AMERICAN UNIVERSITY OF BEIRUT

DEW AS AN ADAPTATION MEASURE FOR CLIMATE CHANGE

by

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AN ABSTRACT OF THE DISSERTATION OF

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Dew is a frequent atmospheric phenomenon in which water droplets naturally condense upon passively cooled surfaces. Pilot studies showed small yet significant yield, particularly in their contribution to the water budget. This interdisciplinary research couples knowledge from hydrology, geostatistics, modeling, and instrumentation to assess the long term potential of dew and its feasibility for crop and reforestation irrigation in the Mediterranean region. An experimental campaign consisting of 6 sites in differing microclimates and elevations across Lebanon revealed dew harvesting is most successful windward at midrange elevation with average nightly yields of 0.13 mm occurring 55% of nights during the Mediterranean dry season (April-October) and a maximum yield of 0.35 mm. This experimental data was used to validate a dew prediction model which was thereby applied to develop a dew atlas for the entire Mediterranean region as well as evaluate differences in predicted yield due to anticipated climate change impacts. In addition, experimental data was coupled with ET-based modeling to assess its effectiveness to potentially eliminate the need for reforestation and agricultural irrigation from traditional water resources during the dry season.

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CHAPTER 1

INTRODUCTION

Water scarcity is an increasing global problem due to projected climate change impacts, population growth, and environmental degradation. Because traditional water resources are strained, increased dependence upon non-conventional supplies are necessary to close the gap. Examples include reclaimed wastewater and desalinated seawater. Although these resources can provide large quantities of water, they require costly infrastructure and operation, deeming them prohibitive for certain regions. Water can also be harvested from the atmosphere in the form of fog or dew at a fraction of the cost.

Dew harvesting has emerged as a viable water resource over the last 20 years due to an increased understanding of formation physics and thermodynamics. Passive harvesting is dependent upon radiative cooling of a surface and high relative humidity. Dew condensers can be constructed using simple designs at minimal cost have limited cooling power (~25-100 W m^{-2} under clear skies) which restricts nightly dew yield to < 1 mm m^{-2} (Beysens et al., 2006a). Although this volume is small, it is significant because dew events are frequent, evidenced by morning droplets upon grass and automobiles, and can occur during dry periods in arid and semi-arid regions when rainfall is nil.

Most research in dew harvesting to date has been limited to pilot studies which measure the quantity and quality of dew. Although research to date has concluded dew harvesting is viable in differing climates and seasons, several gaps remain which impede the unrealized potential of dew. This study aims to promote dew harvesting expansion by assessing which areas best suited for dew, evaluating the long term potential, and appraising increased utilization of dew.

1.1. Research Objectives

This research aims to advance the understanding of dew harvesting by blending hydrology, geostatistical analysis, and modeling with experimental data to promote its use in the Mediterranean region, particularly Lebanon. Examination herein will address the following research objectives:

- Investigate the feasibility of dew harvesting in Lebanon considering differing microclimates and complex orography.
- Determine which areas within the Mediterranean region are best suited for dew harvesting by coupling modeling with geostatistical analysis to develop a dew atlas.
- Assess the long term potential of dew harvesting by evaluating climate change impacts upon meteorological factors which affect dew formation to examine whether dew is projected to escalate or decline.
- Evaluate utilization of dew for reforestation and crop irrigation.

1.2. Thesis Organization

- The justification, scope, and major findings of this research are organized into six chapters.

- Chapter 1 is an introduction of the work. It includes a brief background and justification of the topic. It also presents the innovative aspects and significance of the results.
- Chapter 2 is a comprehensive critical review of the literature including dew physics, experimental studies, modeling, water quality, and utilization of dew.
- Chapter 3 presents the experimental program which studied dew harvesting in multiple locations throughout Lebanon to gage microclimatic effect upon dew.
- Chapter 4 couples modeling with geostatistical analysis to develop a dew atlas for the Mediterranean and uses data obtained from climate models to evaluate the impact upon dew yield.
- Chapter 5 appraises the utilization of dew to supplement water demand for reforestation and agriculture.
- Chapter 6 is a personal statement on dew harvesting which envisions the future in research.

1.3. Innovation and Significance

Although dew harvesting studies have been conducted throughout the Mediterranean deeming the practice feasible, no studies have been conducted concurrently within differing microclimates within a small geographic region. The complex topography of Lebanon facilitates a diverse range of climatic characteristics.

Evaluation of microclimates in conjunction with concurrent dew studies in differing regions helps to refine which areas are best suited for dew harvesting.

Also, this study describes the methodology to develop a detailed dew atlas, which has not been done to date. Potential applications include forecasting as well as long term evaluation, which can help facilitate utilization by assessing which areas are best suited for dew.

Moreover, no studies to date have evaluated project climate change impacts upon dew yield. Whether dew yield is increasing or decreasing can have a large impact on its potential as an adaptation measure.

Lastly, even though few studies to date have proposed the use of dew for potable water or irrigation, none have used evapotranspiration-based modeling to further illustrate the potential use of dew. Similarly, this study will also evaluate the effect harvested dew can have upon soil moisture content.

CHAPTER 2

CRITICAL REVIEW OF LITERATURE[1]

Over the last 20 years, dew harvesting has evolved to fruition due to a better understanding of its physics, thermodynamics, and the radiative cooling process of condensing substrates. Although resultant yields are relatively small, dew positions itself as a viable water resources supplement because it occurs naturally and frequently in many locations globally, particularly in the absence of precipitation or when more traditional water sources are subject to depletion. Moreover, dew water is generally potable, especially in rural locations, where it is most beneficial. This review summarizes dew harvesting research achievements to date including formation processes, collection in various environments, prediction models, water quality, and applications. The paper concludes with outlining existing gaps and future research needs to improve the understanding and performance of dew harvesting in the context of adaptation to climate change.

2.1. Introduction

Due to depletion and degradation of global freshwater resources, consideration of non-conventional sustainable resources is imperative. Although dew is a frequent

[1] An edited version of this chapter has been published in *Environmental Reviews*

phenomenon whereby humid air naturally condenses upon a surface, it is frequently overlooked as a viable water resource. Dew harvesting has been long practiced, but incorrectly (see Nikolayev et al., 1996), and is believed to be an ancient technique used by the Greeks (Jumikis 1965), which supplied sufficient water for the city of Theodosia, located in present-day Ukraine. The re-emergence of the practice was attempted in the early 20th century, but was soon abandoned due to low yield (Nikolayev et al., 1996; Beysens et al., 2003). Over the last two decades, modern dew harvesting has come to fruition, due to a better understanding of associated physics and thermodynamics, which enable its formation, particularly radiative cooling. Reported studies reveal relatively small dew yields, yet non-negligible (*e.g*. Nilsson, 1996; Muselli et al., 2002; Beysens et al., 2003), promoting its role particularly during dry periods in arid and semi-arid regions.

The formation of dew, often called dewfall, erroneously conjures up visions of dew as a form of precipitation. Rather, dew forms as a result of atmospheric moisture condensing upon surfaces at or near the ground (Monteith, 1957). Furthermore, dew distinguishes itself from distillation, which results from soil moisture (Monteith, 1957) and guttation, which occurs when water droplets emerge from plant leaves (Hughes and Brimblecombe, 1994).

This paper presents a critical review on the significance of dew and pilot harvesting applications to consider the role of dew as a sustainable supplemental water resource for agriculture, reforestation, and drinking water. Major areas of research were evaluated, starting with dew physics and thermodynamics, to dew harvesting experimental studies and models of potential yield and duration. Lastly, dew water quality is explored, including chemical contamination due to atmospheric chemistry and its effect upon pollutants and biological contamination (Figure 2.1).

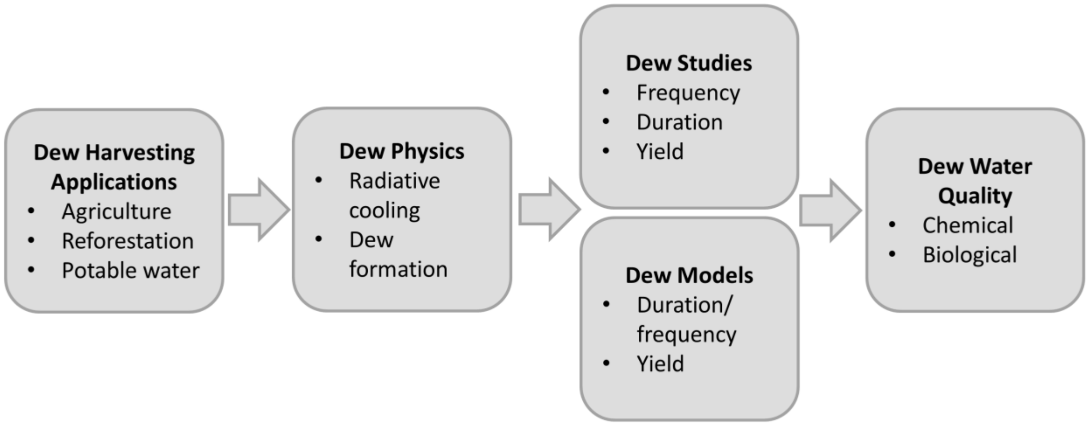

Figure 2.1. Framework of dew critical review

2.2. The Significance of Dew and Harvesting Applications

2.2.1. Terrestrial ecosystems

Dew can augment the water budget and enhance botanical and agricultural systems to varying extents. In desert ecosystems, dew often serves as a primary water resource for some types of biological soil crusts (Jia et al., 2014; Kidron et al., 2002; Zhang et al., 2009; Rao et al., 2009; Pan and Wang, 2014; Uclés et al., 2016), lichens (Kidron and Temina, 2013; del Prado and Sancho, 2007), and small shrubs (Pan et al., 2010; Pan and Wang, 2014) (Table 2.1) and also may trigger photosynthesis (Kidron et al., 2002; Rao et al., 2009; del Prado and Sancho 2007) and reproduction (Kidron et al., 2002). In agricultural and silvicultural systems, few researchers reported evapotranspiration can exceed precipitation and irrigation combined and concluded dew uptake makes up the deficit (Fritschen and Doraiswamy, 1973; Glenn et al., 1996; Malek et al., 1999). Hunt et al. (2008) reported dew and fog affects crop evapotranspiration based on measurements from lysimeters and Moratiel et al. (2013) suggested a simple method to correct soil moisture based on dew, fog, and mist effects. In addition, leaf pubescence (hairs), often present in plants in arid environments, can promote dew formation and storage while preventing its evaporation and reducing transpiration (Konrad et al., 2015).

On the other hand, in some climates evapotranspiration rates may be reduced in the morning during the dry season due to increased stomatal resistance of the plant (Ben-Asher et al., 2010). Therefore, instead of directly contributing to the water budget, dew may solely improve water use efficiency (Ben-Asher et al., 2010) and buffer against drought effects (Tuller and Chilton, 1973). Other studies further downplay the significance of dew, insofar to portray dew negatively due to its potential role in plant fungal disease (Agam and Berliner 2006). In addition, dew seldom forms upon bare soil (Agam and Berliner 2004) and thus may not enhance the plant water budget. Instead, any changes in soil moisture content may be due to absorption of water vapor (Ninari and Berliner 2002; Agam and Berliner 2004).

To date, limited research has been conducted on applying dew harvesting into irrigation, although several dew collection systems are available commercially. Alnaser and Barakat (2000) were the first to suggest coupling passive dew collection with a low-cost and little maintenance drip irrigation system, but no implementation was tested. More recently, a large conical dew harvesting prototype was utilized in West Africa; it was found to provide 50% of the water requirements for maize (Gabin, 2015). Another available system is a single-wall polypropylene tree shelter that demonstrated effective dew harvesting capabilities and an increase in soil moisture content (del Campo et al., 2006). A plastic greenhouse roof in India, although not an effective condenser, harvested 10 mm of dew over 7 months, with a nightly maximum of 0.36 mm (Sharan 2011).

2.2.2. Domestic Use

Thus far, most dew harvesting studies have been devoted to small pilot projects using artificial planar condensers, which are discussed in detail in Section 4. Based on the success of these projects, dew has been proposed as a supplementary water resource for domestic use in some locales. For this purpose, large dew condensers have been placed upon sloped roofs of buildings (Beysens et al., 2007; Sharan et al., 2007; Clus et al., 2013), terraces (Clus et al., 2013), or directly on the ground (Clus et al., 2013; Sharan et al., 2011). These systems are typically made of locally available materials (Table 2.2) and can collect rainwater in addition to dew. Such projects are best suited for developing regions with arid and semi-arid climates during the dry season. For example, in Morocco, a harvesting system collected 0.28 L m^{-2} d^{-1} of dew compared to 0.17 L m^{-2} d^{-1} of rainfall during the study period (12/2008 to 7/2009). In this example, to meet basic water requirements (50 L $capita^{-1}$ d^{-1}) (Gleick 1996), a 112 m^2 condenser would be required per person (collecting dew and rainfall). Although a condenser of this size is impractical, smaller condensers can supplement other water resources.

Furthermore, consideration must be taken when considering the condenser surface. A polyethylene (PE) foil in which radiative mineral particles are embedded can achieve greater radiative cooling and dew drop collection than other materials, thus resulting in higher dew yields, yet PE foils are delicate and have a limited life span (Clus et al., 2013; Sharan et al., 2011; Sharan, 2011; Muselli et al., 2002). On the other hand, galvanized iron (GI) is more durable but requires special painting to enhance radiative cooling and hydrophilic properties (Clus et al., 2013) and yields lower dew volumes (Sharan et al., 2007; Sharan, 2011). Limited studies have been conducted to assess the cost of a dew harvesting system compared to other water sources, but in India, a dew harvesting system costs ≈0.074 USD/L, whereas bottled water costs ≈0.22 USD/L (2010 prices) (Sharan et al., 2011).

The composition of dew water widely differs, more so than rainwater, even diurnally in the same location (Foster et al., 1990; Singh et al., 2006) due to varying factors (Section 2.6). Atmospheric pollutants including particles, microorganisms, heavy metals, and organic substances accumulate upon condensing surfaces and affect water quality during dew formation. Condensing surfaces such as galvanized iron may adversely affect heavy metal concentrations in dew. If collected dew is to be used for human consumption, periodic water quality testing and condenser surface cleaning become essential. Large dew condensers employed for domestic use may be impractical to clean; in such cases, the best method to prevent contaminants from reaching a storage tank may be to divert or flush initially harvested dew. Previous studies in rural water scarce regions, where dew is most likely to be considered, reported alkaline dew attributed to higher mineral content in the local environment nonetheless meeting WHO guidelines (Jiries, 2001; Lekouch et al., 2011; Kidron and Starinsky, 2012). The greatest concern is bacterial contamination, common in an open environment, particularly in the vicinity of livestock (Beysens et al., 2006b; Muselli et al., 2006b), but is easily treatable.

Table 2.1. Dew amounts and duration upon plants in desert ecosystems

Desert	*Country*	*Plant*	*Dominant Species*	*Period of study*	*Average dew amount (mm d^{-1})*	*Average dew duration (hr)*	*Reference*
Gurbantunggut	China	Biological soil crust	*Microcoleus vaginatus*	May, Sep, and Oct 2008	0.090	3.7	Zhang et al. (2009)
			Collema tenax		0.095	3.3	
			Tortula desertorum		0.125	3.4	
Tennger	China	Biological soil crust	*Bryum argenteum*	Jun – Oct 2010	0.115	-	Jia et al. (2014)
			Didymodon vinealis		0.130	-	
			Syntrichia caninervis		0.125	-	
Hopq	China	Biological soil crust	*Microcoleus vaginatus* and *Scytonema javanicum*	Aug - Oct 2007	0.062	-	Rao et al. (2009)
Negev	Israel	Biological soil crust	*Microcoleus* sp.	Apr and Nov 1992 and 1993	0.034[a]	1.0[b]	Kidron et al. (2002)
			Bryum dunense			1.8[b]	
		Lichens	Varying endolithic and epilithic	Summer and Fall 1992	0.320	4.5	Kidron and Temina (2013)
Tabernas	Spain	Lichen	*Teloschistes lacunosus*	Mar 1998 – Mar.1999	-	12.3	del Prado and Sancho (2007)
Tabernas	Spain	Biological soil crust	*Diploschistes diacapsis* and *Squamarina lentigera*	May – Jul 2012	0.09	3.6	Uclés et al. (2016)
(Shapotou	China	Small shrubs	*Artemisia ordosica*	Oct 2009	0.73	3.0[b]	Pan et al. (2010); Pan and Wang (2014)
			Caragana korshinskii		0.62	3.5[b]	

[a]Average dew amount for both species [b] Dew duration during daylight hours only

Table 2.2. Pilot dew harvesting studies for domestic use

Location	*Country*	*Condenser location*	*Condenser surface*	*Area (m^2)*	*Period of study*	*Total yield (L)*	*Total yield ($L\ m^{-2}$)*	*Average yield ($L\ m^{-2}\ d^{-1}$)*	*Reference*
Biševo	Croatia	Rooftop	Planar multi-wall alveolar PC	15	Apr - Oct 05	222	14.8	-	Beysens et al. (2007)
Kothara	India	Rooftop	GI	18	Oct 04 - May 05	113.5	6.3	0.09	Sharan et al. (2007)
Panandhro	India	Ground	Ridged plastic film	850	Jan - Nov 07	6,545	7.7	-	Sharan et al. (2011); Sharan (2011)
Suthari	India	Rooftop	GI	343	Feb - May 05 Oct – Dec 05 Jan – May 06 Oct – Dec 06	3,078	9.0	0.05	Sharan (2011)
Sayara	India	Rooftop	PETB	360	Nov 05 – May 06	3,622	10.1	0.11	Sharan (2011)
Idouassksou	Morocco	Rooftop	Painted GI	21.2	Dec 08 - Jul 09	1,898[a]	30.7[a]	0.22[a]	Clus et al. (2013)
		Terrace	Painted GI	40.6					
		Ground	UV treated white PE	73.8		1,897	25.7	0.19	

PC: polycarbonate; GI: Galvanized iron; PE: polyethylene; [a] Rooftop+Terrace; PETB: PE foil embedded with a mixture of TiO_2 and $BaSO_4$

2.3. Dew Physics

2.3.1. Radiative Cooling

Radiative cooling, or the passive process that permits a body to lose thermal heat, is essential for dew formation whereby a surface is capable of emitting (and receiving) thermal heat by interacting with the surrounding atmosphere. During the night, objects are able of cooling due to lack of heat gain from solar shortwave radiation and because the primary gases of the atmosphere (nitrogen and oxygen) are poor thermal emitters (Bliss, 1961). When dew forms on a condensing surface, the nocturnal net radiation balance (R_{net}) (Figure 2.2) includes the sensible heat exchange with the surrounding air (R_{he}), energy due to the latent heat of condensation (R_{cond}), and irradiation (R_{irr}) (Equation 2.1) (Nikolayev et al., 1996; Beysens et al., 2005). Due to natural and forced convection, the temperature of the condenser first cools from ambient air temperature (T_a) down to the dew point temperature (T_d) due to a loss of sensible heat; it further cools down to allow condensation as a result of the additional loss of sensible heat and latent heat (Awanou and Hazoume, 1996). Assuming the change in condenser temperature ($\mathrm{d}T_c/\mathrm{d}t$) is small, the energy balance can be simplified and described by Equation 2.2, where m_c and m_w are the masses of the working part of the condenser and condensed water, respectively, and C_c and C_w are the specific heats of the condenser material and water. Losses in sensible heat (R_{he}) consider the surface area of the condenser (S_c) and a heat transfer coefficient (a) with respect to the change in temperature (Equation 2.3) whereas losses in latent heat energy

(R_{cond}) factor in the latent heat of condensation (L_w) and the change in the mass of the condensed water ($\mathrm{d}m_w/\mathrm{d}t$) (Equation 2.4). Lastly, R_{irr} (Equation 2.5) can be subdivided into incoming long-wave irradiation (R_l) (Equation 2.6), which considers the radiative heat exchange between the condenser and the sky, and outgoing irradiation of the condenser (R_c) (Equation 2.7) (Nikolayev et al., 1996; Beysens et al., 2005) which are both based on the Stefan-Boltzmann law, where ε_c and ε_{sky} are emissivities of the condenser and the sky, respectively, and σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).

$$R_{net} = R_{\text{he}} + R_{\text{cond}} + R_{\text{irr}} \tag{2.1}$$

$$R_{net} = \frac{\mathrm{d}T_c}{\mathrm{d}t}(m_c C_c + m_w C_w) \tag{2.2}$$

$$R_{he} = aS_c(T_a - T_c) \tag{2.3}$$

$$R_{\text{cond}} = L_w \frac{\mathrm{d}m_w}{\mathrm{d}t} \tag{2.4}$$

$$R_{\text{irr}} = R_l - R_c \tag{2.5}$$

$$R_l = S_c \varepsilon_c \varepsilon_{\text{sky}} \sigma (T_c + 273)^4 \tag{2.6}$$

$$R_c = S_c \varepsilon_c \sigma (T_c + 273)^4 \tag{2.7}$$

Sky emissivity is a function of atmospheric conditions, zenith direction (Awanou, 1998), and altitude (Berger et al., 1992), whereby radiative cooling is maximized during low relative humidity under cloudless skies (Berdahl and Fromberg, 1982; Martin and Berdahl, 1984; Nilsson et al., 1994). A cold sky acts as a radiative sink from which passive cooling systems including dew harvesting can benefit. Clouds, water vapor, and other greenhouse gases absorb and re-emit longwave radiation (Kiehl and Trenberth, 1997), thus inhibiting cooling effects and increasing ε_{sky} above the clear sky value (Martin and Berdahl, 1984). Several studies (Martin and Berdahl, 1984; Berger et al., 1984, 1992; Melchor Centeno, 1982; Prata, 1996; Iziomon et al., 2003) have reported empirical procedures to approximate ε_{sky}.

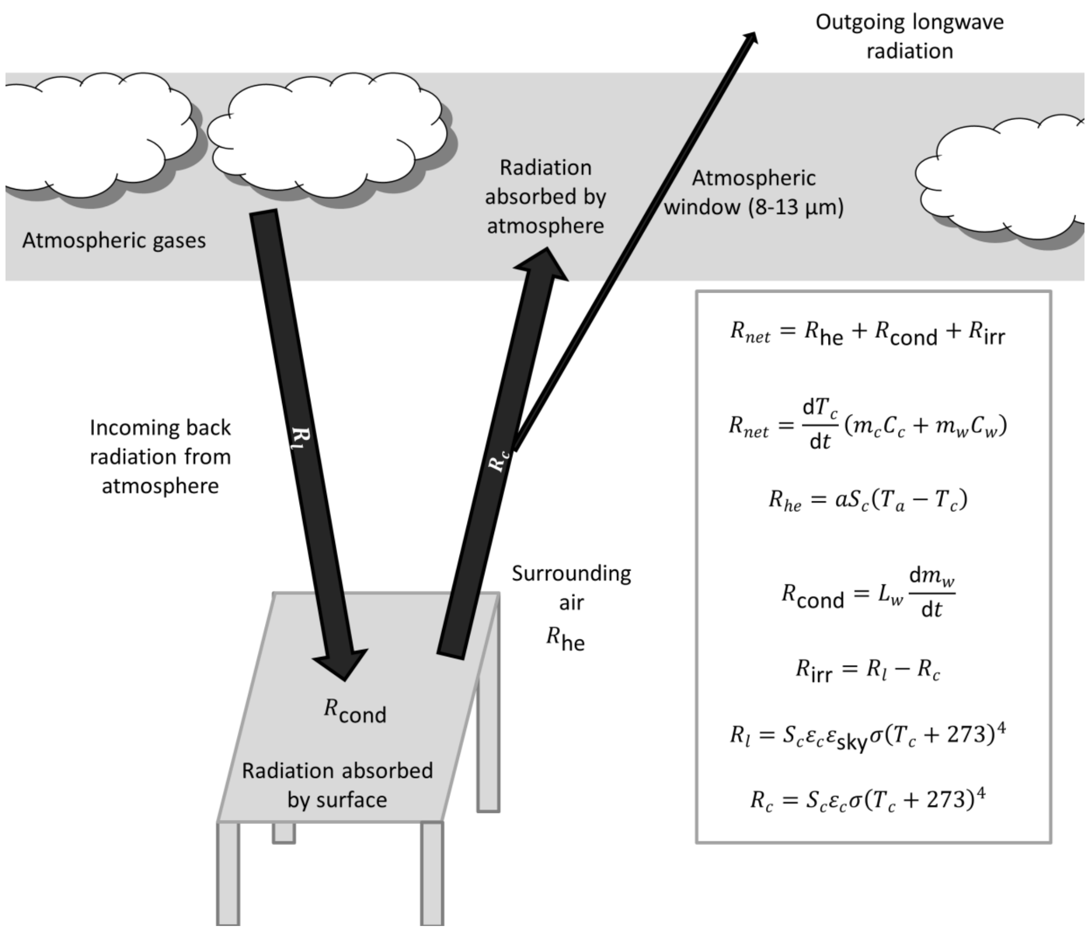

Figure 2.2. Net longwave radiation and radiative cooling of a surface allowing dew formation

The adverse effects of atmospheric conditions are minimized within the infrared band known as the atmospheric window (8–13 μm), where radiation can pass directly into space without intermediate absorption and re-emission. Surfaces known as selective radiators can exploit the atmospheric window by acting as near perfect emitters emulating a black body within this infrared band, whereas emissivity (ε) and absorption (α) are nearly equal to unity, and are weakly absorbing in other wavelengths ($\varepsilon \approx \alpha \approx 0$) facilitating potentially deeper radiative cooling of the surface (Bartoli et al., 1977; Catalonotti et al., 1975). Examples of selective radiators include polyethylene films (Bartoli et al., 1977; Catalonotti et al., 1975) and metal oxide pigments such as TiO_2 (Mastai et al., 2001).

2.3.2. Dew Formation

Dew formation is a phase transition from vapor to liquid, or condensation. Four physical processes, which can be repeated several times during a dew event, can describe formation process: heterogeneous nucleation, self-similar growth, renucleation, and droplet removal (Figure 2.3) (Beysens, 1995, 2006; Beysens et al., 1991; Meakin, 1992). This cycle is made possible provided certain atmospheric conditions are met. Dew generally forms upon a surface when its temperature cools below T_d, which is the saturation temperature of humid air at a constant pressure. Nocturnal radiative cooling promotes surface temperature drop (Beysens et al., 2003; Nikolayev et al., 1996; Nilsson, 1996), facilitated by clear skies (Nilsson, 1996; Hughes and Brimblecombe, 1994), dry air aloft (Hughes and Brimblecombe, 1994) and weak horizontal winds (Monteith, 1957; Beysens et al., 2003). In addition, dew formation is enabled through high humidity near the ground as well as some turbulent mixing bringing fresh moist air to the ground (Beysens et al., 2003; Hughes and Brimblecombe, 1994). The first stage of dew is nucleation of a stable (not evaporating) water micro-droplet (Beysens 1995, 2006). Nucleation in the bulk vapor (homogeneous nucleation) is the formation of a stable micro-droplet from thermally activated density fluctuations of the supersaturated vapor, that is, vapor at temperature below T_d. Nucleation requisites the formation of a liquid-vapor interface and thus crossing an energy barrier. When nucleation occurs on a substrate (heterogeneous nucleation), which is precisely the case of dew, it is favored as the geometry of the droplet and its wetting properties lower the barrier.

The wetting properties of water on a substrate can be characterized by the droplet contact angle θ (Figure 2.4), which varies between zero (purely hydrophilic substrate) and 180° (purely hydrophobic or superhydrophobic substrate). The latter corresponds to homogeneous nucleation and can be approximated on complex surfaces similar to Lotus leaf (see *e.g*. Quéré, 2005). Hydrophilic surfaces (θ <90°) favor dew formation because of a lower nucleation energy barrier (Varanasi et al., 2009), annihilating it for θ=0 where filmwise condensation occurs. In other cases where $\theta \neq 0$, dropwise condensation takes place. Hydrophilic surfaces are more advantageous for dew nucleation as the nucleation barrier is lowered, thus nucleation can proceed for smaller supersaturation, eventually at T_d itself for a purely hydrophilic substrate. Concerning dew, which forms in the open air, substrate imperfections and pollution by fatty acids lead to contact angles of typically 30°

(receding angle) to 70° (advancing angle) leading to privileged nucleation sites on geometrical and chemical defects. Note that dew can form at higher temperatures than the water dew point temperature on substrates like hydrogels or salts, where the dew point temperature is shifted (Beysens 1995, 2006).

