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► **To cite this version:**

I. Lekouch, Marc Muselli, B. Kabbachi, Jalil Ouazzani, Iryna Melnytchouk-Milimouk, et al.. Dew, fog, and rain as supplementary sources of water in south-western Morocco. *Energy*, 2011, 36 (4), pp.2257-2265. 10.1016/j.energy.2010.03.017 . hal-00590605

HAL Id: hal-00590605

<https://hal.science/hal-00590605>

Submitted on 4 May 2011

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Dew, fog, and rain as supplementary sources of water in south-western Morocco

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Abstract

This study reports on one year (May 1, 2007 - April 30, 2008) of dew, fog and rain measurements carried out in the dryland area of Mirleft, Morocco in order to be used as alternative or supplemental sources of water. Four standard dew condensers and a passive fog net collector of 1 m² surfaces were used. Meteorological data were collected. 178 dew events (18.85 mm), 31 rain events (48.65 mm) and 7 significant fog episodes (1.41 mm) occurred, corresponding to almost 40% of the yearly rain contribution (48.65 mm, 31 events). Chemical and biological analyses were carried out. Dew and rain pH were neutral (close to 7) and the total mineralization was considerable (dew: 560 mg/L; rain: 230 mg/L). Ca²⁺, K⁺, SO₄²⁻ and NO₃⁻ are found of continental origin; Cl⁻, Na⁺ and Mg²⁺ are of sea origin. The ions

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concentration agrees with the World Health Organization recommendations for potable water. The biological analysis shows harmless vegetal spores and little contamination by animal/human bacteria. A cost analysis shows that, with little investment, the population of the arid and semi-arid coastal areas of south-western north Africa could make dew water an interesting supplementary alternative water resource.

Keywords: dew water, dew chemistry, rain water, rain chemistry

1. Introduction

The use of radiative cooling during diurnal cycle to design greenhouses concept [1-4] or on nocturnal cycle to condense water from air [5-7] can represent relevant solutions for arid or semi-arid countries to limit heat gains in buildings and collect water using a natural passive physical phenomenon. This is precisely the case for the area of Mirleft, located in a semi-arid region in south-western Morocco (43 m asl, 29° 35' N, 10° 02' W). The region is characterized by low annual rainfall (215 mm avg.) with less than 22 rainy days per year. During the last decade the exploitation of the existing water resources has considerably increased due to both the decrease in annual precipitation and the added population pressures from the growing tourist industry. To face the conventional water shortage and rising water prices, the use of alternative sources of water has been tested over the last 20 years. This has mainly focused on treatment of used water, demineralisation of briny water and desalination of sea water. The cost of these technologies is still more than ten times higher than that of conventional water. There exist, however, alternative sources of water - dew, fog - that have been tested elsewhere in recent years [8-11]. In particular, several studies were carried out to develop passive dew water collecting systems [12-19]. In Crimea (Ukraine), the area of Feodosia holds the vestiges

of a massive dew condenser built in 1912 by F.I. Zibold. It was claimed that the output would have reached 350 L/day [20]. This attempt was followed by several experiments in France [21, 22] that gave only insignificant yields, in contrast to more recent, radiation-cooled dew condensers using special condensing materials [13-15, 23-26]. Also fog net collectors were investigated [27-28].

This aim of the present study was to determine the extent to which dew and fog water can supplement or augment rainfall collection and whether the water was potable. For this purpose, dew water was collected during one year, May 1, 2007 to April 30, 2008, using 4 "standard" planar condensers of 1 m² surface area equipped with a special condensing foil [26] (manufactured by OPUR, France, www.fr) and a fog net collector similar to that described by Schemenauer [29]. The physico-chemical and biological properties were assessed over the course of the study. The composition of water is modified by the absorption of surrounding gases and the dissolution of small particles that settle on the condenser surface [30]. Compared to physical and meteorological studies, few investigations have focused on the quality of dew water [31-39]. Chemical analyses of dew water have been carried out in some parts of the world such as the USA [32], Chile [37], Japan [38] and in Jordan [39]. The dew characteristics were widely different. The dew water was very corrosive in Chile with a high ionic concentration, very acidic in Japan with a high concentration of sulphate and nitrates, and slightly alkaline and slightly mineralized in Jordan. In Corsica island, France [15, 40], the characteristics of dew water are comparable with those of Jordan with a higher alkalinity. A one-year study on the chemistry and the bacteriology of dew was also carried out in in Bordeaux, France [41]. A study over three years in Zadar, Croatia, was recently published [42].

2. Measurement procedure

Four plane dew condensers (1 m²), tilted 30° from horizontal to maximize dew drop flow by gravity [24], were installed as illustrated in Fig. 1a. A condensing foil was used composed of material designed according to Nilsson and collaborators [23, 26] (manufactured by OPUR, France, www.opur.fr). The foil is 0.35 mm thick and includes a small percentage of TiO₂ and BaSO₄ microspheres embedded in a matrix of low-density polyethylene (LDPE). It also contains an insoluble surfactant additive on its surface to enhance dewdrop flow. The foil improves the near infrared emitting properties to provide radiational cooling at room temperature and efficiently reflects the visible (sun) light. Between the foil and the condenser structure is a 2-cm thick polystyrene foam plate to provide thermal insulation. Collected water (dew and rain) by the east-, north-, west-facing condensers was measured manually every morning. Water from the south-facing condenser was recorded every 15 minutes by an automatic rain recorder. A calibration was made to properly account for the relative condenser/pluviometer collecting surfaces. The measurement of rain water on such an inclined plane is not as accurate as made by a standard rain gauge as it should depend on the wind direction with respect to the condenser surface but the error should remain within $1 - \cos(30^\circ)$, i.e. about 15%.

In addition, a 1 m² fog collector oriented perpendicular to the dominant winds (east-west) was placed on a second, identical terrace within a few m from the condensers (Fig. 1b). The collector is made with a polyethylene shading net with two layers (Fig. 1c).

Figure 1

The following physical parameters were continuously recorded at 15 min intervals: relative humidity RH , air temperature T_a (sensors $\pm 0.2\%$ for RH , $\pm 0.1^\circ\text{C}$ for T_a), dew point temperature T_d , wind direction and wind speed V . The latter was measured by a cup

anemometer at 5.6 m height, with a stalling speed of 0.6 m/s and 0.1 m/s resolution. The cloud cover in octas N (values from 0-8 with 8 indicating full sky cover) was measured by visual observations in the morning. The distinction between dew and fog or very light rain was made by (i) visual observation when available, (ii) comparison between the dew point temperature and the air temperature and (iii) the rate of increase of the collected water, much slower for dew than for fog or for a light rain occurrence.

The collection of dew and rain water was carried out from the south-facing condenser just before sunrise using sterilized polyethylene flasks that were then placed in a fresh place (temperature below 20°C) for further chemical analyses. The volume corresponds to water collected through gravity flow of the drops plus the amount of the residual droplets manually scraped at the condenser surface before evaporation. The pH and electrical conductivity (EC) measurements were performed just after water collection. Chemical and biological analyses were carried out at the National Center for Scientific and Technical Research (CNRST) in Rabat (Morocco). The delay between collection and analysis did not exceed 3 months. Due to a severe storm, the foil of the south-facing condenser was replaced between February 15 - March, 20, 2008, by a thin (0.6 mm thick) sheet of galvanized iron that was coated with a hydrophilic infrared radiative paint (manufactured by OPUR, France, www.opur.u-bordeaux.fr).

