

Dew formation and water vapor adsorption in semi-arid environments—A review

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Abstract

The impact of ‘non-rainfall’ water on soil is important in arid zones. In that environment, the amount of dew can exceed that of rainfall, or even be the sole source of liquid water for plants. However, since plants cover only a small fraction of the desert surface, such assessments apply only to a small proportion of the area. In the absence of fog, dew formation and direct water vapor adsorption are two mechanisms by which water can be added to the soil. The latter has been much less extensively studied, even though in many instances the environmental conditions favor its occurrence over dew formation. The different physical mechanisms underlying these two phenomena are described in this review, followed by a description of the most commonly used methods to quantify and monitor them. Which of these two phenomena will occur is determined by soil-surface temperature. Dew forms on the soil surface only if the surface temperature drops below the dew-point temperature. Otherwise, water vapor adsorption is the only possible mechanism for water uptake by the soil. It has become clear that there are areas in which, during the dry season, the dominant process is vapor adsorption, and dew formation is a rare occurrence. Since it is during the dry season that the importance of dew has always been considered to be most significant, these findings put in doubt the role of dew as a water source in desert areas.

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1. Introduction

As far back as biblical times, dew was considered a precious and life-supporting phenomenon. It was mentioned as a source of great fertility (Genesis 27:28; Deuteronomy 33:13; Zechariah 8:12) and its withdrawal was regarded as a curse from God (2 Samuel 1:21; 1 Kings 17:1). It was deemed a symbol of wealth (2 Samuel 17:12; Psalms 110:3), an emblem of brotherly love and harmony (Psalms 133:3), and of rich spiritual blessings (Hosea 14:5). Later, a popular story dating back to the 16th century told of the hundreds of liters of dew water that were formed yearly by condensation of water vapor on a sealed sarcophagus located in the yard of the abbey of Arles-sur-Tech (France) (Beysens et al., 2001). In more modern times, the lack of potable water in certain arid areas has been at the heart of a renewed interest in dew formation and its possible use to supply water needs. Nikolayev et al. (1996) reviewed the idea of dew collection in light of the basic physics of water vapor condensation. Awanou and Hazoume (1997) proposed the use of different types of radiators for hot and dry climates based on the psychrometric diagram. The possibility of storing dew was investigated in the Canary Islands (Hollermann and Zapp, 1991), as was the prospect of condensed atmospheric moisture for use in small-scale irrigation (Alnaser and Barakat, 2000).

In agriculture, dew may play different roles (Wallin, 1967). On the one hand, it may be beneficial to crops by decreasing the vapor-pressure deficit in the vicinity of the dew drops and thus allowing stomatal opening and photosynthesis (Slatyer, 1967). Moreover, despite the small amount of free liquid water involved in the process of dew formation, it can play an important role in the recovery of water content in plants after extreme water loss (Went, 1955). On the other hand, the presence of dew on the leaves of agricultural crops can have a negative effect, as it may lead to the spread of various plant diseases. An important factor in plant disease control and protection is duration of leaf surface wetness, as the spores of many pathogens need a film of water on the leaf tissue in order to germinate and infect the host (Pedro and Gillespie, 1982a; Morin et al., 1993). In particular, the development of bacteria and fungi has been found to be highly influenced by the presence of dew (Auld et al., 1988; Zuberer and Kenerley, 1993; Zhang and Watson, 1997). Thus, most models of crop foliar diseases include factors related to both pathogen biology and the environmental regulation of the presence of dew (Wilson et al., 1999).

The presence of dew is not only important in an agricultural context; it can also potentially affect various remotely sensed parameters. Dew affects the soil-surface albedo (Menenti et al., 1989; Minnis et al., 1997) as well as that of plant canopies (Pinter, 1986; Fraser, 1994). In the passive microwave region (radar), Jackson and Moy (1999) found that dew is unlikely to have a significant effect on soil moisture signals. However, Ridley et al. (1996) and Wigneron et al. (1996) found that radar measurements are highly sensitive to the presence of dew. Dew also affects the retrieval of quantitative crop information from radar imagery (Wood et al., 2002).

The importance of dew is, however, not restricted to its direct utilization. In natural ecosystems, dew serves as an important source of moisture for plants, biological soil crusts, insects, and small animals, especially in desert environments, where water resources are limited (Jacobs et al., 1999). Biological soil crusts can absorb dew water, and this may be particularly important for the total period of potential net CO₂ uptake by these crusts, providing relatively long phases of photosynthesis from a low moisture supply during the early morning hours (Evenari, 1985; Lange et al., 1992, 1998). It has been suggested that the germination of desert annual seeds is enhanced if dew occurs frequently (Gutterman and Shem-Tov, 1997). Dew droplets that condense on plant canopies can provide moisture that helps them overcome the dry season (Willis, 1985). The importance of dew has been specifically examined in sandy areas (Zentay et al., 1985) and in terms of its enhancing the survival of heliophilous species during the dry season (Jacobs et al., 2000a).

Moreover, dew is a source of water for insects and small animals. Examples are the *Diacamma rugosum*, a common ant in India that acquires a substantial fraction of its water requirements from dew (Moffett, 1985), and the snail *Trochoidea seetzenii*, which has also been found to use dew as a source of water (Degen et al., 1992; Shachak et al., 2002).