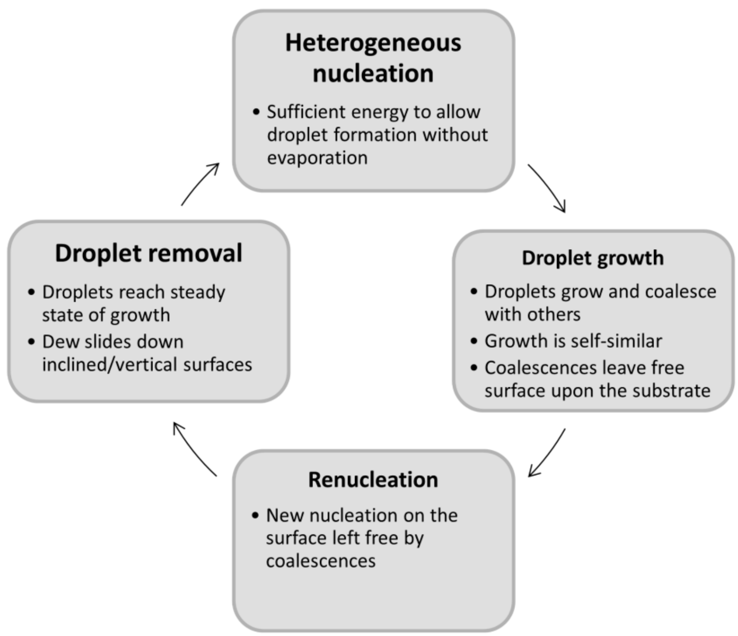

Figure 2.3. Dew formation process

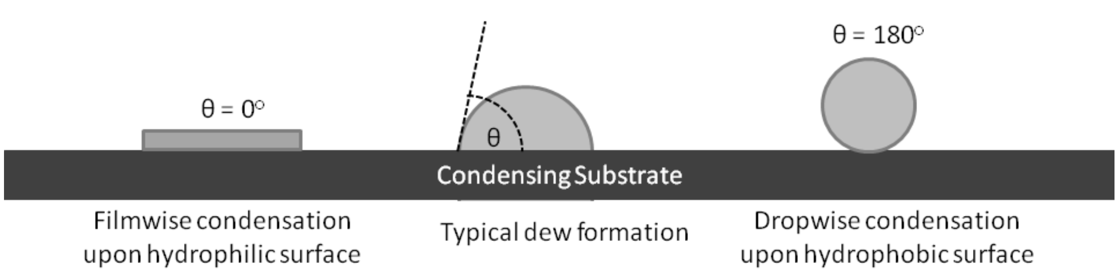

Figure 2.4. Wetting conditions for dew formation upon a substrate, defined by the contact angle θ (Adapted from Beysens 1995, 2006)

When dew forms, the latent heat has to be removed. Substrates can thus inhibit dew formation due to an inappropriate heat balance (Monteith, 1957). The entire process can slow or subside if the latent heat of condensation cannot be released which often observed with increased wind velocities that intensify heat exchange with surrounding warmer air (Beysens, 2006; Gandhidasan and Abualhamayel, 2005).

After successful formation of initial dew droplets, the latter grow due to the formation of a concentration gradient of water molecules around them and above the condensing substrate in a boundary layer where water molecules diffusion is more effective than humid air convection (Beysens, 1995, 2006; Beysens et al., 1991; Medici et al., 2014). The thickness of this boundary layer is generally for dew on the order of ~1 mm and is a function of wind, temperature difference, and shape (Medici et al., 2014). As droplets grow, they will eventually touch and coalesce with each other. This physical process is detailed in Beysens and Knobler (1986), Meakin (1992), Beysens (1995, 2006) and Medici et al. (2014). Mass and volume conservation is a key characteristic of coalescence and a new droplet is formed as a result. In this process, the surface wetted by the new droplet is smaller than the surface previously wetted by the parent droplets. The compensation between the increase of wet surface due to a single drop growth and the reduction due to coalescence give rise to a constant fraction of wet surface (droplet surface coverage) and as a result a self-similar growth with many universal features (Beysens and Knobler, 1986; Viovy et al., 1988). In particular, the distances between drops scale with their radius.

There is no renucleation between drops as long as the water vapor concentration gradient around them overlaps, that is, when the drop inter-distance remains of the order on the diffusion boundary layer (usually ~1 mm) (Guadarrama-Cetina et al., 2014b). Then renucleation occurs in gaps between drops upon the substrate (as well as in vacancies left by droplets were they are removed due to gravity effects) (Beysens, 1995, 2006; Beysens et al., 1991). These new droplet families exhibit the same growth laws as the original droplets and the surface coverage increases to a value near unity (Beysens, 1995).

On inclined or vertical substrates, drops can slide when they reach a critical size where their weight overcomes their pinning forces (Beysens et al., 1991; Medici et al., 2014). For usual substrates, this occurs for 0.3 mm drop size, meaning that smaller dew droplet cannot be collected although micropatterned substrates offer interesting possibilities (Lee et al., 2012). On a pure hydrophilic substrate, where a film forms, water to be collected has to be drained in the film. However, viscous forces prevent it to flow when it becomes very thin, meaning that in filmwise condensation also, some amount of water cannot be collected. Some solutions (Smith et al., 2013) have been proposed where dew drops condense on an oil film insoluble with water. Oil is trapped in a nano-micro patterned substrate. Drops can easily slide on the oil film. However, there is always some oil collected by the drops, which means that after some time the drop cannot slide anymore. In addition, there is always some oil that is found solubilized in water. Other solutions involve micropillars with hydrophilic head for nucleation, making drops rolling as if the contact angle was nearly 180° (Garrod et al., 2007). This solution mixing superhydrophobicity /

hydrophilicity is quite interesting but most probably confined at the laboratory scale because of costs, size and outdoor pollution and dust abrasion.

2.4. Dew Frequency, Duration, and Yield

The frequency and duration of dew events as well as resultant yield are dependent upon favorable atmospheric conditions and the condensing substrate properties and geometry. Such circumstances are not entirely restrictive, however, as it is generally accepted that dew is a recurrent phenomenon as evidenced by droplets upon car windshields and grass observed in the early morning hours. Dew events can occur approximately 200 nights per year (Zangvil, 1996) but harvesting episodes occur less frequently as not all droplets slide from gravity effects and are lost, resulting in approximately 120-180 nights annually which yield dew (Berkowicz et al., 2004, 2007; Beysens et al., 2005; Lekouch et al., 2011; Muselli et al., 2006a, 2009).

Dew duration is a function of radiative cooling and favorable weather conditions. Because passive radiative cooling is only viable at night, longer nights generally correlate with longer dew formation duration (Beysens et al., 2005; Butler, 1980), which often directly links to higher dew yields (Beysens et al., 2005). Dew ceases once the condenser gains radiative energy soon after dawn and the condensate evaporates (Beysens et al., 2005). To date, no universally accepted method of detecting dew and its duration has been established (Figure 2.5). Early studies employed filter paper, the Duvdevani dew block, the Hiltner dew balance, and other similar devices to quantify duration and yield which have been reviewed by Nagel (1962), Hutorowicz (1963), Ashbel (1949). Later studies introduced lysimeters and leaf wetness sensors, optical sensors (Zhu et al., 2014), and an electronic balance (Muselli et al., 2002). Because of dew droplet losses, measured duration is assumed to be longer than harvesting duration.

Similar to varying dew duration detection methods, no criterion has been set for dew harvesting. The proposed standard is a polyethylene (PE) foil with low IR emissivity embedded with a mixture of TiO_2 and $BaSO_4$ (PETB) radiative particles (Nilsson et al., 1994; Nilsson, 1996) and a food-proof water-immiscible surfactant to make the surface hydrophilic, now manufactured and available from OPUR[2]. Pigmented PE foils like PETB are selective radiators, which have properties that match the atmospheric window, promoting radiative cooling (Catalonotti et al., 1975; Bartoli et al., 1977). The addition of TiO_2 based pigment enhances the PE optical properties because it does not absorb radiation in either the visible or IR atmospheric window wavelength ranges, the material is highly stable, and it has a high refractive index suitable for solar scattering (Mastai et al., 2001). Because TiO_2 does not exhibit high emittance across the entire atmospheric window, a composite mixture is recommended to overcome this weakness, such as SiO_2/TiO_2 (Nilsson et al., 1994), TiO_2/ZnS (Orel et al., 1993), or $TiO_2/BaSO_4$, which demonstrated greatest radiative cooling effects (Orel et al., 1993; Nilsson et al., 1994).

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[2] International Organization for Dew Utilization (http://www.opur.fr/)

Although PETB is widely used for dew harvesting, it is less than ideal for practical applications. The material easily degrades due to UV from the sun (Bartoli et al., 1977; Ali et al., 1998), shortening its lifespan (~18 months) (Muselli et al., 2002) and is expensive (currently ≈10 USD/m^2). Other more durable materials have potential radiative cooling capabilities such as PTFE (polytetrafluoroethylene; commercial name: Teflon) (Clus et al., 2008; Takenaka et al., 2003), corrugated and plane alveolar polycarbonate (PC) (Beysens *et al.* 2007), and calcite and hematite deposited on glass (Vazquez et al., 2006), and black low density PE (LDPE) (Table 2.3), all of which have exhibited promise for dew harvesting. Widely used in agricultural applications, Maestre-Valero et al. (2011) obtained a 20% increase for large dew yields using black LDPE (low density polyethylene) compared to a concurrent study using PETB. The improved performance is most likely due to the thicker foil thickness because it correlates to an increase in its radiative properties (Ali et al., 1998). However, water yield becomes much less for lower dew yields because small droplets do not run off the surface.

Dew collection can occur in a wide range of climates provided requisite atmospheric conditions are met, thus eliminating some areas such as polar climates. Theoretically, the maximum nightly dew yield is 0.8 mm (Monteith, 1957; Beysens et al., 2006a) based upon the available cooling power within a given region (25-100 W m^{-2}) with respect to the latent heat of condensation (2.26 kJ g^{-1}); actual yields are less due to nuances in meteorological phenomena. It is difficult to ascertain which areas are best suited for dew harvesting due to the wide variability of condensing surfaces and condenser designs, and limited study periods. Experimental studies reveal coastal desert climates (Köppen climate classification: Bwh) are best suited for dew harvesting with average yields exceeding 0.1 mm and maximum yields greater than 0.5 mm (Table 2.4). These regions benefit from large diurnal temperature differential and high atmospheric moisture content from wind circulation over the sea.

Table 2.3. Spectrally selective materials and optical properties in 8-13 µm IR wavelength range

Material	*Thickness (mm)*	*Emissivity, ε*	*Source*
PETB	0.39	0.976	Maestre-Valero et al. (2011)
LDPE	0.15	0.976	
Corrugated PC	0.8	0.949	Beysens et al. (2007)
Plane alveolar PC	0.6	0.943	
PTFE	1.05	0.94	Clus et al. (2008)
Calcite	-	0.89	Danov et al. (2007)
Hematite	-	0.95	
Galvanized Iron	1.5	0.23-0.30	Sharan et al. (2007)

The highest reported dew yield to date (1.38 mm) was reported in India (Khare et al., 2000), located in a hot semi-arid climate (Köppen climate classification: Bsh). Although January (coinciding with the study period) is most favorable for dew formation in that region (Lakhani et al., 2012), the reported value may have also included rainfall. No other studies have been conducted in a similar climate for comparison.

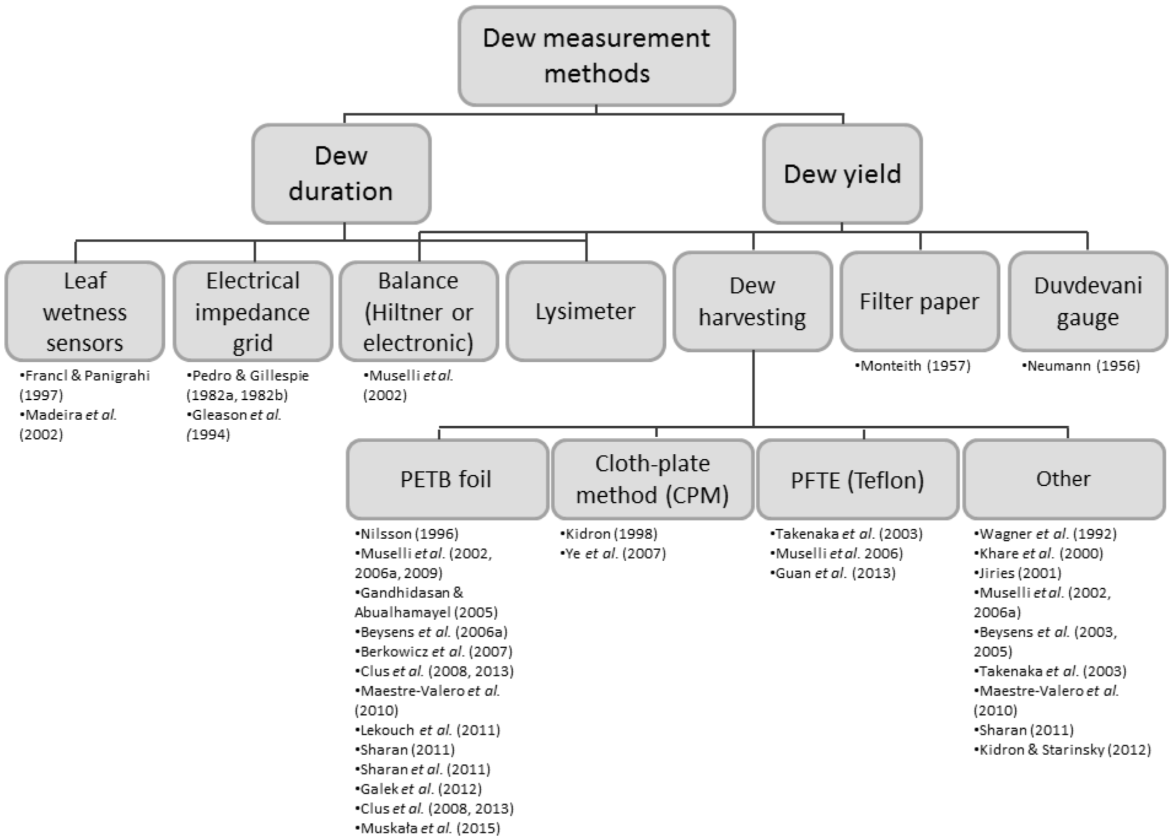

Figure 2.5. Dew measurement methods

Studies conducted in other areas vary widely, even within the same climate. For example, daily dew yield was reportedly high in Jerusalem (0.2 mm on average with a maximum of 0.6 mm), but relatively low in Zadar and Beirut (0.04 mm on average). It should be noted that all three locations are all within a semi-arid Mediterranean climate (Köppen climate classification: Csa/Csb) and studies used similar condensing surface, and covered the same seasons. Differences are likely due to microclimatic effects, which can be influenced by factors such as elevation, urban and rural landscapes, and distance to the sea. Jerusalem, Zadar, and Beirut are all within close proximity to the sea (< 100 km), but the elevation of Jerusalem (750 m asl) gives better atmospheric transmittance and then increases the radiative cooling energy. In addition, Jerusalem benefits from orographic lift resulting in a decrease in atmospheric pressure which causes humid air originating from the sea to expand and cool adiabatically to approach dew point temperature. Orographic effects have also benefitted continental locations such as Brive-la-Gaillarde (Beysens et al., 2006a) and southern Poland (Galek et al., 2012; Muskała et al., 2015), which have reported average and maximum yields within the same magnitude of coastal studies conducted in similar mesothermal climates (Table 2.4).

Table 2.4. Summary of studies using planar dew condensers

City	*Country*	*Climate*	*Lat*	*Long*	*Dist to sea (km)*	*Elev (m)*	*Material*	*Period of Study*	*No. of Days*	*No. of Dew Days*	*Ave Yield (mm)*	*Ann. Yield (mm)*	*Max Yield (mm)*	*Reference*
Cartegena	Spain	Bsk	37.69	-0.95	15	30	PETB	May 09 – May 10	365	175	0.105	17.4		Maestre-Valero et al. (2011)
							Black PE			163	0.128	20.8		
Ajaccio	France	Csa	41.92	8.80	0.4	70	PETB	Nov 00 – Dec 02	729	340	0.114[a]	38.8	0.368[a]	Muselli et al. (2002, 2006a)
							PMMA	Jan 01 – Jan 02	365	120	0.070	8.4	-	Beysens et al. (2005); Muselli et al. (2002, 2006a)
Grenoble		Dfc	45.18	5.70	225	215	PMMA	Jun 00 – Jun 01	365	109	0.036	4.0	-	Beysens et al. (2003, 2005)
Bordeaux		Cfb	44.80	-0.66	46	17	PMMA	Jan 2002 – Jan 2003	365	211	0.046	9.8	-	Beysens et al. (2005)
Brive-la-Gaillarde		Cfb	45.23	1.37	200	150	PETB	Jan 00 – Dec 00	365	231	0.115	31.6	0.45	Beysens et al. (2006a)
Kungsbacka	Sweden	Dfb	57.49	12.08	4	6	PETB	Aug 93 – Sep 93	19	-	0.145	-	0.207	Nilsson (1996)

City	*Country*	*Climate*	*Lat*	*Long*	*Dist to sea (km)*	*Elev (m)*	*Material*	*Period of Study*	*No. of Days*	*No. of Dew Days*	*Ave Yield (mm)*	*Ann. Yield (mm)*	*Max Yield (mm)*	*Reference*
Zadar	Croatia	Csa	44.13	15.22	0.2	5	PETB	Jul 03 – Oct 06	1,219	484	0.043	20	0.338	Muselli et al. (2009)
Komiža	Croatia	Csa	43.05	16.10	1	20	PETB	Jul 03 – Oct 06	1,219	263	0.090	9.3	0.486	
Wrocław	Poland	Dfb	51.12	17.03	355	120	PETB	Apr 09 and Sep 09	31	19	0.179	-	0.389	Galek et al. (2012)
Krakow	Poland	Cfb	50.05	19.89	470	270	PETB	May-Oct 09	183	79	0.110	-	0.360	Muskała et al. (2015)
Gaik-Brzezowa		Cfb	49.87	20.11	510	330	PETB		183	80	0.190	-	0.410	
Beirut	Lebanon	Csa	33.90	35.48	20	0.2	Clear PE	May-Nov 13	174	34	0.046	-	0.272	This study
							PETB	Apr-Oct 13	171	18	0.041		0.256	
Jerusalem	Israel	Csa	31.77	35.20	52	780	PETB	Jun 03 – May 06	1,096	554	0.199	39	0.6	Berkowicz et al. (2007)
Nitzana	Israel	Bwh	30.88	34.42	45	245	CPM	Sum/ Fall 92	-	36	0.09	-	-	Kidron (1999)
							Glass	Fall 2002	-	12	0.15	-	-	Kidron and Starinsky (2012)

City	*Country*	*Climate*	*Lat*	*Long*	*Dist to sea (km)*	*Elev (m)*	*Material*	*Period of Study*	*No. of Days*	*No. of Dew Days*	*Ave Yield (mm)*	*Ann. Yield (mm)*	*Max Yield (mm)*	*Reference*
Sde Boqer	Israel	Bwh	30.87	34.79	75	530	CPM	Sum/ Fall 92	-	34	0.18	-	-	Kidron (1999)
							Glass	Fall 02	-	29	0.21	-	-	Kidron and Starinsky (2012)
Har Harif	Israel	Bwh	30.49	34.55	97	900	CPM	Sum/ Fall 92	-	21	0.22	-	-	Kidron (1999)
Dhahan	Saudi Arabia	Bwh	26.3	50.1	7	30	PETB	Jan/Feb	-	-	0.22	-	-	Gandhidasan and Abualhamayel (2005)
Id Ouasskssou	Morocco	Bwh	29.57	-10.00	8	240	PETB	Jul 07 – Sep 07 Dec 08 – Jul 09	321	187	0.202	-	0.50	Lekouch et al. (2012); Clus et al. (2013)
Mirleft		Bwh	29.59	-10.04	2	43	PETB	May 07 – Apr 08	365	178	0.106	18.9	-	Lekouch et al. (2011, 2012)
Panandhro	India	Bwh	23.67	68.77	48	42	PETB	Oct 05 – Apr 06	192	69	0.189	-	0.566	Sharan et al. (2011)
Kothara		Bwh	23.23	68.75	20	21	Alumi-num	04-05	365	85	0.106	9.0	-	Sharan (2011)
							PETB		365	114	0.170	19.4	0.55	
							GI		365	115	0.136	15.6	-	

City	*Country*	*Climate*	*Lat*	*Long*	*Dist to sea (km)*	*Elev (m)*	*Material*	*Period of Study*	*No. of Days*	*No. of Dew Days*	*Ave Yield (mm)*	*Ann. Yield (mm)*	*Max Yield (mm)*	*Reference*
Dayalbagh		Bsh	27.17	78.08	20	21	PE	Jan 95 and Jan 96	-	-	0.592	-	1.38	Khare et al. (2000)
Guangzhou	China	Cfa	23.19	113.30	80	15	CPM	Aug-Nov	92	37	0.034	-	0.104	Ye et al. (2007)
			23.09	113.29	80	15	CPM	Aug-Nov	92	49	0.009		0.019	
Sakai City	Japan	Cfa	34.56	135.48	7	8	P. Alum[b]	Dec 96 and Dec 00	-	-	0.133	-	-	Takenaka et al. (2003)
							Glass		-	-	0.139	-	-	
							PTFE-SS[c]		-	-	0.092	-	-	
							PTFE-wall[d]		-	-	0.034	-	-	
Adelaide Hills	Australia	Cfa	-35.06	138.66	15	400	PTFE	Apr 09 – May 09	30	14	0.225	-	0.373	Guan et al. (2014)
Punaaui	French Polynesia	Af	-17.6	-149.6	1.3	97	PETB	May 05 – Oct 05	152	81	0.068	-	0.22	Clus et al. (2008)
Tikehau		Af	-14.1	-148.2	0.2	0.5	PETB	Jun 05 – Oct 05	109	26	0.102	-	0.23	

City	*Country*	*Climate*	*Lat*	*Long*	*Dist to sea (km)*	*Elev (m)*	*Material*	*Period of Study*	*No. of Days*	*No. of Dew Days*	*Ave Yield (mm)*	*Ann. Yield (mm)*	*Max Yield (mm)*	*Reference*
Fayetteville, AR	USA	Cfa	36.1	-94.2	715	390	PTFE-Alum[e]	Jul 89 – Jun 90	365	134	0.15	19.7	>0.2	Wagner et al. (1992)

[a] Dew yield from gravity and scraping condensing surface [b] Aluminum painted with car paint [c] PTFE coated stainless steel vat [d]PTFE foil over 15-cm high wall

[e] PTFE coated aluminum

Comparative studies reveal that rural environments have higher dew yield potential than urban locations, and can have a higher event frequency (Ye et al., 2007; Muskała et al., 2015). Urban areas have less nocturnal cooling capacity due to a reduction in sky view from obstructions such as buildings (Spronken-Smith and Oke, 1999). Urban heat island (UHI) effects can be pronounced from late afternoon to dawn resulting in higher nocturnal temperatures, particularly on clear nights with light winds (Kim and Baik, 2002; Gedzelman et al., 2003; Fortuniak et al., 2006). In addition, during warmer months, urban settings have lower relative humidity than nearby rural environments (Unkašević et al., 2001; Fortuniak et al., 2006). Small urban moisture excess (UME), correlated with UHI, can contribute to reduced dew yield (Richards, 2005). The development of UME is debatable, but can be attributed to increased evaporation in city environments which can inhibit condensation and anthropogenic sources of water vapor (combustion, traffic, households, and power plants) (Kuttler et al., 2007). Lastly, urban locations may be exposed to increased atmospheric pollution which inhibits atmospheric transmittance (Beysens et al., 2005).

Certain features of the condenser setup can enhance radiative cooling. The condenser shielded from terrestrial radiation can heat up the surface by placing insulation on the underside of the condensing apparatus (Nilsson, 1996). Protection from low layers of the atmosphere that scatter more infrared radiation than the zenith is suggested (Berger et al., 1992; Clus et al., 2009). While a horizontal planar condenser can maximize radiative cooling from the zenith, it can equally prevent the collection of dew droplets and as such the angle $\theta = 30^{\circ}$ to the horizontal is reportedly a good compromise (Beysens et al., 2003).

Lastly, condensers on natural ground may improve performance whereas manmade surfaces like rooftops can induce an urban heat island effect, inhibiting dew.

The simplest and most common design is a planar condenser (Figure 2.6a) although other innovative designs have been proposed to increase dew yield such as conical shapes or bi-conical forms (Kounouhewa and Awanou, 1999; Gabin, 2015) and demonstrated to have a superior performance (Berger et al., 1992) because of protection from wind and shielding from IR emission of the lower layers of atmosphere. Jacobs et al. (2008) constructed a simplified version of a cone using an inverted pyramid condenser (Figure 2.6b). Clus et al. (2009) used computational fluid dynamics to simulate results using various designs including a conical condenser (Figure 2.6c) and a multi-ridge condenser, both of which exhibited potentially superior performance over a planar standard condenser. A follow-up study (Beysens et al., 2013) showed that a multi-ridge condenser described as origami-shaped (Figure 2.6d) yielded 150 and 400% higher dew volume for large and smaller events, respectively due to the conjugation of hollow parts similar to cones and the effect of edges, where droplets grow faster and detach sooner (Medici et al., 2014) than in the planar regions, acting as natural wipers. These designs improved performance due to a combination of reduced wind effects (Beysens et al., 2013) and better view of the nighttime sky resulting in enhanced radiative cooling (Berger et al., 1992, Jacobs et al., 2008; Kounouhewa and Awanou, 1999).

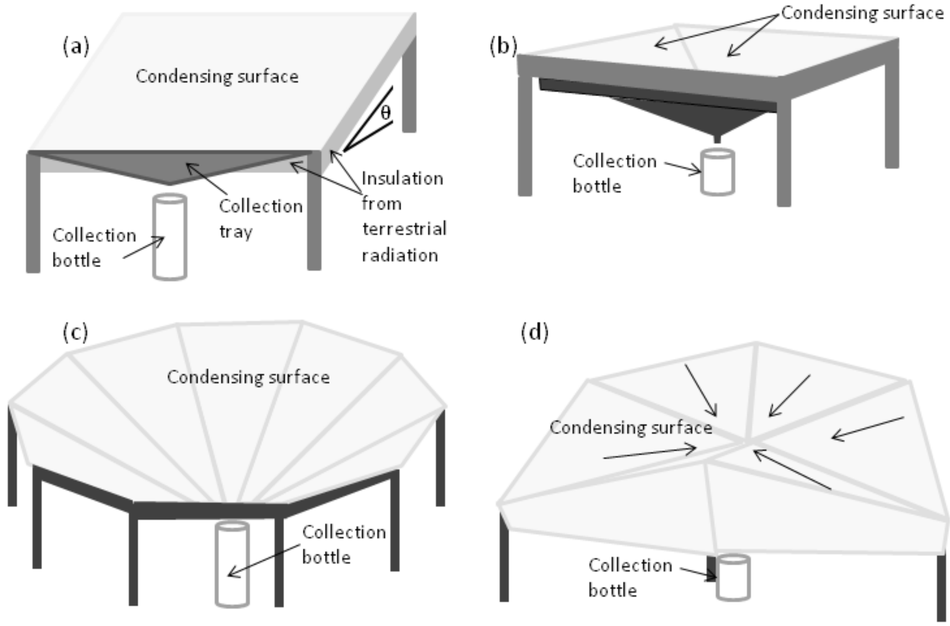

Figure 2.6. Various dew condensers: (a) standard planar (Nilsson, 1996), (b) inverted pyramid (Jacobs et al., 2008), (c) conical condenser (Clus et al., 2009), (d) origami-shaped (Beysens et al., 2013)

2.5. Dew Prediction Models

2.5.1. Dew Duration and Frequency

Increased understanding of plant disease and its direct link to leaf wetness recognized a need to forecast dew duration and frequency. Various means to predict duration have been proposed and can be broadly classified as empirical using regression or artificial intelligence (AI), and analytical (Figure 2.7 and Tables 2.5). Empirical models are based on simple relationships and are easy to use but can be highly site specific. Conversely, analytical models are based upon physical principles, such as an energy balance, and can be applied in different locales but with more complexity and often requiring data not readily available. Models which employ AI, such as fuzzy logic or neural networks (NN), are a relatively new research area in environmental sciences providing a methodology to encode inexact verbal instructions, such as a decision support system, to formulate a result, and/or to model nonlinear systems (Haupt et al., 2008).