3. Dew and rain yields

We report only the main results as a detailed study including the influence of the physical parameters is out of the scope of the present paper. During this one year study, 178 dew events, 20 fog episodes (of which only 7 were significant) and 31 rain days (Fig. 2a) were observed, corresponding to 48.8% of dew days, 2% of significant fog days and 8.5 % of rain days. The cumulated amount of dew water was 18.85 mm as compared to 1.41 mm for fog

water and 48.65 mm for rain water (Fig. 2b). In total, the contribution of dew (and fog, although the contribution of fog is small) represents 41 % of the rain contribution and thus is significant. The dew yield is minimal in summer, in correlation with smaller night duration.

The comparison of the dew yields as obtained on the 4 condensers facing north, east, south and west are shown on Fig. 2c. The differences between them are not systematic. The time period where the south-facing condenser was coated with paint did not lead to a noticeable difference in dew yield. It is not surprising that the 4 condensers show nearly the same yield as they are protected from the wind by the terrace wall. In addition, dew forms mainly when the windspeed is small.

Figure 2

4. Physico-chemical analyses

The results of the analysis of the characteristic elements of dew and rain water are presented in Table 1. The mean dew electrical conductivity (EC) was in the order of 730 $\mu\text{S}/\text{cm}$ (dew) and 316 $\mu\text{S}/\text{cm}$ (rain), corresponding to a low total mineralization $0.77 \text{ EC} = 560 \text{ mg L}^{-1}$ (dew) and 230 mg L^{-1} (rain). The total ions concentration (Table 1) averaged to 534 (without Zn) mg L^{-1} for dew and 287 (without Zn) mg L^{-1} . These figures are in agreement with the EC estimation, thus showing that the chemical analysis was indeed concerned with the major ions. This is also verified by the electric neutrality of cations and anions when looking at the concentrations in mEq.L^{-1} (see below, Section 4.4).

The major elements analysed correspond to the concentration of major anions (Cl^- , NO_3^- , SO_4^{2-}) and major cations (K^+ , Mg^{2+} , Na^+ and Ca^{2+}). The concentrations of these various ions show the predominance of Cl^- as compared to the other elements. Lead (Pb) and Cu were

found in small quantities. Zinc was found negligible except for the months of February and March when a painted galvanized steel foil was used (Table 1).

Table 1

4.1. Dew and rain pH

The dew and rain pH exhibited the same low seasonal variation, with a weak minimum during May, June, July and August (dry season) (Fig. 3). Dew pH varied between 6.75 and 7.93 and rain pH ranged between 6.49 and 7.17. Dew pH is, as usual [30], is less acidic than rain because of the short time that dew is exposed to air, thus limiting the adsorption of gaseous CO_2 , SO_x and NO_x . The seasonal variation of pH - smaller pH when the dew yield is larger (see Fig. 2a and Fig. 3) - can be explained by a volume dependence.

Figure 3

In Fig. 4 is reported the variation of pH with the dew water volume: the largest volume indeed gives rise to the smallest pH. This result is in agreement with the simple assumption of a constant rate deposition of alkaline aerosols (e.g. CaCO_3) that increase the pH. For a larger volume, the concentration of such alkaline aerosols decreases, then pH becomes more acidic and decreases. However, the pH also evolves following the concentration of acidic gases and alkaline aerosols in the atmosphere. These components are influenced by anthropic activities, climatic conditions (origin of air masses, wind speed and direction) and preceding events of rains that remove aerosols from the air before measurements [42, 43]. Such a study is, however, beyond the scope of the present paper.

Figure 4

4.2. Dew and rain electric conductivity

The EC exhibits large fluctuations, reflecting the water mineralization variations. The dew EC ranged between 38.6 $\mu\text{S}/\text{cm}$ and 2680 $\mu\text{S}/\text{cm}$, with an average value of 725 $\mu\text{S}/\text{cm}$. The rain EC varied from 14.5 $\mu\text{S}/\text{cm}$ to 1081 $\mu\text{S}/\text{cm}$, with an average value of 316 $\mu\text{S}/\text{cm}$. The EC of the dew had temporal variations more significant than those observed for rain; the highest values were found during the dry season (Fig. 5). Similar to the pH data, EC values decreased with increasing collected volumes (Fig. 6), in agreement with the dissolution of particles depositing with a constant rate on the surface of the condenser. The same result was found for a study carried out in Bordeaux, France [30], Croatia [42], and in other reports concerning fog and rain in India [43, 44].

Figure 5

Figure 6

4.3. Ionic concentrations

The mean ionic concentrations of the major chemical species obtained from the dew and rain water analyses are presented in Fig. 7. In both dew and rain water, the concentration of anions are in the order $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$, and for cations, $\text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^-$. The probable source of Ca^{2+} and K^+ is from the soil, Ca^{2+} and K^+ being suspended in the lower layer of the atmosphere and settling on the condenser surface. The presence of high concentrations of Cl^-

and Na^+ , and to a lower extent, Mg^{2+} , should correspond to the sea salts (the study site is within 200 m from the ocean). The average values of dew and rain pH (7.4 and 6.85, respectively) are larger than the pH (5.6) of water vapour in equilibrium with atmospheric CO_2 . This alkalinity is due to both the low content of sulphuric (SO_4^{2-}) and nitric (NO_3^-) acids and the large cations concentration ($\text{Ca}^{2+} + \text{Mg}^{2+}$) responsible for the neutralization of these anions. Thus the ratio $(\text{SO}_4^{2-} + \text{NO}_3^-) / (\text{Ca}^{2+} + \text{Mg}^{2+})$ or total acidity/total alkalinity (TA/TC) that can be regarded as an indicator of acidity, is smaller than 1 (Table 2).

Table 2

The concentration of elements in dew and rain is markedly larger than in other oceanic areas such as at Bordeaux, France (see Table 3). This difference can be attributed to the strong contributions of desert particles that characterize the area of study. It is noteworthy (Fig. 7, Table 2) that this chemical composition is within the safety standards of the World Health Organization (WHO) for Cl^- , Mg^{2+} , and Zn (except for the period when the painted galvanized steel was used).

Figure 7

Table 3

4.4. Balance of charges

The quality of chemical analysis can be assessed by the ion balance (sum of cations versus sum of anions). The purpose of calculating the balance of charges is to verify whether ions that are not measured, such as NH_4^+ , might contribute significantly. The number of charges in

solution is estimated by summing the ion concentration in mEq/L. The sum of anions and cations was well correlated in dew and rainwater (Fig. 8) and respecting the electro-neutrality.

