairs, 50×50×10 cm, had different side angles of 30, 45, 60, 75 and 90° and they were placed facing north, east, south and west (Fig. 2). Six velvet-like cloths, 6×6×0.15 cm, were attached each afternoon with staples (using a staple gun) to the center of each

Fig. 2. View of the boxes at the research site.

side (thus on average 5 cm above ground). Cloths were also attached to the horizontal top of the sixth pair, $50\times50\times5$ cm, which served as a control. The cloths were collected just before sunrise into separate flasks that were immediately sealed, taken to a nearby lab and weighed before and after being oven dried at 70 °C for 24 h. The amount of dew and fog in relation to aspect and angle was then determined. In this respect one should however note that although the absolute amounts precipitated onto the cloths may change in accordance with the box material (owing to the fact that the thermal properties of the material determine the surface temperatures and consequently dew and fog condensation), the dew and fog proportions between the angles and aspects would be maintained also when a different material is examined (Kidron, 1998).

Dew and fog measurements were carried out during the fall of 1989 and 1992. Mornings, during which a visible fog was noted, restricting visibility to less than 1000 m for at least half an hour, were defined as foggy mornings. During 9 days, cloth collection took place also throughout the course of the morning. In this way, the evaporation rate was studied in accordance with angle and aspect. A value of 0.03 mm, which also marks the threshold for dew availability for microorganisms (Kappen et al., 1979), was taken as a threshold for dew.

In order to determine whether angle and aspect may determine dew values, a two way ANOVA was executed. In order to examine whether an advective pattern of precipitation is taking place as a result of prevailing northwesterly winds, dew and fog amounts from the windward northern and the western aspects were compared to the leeward southern and eastern aspects. Significantly higher values (paired *t*-test; $P<0.05$) at the windward aspects implied an advective precipitation.

3. Results

3.1. Angle and aspect dependent dew and fog

Twenty seven dewy mornings and six foggy mornings were recorded during the experimental period. When the data of a specific angle and aspect from one box was compared to the same angle and aspect of the second box within the same pair, non-significant differences characterized both data sets, implying that grouping the results from both boxes of the same pair was possible.

A general trend, indicating a decrease in dew and fog values with an increase in angle (from 0 to 90°) was noted within each aspect examined (Fig. 3).

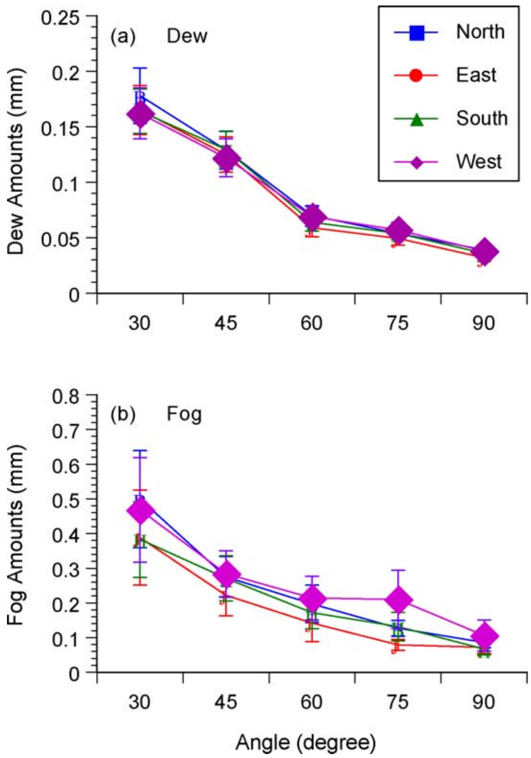

Fig. 3. A change in (a) dew ($n=27$) and (b) fog ($n=6$) amounts with angle in all aspects. Bars represent one SE.

Table 1
A two way ANOVA for dewy mornings

Source of variation	SS	df	F	P-value
Aspect	1993	3	0.26	ns
Angle	668905	4	65.7	5×10^{-45}
Aspect×Angle	2167	12	0.07	ns
Within	1322504	520		
Total	1995569	539		

ns, non-significant.