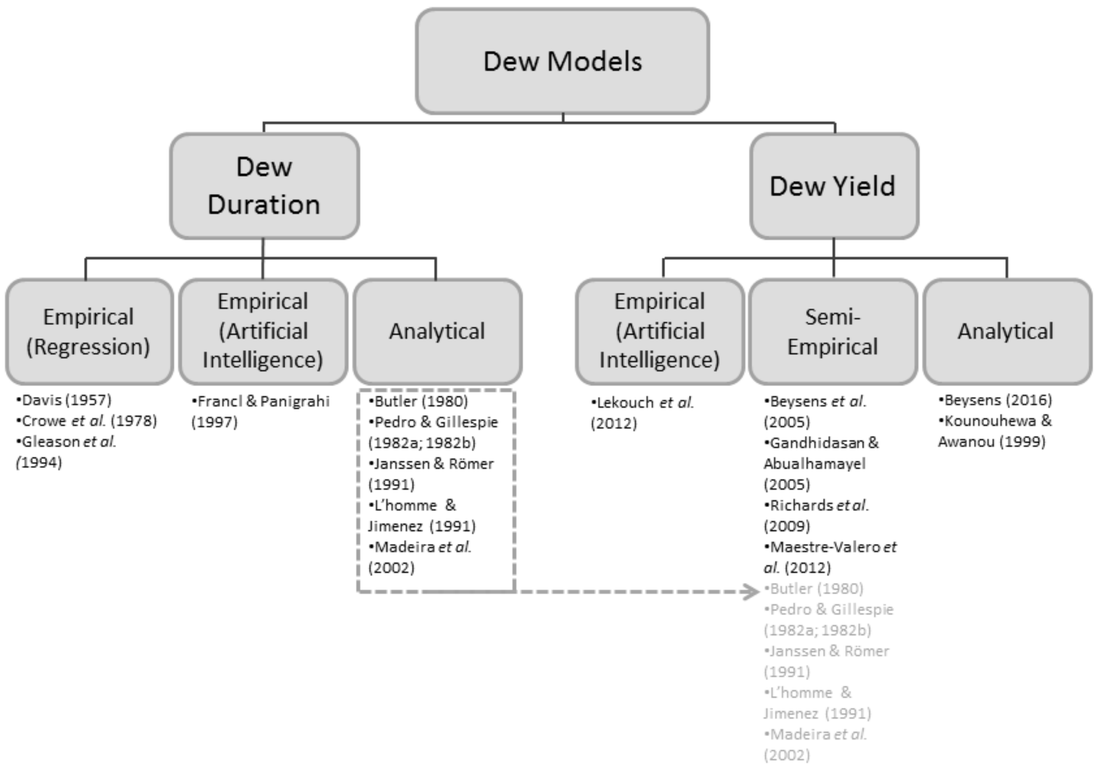

Figure 2.7. Dew modeling methods

Table 2.5. Summary of dew duration and yield models

Type	*Governing principles*	*Input parameters*	*Reference*
Duration	Nomogram	T_a, T_d, u, R_{net}	Davis (1957)
	Linear regression	$T_{a_{\min}}$, RH, u	Crowe et al. (1978)
	Classification and regression tree	T_a, T_d RH, u	Gleason et al. (1994)
	Artificial neural network	T_a, RH, y, r, LW, $S_\downarrow$	Francl and Panigrahi (1997)
	Energy balance	T_c, T_d, e_a, e_s	Butler (1980)
		T_a, T_c, u, P, e_a, e_s, $S_\downarrow$, $L_\downarrow$,a,α,ε_c	Pedro and Gillespie (1982a)
		T_a, u, CC, e_a, k	Pedro and Gillespie (1982b)
		T_a, RH, u, CC	Janssen and Römer (1991)
		T_a, RH, u, CC, $S_\downarrow$	L'homme and Jimenez (1992)
		T_a, T_c, T_{sky}, u, CC , $S_\downarrow$	Madeira et al. (2002)
Yield	Artificial neural network	T_a, RH, u	Lekouch et al. (2012)
	Energy balance	u, e_c, e_s g, K	Beysens et al. (2005)
		e_a, e_c g, K	Gandhidasan and Abualhamayel (2005)
		T_a, q_c, q_a, b_1, b_2	Richards et al. (2009)
		T_a, e_a, e_s, $L_\downarrow$, b_1, b_2, b_3, b_4,	Maestre-Valero et al. (2012)
		T_a, T_d, u, CC, z	Beysens (2016)
	Radiative properties of celestial fault	T_c, T_d, T_{sky}, ε_c	Kounouhewa and Awanou (1999)
	Fick's Law	T_a, T_c, T_d	

T_a	K	Ambient air temperature	e_a	kPa	Vapor pressure at T_a
T_c	K	Condenser surface temperature	e_c	kPa	Vapor pressure at T_c
T_d	K	Dew point temperature	e_s	kPa	Saturated vapor pressure
T_{sky}	K	Sky temperature	R_{net}	W m^{-2}	Net radiation
RH	%	Relative humidity	$S_{\downarrow}$	W m^{-2}	Incoming solar shortwave radiation
u	m s^{-1}	Wind speed	$L_{\downarrow}$	W m^{-2}	Downward longwave radiation
y	-	Wind direction	a	-	Absorptivity
P	kPa	Atmospheric pressure	α	-	Albedo
CC	oktas	Cloud cover	ε_c	-	Emissivity of condensing surface
r	mm	Precipitation	b_x	-	Empirical coefficients
LW	-	Leaf wetness	f	W K^{-1} m^{-2} $s^{1/2}$	Empirical numerical factor
z	km	Site elevation	g	-	Empirical mass exchange coefficient
q_a	g kg^{-1}	Specific humidity at T_a	k	-	Empirical cloud parameter
q_c	g kg^{-1}	Specific humidity at T_c	K	-	Empirical heat exchange coefficient

Early attempts at modeling dew duration employed empirical relationships. Davis (1957) developed a nomogram linking net radiation (R_{net}), dew point (T_d), and wind speed (u) to assess whether conditions are favorable or not for dew formation. Later, Crowe et al., (1978) used a multiple regression approach to define a relationship between relative humidity (RH), u, and minimum air temperature ($T_{a_{\min}}$) which was tested for a single location and performed better in estimating duration during dew events (R^2=0.92) than it did predicting frequency and duration (R^2=0.61). Gleason et al., (1994) improved upon empirical modeling by developing a classification and regression tree (CART) based on meteorological data (RH, T_a, and u), which was tested in 13 locations. This nonparametric classification procedure eliminated periods when dew was unlikely then applied a stepwise linear discriminant (SLD) analysis to classify dew events. Subsequent studies revealed conflicting performance of the CART model, whereby Francl and Panigrahi (1997) noted superior accuracy compared to other models although predicted onset of dew was about 1 hr earlier than actual, whereas Madeira et al. (2002) reported an average predicted duration inaccuracy of 1.6 hr.

Another effort to improve upon empirical models was proposed by Francl and Panigrahi (1997), who employed differing artificial neural networks (ANN) based on standard meteorological data to predict wheat leaf wetness due to precipitation or dew. Dew duration was accurate within ~1 hr with most errors placed during transition periods when condensation begins or ceases due to evaporation. Like other empirical efforts, the model was limited by site specificity and may result in large errors in differing climates by applying it to dew harvesting systems.

Analytical models have proven more popular, particularly since they could be extended beyond leaf wetness to dew harvesting applications. To date, dew duration analytical models have been based on the energy balance. The earliest model was proposed by Butler (1980), based on the heat balance of a cocoa pod (Monteith and Butler, 1979) and simple meteorological data. However, heat flux is not sufficient to accurately predict dew and thus a single layer energy balance model coupled with heat transfer theory was proposed by Pedro and Gillespie (1982b). Although accurate within 1 hr for differing temperate crop canopies, requisite data is difficult to obtain, prompting Pedro and Gillespie (1982a) to propose a simpler model based on an energy balance approach combined with standard meteorological data but sacrificing a level of accuracy (1.5 hr). The model was adapted for tropical crop canopies by L'homme and Jimenez (1992). Similarly, Janssen and Römer (1991) applied an energy balance using meteorological data with application to a dew plate instead of a leaf surface. Later work introduced two slightly different approaches to model the energy balance namely, sky temperature calculated from cloud cover and altitude, and apparent sky emissivity estimated from cloud cover data (Madeira et al., 2002). While the former method is more accurate (91% vs. 88%), cloud altitude data is frequently not readily available.

2.5.2. Dew Yield

Few studies targeted the development of models to predict dew yield (see Figure 2.7 and Table 2.5), particularly ones that are applicable in dew harvesting applications. Most models are semi-empirical (Beysens et al., 2005; Gandhidasan and Abualhamayel, 2005; Richards, 2009; Maestre-Valero et al., 2012) adopting an energy balance similar to analytical dew duration models (Butler 1980; Pedro and Gillespie,1982a, 1982b; Janssen and Römer, 1991; L'homme and Jimenez, 1992; Madeira et al., 2002). Duration models could also be applied to estimate yield, most notably the model presented by Pedro and Gillespie (1982a). In such cases, duration was estimated by only identifying whether dew was present. Yields were estimated by including a mass transfer coefficient.

The first models to explicitly estimate yield were proposed by Beysens et al. (2005) and Gandhidasan and Abualhamayel (2005). The two models are nearly identical and estimate incremental condensed dew ($\mathrm{d}m_w/\mathrm{d}t$) based on vapor pressure (e) differential and an empirical mass transfer coefficient (β). Because parameters such as condenser temperature (T_c) are unknown and dependent on localized conditions like cloud cover, $\mathrm{d}m_w/\mathrm{d}t$ must be estimated via an iterative process by coupling the model with the energy balance. The mass transfer coefficient is reliant on the relative position of the condenser as well as the particular air flow conditions surrounding it among other considerations. A methodology to estimate β for a planar condenser was reported with validity limited to no zero air flow or no natural convection (Beysens et al., 2005). The model was then validated using experimental data in 3 locations. On the other hand, the Gandhidasan and Abualhamayel (2005) model is not clear on how β was estimated and the model was validated only on one location with limited data. In addition, the model is heavily dependent on thermodynamic parameters and neglects key meteorological factors such as wind velocity. Application of the model presents challenges because the mass dew rate of condensation must be solved using an iterative solution for every time step. As such, verification of the model is weak with a tendency to underestimate dew yield.

The other two semi-empirical models (Richards, 2009; Maestre-Valero et al., 2012) are also based on an energy balance with reportedly higher accuracy (R^2>0.66) at the expense of more complexity. The model set forth by Richards was developed for a leaf surface as well as a shingle roof but it can be adopted for dew harvesting. Indirectly, it is dependent on the knowledge of downward and upward longwave radiation ($L_{\downarrow}$, and $L_{\uparrow}$, respectively), wind speed (u), specific humidity (q), condensing substrate and air temperature, and substrate characteristics (*i.e.* α and ε). The model requires an iterative solution to solve for dew yield. In addition, the model's input parameters can be difficult to obtain and potentially large computational errors can occur due to its complexity. For these reasons, Maestre-Valero et al. (2012) simplified the model and used a sensitivity analysis to eliminate parameters which had negligible effect. For both models, empirical coefficients can be estimated for specific conditions and can be optimized.

Lekouch et al. (2012) proposed a model which links condensation volume and simple meteorological parameters using an artificial neural network (ANN). Similar to other empirical models, the model input included T_c, longwave radiation (based on cloud cover), RH, and u. Instead of estimating dew at set intervals each night (for example, hourly), the meteorological data at 06:00 local time (approximately sunrise) was assumed typical for the entire night. This can overestimate dew because often relative humidity is highest in the early morning. The model performed well (R^2=0.85), but only two cities within the same climate were used to verify the model.

Analytical models to estimate dew yield have demonstrated developmental difficulties due to the complexity of thermal and radiative exchanges (Lekouch et al., 2012). Initial efforts presented two methods (Kounouhewa and Awanou,1999) tested using experimental data collected in 3 locations in Benin (West Africa) using a conical condenser: (a) based on the radiative properties of the celestial vault and utilized readily available meteorological data other than T_c, which can be difficult to estimate, with a tendency to perform better in hot and dry climates and (b) using Fick's Law which is complex, also dependent on T_c, and requires several details regarding condenser geometry that can induce error. The latter method was better applied in hot and humid climates. Most recently, Beysens (2016) developed a simpler model valid for planar condensers and dependent only on site elevation and meteorological data (CC, u, T_d, and T_a) with validation at 10 experimental locations. While this model is arguably the strongest dew prediction mechanism to date, it assumes black body condensing substrate when in actuality substrates are grey bodies (ε<1). In addition, applications of the model reveal a tendency to predict dew yield when no dew was collected, presumably because in the measurements a non-negligible fraction of dew remains on the condenser and evaporates at sunrise. For this reason, the model performs better when modeling yield on a cumulative basis.

2.6. Dew Water Quality

2.6.1. Chemical Contamination

Chemical contamination measured in dew water samples (Table 2.6) is influenced by the formation and dissolution of atmospheric aerosols and adsorption of atmospheric gases (Beysens et al., 2006b; Muselli et al., 2002 , 2006b; Lekouch et al., 2010; Singh et al., 2006; Wisniewski, 1982) as well as weather (Jiries, 2001; Blas et al., 2012), atmospheric mixing layer height (Blas et al., 2012), and contaminated deposits from evaporated dew or rain events (Wisniewski, 1982) but their synergetic effects are not fully understood (Figure 2.8). While dew is generally acidic from nitrogen oxides (NO_x), sulfur oxides (SO_x), and hydrogen acids, it can be neutralized by the abundance of atmospheric ammonia (Lakhani et al., 2012) and alkaline soil particles (Acker et al., 2008; Kidron and Starinsky, 2012; Lakhani et al., 2012; Wagner et al., 1992). Not surprisingly, dew chemistry varies widely in differing locales, but can also exhibit significant fluctuation diurnally at any location (Foster et al., 1990; Singh et al., 2006). In addition, dew chemistry tends to differ from rain chemistry because of formation processes in differing atmospheric layers (Jiries, 2001; Wagner et al., 1992) as well as the varying lengths of time of environmental exposure between dew and rain droplets (Beysens et al., 2006b).

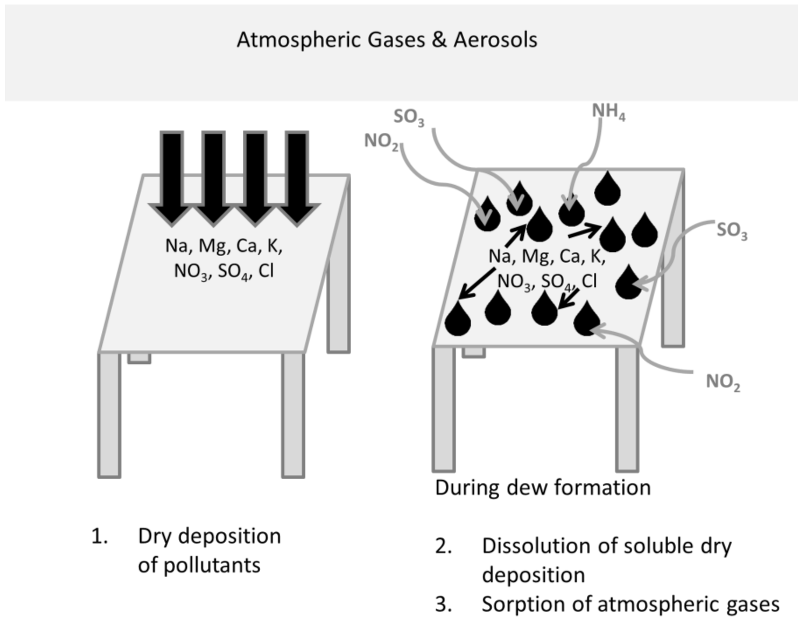

Figure 2.8. Primary processes which affect chemical contamination in dew

Table 2.6. Reported chemical contamination of dew

Country	*City*	*pH*	*EC (µS/cm)*	*Ca^{2+} (µeq/l)*	*Mg^{2+} (µeq/l)*	*Na^{+} (µeq/l)*	*K^{+} (µeq/l)*	*NH_4^{+} (µeq/l)*	*H^{+} (µeq/l)*	*Cl^{-} (µeq/l)*	*NO_3^{-} (µeq/l)*	*NO_2^{-} (µeq/l)*	*SO_4^{2-} (µeq/l)*	*Reference*
France	Bordeaux	6.3	29	73	30	157	10.5	-	1.4	156	45	9.3	78	Beysens et al. (2006b)
	Ajaccio	7.9	114	709	239	422	61	14	-	465	68	1.1	181	Muselli et al. (2002, 2006b)
Poland	Wroclaw	5.5	54	145	27	34	35	93	36	53	114	14	151	Gaiek et al. (2012); Polkowska et al. (2008)
	Szrenica Mt.	5.3	18	68	31	25	10	32	5	31	84	-	31	Blas et al. (2012)
	Krakow	5.2	-	174	56	43	19	31	-	37	167	-	87	Muskała et al. (2015)
	Gaik-Brzezowa	4.4	-	92	21	38	13	42	-	21	134	-	50	
Croatia	Zadar	6.7	195	1710	230	310	59	50	2.6	650	11	-	82	Lekouch et al. (2010)
Morocco	Mirleft	7.4	725	2,409	1,332	4,318	243	-	-	7,207	240	-	382	Lekouch et al. (2011)

Country	*City*	*pH*	*EC (µS/cm)*	*Ca^{2+} (µeq/l)*	*Mg^{2+} (µeq/l)*	*Na^{+} (µeq/l)*	*K^{+} (µeq/l)*	*NH_4^{+} (µeq/l)*	*H^{+} (µeq/l)*	*Cl^{-} (µeq/l)*	*NO_3^{-} (µeq/l)*	*NO_2^{-} (µeq/l)*	*SO_4^{2-} (µeq/l)*	*Reference*
Israel	Negev Desert	7.4	533	2,751	402	954	135	102	-	1,148	785	-	1,651	Kidron and Starinsky (2012)
Jordan	Amman	6.7	129	639	230	157	31	44	-	138	45	-	464	Jiries (2001)
India	Rampur	6.8	-	413	290	192	113	255	-	348	121	-	29	Singh et al. (2006)
India	Panandhro	4.7	230	-	-	-	-	-	-	1,608	-	-	1,666	Sharan et al. (2011); Sharan (2011)
	Sayara	7.2	520							1,608			625	Sharan (2011)
	Suthari	6.9	930							4,541			1,103	Sharan (2011)
	Satapar	6.9	230							903			354	Sharan (2011)
Japan	Yokohama	5.2	-	246	56	128	25	445	-	170	90	73	292	Okochi et al. (1996)
USA	Indianapolis, IN	6.8	-	37	8	4	8	34	-	6	25	4	8	Foster et al. (1990)

Country	*City*	*pH*	*EC (µS/cm)*	*Ca^{2+} (µeq/l)*	*Mg^{2+} (µeq/l)*	*Na^{+} (µeq/l)*	*K^{+} (µeq/l)*	*NH_4^{+} (µeq/l)*	*H^{+} (µeq/l)*	*Cl^{-} (µeq/l)*	*NO_3^{-} (µeq/l)*	*NO_2^{-} (µeq/l)*	*SO_4^{2-} (µeq/l)*	*Reference*
USA	Warren, MI	6.5	-	690	31	20	4	65	-	106	166	-	242	Mulawa et al. (1986)
	Glendora, CA	4.7	-	32	6	40	-	165	18	53	86	15	38	Pierson et al. (1988); Pierson and Brachaczek (1990)
	Allegheny, PA	4.0	-	-	-	-	-	8	91	5	32	0.7	73	Pierson et al. (1986)
	Fayetteville, AR	6.4	-	115	11	8	9	94	0.4	11	38[a]		66	Wagner et al. (1992)
Chile	Santiago	6.4	-	392	45	75	63	384	-	133	110	260	350	Rubio et al. (2002, 2008)

[a] $NO_3^{-} + NO_2$

Atmospheric pollutants originate from both natural and anthropogenic sources and can be in the form of gaseous ions (*e.g.* NH_4^+, NO_2^-, SO_3^{2-}) or particulate aerosols (*e.g.* Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, NO_3^-, SO_4^{2-}). Gravity and other effects cause dry deposition of aerosols onto solid surfaces. When dew forms upon these surfaces, the soluble components are dissolved by the droplets which subsequently react to form new substances (Wagner et al., 1992). In addition, gases are adsorbed into the dew which can equally induce chemical reactions with various products (Okochi et al., 1996; Mulawa et al., 1986; Acker et al., 2008).

Conflicting reasons have been reported to explain why pollutant concentrations can vary daily. Higher ionic concentrations tend to ensue during the dry season when volumes are low and dew is not diluted (Foster et al., 1990; Beysens et al., 2006b; Lekouch et al., 2010) and aerosols are not removed by rainfall (Jiries, 2001). In contrast, Takenaka et al. (2003) reported that pollutant concentrations from aerosols are independent of volume and only vary in the case of gaseous ions. Other studies contend that the ionic content is largely a reflection of the local environment (Acker et al., 2008; Beysens et al., 2006b; Lekouch et al., 2010) although Blas et al. (2012) points out that pollutants are more efficiently transported under anticyclonic unstable conditions enabling dew to be an indicator of long-range transport phenomena.

Concentrations of atmospheric aerosols and gases in dew affect its acidity, which can have adverse impacts on the environment and infrastructure like acid rain. Among the ions which contribute toward acidity, nitrates (NO_3^-) and nitrites (NO_2^-) have gained more attention in dew chemistry literature. Nitric acid in dew is primarily from HNO_3 vapor, which photochemically forms during the day (Chang et al. 1987), as well as dry HNO_3, NO_3^- and N_2O_5 aerosols (Chang et al., 1987; Chameides, 1987; Pierson et al., 1988). Similarly, the dissolution of HNO_2 gases and aerosols can react to form nitrous acid in dew (Acker et al., 2008; Zuo et al., 2006). Both are problematic under early morning sunlight irradiation, as they can be a source of hydroxyl radicals (OH) (Acker et al., 2008; Rubio et al., 2002; Zuo et al., 2006) potentially contributing toward smog in cities (Rubio et al., 2002). Although both are associated with health risks when ingested, nitrite concentrations in dew water samples have exceeded international standards (WHO, 2011) in many highly urbanized cities such as Yokohama (Okochi et al., 1996) and Santiago (Rubio et al., 2002, 2008) and surpassed NO_2^- concentrations in rainwater (Beysens et al., 2006b; Rubio et al., 2002). Elevated air pollution levels in large cities is largely due to vehicle-induced emissions and heavy industry often compounded with geographic effects when cities are surrounded by mountainous terrain such as the case of Santiago and Los Angeles.

2.6.2. Biological Contamination

While dew is expected to exhibit similar trends that affect biological contamination in harvested rainwater, limited efforts targeted its characterization in this context. Contaminants may derive from direct deposition by birds and small mammals, atmospheric deposition of airborne microbes (Beysens et al., 2006b; Muselli et al., 2006b; Lekouch et al., 2011; Evans et al., 2006), decay of accumulated organic debris and chemical pollutants (Evans et al. 2006). Evidence of harmful bacteria such as fecal coliforms or *E. Coli* has also been detected in dew samples (Beysens et al., 2006b; Muselli et al., 2006b). It is likely such contamination derived from the presence of birds, small animals, insects or simply human contact which is generally inevitable because dew condensers must be placed in an open environment. Biological contamination from heterotrophic bacteria originating naturally from the atmosphere is generally harmless when ingested but local conditions may influence the degree of contamination and potential risk. For example, elevated heterotrophic plate counts (HPC) in harvested rainwater was directly correlated with increased wind velocity and consequent greater uplift of organisms from sources and deposition thereof upon collection surfaces (Evans et al., 2006). Also, extended periods between dew events may cause increased biological contamination due to higher potential for deposition upon collection surfaces (Yaziz et al., 1989). Fortunately, prolonged sun illumination may result in UV-irradiated dew condenser surfaces, thereby reducing bacterial count and susceptibility to contamination (Lekouch et al., 2011). Irrespective, where dew water is potentially intended for human consumption, disinfection is imperative.

2.7. Existing Gaps and Future Needs

Although dew harvesting has exhibited promise as a viable non-conventional water resource, there remain several gaps in research which hinder the unrealized potential of dew. Areas of study include surface properties and geometry of dew condensers, meteorology, and dew and atmospheric chemistry (Figure 2.9).

With increased understanding of dew physics and formation processes, improved dew yield through condensing substrates with deeper radiative cooling potential may be introduced. Such substrates may even allow dew formation during the day although the large difference between air and dew point temperature is a challenging shortcoming to overcome. Novel condensing substrates have exhibited potential such as cactus spines and their microstructures (Malik et al., 2015) and nanomaterials which emulate tenebrionind beetles (Guadarrama-Cetina et al., 2014a). Cooling of condensing substrates using an active system may also be achievable. To date, such systems have been introduced to a limited extent using ice bricks (Guan et al. 2014), a solar chimney (Kashiwa and Kashiwa, 2006), and an integrated desiccant and solar collector system (Gad et al., 2001).

Increased yield may also be attained using innovative condenser geometric configurations like Berger et al. (1992), Jacobs et al. (2008), Kounouhewa and Awanou (1999) and Beysens et al. (2013). These systems can increase surface area without utilizing more space on the ground or require less energy to cool down. Expanding dew harvesting research into practical applications is a natural evolution specifically for potable water in rural communities as well as sustainable irrigation, which can be potentially achieved by placing or integrating condensers on rooftop or marginal landscapes.

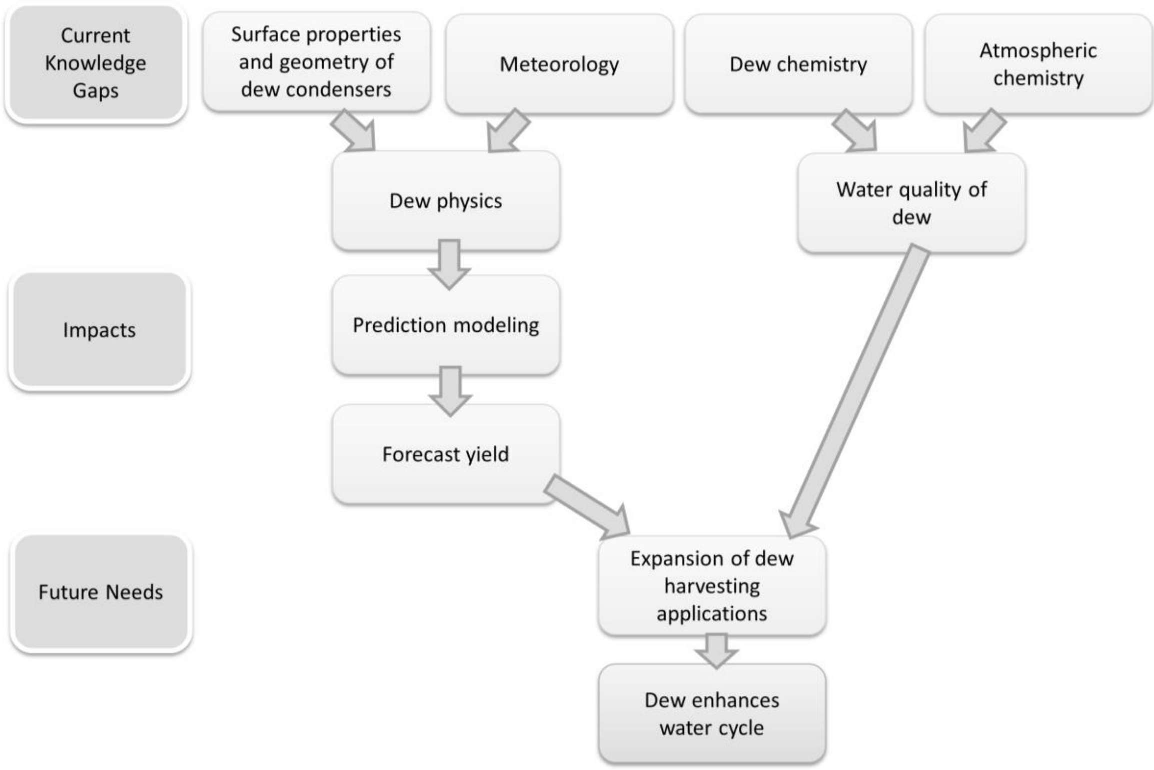

Figure 2.9. Future trends in dew harvesting research

To date, few models have been developed to forecast dew events under favorable atmospheric conditions, actual yield remains difficult to predict. Despite reported successful performance, empirical models are location specific and not applicable at other locations or even differing site conditions. While analytical models have reportedly been applied in differing environments, they are subject to high uncertainties due to variances in condensing surfaces and geometry, meteorological conditions, and other factors such input data and intensive iterative calculation process. The challenge is to develop an improved and user-friendly mechanistic model which can forecast yield and help facilitate dew harvesting applications which can be reached enhancing the understanding of dew physics. The model can then be applied to develop a global dew atlas to help identify which areas are best suited for dew harvesting.