Figure 8

5. Origins of major ionic species

5.1. Statistical analysis

The correlations between the ions in both dew and rain are reported in Table 4. The analysis of correlations can be a useful technique to characterize the relations between the ions present in water and their possible origin. However, one has to analyse carefully these correlations as they can be multiple. For instance, A is correlated with B, B is correlated with C, and then A has a strong correlation with C although it might not be of the same origin. Also both anthropogenic and continental ions might come from the same wind direction.

Table 4

In rain, 4 major correlations (>0.9) are found. The correlations between Na^+ and Cl^- and Mg^{2+} and Cl^- correspond to salts of marine origin. The correlations between NO_3^- and SO_4^{2-} are from anthropogenic origin. The origin of the correlation between K^+ and Mg^{2+} can be indirect as K^+ is from continental origin and Mg^{2+} from marine origin.

Concerning dew, one observes 5 important correlations (>0.9). As for rain, there exists a strong correlation between Na^+ and Cl^- and Mg^{2+} and Cl^- that marks a marine origin. There is also a strong indirect correlation between Na^+ and Mg^{2+} . The two other correlations (SO_4^{2-}

and Mg^{2+} , SO_4^{2-} and Cl^-) are obscure; they might result from indirect correlations. One also notes large correlations between elements of continental origin (Ca^{2+} , K^+) and the anthropogenic ions NO_3^- and SO_4^{2-} , correlations that were not found in rain.

5.2. Sea contribution estimation

In order to measure the marine contribution of the ions in dew and rain, the sea-salt fraction (SSF) and the non sea-salt fraction (NSSF) were calculated, with Na^+ as the reference of a sea contribution [47, 48]. The ionic concentration of sea water is the concentration given by Riley and Chester [49]. The SSF and NSSF are calculated from the following equations:

$$\% \text{ SSF}_X = 100 \times \frac{(\text{Na})(X / \text{Na})_{\text{sea}}}{X} \quad (1)$$

$$\% \text{ NSSF}_X = 100 - \text{SSF}_X \quad (2)$$

where X is the component the origin of which is to be determined.

The results are presented in Table 5 and show that Ca^{2+} and K^+ are of non-marine origin for both dew and rain. In contrast, Mg^{2+} and Cl^- are clearly of sea origin (dew and rain). The case of K^+ is undetermined with SSF (and NSSF) values in order of 50 %.

Table 5

5.3. Neutralization factor

The near neutral pH values in dew and rain are due to the neutralization of acidity and buffering by the alkaline elements of soil origin (Ca^{2+} , K^+). This neutralization is confirmed by a good correlation between the acidic ions SO_4^{2-} and NO_3^- and the major cations Ca^{2+} , K^+

and Mg^{2+} . The correlation between the sum of these cations and the sum of SO_4^{2-} and NO_3^- shows an $R = 0.96$ (not shown).

In order to determine the role played by the cations in neutralizing the sulphuric and nitric acids, a factor of neutralization (NF) is calculated according to the following formula [44, 50]:

$$NF_X = [X] / [NO_3^- + SO_4^{2-}] \quad (3)$$

where X is the species responsible for neutralization (Table 6). The high calcium concentration, as compared with the other ions in dew and rain, suggests that the more important neutralizing cation is Ca^{2+} , which indeed exhibits a higher NF, followed by Mg^{2+} and K^+ . For rain, K^+ shows a NF larger than Mg^{2+} . The NFs of dew are larger than those of rain, except for potassium.

Table 6

6. Dew biological analyses

Two biological analyses of dew water were carried out on October 5, 2007 and January 11, 2008, in order to determine possible contamination sources. The total coliform values were obtained according to the method of filtration on membranes but by modifying the conditions of incubation. The conditions included a temperature of $22^\circ C$ for the determination of vegetal bacteria and $37^\circ C$ for the determination of fecal bacteria of animal or human origin. We found a mean of 170 colony-forming units (CFU)/mL ($22^\circ C$) and 340 CFU/mL ($37^\circ C$), indicating rather clean water. This is presumably due to the strong UV sterilization process of the

collector surfaces by the sun illumination during the day. The most probable source of biological pollution is likely from the excretions of insects drinking the dew water.

7. Applications to human water needs

The basic water requirements for human can be estimated, depending on the country, to a range of 5-50 L/person/day [51]. Considering the above dew yield (18.85 mm/year) and rain yield (48.65 mm/year), collecting surfaces between 37.5 m² and 375 m² (rain only) or between 27 m² and 270 m² (rain plus dew) would be necessary to cover the water needs of a single person. From these figures, one realizes that collecting rain plus dew for human needs necessitates large but still reasonable collecting surface areas. Such surfaces can be partially or totally met by family house roofs when they present a sufficient slope to enable dew water collection or, as was performed in India [52], directly on the ground to reduce the costs. In the latter case, such “water plants” can be run by small village communities and water filtered and bottled at low price as discussed below.

For such already existing slopes, the extra cost to collect rain corresponds to the equipment of gutters, pipes and storage tank. Based on the Morocco cost of manpower and the local price of such equipments that lasts at least 10 years, the amortized cost of water can be estimated to 1.9 € m⁻³. Collecting dew needs to equip the slope with a thermally isolating materials (e.g. polystyrene foam) and special plastic foils or paints. The latter corresponds to the higher expense, on order of 0.5 € m⁻². For a life duration of 10 years (paint) or 4 years (foil), the cost for collecting dew plus rain water will be 5.7 € m⁻³ (paint) or 10 € m⁻³ (foil). The extra cost for collecting dew is thus on order 3 € m⁻³ (paint) or 8 € m⁻³ (foil). The cost of a litre of collected water is sufficiently low such as, after filtration and bottling, it can be sold out at a price that can be much less than the commercial price of bottled spring water in Morocco (1 € L⁻¹).

It has to be noted that the extra cost for dew collection is balanced by a better thermal comfort when the roofs of habitations are used, due to improved thermal insulation and enhanced foil or paint cooling properties (better infrared emission and sunlight reflection).

8. Conclusions

The analysis of data collected during a one-year period shows that the quantity of cumulated dew (18.9 mm, 178 events) corresponds to almost 40% of the yearly rain contribution (48.65 mm, 31 events). During this period, 20 fog events were found, with only 7 events making a significant contribution. The total fog contribution (1.41 mm) is marginal with respect to rain and dew yields. It is very likely that such yields could be maintained over an area that goes within 50-100 km from the coast, depending on the local conditions (e.g. elevation).

Surprisingly, dew exhibits a large mineralization, larger than rain, due to NaCl salt from marine origin and the enhanced deposition of aerosols coming from the dry, arid soil. Both dew and rain exhibit near neutral pH close to 7. The dew chemical composition revealed the abundance of major cations Na^+ and Mg^{2+} (marine origin), Ca^{2+} (continental origin). The acidity from dissolved CO_2 , SO_x , and NO_x is mostly neutralized by Ca^{2+} , thus giving an alkaline character to both dew and rain water.