Dew has some geomorphological effects as well: it contributes to both the chemical and mechanical weathering of rocks (Evenari et al., 1971); it enhances the development of karst formations in arid environments (Castellani and Dragoni, 1987); it plays a role as a source of moisture in the stabilization of sand dunes (Subramanian and Kesava-Rao, 1983), and it has an effect on the consolidation of accumulated atmospheric dust (Goossens and Offer, 1995).

Dew is primarily a physical phenomenon, which affects the energy balance at the soil–plant–atmosphere interface. As such, it should be taken into account whenever exchange processes within the plant canopy are being analyzed (Jacobs et al., 1996) as it appears to be a major sink of available energy in the early morning (Pitacco et al., 1992) and to affect the actual canopy temperature (Bourque and Arp, 1994). On bare soil, nocturnal dew usually evaporates the following morning, creating a diurnal cycle of water content in the uppermost soil layer. This cycle involves exchange of latent-heat flux between the soil and the atmosphere, thereby affecting the energy balance at the soil surface.

The energy balance at the soil surface plays an important role in regional and meso-scale studies. However, little detailed information exists on the daily course of the energy-balance components (Malek and Bingham, 1997). To circumvent this lack of data, the actual latent-heat flux density may be related to an easily computed flux. For meso- and global-scale models, the concept of moisture availability has been proposed and the actual evaporation is computed as a fraction (α) of the easily obtained potential evaporation. As α has been defined as depending on the soil water content of the uppermost soil layer (Carlson et al., 1984; Chen and Dudhia, 2001), changes in the water content resulting from

dew formation may affect these meteorological models. The degree of this effect and the order of the errors introduced by neglecting this phenomenon are unknown.

The abovementioned studies stress the considerable importance of dew in arid and semi-arid ecosystems. Due to the fact that plants cover only a very small fraction of the desert surface, a study of dew formation on bare soil surfaces is essential. However, it has been found that even though dew was observed on plants and artificial surfaces, no visible moistening of the bare soil surface was evident on the same nights, in the same locations (Kidron, 2000; B. Wilske, personal communication). The correlation between the amounts of dew formed on artificial surfaces and the amounts of dew formed on the soil surface should therefore be questioned. Moreover, water vapor adsorption has been put forward as an important link in the water cycle of arid and semi-arid regions (Danalatos et al., 1995; Kosmas et al., 1998, 2001). The link between this phenomenon and the formation of dew (on either soil or artificial surfaces) has not been studied.

The objective of this paper is to review the existing knowledge on dew formation and direct water vapor adsorption, and to determine their magnitude, as well as their contribution to the energy balance of bare soil in desert areas.

2. Physical background

In the absence of precipitation, the three main mechanisms by which water may be added to the uppermost soil surface are fog deposition, dew formation and water vapor adsorption. The later two are surface phenomena, as will be discussed in details in Sections 2.1 and 2.2. Generally, the combination of atmospheric water vapor concentration and temperature close to the soil surface and the surface temperature itself determines which of the three will occur:

- *Fog* occurs only if the water vapor concentration in the atmosphere reaches saturation, regardless of the surface conditions. When formed, fog consists of water droplets floating in the atmosphere, with the deposition of these droplets on a given surface mainly caused by settling and interception by objects (Jacobs et al., 2002).
- *Dew* occurs when the surface temperature is lower than or equal to the dew-point temperature, and water vapor from the air in contact with the cold surface condenses to form dew.
- *Water vapor adsorption* occurs when the surface temperature is higher than the dew-point temperature and the relative humidity of the soil's pores is lower than the relative humidity of the air.

Fog occurs only when given particular atmospheric conditions are met (Jacobs et al., 2002). On the other hand, dew formation, as well as water vapor adsorption, can occur on most nights in many regions of the world, and this review will therefore be limited to the aforementioned surface phenomena.

Water is held within the soil matrix by adsorption to particle surfaces and/or by capillarity in the pores. It is not always possible to distinguish which of these two mechanisms controls water retention, and their combined effect is therefore usually measured. However, the soil's reaction is influenced by these mechanisms. In particular, water attracted by reactive clay minerals (i.e. adsorption) will cause swelling but when water is attracted by capillarity into the pores of sandy soil, swelling does not occur

(Marshall et al., 1996). The relative humidity within the pores has been suggested as the criterion determining which of the two mechanisms is dominant: at high relative humidity (>0.6), the retention curve is determined by capillarity, whereas at low relative humidity (<0.6), it is determined by physical adsorption (De Vries, 1958). The different formation mechanisms of these two processes are discussed in the following sections.

2.1. Dew

Dew is fundamentally a result of phase transition, in which water vapor is transformed into liquid when it comes in contact with a surface. The primary condition for the formation of dew is that the temperature of the surface on which condensation takes place be lower than or equal to the dew-point temperature. The two most critical aspects of phase transition, in the case of dew formation, are the nucleation of the liquid phase and the nature of the droplets' growth (Beysens, 1995).

Nucleation is the formation of the smallest liquid drop that is thermodynamically stable. The nucleation rate depends upon the wetting properties of the surface, and specifically, upon the contact wetting angle. The contact angle is the angle formed at the interface between the liquid droplet and the surface (Fig. 1). A contact angle of zero means a complete flattening of the drop and complete wetting of the solid surface by the liquid. Theoretically, a contact angle of 180° would mean complete rejection of the liquid by the gas-covered solid, and the drop would retain its spherical shape. The wetting angle of pure water on clean, smooth inorganic surfaces is generally zero; however, if the surface is rough or coated with adsorbed surfactants of a hydrophobic nature, this angle can be considerably greater (Hillel, 1971).