The chemical and biological composition of dew is dependent upon local air quality. While contamination does not present a serious constraint (with the exception of nitrates in urban environments), air quality impacts on dew are not well understood. Increased understanding of atmospheric chemistry and reduced emissions can result in improved dew (as well as fog and rainwater) quality. Biological contamination may be inevitable in a natural environment, but a collection system can be integrated with an automated disinfection system to eliminate bacteria.

An integrated framework which considers all the factors can help expand the utilization of dew. Potential applications include agricultural and afforestation/reforestation irrigation and domestic use including drinking water. Thus far, such purposes have been performed to a limited extent but can be expanded as adaptation measures for projected climate change. Through improvements in research, dew can be forecasted, dew yield will increase, and quality will improve, thereby increasing awareness and use. The result will enhance the contribution of dew to the water cycle.

CHAPTER 3

DEW HARVESTING IN LEBANON

Alternative water resources such as dew represent a relatively untapped component of the water budget due to its perceived minor contribution and limited data availability. Such events occur naturally and frequently resulting in small, yet potentially significant yields, particularly during dry seasons of semi-arid regions like the Mediterranean when rainfall is nil and conventional water resources are scarce. We present results from different microclimates of the eastern Mediterranean and distinguish between dew surface wetness and dew harvesting durations. We show stronger correlation between dew yield and dew harvesting (compared to surface wetness) duration, and show limited correlation between the surface wetness and harvesting durations, indicating that harvesting duration is a better predictor of yield. We further analyze the impacts of microclimates upon dew harvesting as well as duration. Results show that the best suited regions in the eastern Mediterranean for dew collection are elevated, rural, and areas running parallel to the coastline due to maritime influences, increased nocturnal cooling potential, and orographic lift resulting in high yields (> 0.1 mm d^{-1}) and event frequency (> 50%) during the dry season (April-October).

3.1. Introduction

Dew harvesting has demonstrated promise as a viable non-conventional water resource, particularly during the dry season in arid and semi-arid regions when traditional water resources are scarce. Dew forms when atmospheric moisture condenses onto radiatively cooled terrestrial surfaces, typically occurring during nights when relative humidity is high, skies are clear, and winds are light. Pilot studies in the semi-arid Mediterranean have revealed that on average, dew yield is 0.14 mm d^{-1}, occurring 40-50% of nights annually with higher yields during the dry season (Muselli et al., 2009). Generally, the maximum dew yield in the region is approximately 0.35 mm d^{-1} (Beysens et al., 2005; Muselli et al., 2009), but experimental data has revealed measurements as high as 0.6 mm d^{-1} in Jerusalem (Berkowicz et al., 2007). This is particularly significant because these regions often receive zero rainfall during extended periods during the warmest months. In addition, passive dew harvesting requires no external energy and condensers can be built using locally-available materials with little cost.

The eastern Mediterranean region is characterized by complex climatological variability due to proximity to the sea, terrain, geography, and atmospheric circulation (Xoplacki et al., 2003). During summer, the region is representative of a dry subtropical climate with warm to hot temperatures, drought conditions, and a strong soil moisture deficit due to high pressure extending from the Azores and North Africa coupled with low pressure originating from the South Asia Monsoon (Zangvil, 1996; Xoplacki et al., 2003). Localized areas within the Mediterranean are affected by differing microclimates due to varying orography, vegetation, soil type, and surface albedo (Geiger et al., 1995). These factors can significantly vary dew yield, duration, and frequency even within a small geographic area. In fact, several studies have conducted concurrent dew harvesting campaigns in differing locales (*e.g.* Beysens et al., 2005; Muselli et al., 2009; Hanisch et al., 2015), but few have evaluated microclimate effects upon dew yield and duration. Scherm and van Bruggen (1993) evaluated dew frequency and duration within a crop canopy during the dry season and found dew exhibited similar behavior within coastal sites compared to interior valley sites. Similarly, Gilead and Rosenan (1954) discovered dew patterns fluctuated between coastal, interior, and hill sites.

Because dew quantities are highly sensitive to differing conditions, yield is difficult to forecast. Some researchers have noted a correlation between yield and surface wetness duration (SWD) (*e.g.* Uclés et al., 2015; Kabela et al., 2009), which is defined by the presence of droplets upon a surface due to condensation, thereby suggesting a sound method to estimate dew amounts. SWD is also the period where a condensing surface temperature (T_c) is below the ambient dew point temperature (T_d) (Beysens et al., 2005). This study aims to further investigate local climatic effects upon dew with focus on dew yield and dew harvesting duration comparing multiple sites within a small area in the eastern Mediterranean. We differentiated harvesting duration from dew surface wetness duration and show that the former is a better predictor of dew yield.

3.2. Experimental Methods

Seven site locations (Figure 3.1/Table 3.1) were selected based on differing microclimates, accessibility, and security. One planar dew condenser (1 m^2) was installed at each site (Figure 3.2a). The condensing surface for the first year of study (2013) consisted of clear low density polyethylene (LDPE), which is widely available and has an approximate emissivity >0.9 (Maestre-Valero et al., 2011). The following year the condensing surface was changed to a polyethylene foil embedded with TiO_2 and $BaSO_4$ microspheres (PETB), specifically manufactured for dew harvesting (Nilsson et al., 1994; Nilsson, 1996) and currently manufactured by OPUR (www.opur.u-bordeaux.fr), which also has an emissivity >0.9 in the infrared (Nilsson, 1994; Maestre-Valero et al., 2011). The condenser was located 1 m above ground and was shielded from terrestrial radiation by 30 mm thick Styrofoam. Each condenser was oriented in the same direction as the dominant nocturnal wind at each location and was tilted 30^0 to the horizontal (Beysens et al., 2003).

A weather station (Decagon Devices) was co-located at each location, with the exception of Bchatfine and Beirut (Figure 3.2a). The following parameters were recorded in 5-minute intervals: wind speed (u), and direction, relative humidity (RH), air temperature (T_a), rainfall ($\pm$ 0.2 mm), and dew yield (h). The wind speed anemometer measured at a height of 1 m above ground, corresponding to the condenser height. In addition, a leaf wetness sensor was placed at Beiteddine to measure surface wetness duration (SWD). Dew yield was continuously measured without scraping using a tipping bucket rainfall gauge. Every bucket tip is 4.5 ml; thus error is approximately

$\pm$ 0.0045 mm. Nightly dew was collected without scraping during the dry season in 2013 and 2014. In case of non-automated dew data collection (Bchatfine and Beirut), dew was collected in a bottle and measured manually shortly after sunrise when conditions for dew formation have ceased. Nocturnal weather conditions were averaged from 21:00pm-05:00am and total dew yield was reported based on results from the previous night. Site visits were conducted approximately monthly for equipment maintenance and data download.

Because weather data was not measured at Beirut, hourly data was obtained for the Beirut Airport, located about 9 km south of the Beirut experimental site located in the campus of the American University of Beirut, using the National Climatic Data Center (NCDC) Climate Data Online (2014). Similarly, meteorological data was not measured at Bchatfine. Instead, meteorological conditions (T_a, RH, u) at Bchatfine were estimated based on neighboring weather stations using ordinary cokriging coupled with terrain data, commonly used to obtain meteorological conditions at unmeasured locations (*e.g*. Apaydin et al., 2011 ; de Carvalho et al., 2010; Benavides et al., 2007)

Secondarily, a fog harvesting station (1 m^2) was co-located with the dew harvesting and weather station at Barouk (Figure 3.2b) similar to the collector described by Schmenauer and Cereceda (1994) which includes a double layer panel of Raschel mesh, typically used for manufacturing potato sacks. A rainfall gauge was also used to measure harvested fog water ($\pm$ 0.0045 mm). The fog collector was located 1 m above the ground.

With respect to climate and site characteristics, all sites were located in Lebanon, along the eastern Mediterranean (Figure 3.1). The area is characterized by a semi-arid climate (Köppen climate classification: Csa) typical of the region. Although the entire country is generally close to the sea (< 100 km) and similar latitude, it has a wide mosaic of microclimates due to two mountain ranges, along the spine and along the eastern boundary, which run the length of the country. The coastal region is adjacent to the sea and continues inland to approximately 700 m in elevation and is characteristic of a maritime climate. The western mid-mountain territory (700-1,400 m) is also subjected to maritime influences but receives cooler temperatures due to higher elevations. This area also is influenced by orographic lift which can carry warm humid air until it reaches saturation, bringing frequent precipitation and fog to the high mountain region (> 1,400 m). Between the two mountain ranges is an island valley plateau which has continental characteristics including lower relative humidity (< 60%) and large diurnal temperature variations.

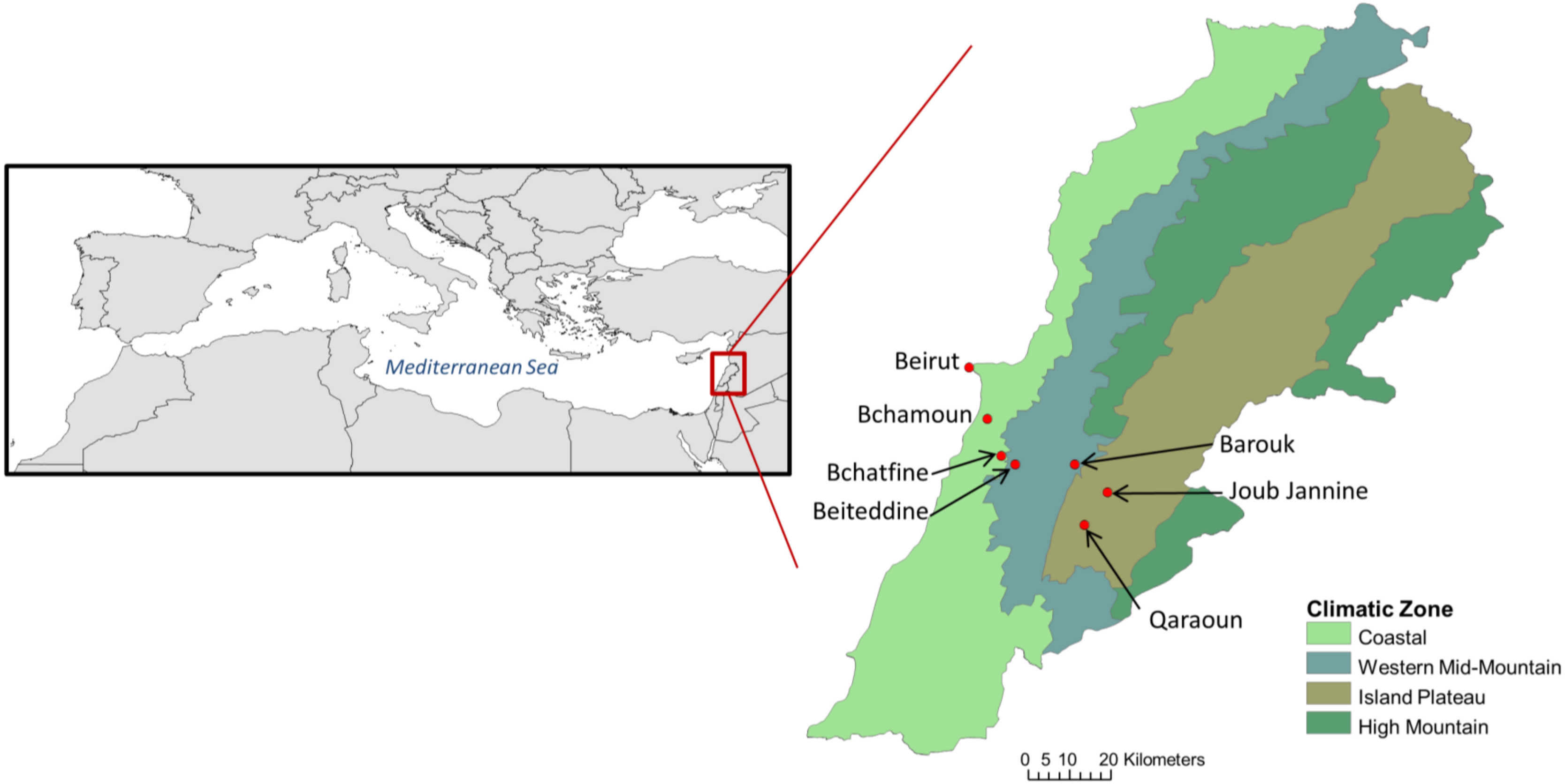

Figure 3.1. Map of Lebanon, meso-climatic zones, and study site locations

Table 3.1. Experimental site locations and climates during study period (2013 and 2014)

Site name	*Location*	*Elev (m)*	*Local climate*	*Average nocturnal conditions (April-October)*		
				T_a (°C)	*RH (%)*	*u (m s⁻¹)*
Beirut	33⁰ 49' N, 35⁰ 29' E	20	Coastal urban maritime	23.8	68	2.8
Bchamoun	33⁰ 47' N, 35⁰ 31' E	350	Coastal residential upland maritime	20.6	78	0.1
Bchatfine	33⁰ 42' N, 35⁰ 33' E	500	Western mid-mountain residential valley maritime	21.1	74	1.0
Beiteddine	33⁰ 41' N, 35⁰ 34' E	920	Western mid-mountain residential upland maritime	17.7	67	0.1
Barouk	33⁰ 41' N, 35⁰ 42' E	1,720	High mountain forest maritime	13.4	51	1.2
Joub Jannine	33⁰ 37' N, 35⁰ 46' E	920	Island valley plateau residential continental	18.7	52	0.3
Qaraoun	33⁰ 33' N, 35⁰ 43' E	1,150	Island valley plateau hilltop continental	18.0	47	1.2

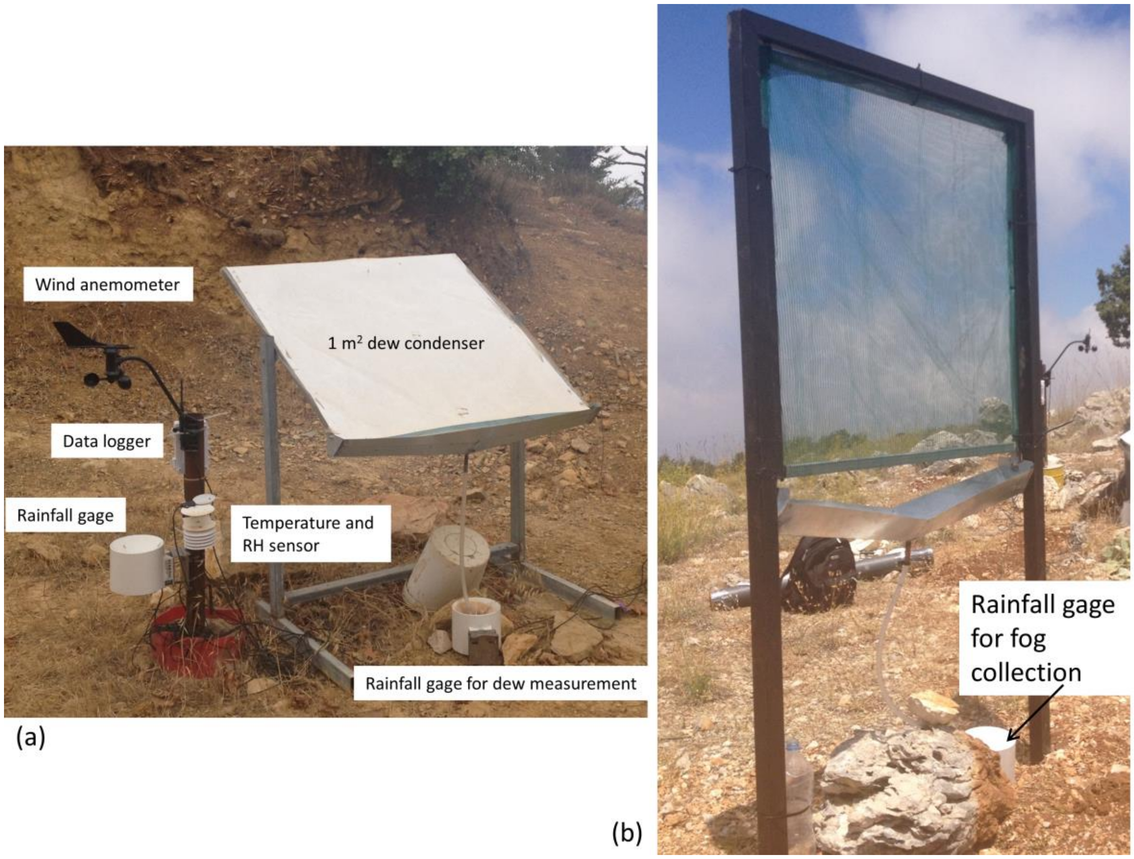

Figure 3.2. (a) Typical dew harvesting station; and (b) Fog harvesting station

3.3. Results and Discussion

3.3.1. General Dew Data

The average dew yield in the seven experimental sites for the years 2013 and 2014 are summarized in Tables 3.2 and 3.3, respectively. Results show that dew yields are generally higher than elsewhere in the Mediterranean, where nightly average measurements are 0.043, 0.090, and 0.070 mm d^{-1} in Zadar (Croatia), Komiža (Croatia), and Ajaccio (France), respectively (Muselli et al., 2009; Beysens et al., 2005). However, nightly maxima in the study area (ranging from 0.13 to 0.46 mm d^{-1}) are normally less than other Mediterranean locations (ranging between 0.34 in Zadar to 0.60 mm d^{-1} in Jerusalem) (Muselli et al., 2009; Berkowicz et al., 2007). The frequency of dew events vary widely in Lebanon (11-51% per collection season) and locations with the highest frequency (*i.e.* Bchamoun and Beiteddine) do not necessarily correlate with the highest measured yields compared to other locations within the study area (during the period of study). However, all locations revealed that as average nightly yield increases, the maximum yield correspondingly increases.

Critical atmospheric considerations for dew formation include wind, cloud cover, and relative humidity. Light winds help facilitate dew formation by transmitting moist air toward a condensing surface (Muselli et al., 2009). In general, the maximum wind speed which permits condensation is 4.4 m s^{-1} (Beysens, 2016) since a greater velocity increases heat exchange with the air by convection and turbulence, thus hindering the dew process (Muselli et al., 2009). In all sites, the threshold of maximum allowable wind velocity seemed apparently less because on dew nights average winds range between 0.1 to 2.7 m s^{-1} depending on location. On non-dew nights, the average wind velocity is slightly higher (0.1 to 2.9 m s^{-1}) although relative humidity remains nearly the same.

3.3.2. Relative Humidity

Although relative humidity is a key factor for dew formation, the parameter has functional sensitivity to temperature. Theoretically, a higher RH is necessary at higher air temperatures to permit the same dew yield at lower temperatures, provided all other atmospheric conditions are the same. The relationship of $(T_d - T_a)$ is preferred (≤ 0) because a condenser cannot radiatively cool more than a few degrees below the ambient air temperature (Beysens et al., 2005). The correlation of $(T_d - T_a)$ to nightly dew yield (h) leads to a typical dependence whereas nearly all data lies below a line (Figure 3.3) which is best fit to

$$h = \frac{h'}{\Delta T_{\max}} [\Delta T_{\max} - \Delta T] \tag{3.1}$$

where ΔT is $(T_d - T_a)$, $\Delta T_{\max}$ is the maximum cooling effect $(T_d - T_a)$ allowing dew formation at a given location for the entire study period, and h' is the maximum dew yield observed at a given location for the entire study period (Clus et al., 2008). Solely nocturnal data when dew harvesting events occurred were considered. Beysens (2016) estimated the resultant envelope slope of the above relationship around ~0.06 mm d^{-1} °C^{-1} using experimental results from 10 different experimental locations. This range is close to the value found under controlled laboratory conditions (~0.072 mm d^{-1} °C^{-1}) (Beysens, 2016). In our study however, this slope is generally less (0.01-0.04 mm d^{-1} °C^{-1}) (Figure 3.3). Differences may be due to several reasons. For example, other experimental sites (*e.g.* Beysens et al., 2005; Muselli et al., 2009) considered data obtained for an entire year including winter when larger dew yields were obtained, whereas this study only collected dew during the dry season. In addition, T_d and T_a are averaged over an entire night in all studies, not solely during dew formation and/or harvesting, and can largely be affected if favorable conditions for dew are more prolonged. In Croatia, ΔT_{max} was reported to be -9.2 ℃ and -8 ℃ in Zadar and Komiža, respectively (Muselli et al., 2009), which are less than absolute values obtained in Lebanon (-9.7 to -15.7 ℃).

Table 3.2. Summary of dew events and yields in Lebanon, 2013 (clear LDPE dew condenser)

Site	*Beirut*	*Bchamoun*	*Beiteddine*	*Barouk*	*Joub Jannine*	*Qaraoun*
Period of study	5/2013 – 11/2013	8/2013 – 11/2013	6/2013 – 11/2013	7/2013 – 9/2013	7/2013 – 11/2013	7/2013 – 10/2013
Number of sample nights	174	101	92	84	145	103
Number of dew nights	34 (20%)	28 (29%)	41 (49%)	12 (15%)	43 (34%)	20 (20%)
Average dew yield (mm d^{-1})	0.046	0.107	0.113	0.097	0.044	0.116
Maximum dew yield (mm d^{-1})	0.272	0.360	0.347	0.275	0.126	0.459
Average dew harvesting duration (hr d^{-1})	-	5.0	4.7	4.5	3.2	4.9
Average dew harvesting rate (mm hr^{-1})	-	0.019	0.027	0.028	0.013	0.031
Average RH, dew nights (%)	69.3	87.6	72.5	80.0	72.0	78.0
Average wind speed, dew nights (m s^{-1})	2.7	0.1	0.1	0.8	0.1	1.1

Surface wetness duration using a leaf wetness sensor was measured continuously from 6/2013 to 10/2014 in Beiteddine

Table 3.3. Summary of dew events and yields in Lebanon, 2014 (PETB dew condenser)

Site	*Beirut*	*Bchamoun*	*Bchatfine*	*Beiteddine*	*Barouk*
Period of study	4/2014 – 10/2014	5/2014 – 11/2014	6/2014 – 9/2014	4/2014 – 10/2014	7/2014 – 10/2014
Number of sample nights	171	182	95	180	107
Number of dew nights	18 (11%)	81 (51%)	52 (55%)	68 (43%)	6 (7%)
Average dew yield (mm d^{-1})	0.041	0.091	0.072	0.139	0.199
Maximum dew yield (mm d^{-1})	0.256	0.414	0.200	0.459	0.365
Average dew harvesting duration (hr d^{-1})	-	4.1	-	5.8	5.1
Average dew harvesting rate (mm hr^{-1})	-	0.028	-	0.026	0.072
Average RH, dew nights (%)	68.5	84.9	77.6	82.2	94.2
Average wind speed, dew nights (m s^{-1})	2.6	0.1	1.0	0.1	1.5

Surface wetness duration using a leaf wetness sensor was measured continuously from 6/2013 to 10/2014 in Beiteddine.

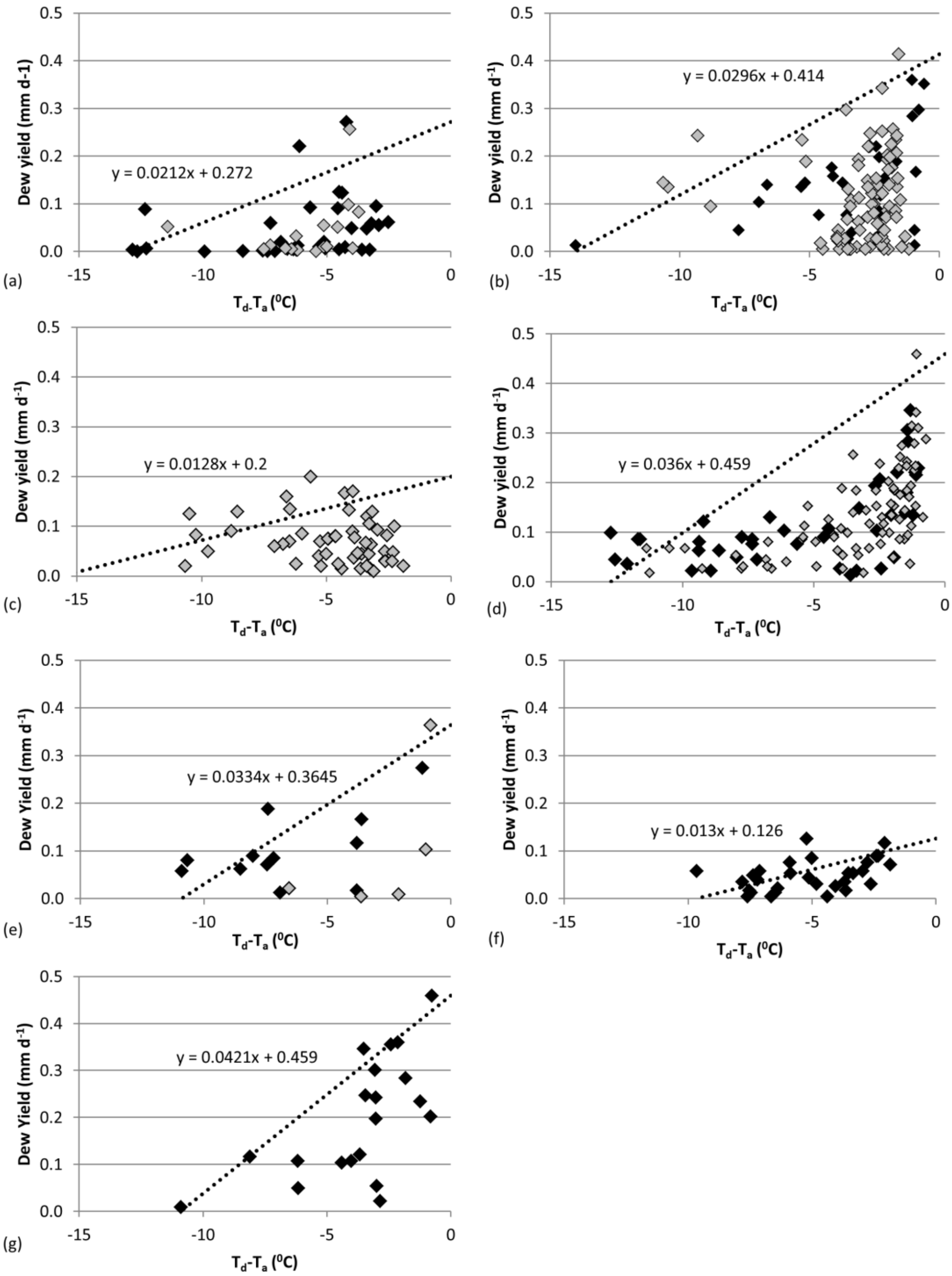

Figure 3.3. Nightly dew yield (h) vs ($T_d - T_a$)) for (a) Beirut, (b) Bchamoun, (c) Bchatfine, (d) Beiteddine, (e) Barouk, (f) Joub Jannine, and (g) Qaraoun for 2013 (black) and 2014 (grey). The interrupted line is the mean envelope slope, where h' is the y-intercept and $\frac{h'}{\Delta T_{\max}}$ is the slope

3.3.3. Dew Harvesting Duration

Harvesting duration (HD) is distinguished from the surface wetness duration (SWD) as it is dependent upon the rate where droplets slide down the condensing surface, detach from the edge, and are subsequently collected. It was monitored with a tipping bucket rain gage which was reporting data in five-minute intervals. Dew droplets may be subjected to losses from evaporation prior to collection. The harvesting duration was measured at all study locations from the start of harvesting to conclusion, including brief periods of inactivity (< 1 hr). During these short periods of inactivity, it is assumed that dew is in the process of forming but has not grown to sufficient size (~0.3 mm) to overcome their pinning forces (Beysens et al., 1991; Medici et al., 2014; Lee et al., 2012). In some cases, dew harvesting resumed after a long gap in activity in a given night; these cases were considered a single dew event and the reported duration was cumulative as measured over the differing harvesting periods. It is known that dew surface wetness duration is longer than harvesting duration.