When all aspects were compared, non-significant differences characterized the dew values, as obtained in the different aspects, within each angle (Table 1). Fog values of the northern and the western aspects were, however, found to be significantly higher than those of the eastern aspect (paired t-test; $P < 0.05$). And thus, whereas grouping of dew values of all aspects within each angle was possible, that was not the case with fog values.

As seen during simultaneous measurements, consistent differences in dew values characterized the different angles following grouping of all aspects within each angle (Fig. 4). A clear trend was noted with the horizontal surface and the 30° angle receiving similar values, followed by a substantial decrease in dew amounts between 30 and 60° and a moderate decrease between 60 and 90°. Dew amounts received at 30, 45, 60, 75 and 90° corresponded to 99.8 (SE±11.9), 78.2 (SE±17.9), 42.0 (SE±18.3),

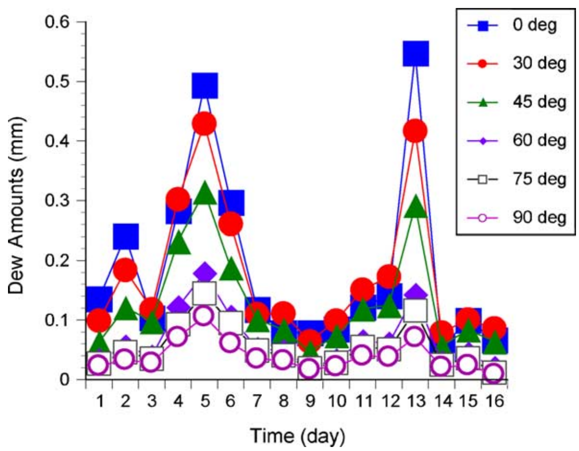

Fig. 4. Simultaneous dew measurements during 16 mornings following grouping of all four aspects within each angle.

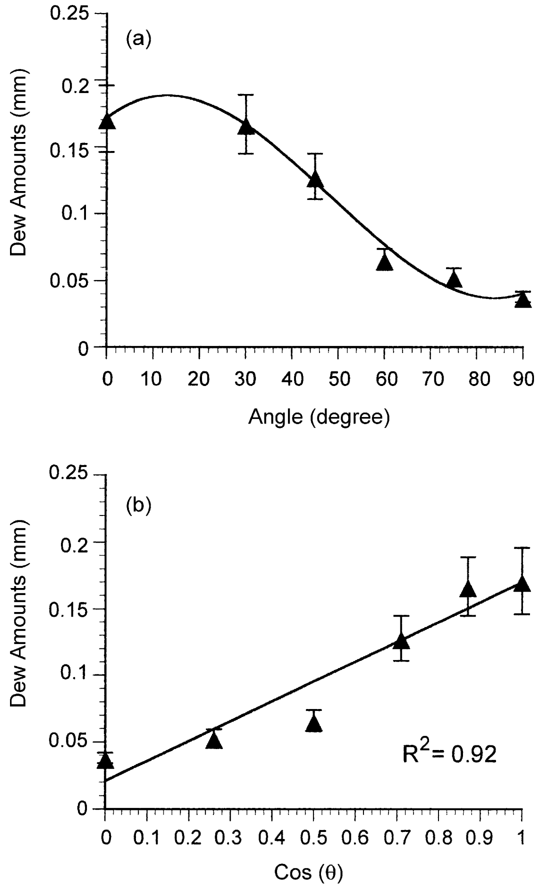

Fig. 5. Dew Amounts in accordance with angle (a) and the relationship between dew amounts and cos (θ) (b) following grouping of all four aspects within each angle. Bars represent one SE.