Once a droplet of water has nucleated on the surface, it begins to grow due to the formation of a concentration gradient of water molecules around the drop. After the coalescence of two drops, a new drop, with a volume equal to the sum of the two initial drops, is formed. This process lowers the surface energy, thus favoring the formation of the new single drop. The droplet growth pattern and the final spatial distribution of the drops on the surface are highly dependent on the properties of that surface (Beysens, 1995).

In natural ecosystems, several factors determine whether dew will be formed: radiation exchange between the earth's surface and the atmosphere, turbulent heat and water vapor transport in the lower internal boundary layer and within the plant canopy if present, and heat and vapor transport in the underlying soil (Atzema et al., 1990). However, the condensation of natural atmospheric humidity is associated with two opposite atmospheric conditions: for dew to deposit, radiative cooling of the surface is needed. The rate of cooling depends on the emissivity of the sky, which, in turn, depends on the water-vapor concentration in the air, i.e. the lower the vapor concentration, the higher the radiative

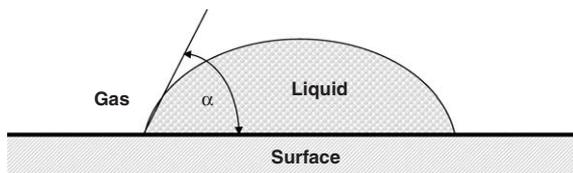


Fig. 1. Contact angle (α) of a drop resting upon a plane solid surface (after Hillel, 1971).

cooling and thus the higher the rate of formation. On the other hand, the process of dew formation obviously requires water vapor, thus the higher the vapor concentration, the higher the rate of formation.

2.2. Direct adsorption

Adsorption is an interfacial phenomenon resulting from the differential forces of attraction and repulsion occurring among molecules or ions in different phases. Various types of adsorption can occur, depending on the phases involved: adsorption of gases on solids, of gases on liquid surfaces, and of liquids on solids. The first type is involved in the process of water vapor adsorption by soils.

The first quantitative discussion of the adsorption of gases on solids was given by Irving Langmuir. The equation relating the amount of gas adsorbed on a surface to the pressure of the gas at constant temperature was defined as the adsorption isotherm, which is derived from a kinetic discussion of the condensation and evaporation of gas molecules at the surface. The Langmuir isotherm is based on the gradual coverage of a surface with adsorbed molecules, with saturation occurring when the adsorbed layer has a uniform thickness of one molecule (Moore, 1963).

Two kinds of adsorption are usually distinguished: physical and chemical. Although there are instances in which it is difficult to definitively assign the adsorption to one of these types, in most cases the decision is not difficult. Chemical adsorption is the result of strong binding forces, comparable with those leading to the formation of chemical compounds, and can be regarded as the formation of a sort of surface compound. This process requires very high energy (80–400 kJ/mol) and is seldom reversible. In contrast, physical adsorption is the result of forces operating between the solid surface and the adsorbed material that are similar to the van der Waals forces between molecules. This process requires much less energy (~20 kJ/mol or less) and is quite readily reversible (Moore, 1963). Under natural conditions, the available energy does not reach levels high enough to cause chemical adsorption. The process responsible for water vapor adsorption by soils is physical adsorption (Hillel, 1998).

The magnitude of vapor adsorption on solid surfaces depends on the surface area: the larger the area, the more sites that exist to which the vapor can attach. In soils, clay particles have the largest surface area, and adsorption takes place mainly on these particles. Therefore, the amount of water adsorbed by the soil increases with increasing clay content (Thomas, 1928). Moreover, due to the different surface areas of different types of clay, the latter also affects the amount adsorbed. Montmorillonite, for instance, adsorbs much more water than kaolinite at the same relative humidity, and illite is intermediate in this respect. The effects of clay properties on adsorption are illustrated in Fig. 2 (Marshall et al., 1996). Under natural conditions, clay particles are never completely dry. A so-called ‘air-dry’ soil is commonly found to have a mass wetness of several percent, the exact percentage depending on the aforementioned soil characteristics, as well as on the humidity of the ambient air (Hillel, 1998).

Regardless of clay type, the strength of the clay water adsorption is clearly greatest for the first layer of water molecules. The second layer is attached to the first by hydrogen bonding, the third layer to the second, and so forth; however, the influence of the attractive force field of the clay surface diminishes with distance so that beyond a few molecular layers, it apparently becomes vanishingly small (Hillel, 1998).

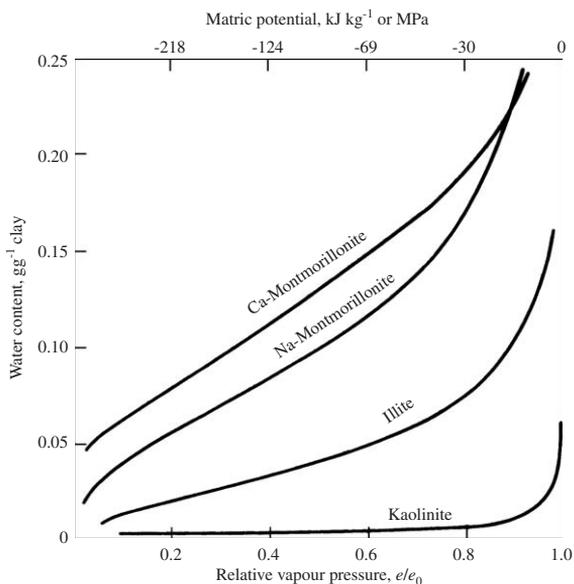


Fig. 2. Adsorption of water vapor by different clays (Source: Marshall et al., 1996).