The average SWD in Beiteddine is 6.5 hr during nights when dew was harvested. However, the average SWD in same location was 4.1 hr on non-harvesting nights during the study period resulting from dew which has not sufficiently formed to permit collection. In Ajaccio (France, located at $41^0$55' N, $8^0$48'E with a Mediterranean climate), the average annual SWD was 6.0 hr and displayed a seasonal periodicity exhibiting shorter periods during the summer and longer periods during the winter, thus suggesting SWD has a strong correlation with night duration (Beysens et al., 2005). In Beiteddine, which measured SWD during the dry and wet seasons, the SWD did not exhibit any unique pattern, which shows that SWD is more a function of favorable atmospheric conditions (Figure 3.4a). Moreover, dew formation seldom occurred during winter in Beiteddine due to lower RH during nights without rainfall (< 70% Nov-Feb).

The harvesting duration (HD) at Beiteddine had a strong correlation with yield (R^2=0.73), whereas the SWD did not (R^2=0.42) indicating studies which predict dew volumes based on SWD (*e.g.* Uclés et al., 2016; Kabela et al., 2009) may be at a disadvantage due to the weak correlation between SWD and yield SWD. Other locations in Lebanon demonstrated a similar relationship between HD and yield (Figure 3.5) but were not instrumented with leaf wetness sensors to monitor SWD.

The better correlation between yield and harvesting (HD) compared to yield and surface wetness duration (SWD) indicates that dew yield models should not only count on atmospheric conditions which may cause dew to form but not get harvested. A new generation of dew yield models should couple physical characteristics such as emissivity and dew collector geometry with atmospheric conditions and examining the relationship between HD and yield may be a start of new mechanistic relationships. In a given night, dew harvesting will last for 4-6 hours which will result in yields which range from 0.05 mm (Joub Jannine) to 0.15 mm (Beiteddine) (Tables 3.2 and 3.3). The longest dew harvesting episode was 13.1 hr, measured in Beiteddine, when dew began prior to sunset, occasionally occurring in the late summer and fall. At all locations, favorable conditions for dew generally occur within 3 hours after sunset. This differs from other locations such as Morocco whereby suitable meteorological conditions likely prevail shortly before sunrise (Lekouch et al., 2011). Lastly, like SWD, HD does not have a correlation with night duration (Figure 3.4a), and HD and SWD exhibit a weak correlation with each other (R^2=0.21 in Beiteddine) (Figure 3.4b and Figure 3.4c). It is possible that SWD and HD can exceed the night duration due to the processes beginning prior to sunset and concluding after sunrise when solar radiation is very low and relative humidity is high.

The dew harvesting rate at all locations (0.01 to 0.07 mm hr^{-1}) is more rapid than obtained in Ajaccio (0.014 mm hr^{-1}). However, in Ajaccio, measurements were obtained upon a horizontal polymethylmethacrylate (Plexiglass) plate instead of a tilted PETB condenser (Beysens et al., 2005) and does not benefit from the sliding of droplets due to gravity. An increased harvesting rate does not necessarily correspond to a longer harvesting duration.

The measured duration and harvesting rates between the different sites in Lebanon vary significantly (Figure 3.6), indicating slow rate in Joub Jannine and more rapid rates in Beiteddine and Bchamoun. This corroborates the favorable conditions in the latter as droplets form, coalesce, and reach critical size where they can slide down from the condensing surface, overcoming their pinning forces (Beysens et al., 1991; Medici et al., 2014). Dew harvesting rates in Barouk and Qaraoun are likely influenced by the addition of mist and fog droplets with dew, artificially increasing the rate.

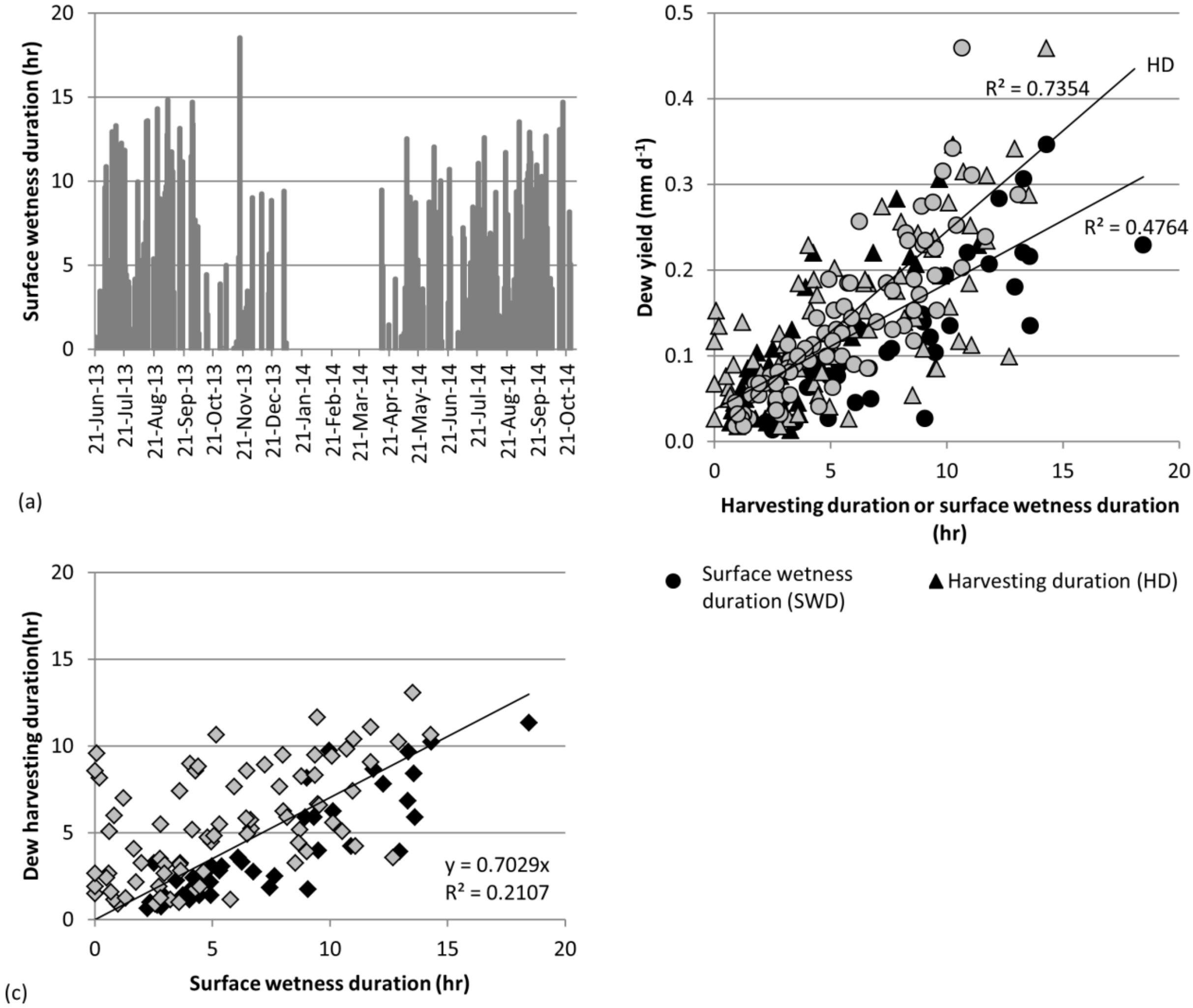

Figure 3.4. (a) Surface wetness duration (SWD) and dew harvesting duration (HD) vs. night duration and (b) yield vs HD and SWD in Beiteddine (c) Dew harvesting duration (HD) vs surface wetness duration (SWD) in Beiteddine for 2013 (black) and 2014 (grey)

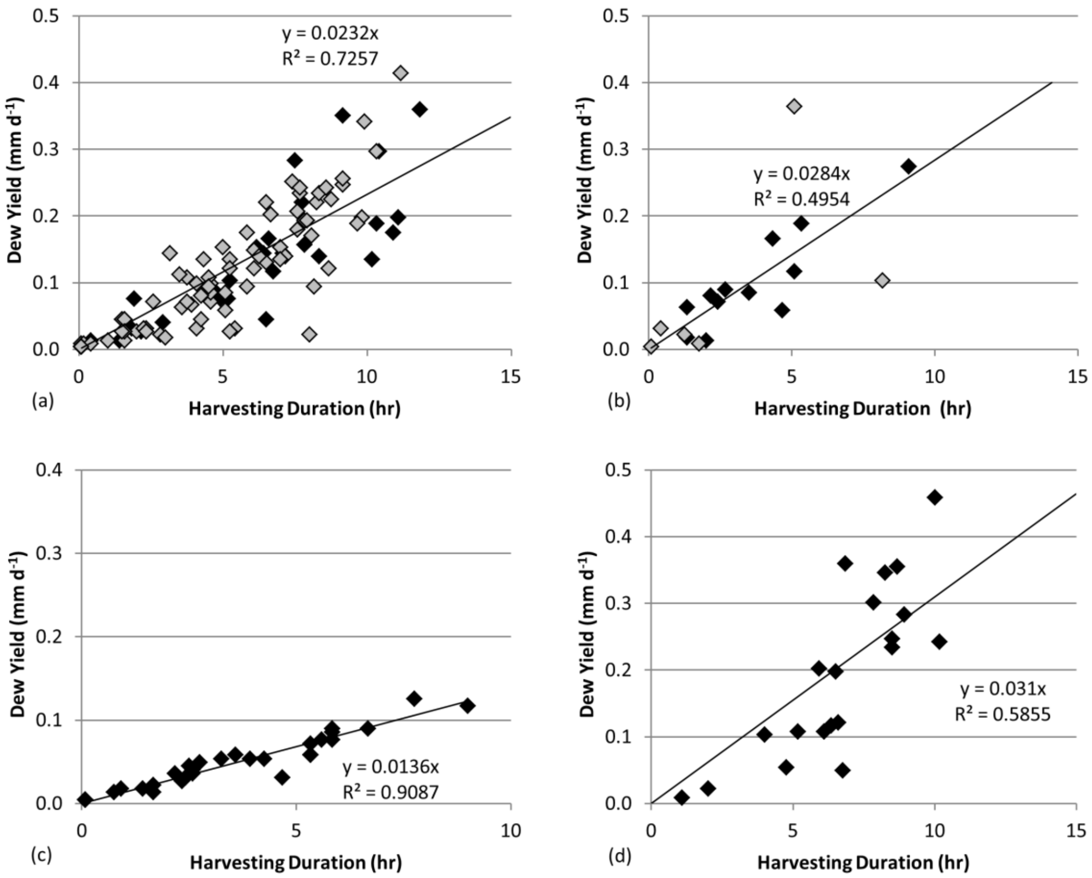

Figure 3.5. Correlation between nightly dew yield and harvesting duration for (a) Bchamoun, (b) Barouk, (c) Joub Jannine, and (d) Qaraoun for 2013 (black) and 2014 (grey)

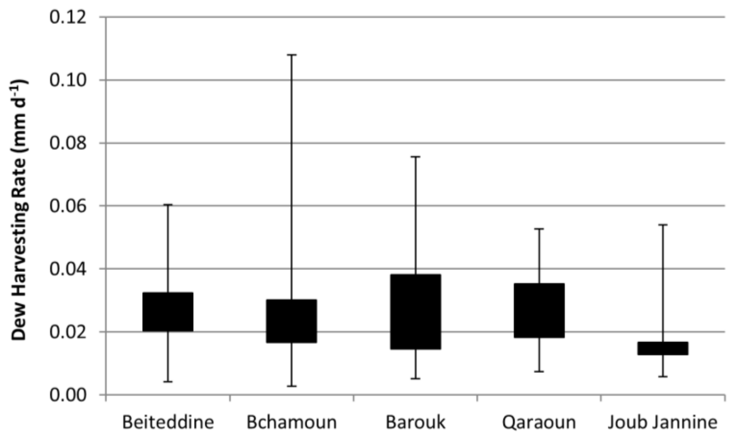

Figure 3.6. Dew harvesting rates for experimental locations in Lebanon (2013 and 2014). The box represents the median (Q2) and the whiskers are the first (Q1) and third quartiles (Q3)

3.3.4. The Effects of Microclimate

The best suited area for dew harvesting among the sampling locations is the western mid-mountain region (Bchamoun, Beiteddine, and Bchatfine). Decreasing atmospheric pressure due to increasing elevation causes the humid air originating from the sea to expand and cool adiabatically to approach dew point temperature (T_d). This results in frequent dew events, particularly in July and August (> 50%) with significant yields (~ 0.11 mm d^{-1}) (Tables 3.2 and 3.3). A similar dew regime was found in an analogous microclimate found in the western Lower Galilee (Gilead and Rosenan 1954).

Although nocturnal conditions are similar within the western mid-mountain region resulting in similar dew yields and frequency between locations (Bchamoun, Beiteddine, and Bchatfine), differing microclimates result in varying dew patterns. For example, dew events tended to be more frequent in July (>71%) in Bchatfine and Bchamoun, compared to 36% in Beiteddine, but the opposite is true in September (36%, 47%, and 92% in Bchamoun, Bchatfine, and Beiteddine, respectively). Throughout the summer, average yield is highest in Beiteddine (0.15 mm d^{-1} in 2014) and lowest in Bchatfine (0.07 mm d^{-1}). It is apparent that Beiteddine benefits from orography and elevation as well as a rural landscape. Although Bchamoun and Bchatfine are located at a similar elevation and within a residential landscape, Bchatfine had less dew on average than Bchamoun (0.07 and 0.11 mm d^{-1}, respectively) during the same period (July, August, and September 2014). This may be because Bchatfine is within a valley and has lessened nocturnal radiative cooling capacity compared to areas with better exposure to the night sky due to its position (Whiteman et al., 1989).

Although higher elevations generally correspond to higher dew yield (Kidron, 1999), results from Barouk may suggest a maximum threshold elevation (below ~1,200 m), above which favorable dew conditions cease. Although this site recorded exceptionally high dew events (up to 0.37 mm d^{-1}), overall event frequency was low (~11%). Moreover, the high yield may be the result of radiation fog, where $RH \cong$ 100%, and is often followed by dry spells (RH < 50%) which can be occasionally exceptionally dry (RH < 15%), typically occurring in mountainous regions in the Mediterranean (Herrero et al., 2009). This generally low nocturnal relative humidity is not conducive for frequent dew formation at very high elevations.

Dew harvesting is also not well-suited for urban environments like Beirut, where dew events had a frequency of 18% and yield of 0.06 mm d^{-1} during the 2013 and 2014 experimental campaigns. Urban areas are subjected to reduced nocturnal cooling potential due to a reduction in sky view from obstructions like buildings (Sproken-Smith and Oke, 1999). In addition, urban heat island (UHI) effects can be pronounced from late afternoon until dawn resulting in increased nocturnal temperatures, particularly on clear nights with light winds conditions which otherwise are favorable for dew formation (Kim and Baik, 2002; Gedzelman et al., 2003; Fortuniak et al., 2006). During warmer months, such as the period of study, urban environments have a lower RH than nearby rural environments (Unkašević et al., 2001; Fortuniak et al., 2006) (Tables 3.2 and 3.3). Small urban moisture excess (UME), correlated with UHI, can contribute to reduced dew yield (Richards, 2005). The development of UME is debatable, but can be attributed to increased evaporation in city environments which can inhibit condensation and anthropogenic sources of water vapor (combustion, traffic, households, and power plants) (Kuttler et al., 2007). Lastly, urban locations may be exposed to increased atmospheric pollution which inhibits atmospheric transmittance (Beysens et al., 2005).

Unfortunately, no other coastal locations were tested other than Beirut for comparison, although a comparative study between a rural coastal location and an inland location in Madagascar obtained higher dew yield at the coastal location (24% increase) (Hanisch et al., 2015). Other studies with comparative urban coastal microclimates to Beirut had reduced dew compared to nearby elevated stations but longer dew duration (Gilead and Rosenan, 1954; Scherm and van Bruggen, 1993).

With respect to inland valley locations, results from Joub Jannine and Qaraoun showed that such locations are also not ideal for dew harvesting. These locations are subjected to reduced relative humidity due to its leeward locale. Likewise, interior valley locations in California exhibited limited dew event frequency and duration (Scherm and van Bruggen, 1993). In late fall, however, when the Mediterranean season transitions from the dry season to the wet season, dew events become more frequent in the valley, particularly in Joub Jannine. Dew event frequency increases to 87% in November resulting in half the total dew yield (0.73 mm month^{-1}) for the entire study period, corresponding to an elevated nocturnal RH (83%).

3.3.5. Fog Harvesting

Because Barouk is at high elevation and has frequent cloud cover, its microclimate is not well-suited for dew harvesting. A pilot study indicates the site is more compatible for fog harvesting (Table 3.4). However, the daily average yield (0.12 mm d^{-1}) is significantly less than other comparable studies in the Mediterranean region during summer months [Valencia, Spain: 2.5 mm d^{-1} (Estrela et al., 2008); Western Cape, South Africa: 4.6 mm d^{-1} (Olivier, 2002); Croatia: 1.3 mm d^{-1} (Mileta and Likso, 2010)]. The daily yield is slightly less than dew yield obtained during the same period in Barouk (0.20 mm d^{-1}), but fog events are far more frequent (7% and 45% for dew and fog, respectively).

Fog events during the study period only occurred during the night and early morning when favorable conditions prevail (high RH and low winds) with an average duration of 4.2 hours. This is longer than a typical fog event in Valencia (2-4 hours), although extended durations have been observed (up to 92 consecutive hours) (Estrela et al., 2008). Longer fog episodes were observed in the Western Cape (8 hours on average) (Olivier, 2002).

Because the measured fog yield was very low in Barouk, it is possible that modifications in the fog collector may increase yield. The mesh used for the collector is similar to the polypropylene Raschel mesh proposed as a recommended standard (Schmenauer and Cereceda, 1994). However, design and site selection criteria did not optimize for the shade coefficient, the area of the collector capable of capturing fog droplets, which can vary due to disparities in overlapping mesh layers, stretching of the mesh during installation thereby reducing width of the ribbons, and discrepancies in the actual value compared to the manufacturer's specifications (de Dios Rivera, 2011). The shade coefficient of the mesh used in Barouk is unknown and the proposed value is 0.35 (Schmenauer and Cereceda, 1994). Lower shade coefficients can result in a suppressed amount of fog droplets that can be captured by the mesh and higher shade coefficients can result in flow resistance (de Dios Rivera, 2011). Other researchers have used innovative fog collector designs such as nylon strings arranged on a cylindrical polyamide frame (Estrela et al., 2008) or high-density polyethylene strands coated with aluminum, which has a higher collection efficiency than Raschel mesh (Abdul-Wahab and Lea, 2008). Lastly, the height of the fog collector installed in Barouk was 1 m to minimize interference in the forest reserve, but the proposed standard height is 2 m to better capture fog (Schmenauer and Cereceda, 1994). We propose additional testing for fog before conclusive insights about the fog potentials can be generated.

3.4. Concluding Remarks

Alternative water resources such as dew and fog may yield small quantities but can occur naturally and frequently, which is significant in semi-arid regions when rainfall is nil. In the Eastern Mediterranean, the best suited areas for dew harvesting run parallel to the coast and at higher elevations, benefitting from maritime influences, orographic lift, and reduced atmospheric pressure. Fog collection is best reserved for the highest elevations in this region. These alternative water resources can be used for adaptation measures to mitigate climate change and surface and groundwater pollution and potential uses include reforestation and potable water.

Table 3.4. Summary of fog harvesting at Barouk

Period of study	7/2014 – 10/2014
Number of calendar days	109
Number of sample days	77
Number of fog days	35 (45%)
Average fog yield (mm d^{-1})	0.122
Maximum fog yield (mm d^{-1})	0.419
Cumulative fog yield (mm)	4.676
Average RH, study period (%)	60.6
Average RH, fog harvesting (%)	82.4
Average T_a, study period (℃)	17.5
Average T_a, fog harvesting (℃)	12.6
Average u, study period (m s^{-1})	1.2
Average u, fog harvesting (m s^{-1})	0.4
Average fog harvesting duration (hr d^{-1})	4.2
Average fog harvesting rate (mm hr^{-1})	0.031

CHAPTER 4

PROJECTED CLIMATE CHANGE IMPACTS UPON DEW YIELD

Water scarcity is increasingly raising the need for non-conventional water resources, particularly in arid and semi-arid regions. In this context, atmospheric moisture can potentially be harvested in the form of dew, which is commonly disregarded from the water budget, although its impact may be significant when compared to rainfall during the dry season. In this study, a dew atlas for the Mediterranean region is presented illustrating dew yields using the data collected for the 2013 dry season. The results indicate that cumulative monthly dew yield in the region can exceed 2.8 mm at the end of the dry season and can exceed 1.5 mm during the driest months, compared to <1 mm of rainfall during the same period in some areas. Forecasted trends in temperature and relative humidity were used to estimate dew yields under future climatic scenarios. The results showed a 27% decline in dew yield during the critical summer months.

4.1. Introduction

In many arid and semi-arid regions, conventional water resources stemming from the ground or the surface are increasingly insufficient to meet continually increasing demands due to population growth and development coupled with environmental degradation and exacerbated by climate change impacts. While alternative non-conventional water resources such as dew harvesting can supplement existing water sources, it has only recently garnered some momentum due to the development of efficient passive condensers, which can achieve significant surface temperature depression due to radiative cooling.

Dew exhibits a frequent occurrence in many geographical locations because it is less constrained by specific climatological and geographic conditions than other meteorological phenomena like fog (Beysens and Milimouk, 2001). It is primarily dependent upon certain common atmospheric conditions such as clear skies, high relative humidity, and low wind speed (Monteith, 1957; Beysens, 2016) with less cloud cover facilitating greater radiative cooling of the earth surface and adjacent air. The temperature of the condensing surface must fall below the dew point temperature (the air temperature at saturation) for condensation to occur on the surface. However, passive cooling potential of surfaces is limited to a few degrees below air temperature, thus requiring a high relative humidity for dew to occur. Light winds can help bring humid air toward a surface, but too much wind can cause condensation to cease completely. Furthermore, strong wind increases the convective heat exchange between the condensing surface and the air, and reduces the achievable temperature difference and the likelihood of reaching dew point temperature. These conditions have enabled frequent dew formation in coastal and alpine terrains, as well as arid and semi-arid regions (Zangvil, 1996; Lekouch et al., 2012).

To date, dew harvesting studies are relatively limited (Chapter 2) causing difficulty in feasibility assessments. In the absence of data, mathematical models can help estimate dew yields. The results from these models can be coupled with geostatistical analysis to develop an atlas forecasting dew yield. A recent attempt in this context is the work of Vuollekoski et al., (2015), who used 34 years of global meteorological reanalysis data (ECMWF 2009), available at a spatial resolution of 0.75^0 (~80 km) grid and coupled the data with an existing dew model developed by Pedro and Gillespie (1982) and Nikolayev et al.

(1996), to estimate yields over a large area. Yet, the resultant atlas is limited by the inherent spatial and temporal coarseness of the data, which fails to consider topography and regional climatic conditions. Moreover, the adopted model did not eliminate daytime dew, which does not occur due to the inability of surfaces to radiatively cool, as a result of the temporal scale of the data used. Comparisons between the atlas and field data was limited to a single location (Negev Desert); results showed that the predicted yield was 4 times larger than actual measurements (Zangvil, 1996). Similar concerns were reported about the atlas due to the high frequency of dew events (reaching 100% of nights in a season) it predicted for regions such as Spain and the Netherlands, where such a rate is inconsistent with experimental studies (Maestre-Valero et al., 2011; Jacobs et al., 2008).

In this study, we target the development of a dew atlas for the reference year 2013 using geostatistical analysis coupled with hourly meteorological data, while considering additional factors impacting dew such as terrain and distance to the sea. Potential climate change impacts on dew yield were then tested under low and high emissions scenarios (RCP 4.5 and RCP 8.5, respectively) using two differing climate simulations (EC-EARTH and HadGEM2-ES). These were used to develop comparative dew atlases for 2030, 2050, and 2080.

4.2. Methodology

4.2.1. Dew model

Nightly dew yield (dh/dt) (mm d^{-1}) was evaluated based on the model developed by Beysens (2016). The model assumes that dew harvesting occurs on a planar surface with an emissivity of 1 (Equation 4.1):

$$\frac{dh}{dt} = \begin{cases} \left\{a \times b \times \left(1 - \frac{N}{8}\right)\left[exp\left(-\left(\frac{u}{c}\right)^{20}\right)\right]\right\} + [d(T_d - T_a)] & \text{if } \frac{dh}{dt} > 0 \\ 0 & \text{if } \frac{dh}{dt} < 0 \end{cases} \quad (4.1)$$

where T_d and T_a are dew point and air temperatures (℃), respectively, N is cloud cover (oktas), and u is wind velocity (m s^{-1}). Note that formulation used is a simplification of the original model proposed by Beysens (2016), as the wind velocity cutoff is placed in the energy term instead of being in the heat exchange term. Both formulations give fundamentally identical results. Empirical coefficients in the model include maximum natural dew yield (a)[3], sky emissivity (b)[4], the maximum wind velocity (c)[5], and the average envelope slope (d)[6]. The model requires readily available data (*i.e.* H, T_d, and T_a) and was tested and validated with experimental data at 10 locations with differing climates[7] (Beysens, 2016). The model can be applied at a given time typical for dew formation, such as sunrise, or incrementally every hour, whereby average night duration of 12 hours is assumed and the model is applied during the nocturnal period only.

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[3] Estimated at 0.37 mm d^{-1} based on a mean maximum temperature differential of -6 ℃ (Beysens, 2016)

[4] Estimated as $[1 + 0.204323H - 0.0238893H^2 - (18.0132 - 1.04963H + 0.21891H^2) \times 10^{-3}T_d]$ (Berger and Bathiebo, 1992), where H is site elevation (km)

[5] Equivalent to 1 when $u < 4.4$ m s^{-1} and 0 otherwise because in nearly all cases, dew cannot form when wind velocity exceeds this limit (Beysens, 2016)

[6] Estimated at 0.06 mm d^{-1} K^{-1} for dew yield vs $T_d - T_a$ (Beysens, 2016)

[7] Ajaccio (France), Bahar-Dar (Ethiopia), Bakou (Azerbaijan), Bordeaux (France), Čres (Croatia), Grenoble (France), Kothara (India), Mirleft (Morocco),Tahiti (French Polynesia), and Zadar (Croatia)

Because the empirical coefficient values can have substantial effects on predicted dew yield, a parametric sensitivity analysis was performed on both a and d using the one-at-a-time method by varying input parameters $\pm$ 20% because they were obtained from 10 experimental stations (Beysens, 2016) and monitoring the output. No sensitivity analysis was performed on the other coefficients (b and c) because sky emissivity (b) was based on a widely used empirical model (Berger and Bathiebo, 1992), which considers the night sky in addition to T_d. Furthermore, the maximum wind velocity (c) is valid based on a review of all global experimental studies (Chapter 2).