In general, dew and rain water mean characteristics are compatible with drinking standards when compared to WHO recommendations. The small content of animal and/or vegetal bacteria makes dew water potentially drinkable after a light antibacterial treatment, e.g. by ebullition, chlorination or microfiltration. It should be specified that this study was undertaken in an area (Mirleft) without industrial pollution and with very low annual rainfall. A cost analysis shows that, with little investment, the population of the arid and semi-arid coastal areas of south-western North Africa, characterized by important air humidity and clear skies

in a large area along the coast, could make dew water an interesting supplementary water resource that can be made drinkable with only a light sterilizing treatment.

Acknowledgment

We gratefully thank S. Berkowicz for a critical reading of the manuscript.

References

- [1] Bahadori MN. Natural cooling systems and an economic feasibility study of long-term storage of coolness. *Energy* 1984; 9(7):589-604
- [2] Han H.J., Jeon Y.I., Lim S.H., Kim W.W., Chen K. New developments in illumination, heating and cooling technologies for energy-efficient buildings. *Energy*, In Press
- [3] Al-Jamal K. Greenhouse cooling in hot countries. *Energy* 1994; 19(11): 1187-1192
- [4] Argiriou A., Santamouris M., Assimakopoulos D. N. Assessment of the radiative cooling potential of a collector using hourly weather data. *Energy* 1994; 19(8): 879-888
- [5] Icerman L. Energy from humid air. *Energy* 1979; 4(1): 132-133
- [6] Beysens D., Clus O., Mileta M., Milimouk I., Muselli M., Nikolayev V.S. Collecting dew as a water source on small islands: the dew equipment for water project in Bisevo (Croatia). *Energy* 2007; 32(6): 1032-1037
- [7] Beysens D., Muselli M., Milimouk I., Ohayon C., Berkowicz S.M., Soyeux E., Mileta M., Ortega P. Application of passive radiative cooling for dew condensation. *Energy* 2006; 1(13): 2303-2315
- [8] Agam N, Berliner PR. Dew formation and water vapor adsorption in semi-arid environments-A review. *Journal of Arid Environments* 2006;65:572-590.
- [9] Richards K. Observation and simulation of dew in rural and urban environments. *Progress in Physical Geography* 2004;28:76-94.
- [10] Graf A, Kuttler W, Werner J. Mulching as a means of exploiting dew for arid agriculture? *Atmospheric Research* 2008;87:369-376.
- [11] Kashiwa B.A., Kashiwa C.B. The solar cyclone: A solar chimney for harvesting atmospheric water. *Energy* 2008; 33(2): 331-339
- [12] Jumikis AR. Aerial wells:secondary sources of water. *Soil Sci* 1965;100:83-95.
- [13] Beysens D. The formation of dew. *Atmos Res* 1995;39:215-237.

- [14] Nikolayev VS, Beysens D, Gioda A, Milimouk I, Katiushin E, Morel JP, Water recovery from dew. *J Hydrol* 1996;182:19–35.
- [15] Muselli M, Beysens D, Marcillat J, Milimouk I, Nilsson T, Louche A. Dew water collector for potable water in Ajaccio (Corsica Island, France). *Atmos Res* 2002;64:297–312.
- [16] Beysens D, Milimouk I, Nikolayev V, Berkowicz S, Muselli M, Heusinkveld B, Jacobs AFG. Comment on “The moisture from the air as water resource in arid region:hopes, doubt and facts” by Kogan & Trachtman”. *J Arid Env* 2006a;67:343–352.
- [17] Sharan G, Beysens D, Milimouk I. A study of dew water yields on Galvanized iron roofs in Kothara (North-West India). *J Arid Env* 2007;69:259–269.
- [18] Jacobs FG, Heusinkveld BG, Berkowicz SB. Dew and fog collection in a grassland Area. In:Proceedings of the Third International Conference on Fog, Fog Collection and Dew, Cape Town, South Africa, 2004.
- [19] Jacobs, F.G., Heusinkveld, B.G., and Berkowicz, S.M., Passive dew collection in a grassland area, The Netherlands. *Atmos Res* 2008;87:377-385.
- [20] Jukov NN. O drevnih gydrotehnicheskikh sooruzeniyah goroda Fodosii v sviazi s voprosom ob izuchenii principov dobychi vlagi iz atmosfery. Feodosijskoie otdelenie obshchestva po izucheniu Kryma i arheologicheskij muzej, Sbornik statej po ekonomike, bytu i istorii Feodosijskogo rajona, Vol. 1, Feodosia, (in Russian);translated in French by Milimouk I., Beysens D., 1995. Recueil d’articles sur la condensation de l’eau atmosphérique. Rapport CEA-Saclay, DIST 95002495, 1931. pp. 68–74.
- [21] Knapen MA. Dispositif intérieur du puits aérien Knapen. Extrait des mémoires de la société des ingénieurs civils de France. Imprimerie Chaix, Paris, 1929.
- [22] Chaptal L. La lutte contre la sécheresse-la captation de la vapeur d’eau atmosphérique. *Nature (Paris)* 1932;60:449– 454.

- [23] Nilsson T, Vargas WE, Niklasson GA, Granqvist CG. Condensation of water by radiative cooling. *Sol Energy* 1994;5 (f):310-317.
- [24] Beysens D, Milimouk I, Nikolayev VS, Muselli M, Marcillat, J. Using radiative cooling to condense atmospheric vapour: a study to improve water yield. *J Hydrol* 2003;276:1–11.
- [25] Clus O, Ortega P, Muselli M, Milimouk I, Beysens D, Dew formation and collection in a humid tropical climate (French Polynesia). *J Hydrol* 2008;361:159-171.
- [26] Nilsson T. Initial experiments on dew collection in Sweden and Tanzania. *Sol Energy Mater Sol Cells* 1996;40:23-32.
- [27] Abdul-Wahab SA, Al-Hinai H, Al-Najar KA, Al-Kalibani MS. Fog water harvesting: Quality of fog water collected for domestic and agricultural use. *Environmental Engineering Science* 2007;24:446-456.
- [28] Marzol MV. Temporal characteristics and fog water collection during summer in Tenerife (Canary Islands, Spain). *Atmospheric Research* 2008;87:352-361.
- [29] Schemenauer RS, Fuenzalida H, Cereceda P. A neglected water resource: the Camachanca of South America. *Bull Amer Meteor Soc* 1988;69:138-147.
- [30] Beysens D, Ohayon C, Muselli, M, Clus O. Chemical and biological characteristics of dew and rain water in an urban coastal area (Bordeaux, France). *Atmos Environ* 2006;40:3710-3723.
- [31] Pierson WR, Brachaczek WW, Gorse RA, Japar SM, Norbeck JM, On the acidity of dew. *Journal of Geophysical Research* 1986;91:4083-4096.
- [32] Mulawa PA, Cadle SH, Lipari F, Ang CC, Vandervennet RT. Urban dew: Its composition and influence on dry deposition rates. *Atmos Environ* 1986;20:1389-1396.
- [33] Okochi H, Kajimoto T, Arai Y, Igawa M. Effect of acid deposition on urban dew chemistry in Yokohama, Japan. *Bull Chem Soc Japan*, 69; 1996/3355- 3365.