2.3. Terminology

Many long-standing terms describing the dew phenomenon, such as ‘dew deposition’ and ‘dewfall’, are perpetually used although physically incorrect. As has been detailed in Section 2.1, dew is a surface phenomenon, and as such, occurs solely at the surface. When using the terms ‘dew deposition’ or ‘dewfall’ one may mistakenly understand that the water droplets first form in the air and then deposit on the surface. Water droplets in the air form fog or haze, but do not form dew.

Water vapor may fall on the surface and either condense to form dew or directly be adsorbed by the soil particles. The correct term that should be used is, therefore, ‘*dew formation*’.

To reveal the importance and magnitude of dew formation vs. water vapor adsorption, these processes have to be quantified. Quantification attempts have been undertaken both by modeling these phenomena and by direct measurements.

3. Quantitative methods

Diurnal changes in the water content of the uppermost soil layer have been predicted by various models (e.g. Parlange et al., 1998), based on theories that describe the coupled flow of energy and mass in the soil (e.g. Philip, 1957; De Vries, 1958; Milly, 1982, 1984). The role of water vapor transport has been recognized and incorporated into these models. Under extremely dry conditions, water movement in the liquid phase becomes negligible and the change in water content at any given depth will be the result of water vapor movement and physical adsorption or desorption (Scanlon and Milly, 1994). A large number of publications have been dedicated to the problem of energy and mass transport

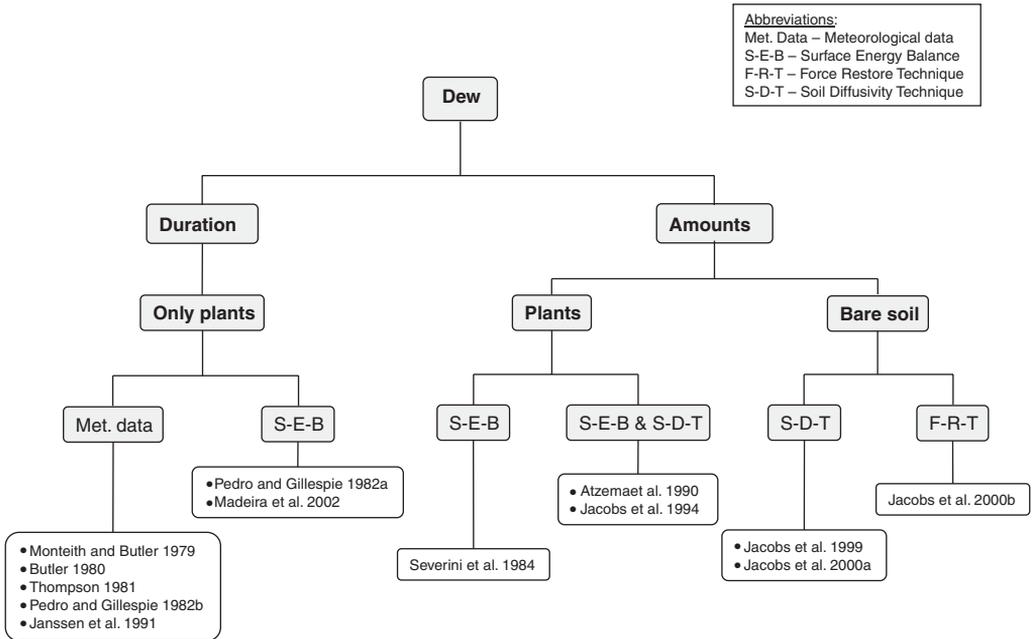


Fig. 3. Summary of the main dew models and computational methods.

within the soil (e.g. Bristow et al., 1986; Passerat et al., 1989; Van de Griend and Owe, 1994; Yakirevich et al., 1997; Chiu-On, 1999). Recently, for example, Qin et al. (2002) presented a detailed model that linked energy fluxes in the atmospheric boundary layer to the coupled transport of mass and energy in a sand dune in the Negev desert. Their model is based on the aforementioned theories, and does not distinguish between dew formation and vapor adsorption. However, models of this kind are not easy to implement and require a large number of variables.

Studies of dew have been largely devoted to two main aspects. The first is the duration of the dew (how long the surface remains wet), as the duration of leaf wetness determines the risk for diseases, and is as well important in remote-sensing applications. The second is the amount of dew (how much water the soil-plant system gains), which is important for ecologists, meteorologists and micro-meteorologists. The studies that have contributed significantly to the understanding of these two aspects are summarized in Fig. 3 and discussed in Sections 3.1 and 3.2.

3.1. Dew duration

During the late 1970s and the 1980s, a growing awareness of the fact that leaf wetness influences the spread of plant diseases led to a number of attempts to model dew duration. A simple model describing the link between the period during which the leaf is wet and the environment of a cacao pod was first proposed by Monteith and Butler (1979). Later, Butler (1980) suggested some revisions of this latter model to enable the computation of air and dew-point temperature changes after dawn using common meteorological data.