It is worth noting that other dew models were initially considered but excluded either because they involved empirical coefficients (Beysens et al., 2005; Maestre-Valero et al., 2012; Gandhidasan and Abualhamayel, 2005; Lekouch et al., 2012), were highly local, required a highly iterative process to solve (Nikolayev et al., 1996; Gandhidasan and Abualhamayel, 2005; Richards, 2009), or required data that may be difficult to obtain (Richards, 2009).

4.2.2. Area of study and hindcast dew yield estimation

Actual historical meteorological data was used to avoid inaccuracies in dew yield estimations associated with spatial and temporal coarseness of climate data. As such, 142 sites located in the Mediterranean basin and characterized with a dry-summer subtropical climate (classified as Csa/Csb by the Köppen Climate Classification) were selected (Figure 4.1). All selected sites had hourly (or more frequent) nocturnal data needed to estimate dew yields. Data were obtained from the National Climatic Data Center (NCDC) Climate Data Online (2013) and supplemented by Weather Underground (2013) of which the accuracy was validated against NCDC data. Where large spatial gaps in calculated dew were discerned, additional sites with nocturnal relative humidity (*RH*) were used to augment the 142 stations through the adoption of a geostatistical analysis. Gaps in data (up to 2 hours) were interpolated linearly; larger gaps resulted in discarding the entire night. In addition, nights with measurable precipitation were assumed not to form dew.

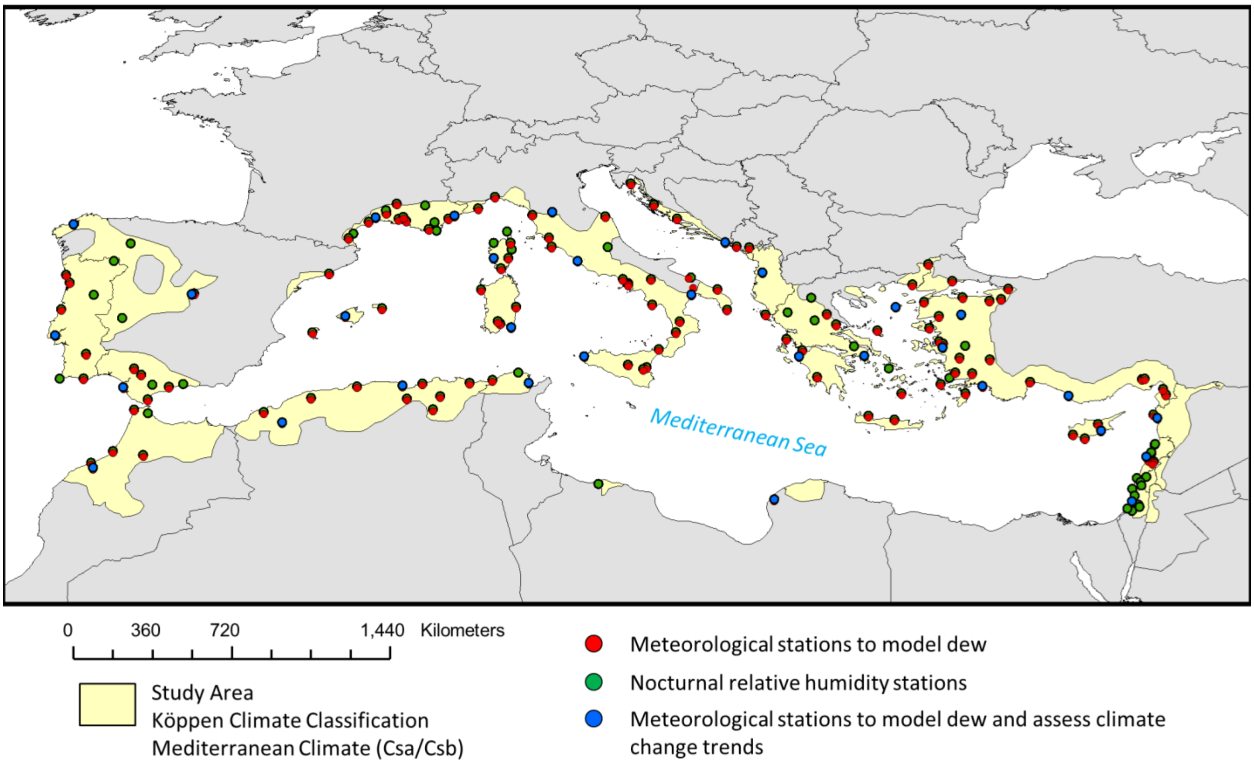

Figure 4.1. Study area and meteorological stations selected to model dew

Cloud data in oktas (eighths of the sky) were estimated by converting descriptor data (*e.g*. clear, broken clouds) using reported guidance from NOAA/NWS (1998) (Table 4.1). In cases where *RH* exceeded 98.5%, fog conditions were assumed (4 oktas) unless more cloud cover was indicated. Selected values used in the model were generally mid-range in each category unless the next (or previous) hourly increment indicated differing descriptive cloud coverage, in which case values were interpolated.

Table 4.1. Cloud descriptor data and equivalent coverage (oktas) (NOAA/NWS, 1998)

Cloud descriptor data	*Cloud cover (N), oktas*
Clear (CLR)	0
Few clouds (FEW)	1-2
Scattered clouds (SCT)	3-4
Broken clouds (BKN)	5-7
Overcast (OVC)	8

The model results were validated using experimental data collected during the 2013 dry season in Lebanon and Croatia (Table 4.2). Dew was harvested using a standard planar condenser inclined 30^0 to the horizontal. Stations in Lebanon used clear polyethylene as a condensing surface whereas the station in Croatia used a polyethylene foil embedded with TiO_2 and $BaSO_4$ microspheres, specifically formulated for dew harvesting (Nilsson, 1996; manufactured by OPUR, 2015). Meteorological data were co-collected with dew data in Lebanon except for cloud coverage, which was estimated using the nearest Weather Underground station. Weather Underground data was used to model dew in Croatia.

Table 4.2. Experimental dew harvesting stations for model validation

Dew harvesting station			*Weather Underground station*	
Site	*Location*	*Dates of Collection*	*Site*	*Location*
Bchamoun (Lebanon)	33° 47' 45.5" N, 35° 31' 9.9" E	8/2013 – 10/2013	Beirut	33° 49' 1.2" N, 35° 28' 58.8" E
Beiteddine (Lebanon)	33° 41' 14.3" N, 35° 35' 0.6" E	6/2013 – 9/2013		
Barouk (Lebanon)	33° 41' 44.4" N, 35° 42' 42.1" E	7/2013 – 9/2013		
Joub Jannine (Lebanon)	33° 37' 53.6" N, 35° 47' 2.9" E	7/2013 – 10/2013	Houche-al-Oumara	33° 49' 1.2" N, 35° 51' 0.0" E
Qaraoun (Lebanon)	33° 33' 42.8" N, 35° 44' 2.4" E	7/2013 – 10/2013		
Čres (Croatia)	44° 57' 33.0" N, 14° 24' 56.4" E	4/2013-10/2013	Zadar	44° 6' 0.0" N, 15° 20' 60.0" E

4.2.3. Geostatistical analysis

Results generated from the dew models were used to interpolate dew yields across the Mediterranean coastline. Differing interpolation methods were tested including deterministic interpolation methods (*i.e.* inverse distance weighting or spline interpolation) and geostatistical analysis using kriging, which relies on geostatistical methods to interpolate data assuming that the distance or direction between observed points reflects spatial correlation. Kriging utilizes a semivariogram model to fit observations within a specified radius to determine the predicted value at each location. Two of the most commonly used semivariogram models were tested namely, the spherical and exponential. While several kriging methods are available for environmental applications, in this study, single and multi-variate ordinary kriging was tested. Ordinary kriging makes use of related auxiliary variables, which may have more observations than the primary variable and hence, partially heterotropic or collocated (Wackernagel, 2003). This approach has been used to interpolate precipitation (Goovaerts, 1999; Hevesi et al., 1992; Martínez-Cob, 1996) and air temperature (Benavides et al., 2007) with terrain data. Details pertaining to multivariate ordinary kriging can be found in Wackernagel (2003) and Ver Hoef and Cressie (1993). Dew, as the primary variable of interest, was interpolated on a monthly basis with nocturnal *RH* obtained from weather data, elevation, and distance to the sea because these extrinsic factors known to affect yield output. For example, areas along the coastline lend themselves toward higher dew yields due to on-shore winds and sea breeze circulation. In addition, urban centers are subjected to heat island effects, which inhibit dew (Ye et al., 2007; Muskała et al., 2015). Lastly, dew quantities can be higher in mountainous areas that benefit from orographic lift (Beysens et al., 2005). All interpolation methods were assessed based on the root mean square error, which indicates how closely they predicted dew yields as compared to dew yields obtained from the model at the meteorological stations.

4.2.4. Climate change assessment

Gridded climate data generally does not have a sufficient temporal resolution for dew modeling because it tends to be data average data rather than minimum temperature and maximum relative humidity. Instead, annual projected trends in temperature and relative humidity for selected months (June, July, and August) were obtained for 31 locations (noted in blue; see Figure 4.1) in the Mediterranean using data obtained from the Coordinated Downscaling Experiment over Europe (EURO-CORDEX; Jacob et al., 2014), which represents the latest generation of high-resolution gridded climate data based on the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). The daily data is characterized by fine spatial resolution (up to 0.11^0 or ~12.5 km). Available data includes historical (1970-2005) and projected data (2006-2100) based on differing scenarios of representative concentration pathways (*e.g.* RCP4.5 and RCP8.5) across the European domain. Four different scenarios were examined: (a) RCP4.5 and (b) RCP8.5 based on the EC-EARTH (Hazeleger et al., 2012) driving model and (c) RCP4.5 and (d) RCP8.5 for the HadGEM2-ES (Collins et al., 2011) driving model. The differing greenhouse gas concentration scenarios, RCP4.5 and RCP8.5, represent a midrange mitigation emissions scenario (~4.5 W m^{-2} at stabilization after 2100) and a high emissions scenario (> 8.5 W m^{-2} in 2100), respectively (Moss et al., 2010; Taylor et al., 2012). Although the projected regional change in wind speed is -0.3 to -0.1 m s^{-1} $decade^{-1}$ (McVicar et al., 2012), it was assumed constant for this evaluation because the model is not sensitive to the parameter. Cloud cover was also assumed constant because the regional trend is relatively small (-0.9 %

decade^{-1}; Warren et al., 2006) which is not significant enough to impact results because cloud cover is measured in oktas.

The resultant trends predicted monthly average temperature and relative humidity for 2030, 2050, and 2080 based on a revised 2013 baseline (denoted 2013*). Incremental temperature and relative humidity values obtained for the original 2013 baseline modeling were adjusted to reflect the projected monthly average values for each period. Calculated dew yields were adjusted so as to eliminate forecast rain days, obtained from the EURO-CORDEX data for each scenario. The results (based on the 31 stations) were interpolated using geostatistical analysis and were added using a raster calculator to the original 2013 maps to obtain estimated dew yield maps for 2013*, 2030, 2050, and 2080.

4.3. Results and discussion

4.3.1. Dew model validation and sensitivity analysis

The Beysens (2016) model was validated using the 2013 data (Table 4.3) collected from 6 stations in Lebanon and Croatia. Overall, the correlation between observed and predicted yields was good (Pearson's $r = 0.6$). Yet, the model exhibited a tendency to forecast dew events when none occurred, resulting in a much higher event frequency than measured (Table 4.3), and under-estimate the yield. For this reason, the estimated frequency of dew events was not mapped. Yield under-estimation was likely a result of the coarse temporal scale (hourly) of the meteorological data. Nevertheless, when assessing yields on a cumulative basis, the model performed well ($r > 0.9$) (Figure 4.2) because the high event frequency and yield under-estimation tended to cancel each other out.

A parametric sensitivity analysis using the one-a-time-method was performed on both the maximum natural dew yield (a) and the average envelope slope (d) (see Equation 4.1) based on typical dew harvesting conditions (*i.e.* H=100 m, *RH*=90%, u=1 m s^{-1}) at different air temperatures (T_a) and corresponding dew point temperatures (T_d). The calculated dew yields were greatly affected (increased by 82%) when the maximum dew yield (a) was increased by 20% from the reported value (0.37 mm d^{-1}; Beysens, 2016) (Figure 4.3a). Likewise, calculated dew yield decreased by 61% when the average envelope slope (d) was increased by 20% from the reported value (0.06 mm d^{-1} K^{-1}; Beysens, 2016) (Figure 4.3b). The results show that the model's high sensitivity to both parameters. The original model was unchanged to avoid biasing the results, but this sensitivity analysis provides a bracket for the uncertainty in the results and underlines the importance of carefully estimating these coefficients for the assessment of potential dew harvesting projects. This uncertainty however does not affect the spatial patterns we produce in this paper (which are mostly sensitive to meteorological inputs at constant a and d), nor do they affect the conclusions on the influence of climate change on dew yield.

Table 4.3. Summary of dew events and yields for model validation

Site	*Bchamoun*	*Beiteddine*	*Barouk*	*Joub Jannine*	*Qaraoun*	*Cres*
Period of study	8/2013 – 10/2013	6/2013 – 9/2013	7/2013 – 9/2013	7/2013 – 10/2013	7/2013 – 10/2013	4/2013 – 10/2013
Number of sample nights	71	102	84	115	115	214
Number of dew nights (experimental)	17 (24%)	53 (52%)	15 (18%)	18 (16%)	20 (17%)	79 (37%)
Average dew yield (mm d^{-1}) (experimental)	0.134	0.087	0.083	0.043	0.196	0.067
Maximum dew yield (mm d^{-1}) (experimental)	0.302	0.333	0.239	0.126	0.459	0.188
Number of dew nights (modeled)	46 (65%)	65 (64%)	26 (31%)	35 (30%)	28 (24%)	94 (44%)
Average dew yield (mm d^{-1}) (modeled)	0.051	0.063	0.038	0.035	0.067	0.068
Maximum dew yield (mm d^{-1}) (modeled)	0.144	0.194	0.160	0.124	0.196	0.307
Correlation coefficient (Pearson's r)	0.93	0.97	0.97	0.99	0.97	0.97

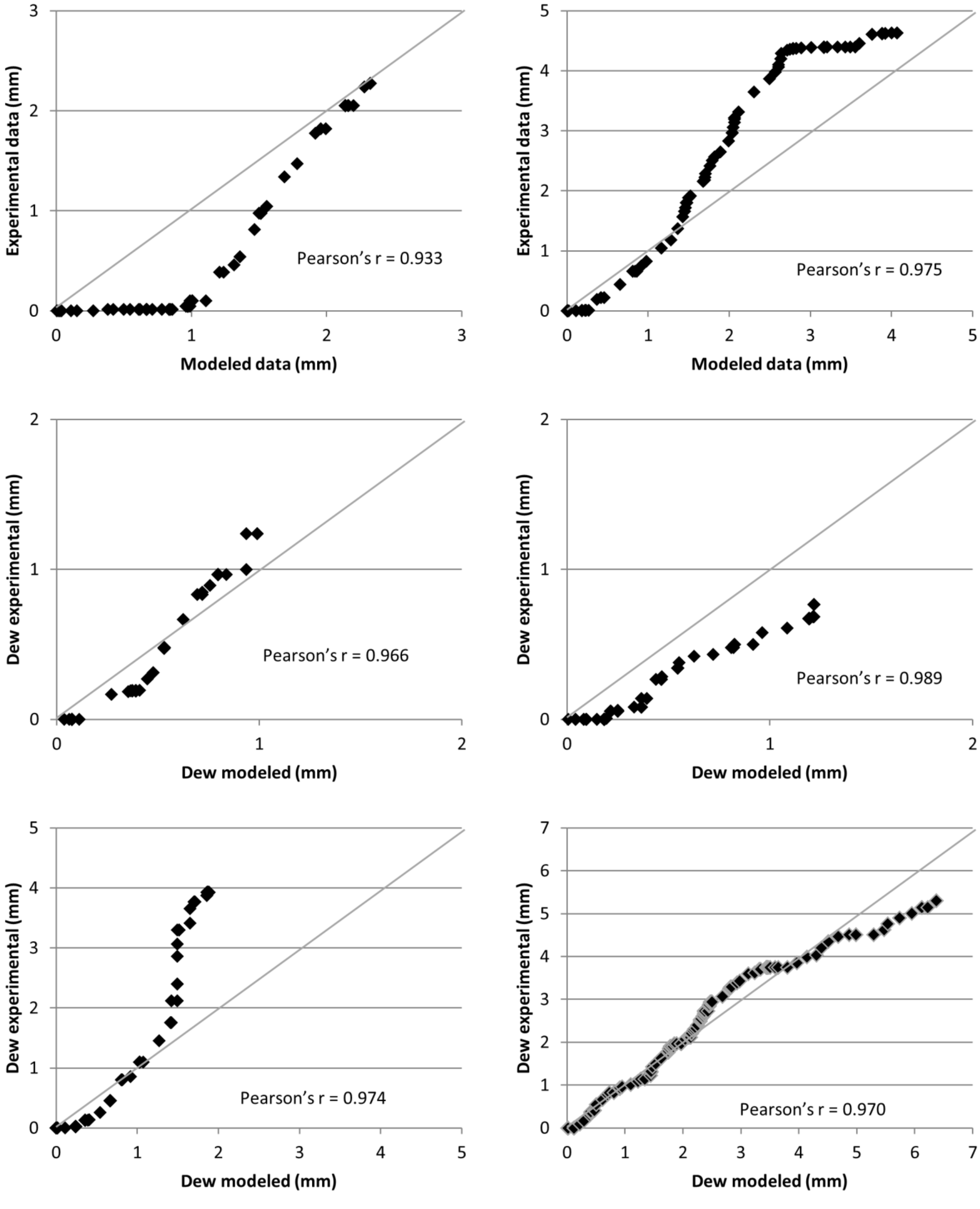

Figure 4.2. Modeled vs. experimental cumulative dew yield for (a) Bchamoun, (b) Beiteddine, (c) Barouk, (d) Joub Jannine, (e) Qaraoun, and (f) Cres

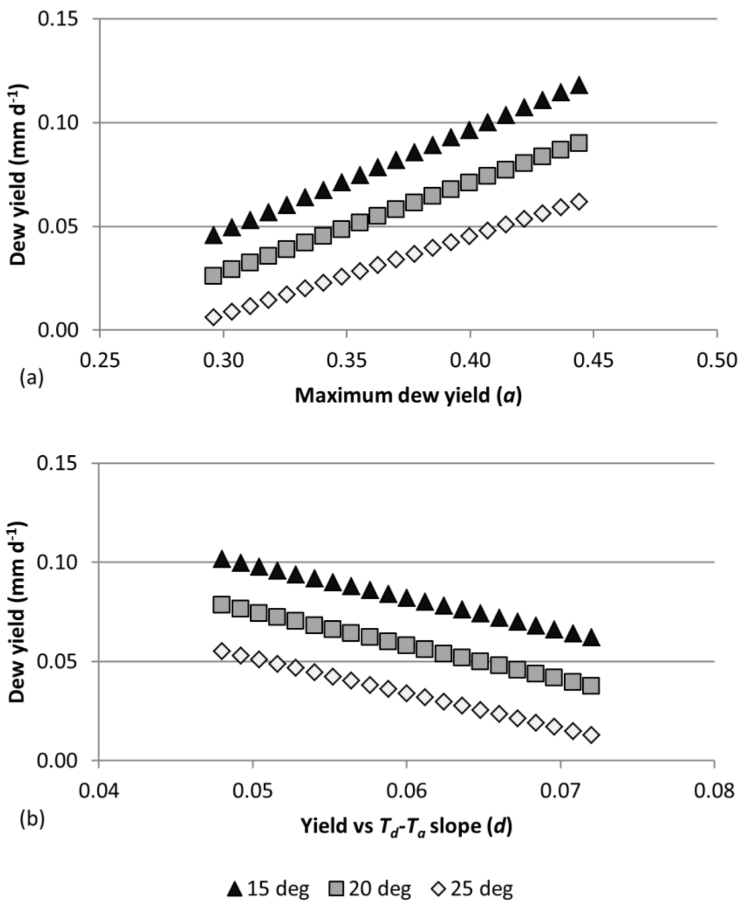

Figure 4.3. Sensitivity analysis of (a) the maximum dew yield and (b) the mean enveloping slope of dew yield vs. $(T_d - T_a)$ (mm d^{-1} K^{-1}) based on different air temperatures (T_a) (15, 20, and 25 ℃), 90% *RH*, 1 m s^{-1} wind speed, 3 oktas cloud cover, and 100 m altitude

4.3.2. Dew yield atlas

The model was used to predict dew yields during the 2013 dry season for the 142 stations around the Mediterranean. The average monthly modeled dew yield was found to be highest in October (1.2 mm) and lowest in August (0.5 mm) (Table 4.4). Yield tended to be lowest in the Eastern Mediterranean (~0.05 mm) and highest along the Algerian coast (~1.2 mm). Although dew yield is closely linked with *RH*, that latter had a weak correlation (R^2=0.38) with yield, indicating other factors influence yield. Low correlation was obtained between yield on one hand and elevation and distance to the sea on the other, even though previous experimental studies have indicated that these factors influence dew formation and yield (Zangvil, 1996; Kidron, 1999).

Table 4.4. Summary of simulated dew yield and relative humidity from meteorological data collected from the 142 meteorological stations along the Mediterranean coast

Parameter	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
Dew (mm)							
Min	0.10	0.03	0.00	0.00	0.00	0.00	0.00
Max	3.21	2.59	2.65	2.53	2.12	2.31	3.11
Average	1.02	0.77	0.75	0.53	0.53	0.72	1.21
RH (%)							
Min	49	50	46	35	35	43	48
Max	92	96	90	93	90	93	94
Average	77	76	72	70	69	73	77

The interpolation results generate from the deterministic interpolation methods (IDW and spline) were found to be poor as they depended solely on the surrounding observations (Table 4.5). The semivariogram models performed better. The ordinary multivariate kriging with an exponential model that used dew, *RH*, elevation, and distance to the seas as covariates performed the best; it had both low RMS errors and a small nugget. Moreover, the correlation coefficient between the dew yield obtained from the Beysens model and the geostatistical interpolated values was acceptable (r=0.73). Results from the geostatistical analysis revealed low errors in general, with the exception of October (Figure 4.4). Errors were largely due to the gaps between the meteorological stations (up to 250 km). As typical with all interpolation schemes, the generated yields in the atlas were smoothed, eliminating localized extremes. Thus, the atlas cannot be expected to discern variations in microclimates.

Table 4.5. Comparison of interpolation methods to map dew yield (September 2013)

Interpolation method	*Variate(s)*	*Semivariogram Model*	*RMS Error*	*Nugget*	*Sill*	*Range (10^3 km)*	*Pearson's r*
IDW	Dew	-	0.532	-	-	-	1.0
Thin plate spline	Dew	-	0.867	-	-	-	1.0
Ordinary kriging	Dew	Spherical	0.494	0.23	0.34	2.3	0.64
	Dew	Exponential	0.492	0.21	0.35	3.2	0.68
	Dew, *RH*	Spherical	0.510	0.38	0.38	0.8	0.59
	Dew, *RH*	Exponential	0.510	0.38	0.38	0.8	0.59
	Dew, *RH*, elev	Spherical	0.493	0.41	0.43	0.2	0.67
	Dew, *RH*, elev	Exponential	0.489	0.41	0.45	0.2	0.65
	Dew, *RH*, elev, distance	Spherical	0.464	0.23	0.32	0.5	0.73
	Dew, *RH*, elev, distance	Exponential	0.459	0.23	0.33	0.7	0.73

In an effort to determine the atlas's accuracy, it was compared with historical dew records from two stations that were not used in the model calibration. The results from the generated atlas (Table 4.6) were found to be in the same order of magnitude as the experimental data collected in two long-term dew yield stations in France and Croatia. This provides evidence that the results from the geostatistical analysis provide reasonable depiction of the spatial patterns of dew yield potential.

Based on the generated atlas, higher dew yields are found (Figure 4.5) along the Algerian and Italian coastlines. These yields can be attributed to seasonal regional wind circulation originating over the Sahara Desert, which is comparatively cool during the night and picks up moisture as it crosses the Mediterranean Sea. Moreover, the nocturnal *RH* is higher than average in both Algeria and Italy. Similarly, Morocco and Spain exhibited higher dew yields during certain periods due to wind circulation carrying humid air originating from the Atlantic Ocean. Similar spatial trends were reported by Vuollekoski et al. (2015). While dew volumes are small, they are particularly advantageous in the dry season, where most of the study area has no rainfall at all (Figure 4.6). Monthly estimated dew yields exceeded rainfall in 21% of the study area in June, specifically in Southern Spain, the North African Coastline, Corsica, Sardinia, Sicily, and the Eastern Mediterranean. Similarly, dew yields were larger than rainfall in 14-15% of the study area in July and August. During these months, dew can reduce the dependency on surface and groundwater to meet the high demands, especially with regards to the agricultural sector.

Moreover, dew has considerable significance in semi-arid natural ecosystems (Agam and Berliner, 2006) as demonstrated by comparing potential evapotranspiration (*PET*) (CRU TS v. 3.23; Harris et al., 2014) to dew yield (Figure 4.7). During the driest months (June, July, and August), PET is ~40 times greater than dew yield in some areas (Algeria, Italy, and Spain). However, actual evapotranspiration (*ET*) of many native plants in the region is far less and would thus close the gap between *ET* and dew yield.