- [34] Pierson WR, Brachaczek WW, Japar SM. Dry deposition and dew chemistry in Claremont, California, during the 1985 Nitrogen species methods comparison study. *Atmos Environ* 1988;22:1657-1663.
- [35] Pierson WR, Brachaczek WW. Dew chemistry and acid deposition in Glendora, California, during the 1986 Carbonaceous species methods comparison study. *Aerosol Sci Tech* 1990;12:8-27.
- [36] Sceller E. Amino-acids in dew – origin and seasonal variation. *Atmos Environ* 2003;35:2179-2192.
- [37] Rubio MA, Lissi E, Villena G. Nitrite in rain and dew in Santiago City, Chile. Its possible impact on the early morning starts of the photochemical smog. *Atmos Environ* 2002;36:293-297
- [38] Chiwa M, Oshiro N, Miyake T, Nakatani N, Kimura N, Yuhara T, Hashimoto N, Sakugawa H. Dry deposition washoff and dew on the surfaces of pine foliage on the urban- and mountain-facing sides of Mt. Gokurakuji, western Japan. *Atmos Environ* 2003;37:327–337.
- [39] Jiries A. Chemical composition of dew in Amman. *Atmos Res* 2001;37:261-268.
- [40] Muselli M, Beysens D, Soyeux E. Is dew water potable? Chemical and biological analyses of dew water in Ajaccio (Corsica Island, France). *J Environ Qual* 2006;35:1812-1817.
- [41] Beysens D, Muselli M, Nikolayev VS, Narhe R, Milimouk I. Measurement and modelling of dew in island coastal and alpine areas. *Atmos Res* 2005;73:1–22.
- [42] Lekouch I, Mileta M, Muselli M, Milimouk-Melnytchouk I, Šojat V, Kabbachi B, Beysens D. Comparative chemical analysis of dew and rain water (Zadar, Croatia). In press, 2010.

- [43] Ali K, Momin GA, Tiwari S, Safai PD, Chate DM, Rao PSP. Fog and precipitation chemistry at Delhi, north India. *Atmos Environ* 2004;38:4215–4222.
- [44] Das R, Das SN, Misra VN. Chemical composition of rainwater and dustfall at Bhubaneswar in the east coast of India. *Atmos Environ* 2005;39:5908–5916.
- [45] Clus O. Rapport d'implantation d'un condenseur de rosée sur l'atoll de Tikehau (Tuamotus, Polynesie Francaise) du 16 au 23 août 2005. Unpublished.
- [46] WHO:third edition of the WHO Guidelines for Drinking- Water Quality
http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/index.html
- [47] Keene WC, Pszenny AP, Gallowa JN, Hawley ME. Sea salt corrections and interpretations of constituent ratios in marine precipitation. *J Geophys Res* 91, 1986;91:6647–6658.
- [48] Kulshrestha UC, Sarkar AK, Srivastava SS, Parashar DC. Investigation into atmospheric deposition through precipitation studies at New Delhi (India). *Atmos Environ* 1996;30(24):4149–4154.
- [49] Riley JP, Chester R. *Introduction to Marine Chemistry*. Academic Press, London and New York 1971.
- [50] Possanzini M, Buttini P, Palo VD. Characterization of rural area in terms of dry and wet deposition. *Sci. Total Environ* 1988;74:111– 120.
- [51] Gleick P. H., Basic water requirements for human activities:meeting basic needs. *Water International* 1996;21:83-92.
- [52] Clus O, Sharan G, Singh S, Muselli M, Beysens D. Simulating and testing a very large dew and rain harvester in Panandhro (NW India). In: *Proceedings of the 4th Conference on Fog, Fog Collection and Dew, La Serena, Chile. 2007, p. 311-312. See also:*
<http://www.iimahd.ernet.in/download.php?downloadid=476>

Figures Captions

Fig. 1. Measurement site located on a 3.5 m height terrace including (panel a) a meteorological station and 4 condensers facing north (N), east (E), south (S), west (W), with the south condenser equipped with a rain recorder and (b) a fog net collector (F) oriented east-west. (c) Details of the fog net. The net is 0.24 mm thick.

Fig. 2. (a) Evolution of the daily water yield (mm) in a double ordinate. The dew yield (black bars) is averaged over the 4 condensers and corresponds to the positive ordinate. Rain yield (grey bars) corresponds to the negative ordinate. The curves are a 60% weighting function (dew: full black line; rain: grey interrupted line). (b) Cumulative dew (black dots) and rain (open circles) yields (mm). (c) Comparison of dew

Fig. 3. Time series of dew (■) and rain (o) pH. The curves are a 100% weighting function (dew: full black line; rain: grey interrupted line).

Fig. 4. pH with respect to dew yield. The curve is a weighing fitting function (100%).

Fig. 5. Time series of dew (■) and rain (o) electric conductivity EC. The curves are a 60% weighted fit (dew: full black line; rain: grey interrupted line).

Fig. 6. Variation of the electric conductivity EC with dew yield. The line is a 100% weighing function.

Fig. 7. Mean ion concentrations for dew as compared to rain water.

Fig. 8. Correlation between total cationic and anionic charges in dew and rain water. The line is a linear fit with slopes 1.01 ± 0.02 (dew) and 0.97 ± 0.03 (rain).

Tables Captions

Table 1. Main physico-chemical properties of dew and rain water.

Table 2. Ion concentrations for dew and rain collected from a passive dew foil condenser in Mirleft (Morocco) as compared to dew from Bordeaux (France, near the Atlantic Ocean) and World Health Organization recommendations.

Table 3. Electric conductivity (EC) ($\mu\text{S}/\text{cm}$) and total mineralization in mg/L ($\approx 0.77 \text{ EC}$) in Mirleft as compared to other sites. (a): this study; (b): [40]; (c): [37]; (d): [34]; (e): [35]; (f) : [25] ; (g) : [41].

Correlation coefficients among ionic constituents in dew water (above the diagonal) and rain water (below the diagonal). (Bold-underlined: major correlations > 0.9).

Table 5. Comparison of sea water ratios (%SSF) and non sea water ratios (%NSSF) with dew and rain water components. Ratios greater than 60 have been outlined; the ratios in the order of 50 have been underlined by an interrupted line.

Table 6. Neutralization factors. NF = factor of neutralization.