Thompson (1981) approached the problem from a different angle. His objective was to assess the commonly held belief that plants remain wet after rain or dew as long as the relative humidity remains above 90%, and he developed a multi-layer model of crop canopies. This model was based on applying the Penman-Monteith equation (Monteith et al., 1965) to a number of horizontal crop layers. This criterion was found to be more successful when the duration of leaf wetness in cases of light dew with a dry soil surface was the objective. In these cases distillation [≡condensation of water vapor from transpiring lower leaves or warmer moist soil (Noffsinger, 1965)] is small and dew forms almost exclusively in the upper parts of the canopy. The aim of this model was, however, to quantify the duration of leaf wetness *after* dew had formed, and not to predict dew duration. To apply this model, variables of the Penman-Monteith equation are needed (e.g. radiation, soil heat flux, air temperature and humidity, and wind speed), most of which are not consistently available at meteorological stations.

Pedro and Gillespie (1982a) estimated dew duration from micro-meteorological measurements for three different crop canopies by using an energy-balance technique combined with heat-transfer theory applied to flat plates. Computed values of total dew duration on exposed leaves differed from observed durations by less than 30 min. Estimated dew duration on shaded leaves was less accurate, differing from observations by an average 60 min. These differences in accuracy were attributed to the use of diffuse solar radiation measured outside the canopy as an estimator of incoming radiation on shaded leaves. In an additional study, the adoption of an energy-balance approach to estimating dew duration from standard weather-station observations was examined in three widely different canopies (Pedro and Gillespie, 1982b). Average errors of approximately 60 min in dew duration were found in all three cases. This may represent the limit of accuracy for a practical, operational system, since weather stations generally report at 1-h intervals (Pedro and Gillespie, 1982b).

Janssen et al. (1991) developed a simple model to estimate the frequency and duration of dew using only data on cloud cover, relative humidity, air temperature, and wind velocity. This model ignored heat flux and heat storage within the canopy. The results proved to be generally in agreement with measurements of dew occurrence on the surface of an automatic sequential dew sampler.

Recently, Madeira et al. (2002) used energy-balance analyses to estimate dew, using two different methods to quantify the downward long-wave radiation. The first uses cloud cover and cloud altitude to calculate sky temperatures, whereas the second is based only on cloud cover to estimate apparent sky emissivity. These models correctly predicted dew occurrence in 91% and 88% of the cases, respectively.

The aforescribed models make use of various approaches to relate different environmental factors to the duration of dew. However, each of the models was applied and examined in different environments and on different plants, making it impossible to compare them. Results of a sensitivity analysis of the dew-simulation approach proposed by Pedro and Gillespie (1982b) indicated that the sensitivity of any variable depends to a large extent on the values of all the other variables, and therefore varies both spatially and temporally (Scherm and Van Bruggen, 1993). It is reasonable to assume that these kinds of uncertainties would be found if similar sensitivity analyses were performed on the other models.

As already mentioned, the duration of dew, or the presence of water droplets on the leaves, is an important factor in plant-disease development and has therefore been

intensively studied. In studies that focus on bare soil, this issue is less important. The amounts of dew, however, are very important, in both studies that focus on plants and those that focus on bare soil, as discussed in the next section.

3.2. Dew amounts

Being a potential source of water in arid and semi-arid regions, it is important to quantify the amount of dew. As dew formation is the opposite of evaporation, it is possible to compute the amount of dew formation using conventional micro-meteorological methods developed for computing evaporation, provided that the sensitivity of the instruments is sufficient to detect the very small fluxes involved.

A few attempts have been made to compute the amounts of dew formation. These can be classified according to the approach used for the computations and to the environment in which they were applied. Dew is an interface problem. It occurs at the boundary between the atmosphere and the condensing surface which, in natural environments, can be bare soil, rocks, or plant canopy. As such, it is possible to apply computations of transport processes from both sides of the boundary. Two main approaches have been used, one which involves the transport equations of energy and mass in soil, while the other is based upon computations of latent-heat flux in the atmosphere. Theoretically, these two different approaches should yield the same amounts.

Several attempts have been made to quantify the daily dew formation on plants, their main objective being usually the development of methods to compute these amounts. However, each of these methods was assessed by comparing the results to a different measurement method.

Severini et al. (1984) computed the daily course of dew formation on grass and the subsequent evaporation by combining the energy-balance equation with standard micro-meteorological measurements. The computed fluxes were compared to those measured by a lysimeter with a special setup of seven aluminum trays filled with grass and roots in order to achieve a better resolution of the measurement. The determined values of actual evapotranspiration and dew were generally in good agreement with the measurements.

Atzema et al. (1990) tried to gain a better insight into the distribution of dew within a moderately tall crop canopy by considering two possible sources of moisture: the atmosphere and the moist soil. The amount of dew formed by condensation of atmospheric water vapor was estimated by measuring the above-crop vapor flux towards the canopy through the Energy-Balance-Bowen-Ratio technique. The amount formed by condensation of water vapor rising from the soil was estimated by computing the moisture flux in the upper layer of the soil using the water-transport equation (Philip and de Vries, 1957). Total water condensation was computed as the sum of both. The same approach of separating the source of dew from condensation of water vapor from the atmosphere and from the soil, and then combining the two was used by Jacobs et al. (1994). They attempted to describe the development of the free-water profile within a crop canopy due to dew and the course of the drying process during the early morning, and compared the model results to the measured flux using artificial condensing plates.