Table 4.6. Simulated dew yield compared to previous studies (prior to 2013) in the Mediterranean region

Location	*Model*			*Experimental*		*Reference*
	Period	*Analytical model yield (mm)*	*Geostatistical analysis yield (mm)*	*Period*	*Yield (mm)*	
Ajaccio (France)	Apr- Oct 2013	5.87	6.81	Apr-Oct 2000	3.55	Beysens et al. (2005)
				Apr-Oct 2001	5.61	
				Apr-Oct 2002	4.51	
Zadar (Croatia)	May-Oct 2013	7.83	6.09	May-Oct 2004	7.59	Muselli et al. (2009)
				May-Oct 2005	6.89	

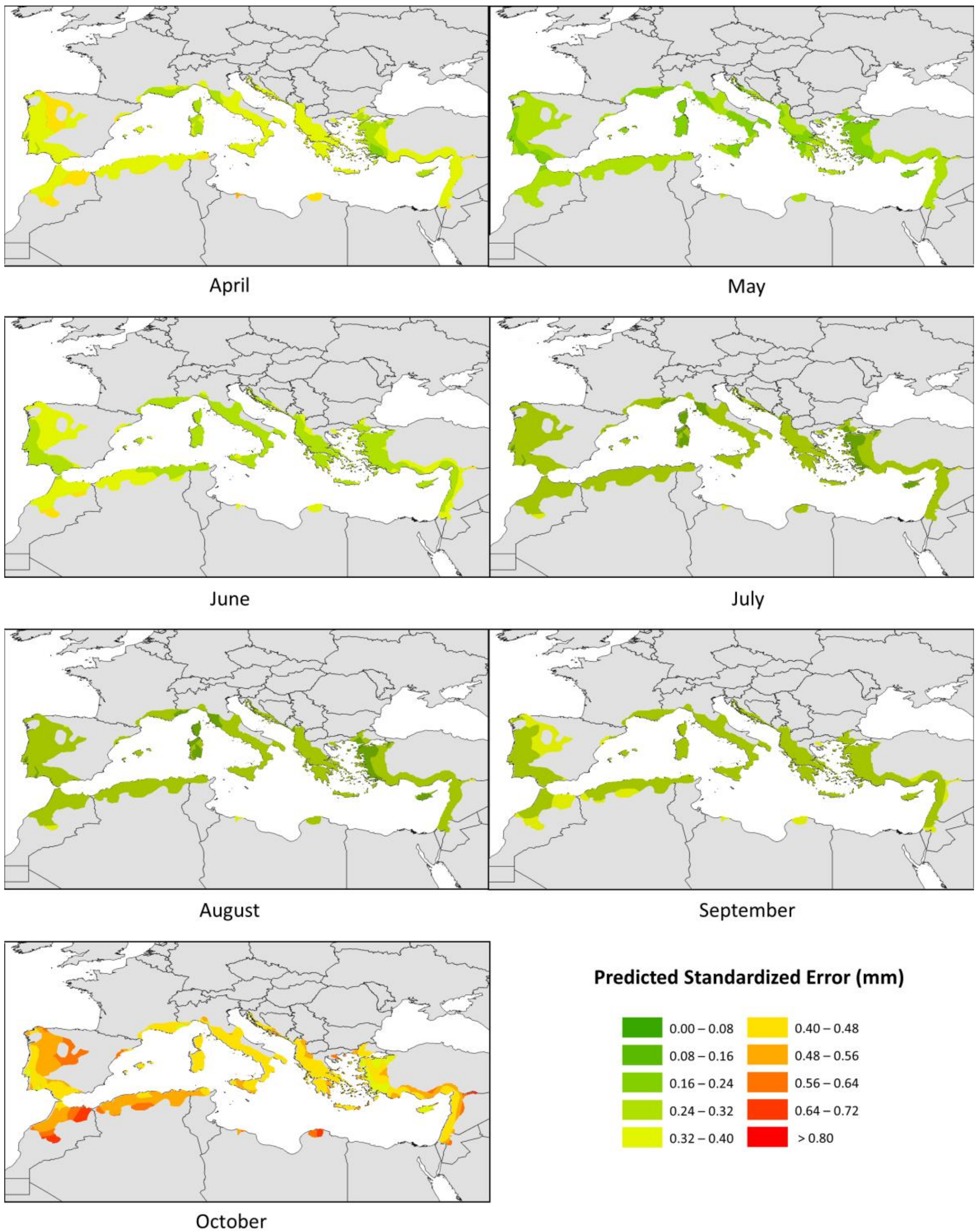

Figure 4.4. Predicted standardized error ($\sqrt{\sigma}$) of monthly dew for the 2013 Mediterranean dry season (compare modeled dew at 142 meteorological stations to modeled dew determined from geostatistical analysis)

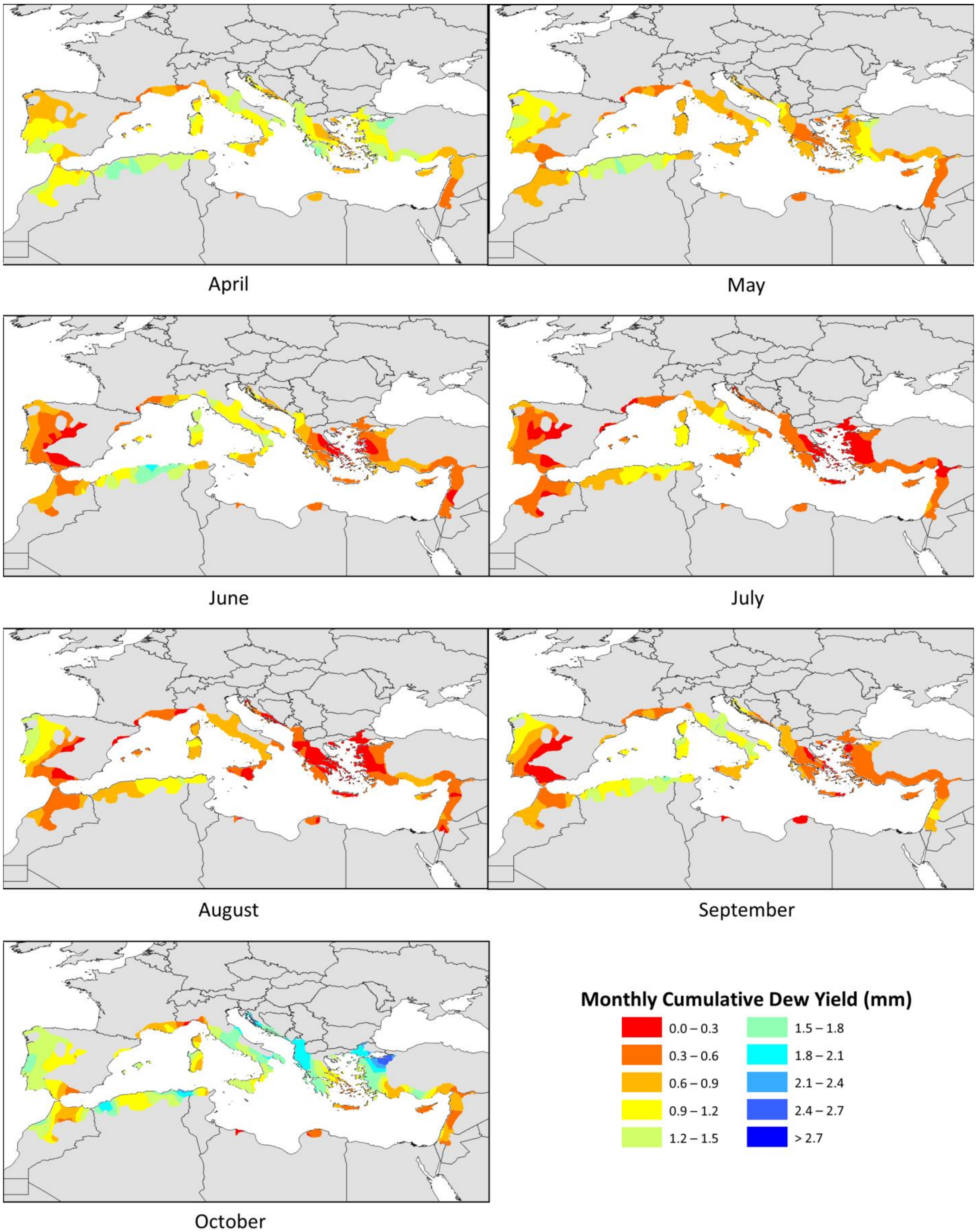

Figure 4.5. Estimated dew yield for the Mediterranean during the 2013 dry season

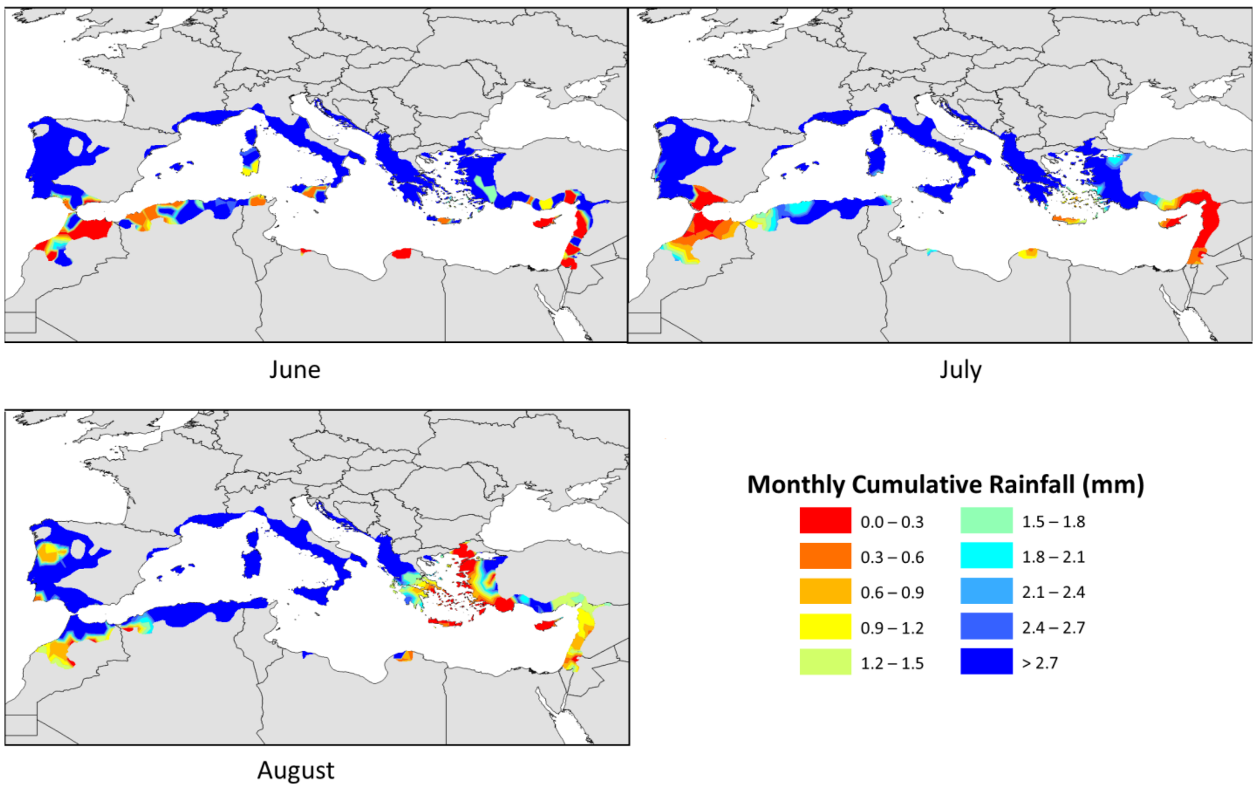

Figure 4.6. Actual rainfall during selected months in the Mediterranean, 2013

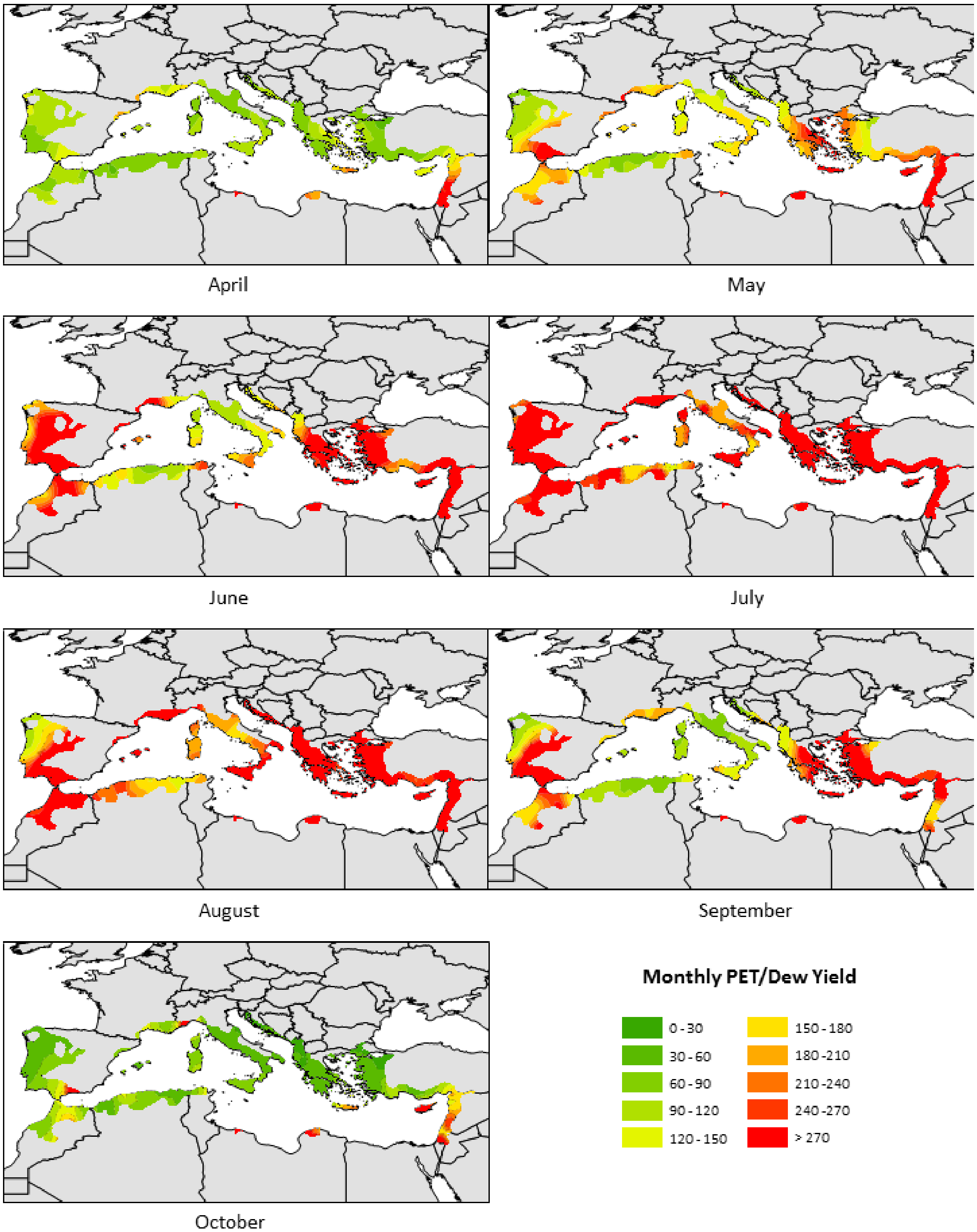

Figure 4.7. Ratio of monthly potential evapotranspiration (*PET*) to monthly dew yield 2013

4.3.3. Projected temperature and relative humidity trends

Based on an ensemble of the models run under CMIP5, the projected temperature increase over the Mediterranean is expected to be prominent during the summer months (~0.55 ℃ decade^{-1} for RCP8.5) (Cattiaux et al., 2013). The HadGEM2-ES model has demonstrated superior performance to simulate projected temperature within the region and as a result (Elguindi et al., 2014), the resultant trends are similar to the ensemble average (0.35 ℃ decade^{-1} and 0.60 ℃ decade^{-1} for RCP4.5 and RCP8.5, respectively) (Tables 4.7 and 4.8). On the other hand, EC-EARTH has revealed a cool bias in some regions (McSweeney et al., 2015) which may explain why the projected increase in temperature is less (0.24℃ decade^{-1} and 0.35 ℃ decade^{-1} for RCP4.5 and RCP8.5, respectively).

Across the region, temperature increases tend to be the greatest in interior Spain, Greece, and the Algerian and Tunisian coastline for all scenarios run under both the EC-EARTH and the HadGEM2-ES models. Conversely, projected temperature increases are lowest in southwestern Spain, southern Italy, and the eastern Mediterranean. The model results do not show a consistent pattern with regards to changes in RH. While in general there appears to be a decline, in some cases *RH* is projected to increase particularly under the EC-EARTH RCP4.5 scenario. Spatially, *RH* tends to follow those observed for temperature; the greatest decreases tended to be in interior Spain, Greece, and the Algerian and Tunisian coastline, with less pronounced drops in southwestern Spain, southern Italy, and the eastern Mediterranean.

4.3.4. Climate change and dew yield

4.3.4.1. EC-EARTH RCP4.5

Among the four scenarios studied, the sole scenario which predicted a general increase in dew yield was the EC-EARTH RCP4.5 (Figure 4.8 and Table 4.7), attributed to the comparatively lower increase in temperature and decrease in relative humidity for June, July, and August (JJA) (0.24℃ decade^{-1} and -0.06 % decade^{-1}, respectively). Differences between the 2013 and 2013* baseline mapping differed both spatially and in magnitude (average JJA dew yield was 1.81 and 2.06 mm, respectively) due to using modeled climate data instead of actual data. (Similar differences were observed for all scenarios and consequently, comparisons were between 2013* and future years). Under this scenario, the average monthly dew yield is increasing 0.01 mm decade^{-1} and although this quantity is small, it results in an overall increase in dew (9%) with localized areas (Spain, eastern Mediterranean) increasing significantly (up to 80%) (Figures 4.12 and 4.13). A closer monthly examination reveals the largest increases in dew yield during July in southeastern Sardinia (Italy) (0.06 mm decade^{-1}), attributed to the localized increase in *RH* (0.23 % decade^{-1}) and relatively low increase in temperature (0.19 ℃ decade^{-1}) (Table 4.8). Conversely, the largest decline in dew (-0.04 mm decade^{-1}) was observed in coastal Turkey (adjacent to the Aegean Sea) in June resulting from both a decline in *RH* (-0.39 % decade^{-1}) and increase in temperature (0.41 ℃ decade^{-1}).

4.3.4.2. EC-EARTH RCP8.5

Because RCP 8.5 is a higher emissions scenario than RCP4.5 (8.5 and 4.5 W m^{-2}, respectively), there was a resultant larger projected increase in temperature and greater decline in relative humidity (0.48 ℃ $decade^{-1}$ and -0.31 % $decade^{-1}$, respectively, for JJA) under the EC-EARTH RCP8.5 scenario compared to EC-EARTH RCP4.5, although the driving model is the same. Correspondingly, a general decline in dew was predicted (-0.01 mm $decade^{-1}$) (Figure 4.9 and Table 4.7). The largest decreases were detected in Italy and the Tunisian Coast (Figure 4.12), with a localized decline of -0.1 mm $decade^{-1}$ in July (-96%).

This scenario also detected projected increases in dew yield in some areas, particularly along the Turkish Mediterranean coastline (0.05 mm $decade^{-1}$ or 18%) due to a general increase in *RH* (0.26 % $decade^{-1}$). On a monthly basis, the increase in volume was greatest in June (0.07 mm $decade^{-1}$) which was comparatively low on a percentage basis (16%). However, a significant percentage increase in yield was noted in August (26%), although the net increase was small (0.03 mm $decade^{-1}$).

4.3.4.3. HadGEM2-ES RCP4.5

Both scenarios conducted using data obtained from the HadGEM2-ES model revealed a projected general decline in dew yield for JJA. Like the previous scenarios, changes in yield for HadGEM2-ES RCP 4.5 are small (-0.02 mm $decade^{-1}$) (Figure 4.10 and Table 4.7) with the largest decreases in volume found in Portugal, Spain, and Italy

(Figure 4.12). Correspondingly, these areas had the largest increase in temperature and decrease in *RH* (0.59 ℃ $decade^{-1}$ and -1.2 % $decade^{-1}$, respectively; Table 4.9). The net decrease in dew yield is the largest compared to the other three scenarios (-0.43 mm; -27%) (Figures 4.12 and 4.13). This is attributed to a significant reduction in dew yield in July and August from 2013 to 2080 [-0.18 mm (-29%) and -0.12 (-23%), respectively] due to a comparatively large declining trend in relative humidity (-0.3 % $decade^{-1}$). No areas detected an increase in yield.

4.3.4.4. HadGEM2-ES RCP8.5

Although HadGEM2-ES RCP8.5 is the result of a higher emissions scenario than the previous, net and percentage decrease in dew yield are smaller (Figures 4.11, 4.12, and 4.13) despite the larger increase in temperature and decline in *RH* (0.60 ℃ $decade^{-1}$ and -0.37 % $decade^{-1}$, respectively, for JJA). This is because the predicted dew volumes were comparatively less than other scenarios and often nil (particularly during August in the eastern Mediterranean) and thus decline was of smaller magnitude. On average, the decline was -0.02 mm $decade^{-1}$ (-23%) and the largest decreases were observed in the central Mediterranean (-0.08 mm $decade^{-1}$).

Table 4.7. Projected trends in temperature and relative humidity for selected locations based on Euro-CORDEX gridded data and the EC-EARTH climate model

Location	*Lon*	*Lat*	*EC-EARTH RCP4.5*						*EC-EARTH RCP8.5*					
			Temperature (^0C decade^{-1})			*Relative Humidity (% decade^{-1})*			*Temperature (^0C decade^{-1})*			*Relative Humidity (% decade^{-1})*		
			Jun	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*
Lisbon (Portugal)	-9.133	38.767	0.20	0.15	0.23	0.18	0.05	0.29	0.40	0.33	0.35	0.09	0.11	0.11
La Corona (Spain)	-8.383	43.300	0.13	0.17	0.39	0.22	-0.19	-0.17	0.77	0.69	0.69	-0.32	-0.24	-0.45
Rota (Spain)	-6.350	36.650	0.16	0.14	0.20	0.45	-0.27	-0.47	0.28	0.25	0.27	0.39	0.07	-0.47
Madrid (Spain)	-3.550	40.450	0.40	0.43	0.62	0.36	-0.23	-0.97	0.92	0.90	0.90	-0.96	-0.72	-0.94
Palma de Mallorca (Spain)	2.733	39.550	0.19	0.19	0.21	0.22	0.00	0.16	0.37	0.40	0.38	0.32	0.10	0.16
Montpellier (France)	3.967	43.583	0.25	0.23	0.36	-0.21	0.03	0.04	0.57	0.58	0.58	-0.19	-0.46	-0.60
Nice (France)	7.200	43.650	0.24	0.22	0.36	-0.01	0.08	-1.07	0.52	0.52	0.55	0.05	0.06	-0.51
Ajaccio (France)	8.800	41.917	0.26	0.17	0.32	0.05	-0.24	-1.29	0.57	0.54	0.49	-1.16	-0.60	-0.20
Capo Carbonara (Italy)	9.517	39.100	0.17	0.19	0.23	0.37	0.23	0.03	0.40	0.41	0.41	-0.16	0.03	0.07
Florence (Italy)	11.200	43.800	0.32	0.28	0.45	-0.51	-0.51	-1.54	0.84	0.71	0.67	-1.62	-0.85	-0.68
Rome (Italy)	12.233	41.800	0.18	0.17	0.23	0.22	-0.26	-0.61	0.36	0.40	0.42	-0.33	-0.01	0.10
Trapani (Italy)	12.500	37.917	0.18	0.19	0.21	0.03	-0.15	-0.11	0.40	0.42	0.39	-0.69	-0.60	-0.02

Location	Lon	Lat	EC-EARTH RCP4.5						EC-EARTH RCP8.5					
			Temperature (^{0}C decade^{-1})			Relative Humidity (% decade^{-1})			Temperature (^{0}C decade^{-1})			Relative Humidity (% decade^{-1})		
			Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug
Marina di Ginosa (Italy)	16.883	40.433	0.20	0.18	0.21	0.03	0.00	-0.63	0.36	0.36	0.37	-1.30	-0.22	-0.46
Dubrovnik (Croatia)	18.267	42.567	0.19	0.60	0.17	0.13	0.10	-0.26	0.29	0.35	0.33	0.10	0.28	0.33
Tirana (Albania)	19.783	41.333	0.33	0.24	0.41	0.27	-0.03	-1.08	0.73	0.63	0.59	-1.67	-0.77	-0.64
Andravida (Greece)	21.283	37.917	0.25	0.22	0.29	0.35	-0.34	-0.98	0.53	0.54	0.51	-1.01	-0.70	-0.41
Athens (Greece)	23.950	37.933	0.29	0.24	0.21	-0.05	0.15	-0.38	0.53	0.51	0.54	-0.96	-0.59	-0.51
Limnos (Greece)	25.233	39.917	0.22	0.20	0.17	-0.22	0.01	-0.66	0.38	0.35	0.39	-0.77	-0.79	-0.62
Izmir (Turkey)	27.150	38.267	0.41	0.23	0.30	-0.39	-0.06	-0.43	0.66	0.62	0.63	-1.26	-0.84	-0.57
Balıkesir (Turkey)	27.917	39.617	0.31	0.22	0.16	-0.08	0.29	0.38	0.47	0.47	0.52	-0.22	-0.66	-0.46
Dalaman (Turkey)	28.783	36.700	0.19	0.17	0.20	0.21	0.07	0.15	0.28	0.31	0.38	0.48	0.14	0.15
Gazipaşa (Turkey)	32.299	36.300	0.19	0.19	0.21	0.99	0.13	0.50	0.34	0.39	0.43	0.76	-0.41	0.26
Larnaca (Cyprus)	33.633	34.883	0.19	0.18	0.20	1.03	0.10	0.55	0.30	0.41	0.41	0.74	-0.26	0.43
Lattakia (Syria)	35.933	35.400	0.19	0.20	0.20	0.19	-0.12	0.08	0.29	0.36	0.39	0.24	-0.17	0.05
Beirut (Lebanon)	35.483	33.817	0.20	0.21	0.23	0.58	-0.09	0.03	0.32	0.38	0.43	0.35	-0.33	-0.09
Tel Aviv (Israel)	34.900	32.000	0.20	0.24	0.27	0.03	-0.08	-0.39	0.43	0.41	0.49	-0.02	-0.22	-0.25

Location	Lon	Lat	EC-EARTH RCP4.5						EC-EARTH RCP8.5					
			Temperature (^{0}C decade^{-1})			Relative Humidity (% decade^{-1})			Temperature (^{0}C decade^{-1})			Relative Humidity (% decade^{-1})		
			Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug
Nouasseur (Morocco)	-7.583	33.367	0.22	0.23	0.33	0.00	-0.03	-0.16	0.37	0.40	0.44	0.34	-0.11	-0.01
Ghriss (Algeria)	0.150	35.217	0.32	0.24	0.37	-0.26	-0.33	-0.99	0.70	0.53	0.45	-0.77	-0.63	0.08
Béjaïa (Algeria)	5.067	36.717	0.31	0.15	0.24	0.43	0.18	-0.57	0.68	0.47	0.43	-0.98	-0.83	-0.14
Tunis (Tunisia)	10.233	36.833	0.21	0.17	0.26	0.44	-0.07	-0.14	0.68	0.49	0.45	-1.15	-0.55	0.00
Benghazi (Libya)	20.270	32.080	0.19	0.15	0.11	0.25	0.28	0.70	0.27	0.44	0.43	0.31	-0.52	-0.24

Table 4.8. Projected trends in temperature and relative humidity for selected locations based on Euro-CORDEX gridded data and the HadGEM2-ES climate model

Location	*Lon*	*Lat*	*HadGEM2-ES RCP4.5*						*HadGEM2-ES RCP8.5*					
			Temperature (^{0}C decade^{-1})			*Relative Humidity (% decade^{-1})*			*Temperature (^{0}C decade^{-1})*			*Relative Humidity (% decade^{-1})*		
			Jun	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*
Lisbon (Portugal)	-9.133	38.767	0.35	0.24	0.25	-0.78	-0.30	0.01	0.38	0.41	0.45	-0.18	-0.20	0.06
La Corona (Spain)	-8.383	43.300	0.30	0.36	0.51	-0.47	-0.51	-0.60	0.41	0.57	0.72	-0.08	-0.40	-0.63
Rota (Spain)	-6.350	36.650	0.20	0.16	0.17	-0.29	-0.01	0.07	0.22	0.18	0.18	0.07	-0.20	0.24
Madrid (Spain)	-3.550	40.450	0.53	0.44	0.59	-1.19	-0.85	-0.98	0.79	0.87	0.82	-1.09	-1.11	-1.00
Palma de Mallorca (Spain)	2.733	39.550	0.29	0.33	0.36	-0.17	-0.11	-0.10	0.50	0.58	0.62	0.07	-0.33	-0.79
Montpellier (France)	3.967	43.583	0.35	0.40	0.42	-0.56	-0.41	-0.95	0.65	0.72	0.68	-0.20	-1.01	-1.10
Nice (France)	7.200	43.650	0.39	0.41	0.39	-0.80	-0.36	-0.52	0.66	0.64	0.62	-0.17	0.10	-0.21
Ajaccio (France)	8.800	41.917	0.43	0.45	0.35	-1.07	-0.84	-0.32	0.73	0.64	0.54	-1.23	-0.02	0.42
Capo Carbonara (Italy)	9.517	39.100	0.34	0.37	0.32	-0.31	-0.35	-0.54	0.54	0.59	0.57	0.02	-0.22	-0.67
Florence (Italy)	11.200	43.800	0.47	0.48	0.42	-0.92	-0.65	-0.96	0.97	0.84	0.55	-1.25	-0.60	-0.29
Rome (Italy)	12.233	41.800	0.32	0.34	0.28	-0.27	-0.51	-0.60	0.54	0.61	0.56	-0.09	-1.32	-1.60
Trapani (Italy)	12.500	37.917	0.34	0.34	0.28	-0.29	-0.14	-0.02	0.56	0.57	0.54	-0.79	-0.25	-0.25