33.8 (SE±10.8), and 25.6 (SE±9.7) percent of the amounts condensed on the horizontal surface, respectively (Fig. 5a). Average daily dew amount showed positive linear relationships with cos (θ), with θ varying from 0 to 90° (Fig. 5b), following the equation:

$$\text{Dew (mm)} = 0.149x + 0.021$$

When $x = \cos(\theta)$

In order to examine whether an advective precipitation took place in accordance with the northwesterly direction of the prevailing wind, average dew and fog amounts of the windward (northern and western) and the leeward (southern and eastern) aspects was calculated across all angles. Whereas non-significant differences characterized the dew values of the windward and leeward aspects, significant differences characterized the fog values with the windward aspects receiving higher values than the leeward aspects. Windward fog values were on an average 31.0 (SE ± 5.2) percent higher than those of the leeward aspects.

3.2. Time duration

The pattern of dew evaporation was studied during eight mornings and during an additional morning with fog. During all mornings, condensation continued also following dawn. This was clearly seen when the dew condensation and evaporation pattern was studied at 45° (Fig. 6). A similar pattern characterized also the other angles (not shown). However, whereas condensation was extremely short at the eastern aspect, exposed to the first sunbeams, it was the longest at the western aspect following the order: west > north > south > east.

Dew duration time was also affected by angle. A general decrease in time duration with angle was noted (Fig. 7a). Average dew duration showed positive linear relationships with cos (θ), with θ varying from 0° to 90° (Fig. 7b), following the equations:

Dew Duration (h) (for the northern aspect)

$$= 1.92x + 1.73 \quad R^2 = 0.93$$

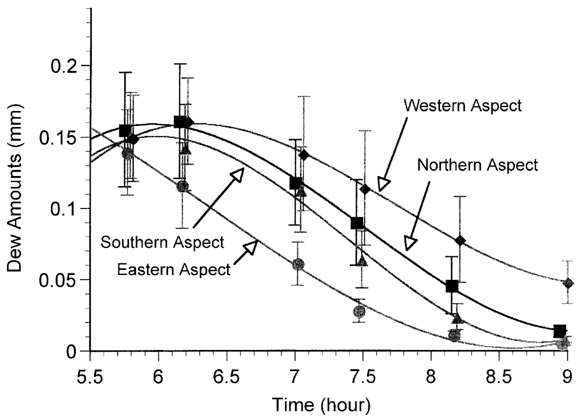

Fig. 6. Dew condensation and evaporation pattern of the four aspects at 45° during the early morning (dawn during the measurements was at 4:45). Bars represent one SE.

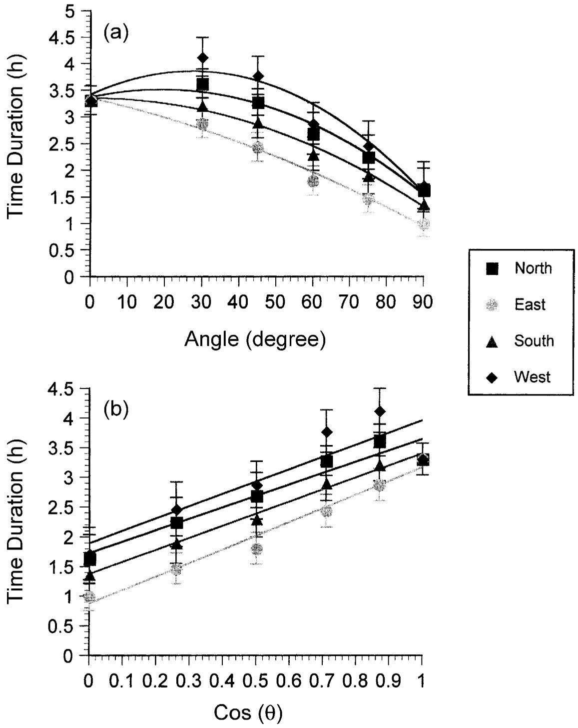

Fig. 7. Time duration in accordance with angle (a) and the relationships between time duration and cos (θ). Bars represent one SE.