Because plants cover only a very small fraction of the surface of deserts, and because dew serves as an essential source of water in desert regions, the study of dew formation on bare soil surfaces is of interest. Major attempts at quantifying the amounts of dew formation on bare soil were made at a research site in Nizzana in the northwestern Negev

desert of Israel, within the interdune of a linear dune system. Jacobs et al. (1999, 2000a) presented a simple simulation model to describe the daily dew and the early drying processes. They made an important implicit assumption that under dry conditions, soil water is mainly transported in the vapor phase. Based on this assumption, the transport equations (Philip and de Vries, 1957) were reduced to include only the two terms describing the movement of water vapor by moisture and temperature gradients. The final equation for computing dew formation was similar to that obtained by Kondo et al. (1990) for evaporation.

Jacobs et al. (2000b) suggested a different approach for computing the amounts of dew formation. A simple physical model including the force-restore technique for surface moisture was developed. This model simulates the accumulated dew amounts as well as the early morning drying process. Actual dew amounts were assessed using micro-lysimeters. Model simulations agreed well with the observations. Their results suggested that the reduction in vapor pressure in the soil pores under extremely dry soil conditions is essential for the dew process.

Models are not easy to implement, and require a large number of variables. Although several models have been proposed to compute the amounts of dew formation, they were developed under specific conditions and no attempts to implement them under varying conditions were undertaken. Moreover, they were validated by comparing their output to different methods of direct measurements. An accurate and sensitive method is clearly needed to evaluate these and future models. Available methods of directly measuring dew formation are critically reviewed in the next section.

4. Measurement methods

Various dew-measuring devices are described in the literature. Some of them are used to measure dew duration, others to measure dew amounts, and yet others are used to simulate both the duration and amount of dew. Duration measurements depend upon a response to moisture deposits, be it a change in weight, length or electrical resistance of the sensing equipment (Noffsinger, 1965). Pedro and Gillespie (1982a, b) used an electrical impedance grid that was found to mimic the wetness duration on nearby leaves to within 15–30 min of the actual duration. In other studies, commercial leaf wetness sensors, made of a gold grid (5.5 × 5.5 cm), were used (Scherm and Van Bruggen, 1993; Kidron et al., 2000). Because it is relatively simple to accurately detect the duration of dew, a number of devices have been developed. The commercially developed leaf wetness sensors are sufficiently accurate for most needs.

The situation is completely different when it comes to devices for measuring dew amounts. As early as 1965, a review of methods and techniques for measuring dew revealed three main approaches: weighing lysimeters, weighing dew gauges and Duvdevani blocks (Noffsinger, 1965). Of these three approaches, only the lysimeters can detect adsorption, as they weigh soil samples in which adsorption can take place. Artificial condensation surfaces (whether dew gauges or blocks) cannot adsorb vapor and thus cannot detect this process.

The Duvdevani dew gauge is one of the first devices designed for measuring dew amounts (Duvdevani, 1947). A specially treated wooden block, 32 × 5 × 2.5 cm, is exposed at sunset 1 m above the ground. The dew distribution found in the early morning on the wood is compared with a series of photographs showing increasing steps of dew incidence.

These gauges were used in Israel, introducing a countrywide network of dew observations (Gilead and Rosenan, 1954). Despite the ability to measure dew amounts using this gauge, the observed amounts have only a climatological meaning, as they are strongly affected by the thermal (i.e. capacity and conductivity) and radiative (i.e. color and roughness) properties of the wood. Thus, the observed values can serve only as a means for comparing between different sites, and not for obtaining absolute values. Another disadvantage of this method is that it requires manual collection and evaluation of the blocks during the early morning. Nevertheless, it was used in the Rajasthan desert in India to assess the contribution of dew to sand-dune stabilization (Subramanian and Kesava-Rao, 1983).

An improved method for manually measuring dew amounts was recently suggested (Kidron, 1998). The Cloth-Plate method consists of $10 \times 10 \times 0.2$ -cm glass plates attached to $10 \times 10 \times 0.5$ -cm plywood plates. A highly absorbent synthetic cloth (6×6 cm) is attached to the center of the glass plate. This method can be used to compare dew-amounts at different locations and heights. This method was used in the Negev desert to study the effect of elevation on dew and fog precipitation (Kidron, 1999), to assess the contribution of dew to the development of biological crusts over sand dunes (Kidron et al., 2000), and to evaluate the condensation and evaporation patterns in three different habitats (Kidron, 2000). As these methods are based on manual collection in the early morning, the measurements reflect the total dew amount per night. They cannot be used to evaluate the rate of dew formation or duration.

In many cases, however, it might be desirable to measure both the duration and the amounts of dew. To do so, a method for continuous measurements is needed. A dew recorder of the Kessler-Fuel type has been described (Noffsinger, 1965). It consists of a blackened aluminum plate in a flattened conical shape with its aperture directed upwards. The weight changes resulting from dew formation are mechanically transmitted to the recording beam. A similar approach was used to design the Hiltner dew balance, with which long-term measurements of dew formation were undertaken in the Negev Heights of Israel (Zangvil and Druian, 1980; Zangvil, 1996). The Hiltner balance is based on the continuous weighing of an artificial condensation plate that hangs from a beam 2 cm above the ground. Although this device is very convenient and simple to use, its adequacy has yet to be proven since the energy balance of its condensation plate is very different from that of the soil surface above which it is installed. The Hiltner dew balance can therefore be considered a 'potential dew' gauge, the results of which are most likely correlated to atmospheric conditions. These limitations also apply to the other methods mentioned here. Different approaches must be used if the goal is to measure actual dew formation on the soil surface.