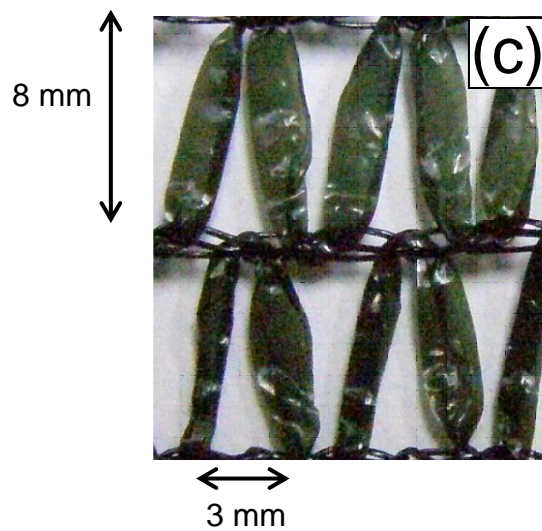
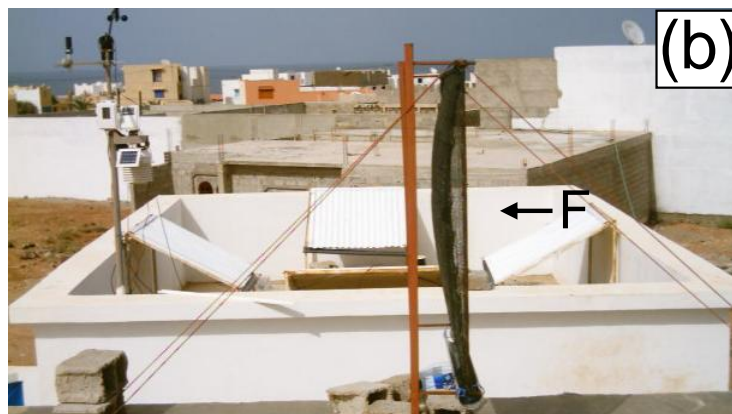
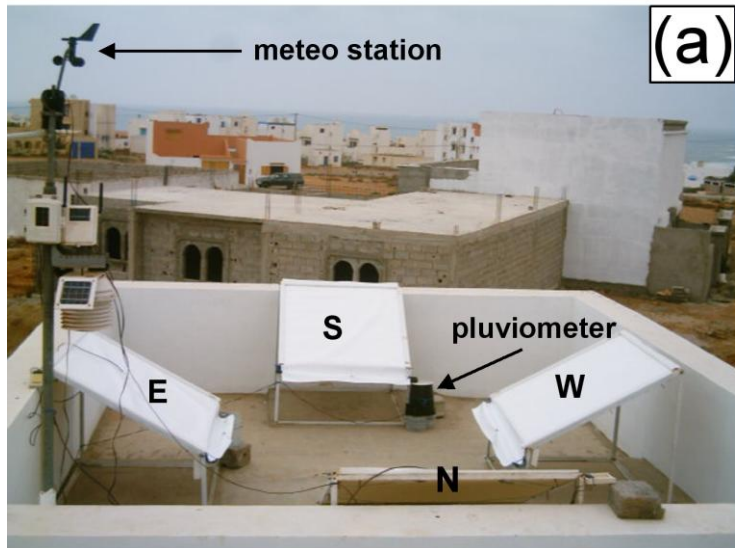


Fig. 1. Measurement site located on a 3.5 m height terrace including (a) a meteorological station and 4 condensers facing north (N), east (E), south (S), west (W), with the south condenser

equipped with a rain recorder and (b) a fog net collector (F) oriented east-west. (c) Details of the fog net. The net is 0.24 mm thick.

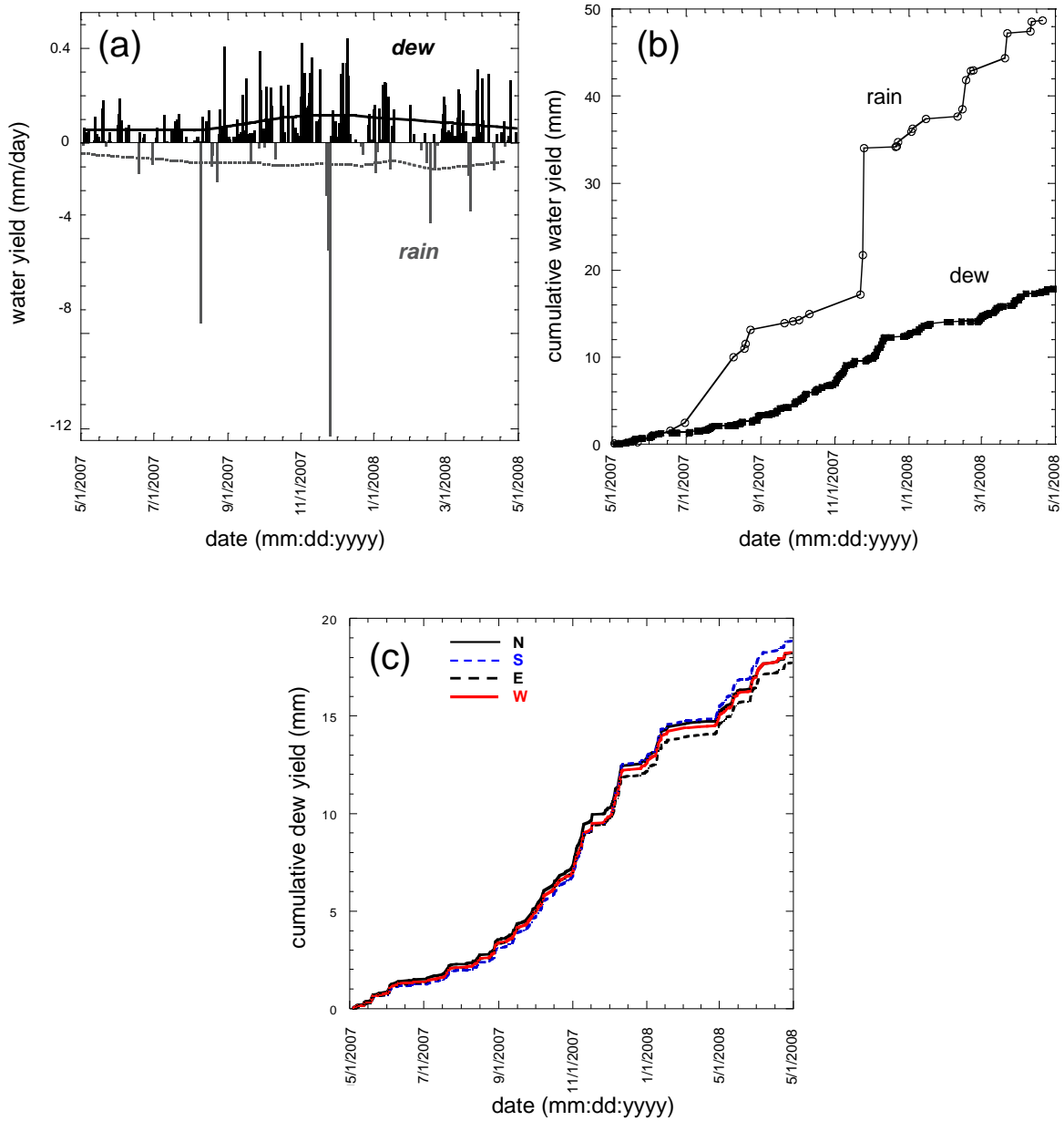


Fig. 2. (a) Evolution of the daily water yield (mm) in a double ordinate. The dew yield (black bars) is averaged over the 4 condensers and corresponds to the positive ordinate. Rain yield (grey bars) corresponds to the negative ordinate. The curves are a 60% weighting function (dew: full black line; rain: grey interrupted line). (b) Cumulative dew (black dots) and rain (open circles) yields (mm). (c) Comparison of dew yields (cumulative, mm) between condensors facing north (N), south (S), east (E), west (W).