Dew Duration (h) (for the eastern aspect)

$$= 2.29x + 0.88 \quad R^2 = 0.98$$

Dew Duration (h) (for the southern aspect)

$$= 2.0x + 1.38 \quad R^2 = 0.99$$

Dew Duration (h) (for the western aspect)

$$= 2.1x + 1.90 \quad R^2 = 0.79$$

When $x = \cos(\theta)$

This was also the case with the single fog event recorded, which showed a similar pattern of evaporation to that of the dew (not shown).

Both variables, aspect and angle, determined the initial dew amount and consequently, to a large extent, also the dew duration time (Fig. 8). The effect of both variables could have been also deduced once

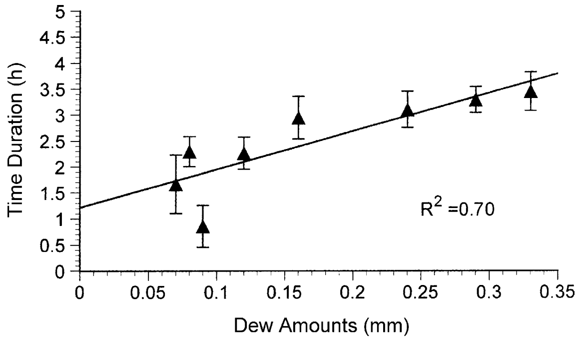

Fig. 8. The relationships between dew amounts and time duration.

the sun-shaded western and the northern aspects were compared to the non-shaded eastern and southern aspects, respectively. Significantly higher ratios were obtained between the dew duration time of the western and eastern aspect than that of the northern and southern aspect, with the western aspect retaining its moisture up to 72% longer than the eastern aspect. An increase in ratio with angle was noted (Fig. 9). Similar trends characterized the single fog measured with the western aspect retaining its moisture up to twice as long as the eastern aspect (not shown).

4. Discussion

The occurrence of higher biomass on sun-shaded slopes within arid or sub-humid regions is a well-known

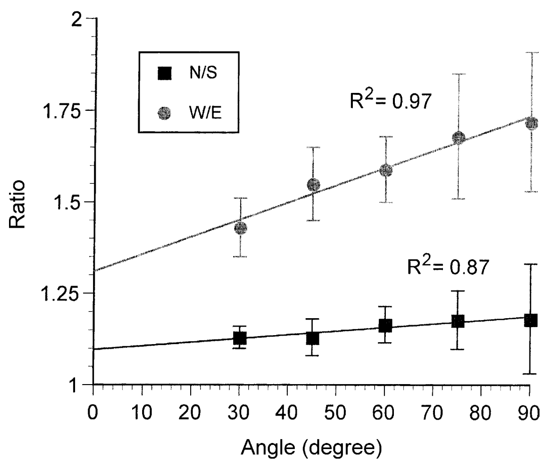

Fig. 9. The relationships between angle and dew duration of windward versus leeward aspects (N=north; S=south; E=east; W=west). Bars represent one SE.

phenomenon. Explained by slower daylight evaporation rates, much higher biomass characterizes the northern exposure at the northern hemisphere (Noy-Meir, 1973). In the dewy Negev Highlands, much denser cover of mesic lichens characterizes the northern and the western exposures in comparison to the southern and eastern exposures, respectively (Kappen et al., 1980). These differences may be attributed to longer wetness duration following dew and rain (Kidron, 2000; Kidron et al., 2000). Kappen et al. (1980) hypothesis, suggesting an advective pattern of precipitation, may have yielded an additional advantage to the windward exposures, i.e. to the northern and western exposures. However, this conclusion was not supported by dew measurements along slopes of a second order drainage basin (Kidron, 2000), and the current research was designed to examine the validity of the aforementioned hypothesis at a single habitat, a hilltop, exposed to the prevailing wind. Different side angles of boxes placed on top of a hilltop were chosen to assess the role of aspect and angle upon dew amounts and duration.