One possible way of evaluating actual condensation and evaporation from the soil is by determining the water's movement in the upper soil layers. To this aim, an electrical conductance soil-moisture meter was developed (Bunnenberg and Kuhn, 1980). It is based on measuring a disturbed soil sample under arid climatic conditions, i.e. conditions in which vapor movement predominates. Although its performance is good, this device has two main drawbacks: it measures disturbed samples, and thus it cannot measure in situ, and its presence changes the heat transport, thus affecting the condensation and evaporation fluxes.

An alternative manner of assessing the actual dew formation rates and amounts is the use of lysimeters and micro-lysimeters (Rosenberg, 1969; Waggoner et al., 1969; Sudmayer et al., 1994; Jacobs et al., 2000a). The resolution and accuracy of the lysimeters need to be

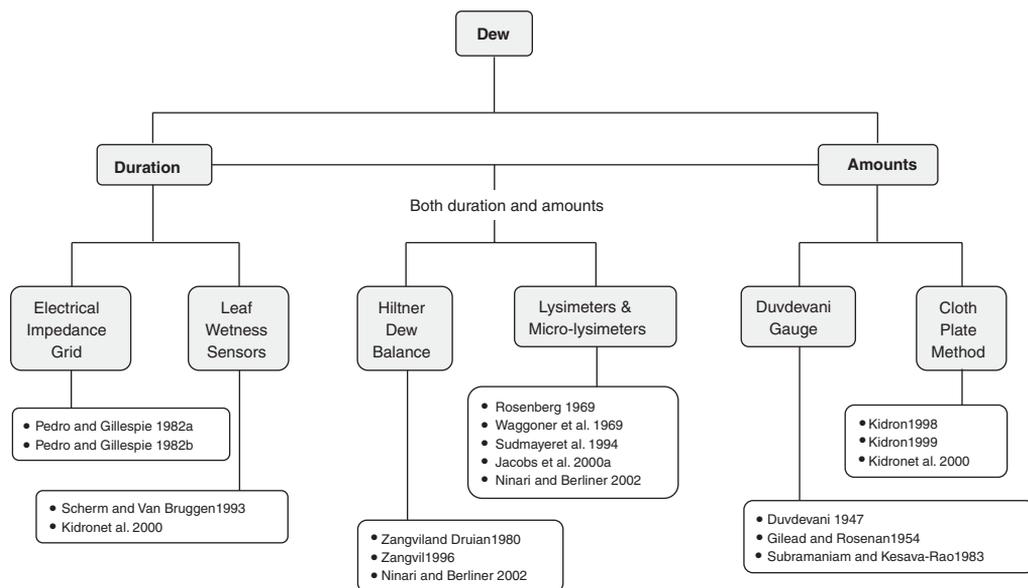


Fig. 4. Summary of the main dew-measurement methods.

very high, as the measured fluxes are extremely small. A detectable change of 0.01 mm was found to be insufficient, as in most cases the observed quantities were equal to or less than the device uncertainty (Rosenberg, 1969). If this technical limitation were to be overcome, lysimeters and micro-lysimeters could theoretically provide the absolute reference for latent-heat fluxes as long as the soil and the heat balance of the sample are similar to those of the surrounding area.

Recently, Ninari and Berliner (2002) found that the specifications of the commonly used micro-lysimeter for measuring evaporation are not sufficient for dew formation measurements. They showed that to measure dew, the minimum depth of a micro-lysimeter should be the depth at which the diurnal temperature of the soil is constant in order to ensure similar temperature profiles inside and outside the device. Specifically, they concluded that for a dry loess soil in the Negev desert, a minimum depth of 50 cm is required.

Fig. 4 summarizes the major direct dew-measurement methods. Of the methods described here, those that measure dew formation directly on the soil surface (the electrical conductance soil-moisture meter, and the lysimeters and micro-lysimeters) essentially measure latent-heat flux and can, therefore, be used to measure water vapor adsorption as well. In fact, distinguishing between dew formation and direct vapor adsorption using these methods with no additional data is impossible. Although beyond the scope of this review, the same should be mentioned regarding the differentiation between dew formation and fog deposition, thus the abovementioned dew amounts should be considered carefully.

5. Distinguishing between dew formation and direct water vapor adsorption

For dew to deposit on a surface, the temperature of the surface has to be equal to, or less than the dew-point temperature of the air mass it is in contact with. Measurements

carried out in the northern Negev, Israel, during the dry season (Agam (Ninari) and Berliner, 2004) revealed that the soil-surface temperature does not usually drop below the estimated dew-point temperature. Thus it was expected that no dew would deposit on the soil surface and indeed, dew was not visually observed. However, a clear daily cycle in the gravimetric water content of the uppermost 10 mm of the soil was observed, indicating that moisture was absorbed by the soil during the late afternoon and night, evaporating thereafter.

The magnitude of the changes in water content was very small and the average water contents throughout the entire measurement period were very low: a maximum of approximately 2% and a minimum ranging from 1% to 1.5%. These gravimetric water contents correspond to approximately 4×10^2 and 5×10^6 bar, respectively. The relative humidity in the soil pores, corresponding to these potentials, reached a maximum 75% before sunrise and dropped close to 0 at noon. Under these conditions, the dominant mechanism is adsorption, rather than capillary condensation (Philip and de Vries, 1957).