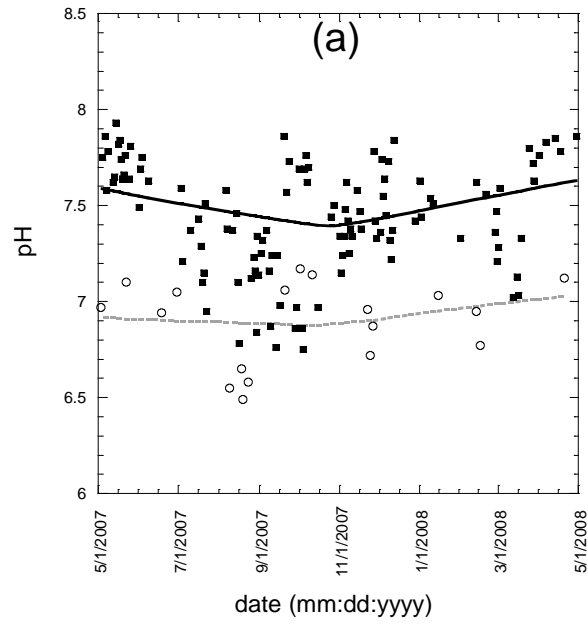


Fig. 3. Time series of dew (■) and rain (○) pH. The curves are a 100% weighting function (dew: full black line; rain: grey interrupted line).

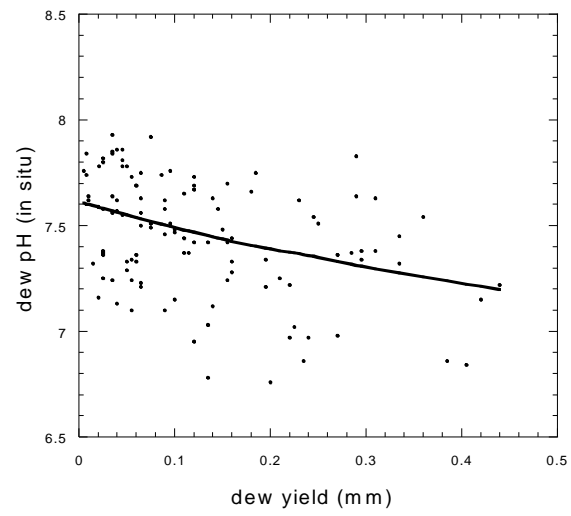


Fig. 4. Dew pH with respect to dew yield. The curve is a weighting fitting function (100%).

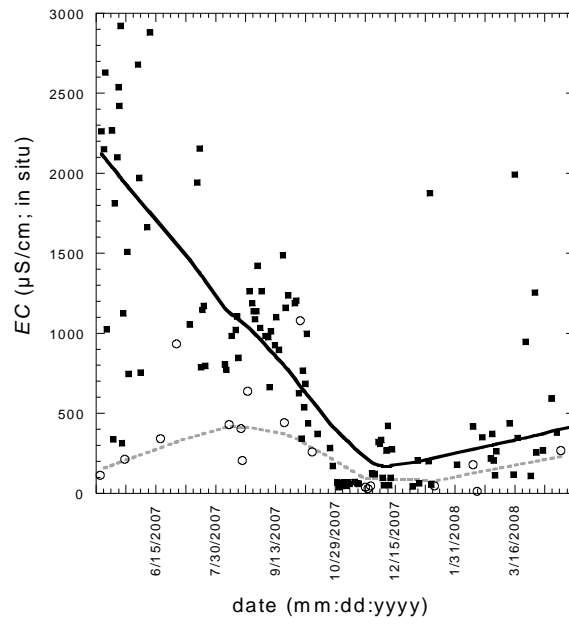


Fig. 5. Time series of dew (■) and rain (○) electric conductivity EC. The curves are a 60% weighted fit (dew: full black line; rain: grey interrupted line).

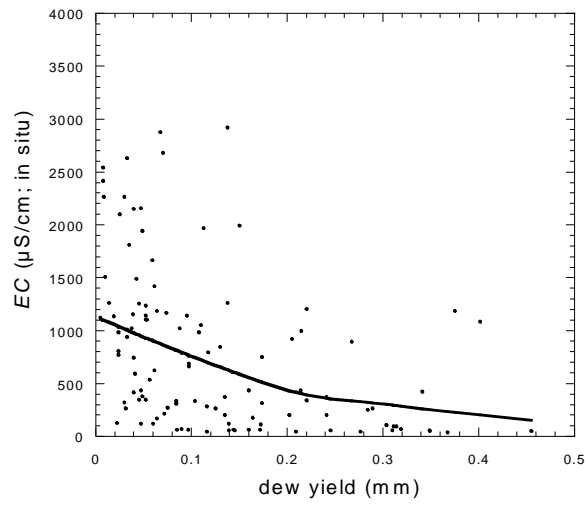


Fig. 6. Variation of the electric conductivity EC with dew yield. The line is a 100% weighing function.

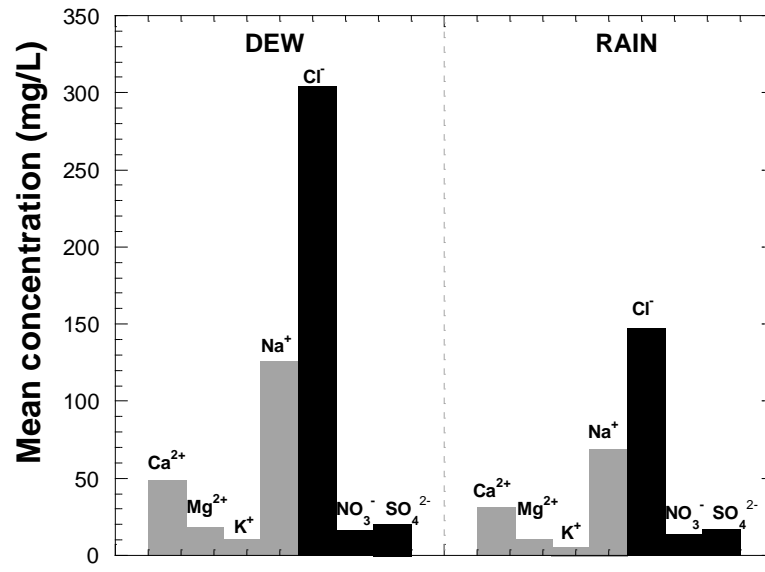


Fig. 7. Mean ion concentrations for dew as compared to rain water.