Although maximal dew amounts on cloths placed horizontally were obtained 0.5–1.0 h following sunrise, explained by vapor turbulence by the first sunbeams (Kidron et al., 2000), the extremely variable position of the cloths in relation to the early sunbeams necessitated a relatively early collection of the cloths. Owing to the fact that the cloths were placed at an angle, cloths at the eastern aspect were normal or nearly normal to the first sun beams while cloths at the western aspect remained shaded. Any delay in cloth collection during the early morning hours may have resulted in simultaneous opposing processes in both aspects: evaporation at the sun-exposed eastern aspect and a continuous condensation at the sun-shaded western aspect. The longer the delay in cloth collection during the first daylight hours - the higher the expected difference between the western and the eastern aspect.

Indeed, when the dew values on cloths collected after sunrise were examined, a substantial increase in dew ratio with time was obtained between the western and eastern aspect (Fig. 10). The fact that the ratio between the western and the eastern aspect increased while the ratio between the northern and the southern aspect remained relatively constant, highlighted the fact that simultaneous evaporation and condensation

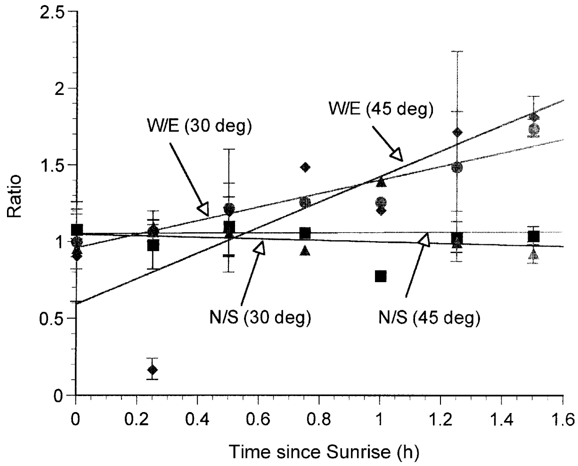

Fig. 10. The ratio of dew amounts of two opposing aspects (N = north; S = south; E = east; W = west) in accordance with time of collection. Bars represent one SD.

were taking place at the opposing east- and west-facing aspects, respectively. Early dew collection was thus required.

Once simultaneous evaporation and condensation were avoided, early dew collection may thus reflect nocturnal condensation. And thus, if an advective precipitation would have taken place, higher dew amounts would have been expected at dawn, i.e. prior to evaporation, at the windward aspects in comparison to the horizontal surface. Additionally, dew values at the windward aspects should have been significantly higher than those of the leeward aspects, and the ratio between the windward and leeward aspects should have been substantially above one. Such a ratio would have reflected the preferential windward precipitation according to the 'advective precipitation' hypothesis.

This, however, was not the case as far as the dew values are concerned. The higher dew values condensed on the horizontal surface, the non-significant differences in dew values of the different aspects within each angle, and the fact that the ratio between windward and leeward aspects was approximately one, excluded the possibility that a significant pattern of advective precipitation is taking place. This conclusion is in agreement with a previous conclusion regarding the possibility of advective precipitation on slopes (Kidron, 2000). However, having a ratio of 1.30 between the windward and the leeward aspects, fog condensation seems to follow an advective pattern of precipitation. These results are in agreement with the transient character of many fogs in the Negev Highlands, passing across the drainage basin (Levi, 1967), and with similar observations concerning advective fog precipitation in other parts of the world, such as the Namib Desert (Kappen et al., 1980).

The fact that a significant pattern of advective dew precipitation did not take place facilitated the grouping of all aspects within each angle and the evaluation of dew precipitation patterns in accordance with angle was made possible. Thus, dew amounts showed a positive linear relationship with cos (θ). One should note that also for dust deposition in the Negev Desert a link was found between the amounts deposited and cos (θ) (Biryukov, 1997).

Explained by the decrease in the proportion of the sky "seen" by the depositional surface—the Sky View Factor (SVF; Oke, 1978), dew data reflect changes in longwave radiational cooling and hence in substrate temperatures. Apparently, whereas the change in angle of up to 30° did not substantially affect the SVF and hence the dew amounts, a sharp decrease in dew amounts characterized the change in angles from 30 to 60°, followed by a much gradual change thereafter from 60 to 90°. The sharp decrease in dew amounts between 30 and 60° is explained by a substantial change in the SVF and consequently in substrate temperatures. That is apparently not the case between 60° and 90°. At these angles longwave radiational cooling is highly impeded, being apparently reflected by more moderate changes in substrate temperatures and hence in dew amounts.