It was concluded that in the area in which this study was carried out, actual dew formation *on a bare soil surface* is probably a rare occurrence. Furthermore, the lack of any evidence of soil-surface wetting, together with the clear discernible daily cycle of water content in the upper soil layer, led to the conclusion that the main process responsible for the observed diurnal changes in water content is the direct adsorption of water vapor by the soil (Agam (Ninari) and Berliner, 2004).

It should be borne in mind that the above-described research was carried out over a sandy loam Aridisol (loess) soil. Since the thermal and hydraulic properties of different soil types vary significantly, different findings may be revealed by similar experiments carried out over different soils. The soil-surface temperature is, however, a result of the entire energy balance of the soil-atmosphere system and includes the thermal and hydraulic properties of the soil. Moreover, dew cannot be formed if the soil-surface temperature is higher than the dew temperature. Therefore, the soil-surface temperature can serve as the determining factor in distinguishing between dew formation and direct water vapor adsorption.

Regardless of the process involved, the daily water-content cycle of the uppermost soil layer involves a daily cycle of latent-heat flux, thus changing the water and energy surface balances. In the next section, the role of these processes in the energy-partitioning patterns in desert areas is discussed.

6. The contribution of dew formation and direct adsorption to energy dissipation

Land surface processes in general, and energy partitioning at the soil surface in particular, play an important part in global and meso-scale studies. These processes are usually integrated as sub-models of global and meso-scale models. During the last decade, however, a number of land surface models have been developed (Yang et al., 1998). One of their main tasks is to describe the patterns of radiant energy dissipation at the land-atmosphere interface, which above bare soil are determined by the moisture content of the soil surface. It is therefore reasonable that the quality of land surface models be judged by the accuracy with which they compute this soil water content (Irannejad and Shao, 1998).

It is a commonly accepted fact that the magnitude of the latent-heat flux above desert areas is linked to the occurrence of precipitation events, and is negligible during the dry

season when the radiant energy reaching the surface of the desert is partitioned between convective and conductive sensible heat only (Cleugh and Roberts, 1994; Unland et al., 1996). This pattern can be altered by the presence of diurnal dynamics of soil–water content due to dew deposition and/or direct water vapor adsorption.

Measurements that were carried out in the northern Negev, Israel during the dry season (Agam (Ninari) et al., 2004) revealed that the soil is drier than the wilting point (–15 bar) throughout the entire period. The soil matric potential at wilting point is used in many models as the critical value for ‘latent-heat flux shut-down’. Most models would, therefore, predict no latent-heat flux in such a case.

Nonetheless, it was found that during the daytime, although a large fraction of the net radiation was dissipated as sensible heat, the soil- and the latent-heat flux densities were not negligible. The latent-heat flux was found to be 10–15% of the net radiation. During the night, the soil-heat flux density was the most dominant component of the energy balance, the sensible-heat flux density was very small, and in most cases, the latent-heat flux density was significantly larger than the sensible one, reaching ~20% of the net radiation. It is therefore clear that under these and similar conditions, models that assume no latent-heat flux during the dry season may lead to erroneous results.

7. Concluding remarks

The considerable importance of dew as a water source in both natural ecosystems and humans’ activities and existence, especially in arid and semi-arid environments, has been widely noted. In these environments, as well as during periods of drought, dew can exceed rain in amount or frequency, or even be the sole source of liquid water for plants (Richards, 2004). However, since plants cover only a very small fraction of the surface of deserts, these assessments apply only to a small portion of such areas.

Direct water vapor adsorption has been much less extensively studied, although in many cases the environmental conditions are such that its occurrence is favored over dew formation. One possible reason is the fact that dew droplets that form on the surface are actual liquid water that can be used by plants, insects and even humans. On the other hand, adsorption of water vapor involves mainly energy exchange between the soil and the atmosphere: the phase transition occurs on the soil particle surface and is not available for use as free water by plants or insects.

The soil-surface temperature determines which of these two phenomena will occur. For dew to deposit on the soil surface, the latter’s temperature must drop below the dew-point temperature. If the temperature does not get to the dew point, water vapor adsorption is the only possible mechanism for water uptake by the soil. By now it should be clear that there are areas in which, during the dry season, the dominant process is vapor adsorption, and dew formation is a rare occurrence. Since the dry season is the period during which the importance of dew has been considered to be the most significant, these findings put the role of dew in desert areas into question.

The soil-surface temperature is a result of the interactions between meteorological and soil conditions. The soil’s thermal and hydraulic properties therefore play a crucial role in determining the surface temperature and thus the type of phenomena: dew or adsorption. It is reasonable to assume that in areas with different soil types, different results will be obtained. Further research is needed to assess the areas in which dew formation is dominant, in order to re-assess its importance in arid and semi-arid environments.

Regardless of the phenomenon, a diurnal cycle of latent-heat flux is involved in the process. Nevertheless, most meteorological models assume that in arid and semi-arid environments, latent-heat flux occurs only as a result of precipitation, and thus that there is no latent-heat flux during the dry season. However, it has been recently found that the latent-heat flux involved in water vapor adsorption can reach 10–15% of the net radiation during the day and ~20% of that at night. These magnitudes are rather large and perhaps the assumption of no latent-heat flux under dry conditions should be reconsidered.

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