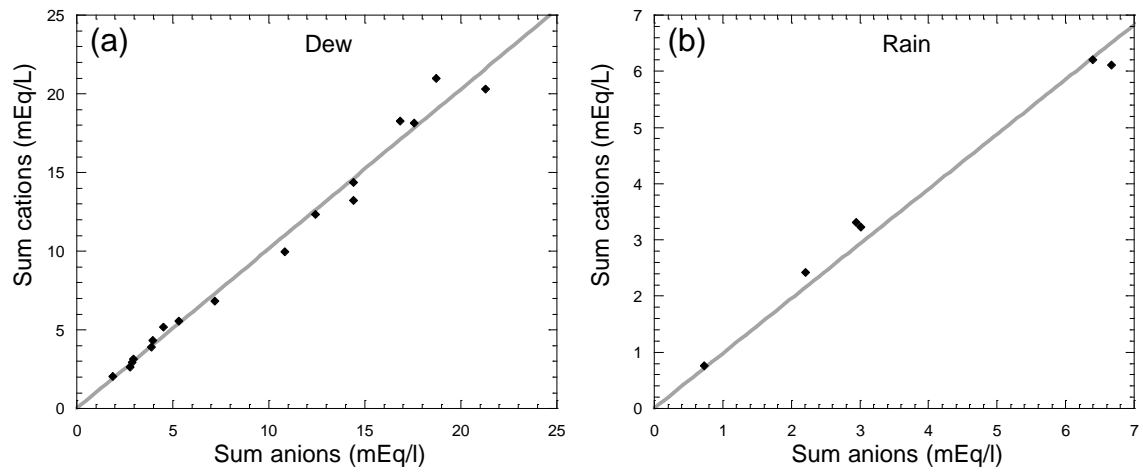


Fig. 8. Correlation between total cationic and anionic charges in dew and rain water. The line is a linear fit with slopes 1.01 ± 0.02 (dew) and 0.97 ± 0.03 (rain).

Table 1. Main physico-chemical properties of dew and rain water.

	Dew			Rain		
	Mean	Min	Max	Mean	Min	Max
pH in situ	7.40	6.75	7.93	6.85	6.49	7.17
EC ($\mu\text{S}/\text{cm}$)	725.25	38.6	2680	316	14.50	1081
Ca²⁺ mg/L	48.27	16.65	108.18	30.86	7.38	50.61
Na⁺ mg/L	99.27	17.65	287.91	68.76	6.10	188.43
Mg²⁺ mg/L	16.19	4.3	38.09	10.34	1.38	26.75
K⁺ mg/L	9.50	1.81	18.65	5.12	0.71	9.68
Cl⁻ mg/L	255.52	60.84	571.05	147.05	24.79	386.81
SO₄²⁻ mg/L	18.34	5.54	54.13	16.85	1.24	47.77
NO₃⁻ mg/L	14.90	5.43	28.79	7.73	0	24.47
Cu²⁺ mg/L	0.018	0.001	0.033	0.018	0.002	0.022
Pb mg/L	0.005	0.004	0.008	0.017	0.004	0.01
Zn²⁺ (without Feb.-Mar.)	0.022	0.001	0.147	0.006	0.003	0.01
Zn²⁺ (with Feb.-Mar.)	46	0.001	45.8	2.57	0.003	20.6
CFU mL⁻¹, 20 °C	170	160	180			
CFU mL⁻¹, 37 °C	340	280	400			

Table 2. Ion concentrations for dew and rain collected from a passive dew foil condenser in Mirleft (Morocco) as compared to dew from Bordeaux (France, near the Atlantic Ocean) and World Health Organization recommendations.

	Dew (Mirleft)	Rain (Mirleft)	Dew (Bordeaux)	Max WHO
pH in situ	7.4	6.85	6.26	6.5 – 8.5
EC ($\mu\text{S}/\text{cm}$)	725.25	316	45.1	
Ca²⁺ mg/L	48.27	32.97	1.47	
Na⁺ mg/L	99.27	52.4	3.6	200
Mg²⁺ mg/L	16.19	10.81	0.36	
K⁺ mg/L	9.5	5.25	0.41	
Cl⁻ mg/L	255.52	157.02	5.52	250
SO₄²⁻ mg/L	18.34	12.43	3.75	250
NO₃⁻ mg/L	14.9	11.67	2.8	50
Cu²⁺ mg/L	0.018	0.017	0.0027	2
Pb mg/L	0.005	0.006		0.01
Zn²⁺ mg/L	0.022	0.006	0.036	4
TA/TC	0.4	0.6		

Table 3. Electric conductivity (EC) ($\mu\text{S}/\text{cm}$) and total mineralization in mg/L (≈ 0.77 EC) in Mirleft as compared to other sites. (a): this study; (b): [45]; (c): [42]; (d): [39]; (e): [40]; (f) : [30].

Site	EC ($\mu\text{S}/\text{cm}$)	Total mineralization
Mirleft (coastal, Morocco) ^(a)	725	560
Tikehau (atoll island, French Polynesia) ^(b)	580	450
Zadar (coastal, Croatia) ^(c)	204	160
Amman (near-coastal, Jordan) ^(d)	129	100
Ajaccio (island, France) ^(e)	114	88
Bordeaux (near coastal, France) ^(f)	45	35

Table 4. Correlation coefficients among ionic constituents in dew water (above the diagonal) and rain water (below the diagonal). (Bold-underlined: major correlations > 0.9).

	<hr/>								
Dew	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Cu	Pb
Rain	<hr/>								
Ca ²⁺		0.75	0.78	0.64	0.72	0.89	0.89	-0.43	-0.49
Mg ²⁺	0.62		0.78	0.91	0.92	0.87	0.91	-0.81	-0.71
K ⁺	0.73	0.94		0.73	0.78	0.89	0.81	-0.43	-0.35
Na ⁺	0.33	0.87	0.70		0.98	0.78	0.88	-0.90	-0.70
Cl ⁻	0.55	0.96	0.88	0.95		0.85	0.91	-0.85	-0.70
NO ₃ ⁻	0.14	0.40	0.42	0.57	0.59		0.89	-0.59	-0.56
SO ₄ ²⁻	0.02	0.26	0.33	0.44	0.47	0.94		-0.73	-0.65
Cu	-0.28	-0.67	-0.43	-0.70	-0.60	0.06	0.29		0.80
Pb	-0.41	-0.15	-0.10	0.13	0.08	0.76	0.89	0.51	

Table 5. Comparison of sea water ratios (%SSF) and non sea water ratios (%NSSF) with dew and rain water components. Bold, underlined: ratios greater than 60; underlined: ratios in the order of 50.

	Dew ratios	Sea water ratio	Dew %SSF	Dew %NSSF	Rain %SSF	Rain %NSSF
Ca²⁺ mEq /L	0.45	0.044	9.86	<u>90.14</u>	8.54	<u>91.46</u>
Mg²⁺ mEq /L	0.27	0.227	<u>84.47</u>	15.53	<u>79.85</u>	20.15
K⁺ mEq/L	0.05	0.022	<u>48.14</u>	<u>51.86</u>	5.82	<u>94.18</u>
Cl⁻ mEq/L	1.57	1.166	<u>74.42</u>	25.58	<u>84.21</u>	15.79

Table 6. Neutralization factors. NF = factor of neutralization.

	Dew	Rain	Dew NF	Rain NF
Ca²⁺ mEq /L	2.44	1.54	3.64	2.65
Mg²⁺ mEq /L	1.47	0.85	2.19	1.46
K⁺ mEq/L	0.25	1.13	0.37	1.95