Following dawn, dew first showed continuous condensation (due to air turbulence), followed by high evaporation rate during the continuation of the morning (owing to increase radiation), and then a very moderate evaporation rate during the late hours of the morning (due to strong adhesion between the remaining thin film of water and the cloth). This pattern was in agreement with previous findings (Kidron, 1998). When the total duration time was examined, dew evaporation and condensation time showed a positive linear relationship with cos (θ). Similar results were obtained during the single fog event recorded. The data thus imply that contrary to different meso-habitats, such as slopes, in which northern and southern exposures will exhibit the most pronounced differences in dew and fog amounts (Kidron et al., 2000), the western and eastern aspects of an object located within a single habitat will exhibit the largest differences. This will be apparently the case when dew at different aspects of cobbles, stones or plant leafs will be measured.

And thus, owing to the fact that wetness duration, rather than the amounts of moisture, may be of greater ecological importance (Lange et al., 1977; Kappen et al., 1980; Lange and Tenhunen, 1982), these findings may assist in the evaluation of biomass diversity within micro-habitats and thus may assist in the evaluation of abiotic factors responsible for genotypic and phenotypic diversity in nature (Nevo, 2001). Aspect and angle may affect lichen distribution on cobbles as well as the distribution of lichen-grazing snails (Shachak et al., 1987, 1995). Since snail grazing on lichens was found to largely affect limestone weathering (Shachak et al., 1987), dew and fog distribution patterns may thus assist in the evaluation of geomorphological processes such as rates of weathering and soil forming processes.

The change in dew values in accordance with angle, and the substantial differences found in the desiccation patterns according to aspect, may contribute to our understanding of the effect of dew and fog upon plants. It may assist in model construction of spatial and temporal variability in leaf photosynthesis and transpiration. It may also assist in evaluating patterns of fungal infections, in accordance with aspect, and angle.

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References

Angus, D.E., 1958. Measurements of dew. Arid Zone Res. 11, 301–303.

Biryukov, S., 1997. An experimental study of the dry deposition mechanism for airborne dust. J. Aerosol. Sci. 29, 129–139.

Broza, M., 1979. Dew, fog and hygroscopic food as a source of water for desert arthropods. J. Arid Environ. 2, 43–49.

Danin, A., Garty, J., 1983. Distribution of cyanobacteria and lichens on hillsides of the Negev highlands and their impact on biogenic weathering. Z. Geomorph. 27, 423–444.

Duvdevani, S., 1964. Dew in Israel and its effect on plants. Soil Sci. 2, 14–21.

Duvdevani, S., Reichert, J., Palti, J., 1946. The development of downy and powdery mildew of cucumber as related to dew and other environmental factors. Palestine J. Bot. Hort. Sci. (Rehovot Ser.) 5, 127–151.

Evenari, M., 1981. Ecology of the Negev desert, a critical review of our knowledge, in: Shuval, H. (Ed.), Developments in Arid Zone Ecology and Environmental Quality. Balaban ISS, Philadelphia, PA, pp. 1–33.

Evenari, M., Shanan, L., Tadmor, N., 1971. The Negev, The Challenge of a Desert. Harvard Univ. Press, Cambridge, Massachusetts pp. 345.

Friedmann, E.I., Galun, M., 1974. Desert algae, lichens and fungi, in: Brown, G.W. (Ed.), Desert Biology II. Academic Press, New York, pp. 165–212.

Kappen, L., Lange, O.L., Schulze, E.-D., Evenari, M., Buschbom, U., 1972. Extreme water stress and photosynthetic activity of the desert plant *Artemisia herba-alba* Asso. Oecologia 10, 177–182.

Kappen, L., Lange, O.L., Schulze, E.-D., Evenari, M., Buschbom, U., 1979. Ecophysiological investigations on lichens of the Negev Desert, IV: Annual course of the photosynthetic production of *Ramalina maciformis* (Del.) Bory. Flora 168, 85–105.

Kappen, L., Lange, O.L., Schulze, E.-D., Buschbom, U., Evenari, M., 1980. Ecophysiological investigations on lichens in the Negev Desert, VII: The influence of the habitat exposure on dew imbibition and photosynthetic productivity. Flora 169, 216–229.

Kidron, G.J., 1998. A simple weighing method for dew and fog measurements. Weather 53, 428–433.

Kidron, G.J., 1999. Altitude dependent dew and fog in the Negev Desert. Israel. Agric. Forest Meteorol. 96, 1–8.

Kidron, G.J., 2000. Analysis of dew precipitation in three habitats within a small arid drainage basin. Negev Highlands, Israel. Atmos. Res. 55, 257–270.

Kidron, G.J., Yair, A., Danin, A., 2000. Dew variability within a small arid drainage basin in the Negev Highlands. Israel. Quart. J. Royal Meteorol. Soc. 126, 63–80.

Lange, O.L., Tenhunen, J.D., 1982. Water relations and photosynthesis of desert lichens. J. Hattori Bot. Lab. 53, 309–313.

Lange, O.L., Schulze, E.D., Koch, W., 1970. Ecophysiological investigations on lichens of the Negev Desert II: CO_2 gas exchange and water conservation of *Ramalina maciformis* (Del.) Bory in its natural habitat during the summer dry period (technical translation 1655 National Research Council of Canada). Flora 159, 38–62.

Lange, O.L., Geiger, I.L., Schulze, E.-D., 1977. Ecophysiological investigations on lichens in the Negev Desert. V. A model to simulate net photosynthesis and respiration of *Ramalina macifomis*. Oecologia 28, 247–259.

Levi, M., 1967. Fog in Israel. Isr. J. Earth Sci. 16, 7–21.
Nevo, E., 2001. Evolution of genome-phenome diversity under environmental stress. PNAS 98, 6233–6240.
Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Ann. Rev. Ecol. Syst. 4, 25–51.
Noy-Meir, I., 1974. Desert ecosystems: higher trophic levels. Ann. Rev. Ecol. Syst. 5, 195–214.
Oke, T.R., 1978. Boundary Layer Climates. John Wiley and Sons, New York pp. 372.
Rosenan, N., Gilad, M., 1985. In: Meteorological data Atlas of Israel, Carta 1985.
Rotem, J., Reichert, J., 1964. Dew—a principal moisture factor enabling early blight epidemics in a semi-arid region of Israel. Plant Dis. Reptr. 48, 211–215.
Schulze, E.-D., Lange, O.L., Buschbom, U., Kappen, L., Evenari, M., 1972. Stomatal responses to changes in humidity in plants growing in the desert. Planta 108, 259–270.
Seely, M.K., 1976. Fog basking by the Namib Desert beetle Onymacris unguicularis. Nature 262, 284–285.
Shachak, M., Jones, C.G., Granot, Y., 1987. Herbivory in rocks and the weathering of a desert. Science 236, 1098–1099.
Shachak, M., Jones, C.G., Brand, S., 1995. The role of animals in an arid ecosystem: Snails and isopods as controllers of soil formation, erosion and desalinization. Adv. GeoEcol. 28, 37–50.
Stone, E.C., 1957a. Dew as an ecological factor I. A review of the literature. Ecology 38, 407–413.
Stone, E.C., 1957b. Dew as an ecological factor II. The effect of artificial dew on the survival of Pinus ponderosa and associated species. Ecology 38, 414–422.
Wallin, G.R., 1967. Agrometeorological aspects of dew. Agric. Meteorol. 4, 85–102.
Zangvil, A., 1996. Six years of dew observation in the Negev Desert, Israel. J. Arid Environ. 32, 361–372.