Location	*Lon*	*Lat*	*HadGEM2-ES RCP4.5*						*HadGEM2-ES RCP8.5*					
			Temperature (^{0}C decade^{-1})			*Relative Humidity (% decade^{-1})*			*Temperature (^{0}C decade^{-1})*			*Relative Humidity (% decade^{-1})*		
			Jun	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*
Marina di Ginosa (Italy)	16.883	40.433	0.37	0.42	0.40	-0.64	0.06	-0.50	0.61	0.72	0.68	-0.58	-0.69	-0.17
Dubrovnik (Croatia)	18.267	42.567	0.32	0.43	0.44	-0.39	-0.27	-0.56	0.57	0.73	0.76	-0.18	-0.62	-0.43
Tirana (Albania)	19.783	41.333	0.45	0.35	0.40	-0.65	-0.05	-0.42	0.77	0.79	0.51	-0.90	-0.54	0.51
Andravida (Greece)	21.283	37.917	0.39	0.37	0.41	-0.47	-0.35	-0.37	0.77	0.75	0.66	-0.90	-0.32	-0.02
Athens (Greece)	23.950	37.933	0.33	0.33	0.37	-0.35	-0.10	-0.14	0.63	0.71	0.67	-0.67	-0.62	-0.06
Limnos (Greece)	25.233	39.917	0.31	0.28	0.35	-0.33	-0.24	-0.33	0.53	0.57	0.59	-0.46	-0.32	-0.11
Izmir (Turkey)	27.150	38.267	0.46	0.36	0.39	-0.60	-0.21	-0.07	0.70	0.74	0.71	-1.64	-1.56	-0.93
Balıkesir (Turkey)	27.917	39.617	0.32	0.34	0.36	-0.18	-0.23	-0.05	0.49	0.66	0.68	-0.19	-0.62	-0.13
Dalaman (Turkey)	28.783	36.700	0.24	0.29	0.34	0.13	-0.23	-0.26	0.46	0.58	0.62	-0.04	-0.15	-0.18
Gazipaşa (Turkey)	32.299	36.300	0.26	0.27	0.33	0.16	0.16	-0.24	0.46	0.47	0.46	0.13	0.33	0.60
Larnaca (Cyprus)	33.633	34.883	0.29	0.32	0.35	-1.19	-0.99	-1.19	0.47	0.52	0.55	0.45	0.21	0.04
Lattakia (Syria)	35.933	35.400	0.27	0.32	0.34	-0.21	-0.31	-0.33	0.48	0.53	0.49	-0.07	-0.35	-0.25
Beirut (Lebanon)	35.483	33.817	0.27	0.31	0.32	0.14	-0.35	-0.14	0.48	0.55	0.53	0.17	-0.27	-0.24
Tel Aviv (Israel)	34.900	32.000	0.27	0.33	0.33	0.11	-0.33	-0.23	0.51	0.57	0.59	-0.11	-0.42	-0.45

Location	*Lon*	*Lat*	*HadGEM2-ES RCP4.5*						*HadGEM2-ES RCP8.5*					
			Temperature (^{0}C decade^{-1})			*Relative Humidity (% decade^{-1})*			*Temperature (^{0}C decade^{-1})*			*Relative Humidity (% decade^{-1})*		
			Jun	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*	*Jun*	*Jul*	*Aug*
Nouasseur (Morocco)	-7.583	33.367	0.30	0.22	0.35	-0.14	-0.21	-0.32	0.42	0.47	0.41	-0.29	-0.29	-0.35
Ghriss (Algeria)	0.150	35.217	0.47	0.31	0.45	-0.49	0.18	-0.32	0.72	0.67	0.62	-0.58	-0.07	-0.30
Béjaïa (Algeria)	5.067	36.717	0.57	0.40	0.37	-1.03	-0.03	-0.44	0.87	0.68	0.48	-1.17	-0.16	0.37
Tunis (Tunisia)	10.233	36.833	0.42	0.41	0.42	-0.51	-0.29	-0.53	0.85	0.77	0.62	-0.99	-0.60	-0.42
Benghazi (Libya)	20.270	32.080	0.16	0.39	0.32	0.65	-0.48	0.14	0.57	0.60	0.63	-0.25	-0.17	-0.45

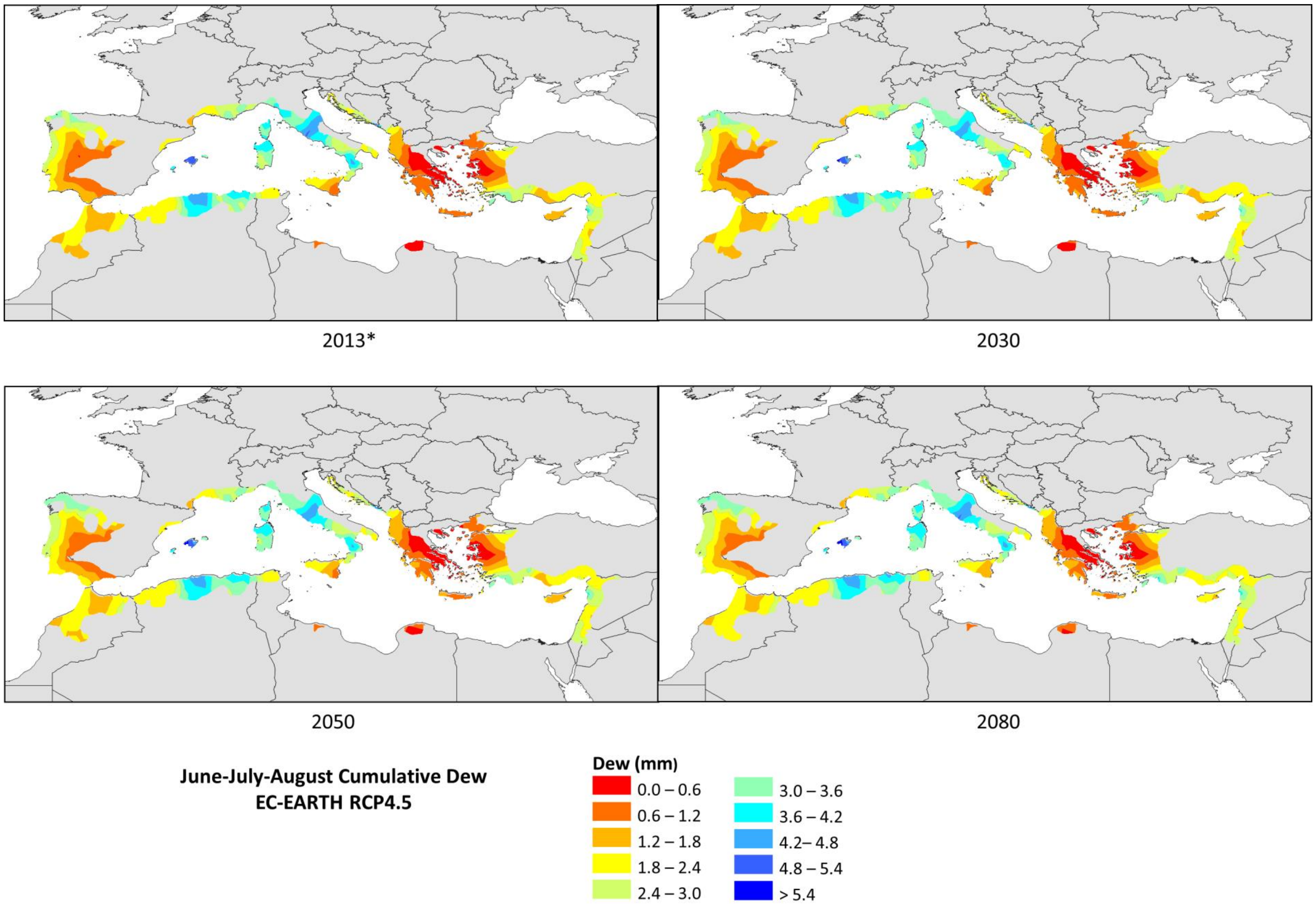

Figure 4.8. Projected dew yield for 2013*, 2030, 2050, and 2080 based on the EC-EARTH RCP4.5 scenario

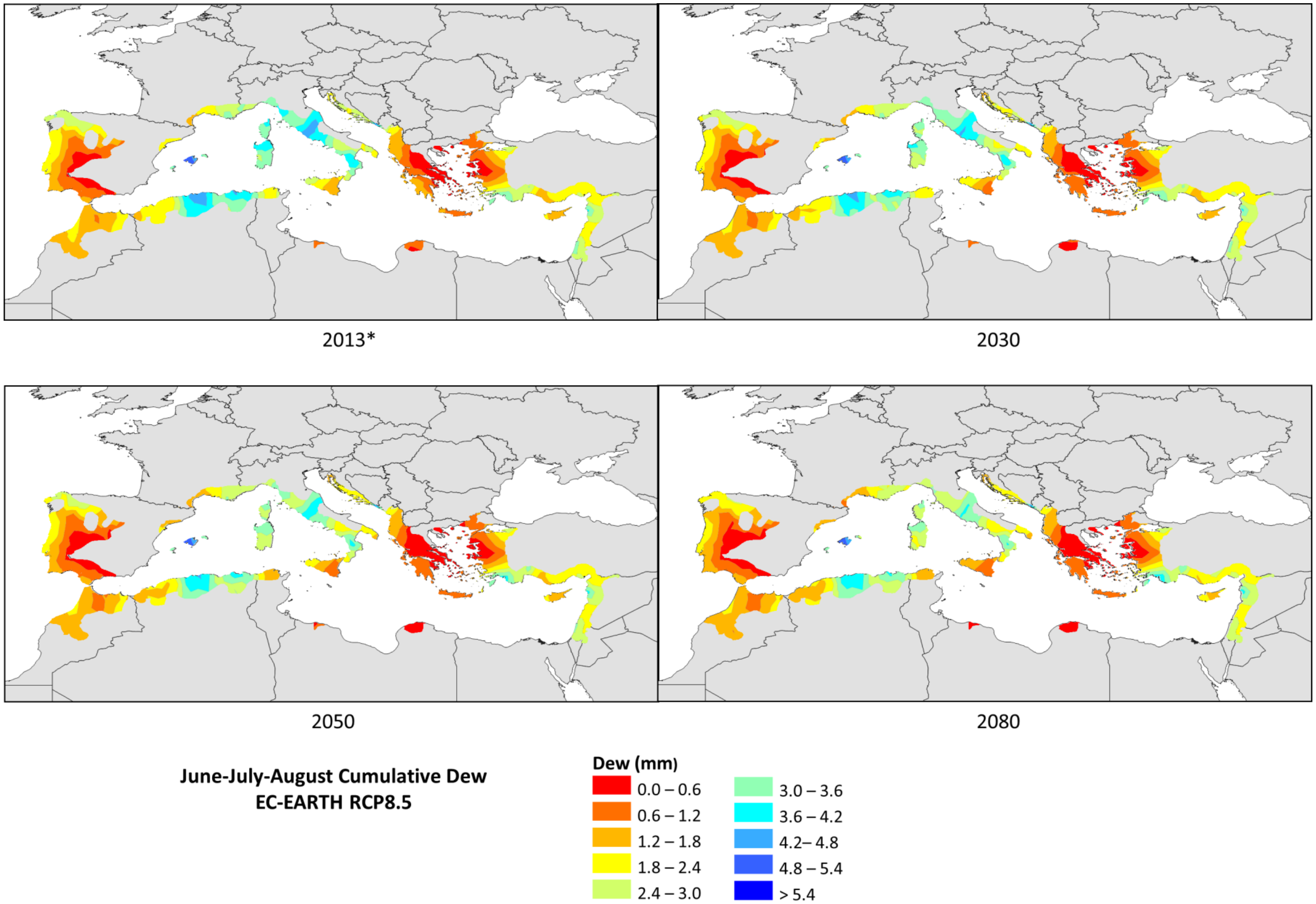

Figure 4.9. Projected dew yield for 2013*, 2030, 2050, and 2080 based on the EC-EARTH RCP8.5 scenario

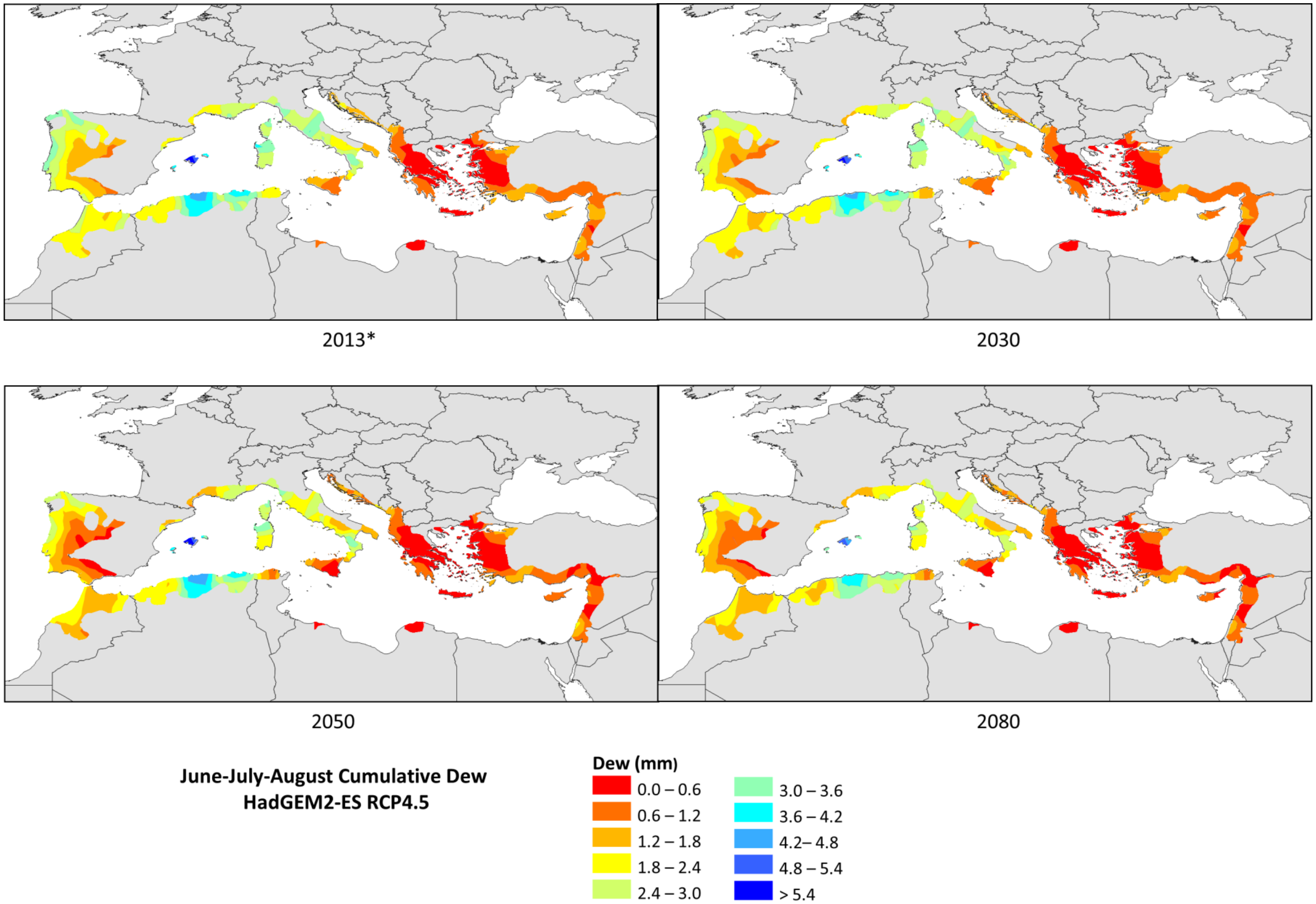

Figure 4.10. Projected dew yield for 2013*, 2030, 2050, and 2080 based on the HadGEM2-ES RCP4.5 scenario

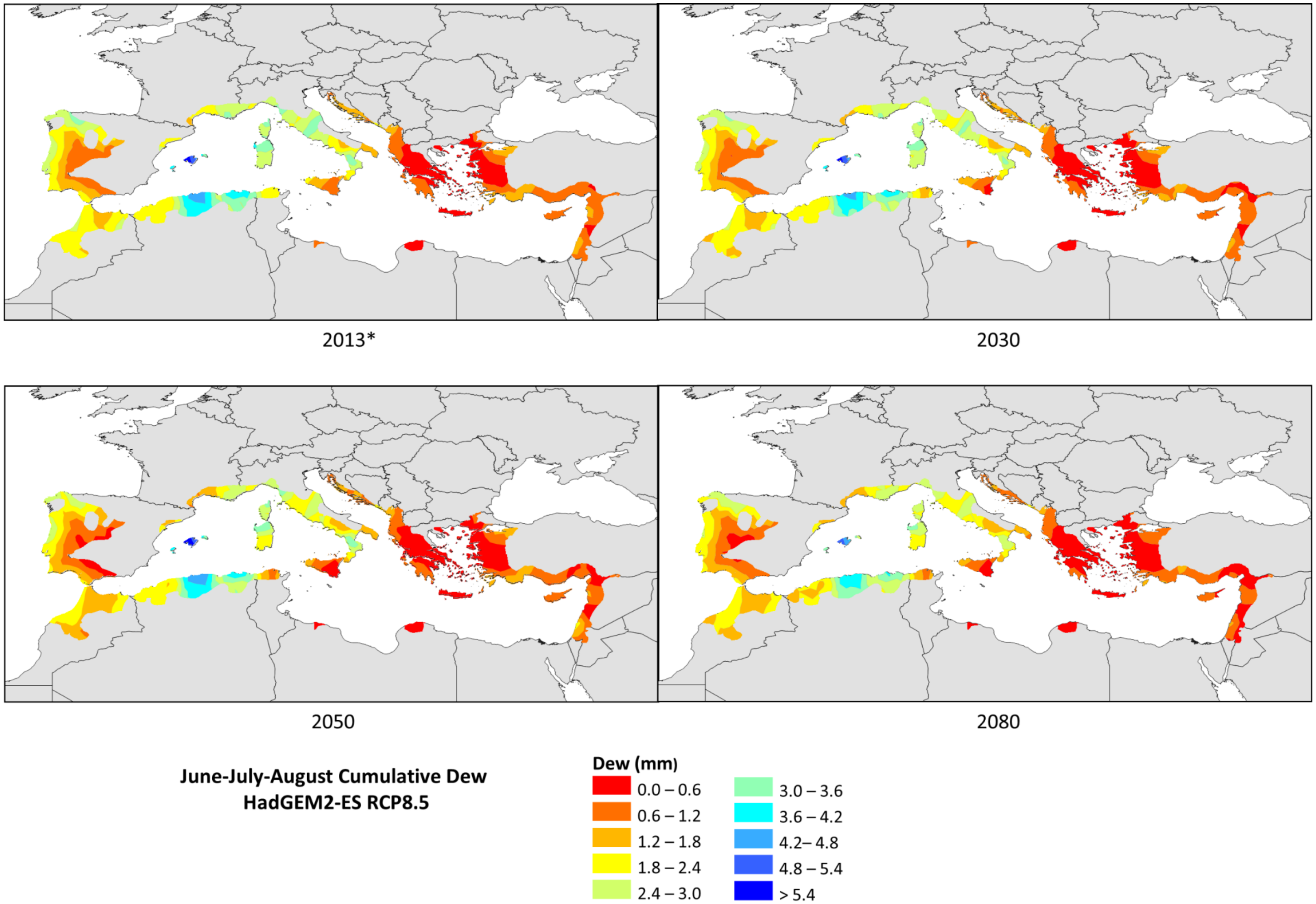

Figure 4.11. Projected dew yield for 2013*, 2030, 2050, and 2080 based on the HadGEM2-ES RCP8.5 scenario

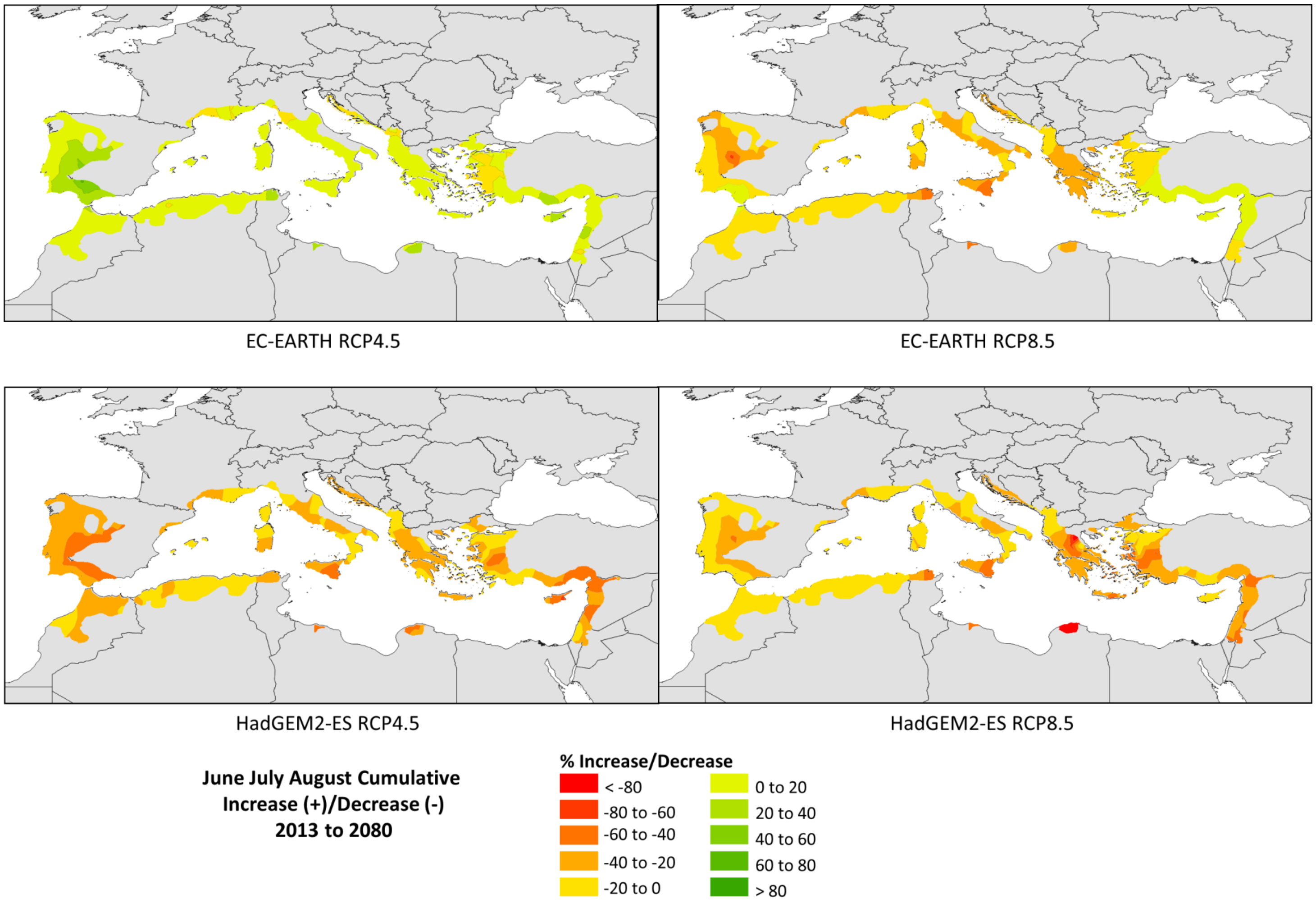

Figure 4.12. Projected percentage increase (or decrease) in dew yield from 2013 to 2080 for differing climate model scenarios

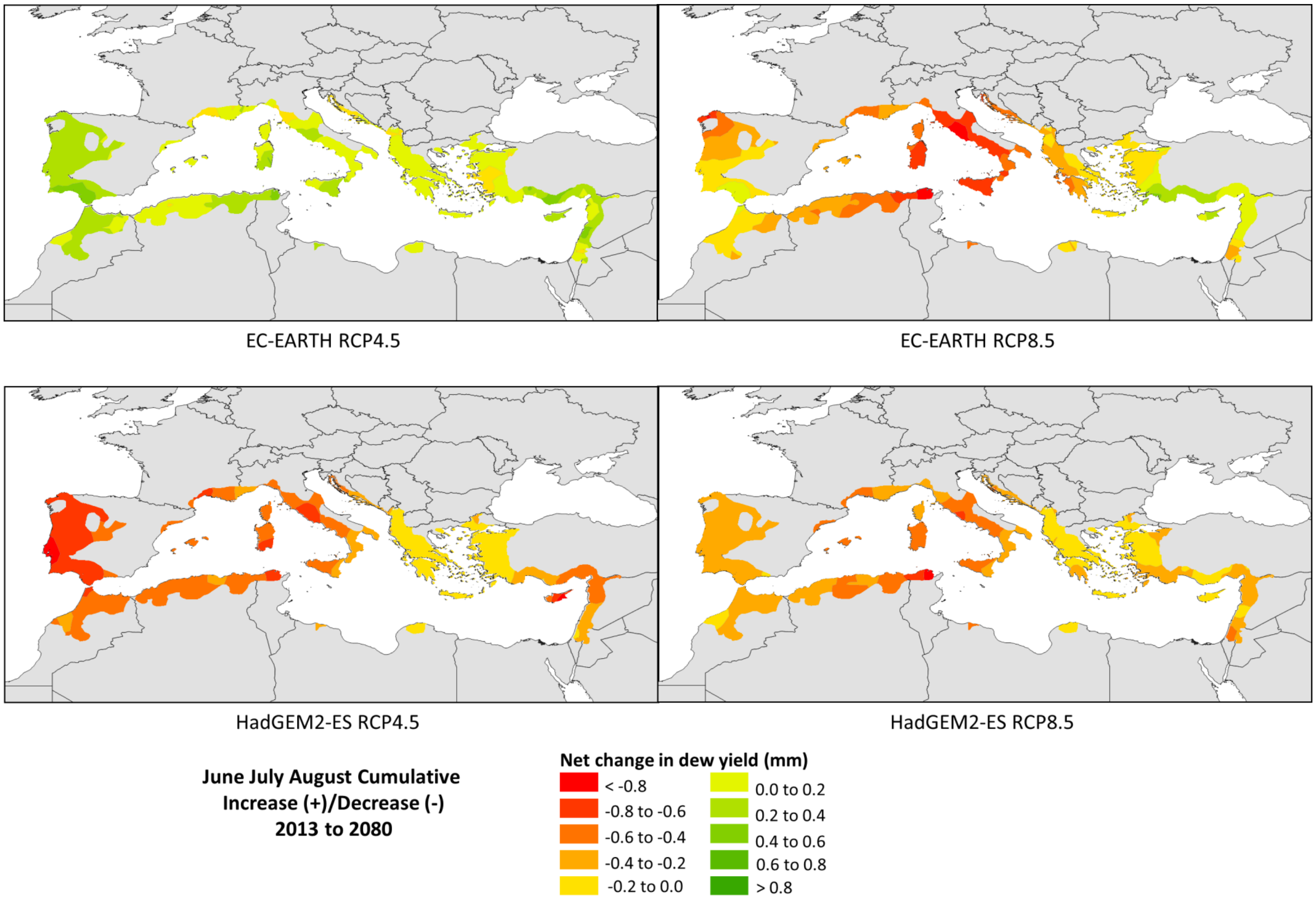

Figure 4.13. Projected net increase (or decrease) in dew yield from 2013 to 2080 for differing climate model scenarios

Table 4.9. Summary of average projected dew yield (mm) for the Mediterranean region based on 4 different climate scenarios

	Dew yield (mm)				*Dew yield (mm)*				*Dew yield (mm)*				*Dew yield (mm)*			
Scenario	*EC-EARTH RCP4.5*				*EC-EARTH RCP8.5*				*HadGEM2-ES RCP4.5*				*HadGEM2-ES RCP8.5*			
Year	*2013*	*2030*	*2050*	*2080*	*2013*	*2030*	*2050*	*2080*	*2013*	*2030*	*2050*	*2080*	*2013*	*2030*	*2050*	*2080*
June	0.55	0.55	0.57	0.59	0.56	0.52	0.49	0.46	0.47	0.43	0.38	0.33	0.44	0.39	0.36	0.32
July	0.77	0.79	0.81	0.85	0.76	0.72	0.69	0.67	0.67	0.62	0.57	0.50	0.62	0.59	0.57	0.53
August	0.73	0.75	0.77	0.81	0.71	0.67	0.65	0.64	0.69	0.66	0.62	0.58	0.65	0.62	0.60	0.57
Total	2.06	2.09	2.15	2.24	2.02	1.91	1.83	1.77	1.84	1.71	1.57	1.41	1.71	1.61	1.52	1.42

4.4. Concluding remarks

Water resources which derive from atmospheric moisture, such as dew, can be significant contributors to the water cycle, particularly when precipitation is negligible during the dry season in arid and semi-arid regions. In this study, an analytical method was adopted to predict yields across 142 stations within the Mediterranean. Geostatistical interpolation was used to generate a baseline comprehensive atlas across the entire Mediterranean basin. Forecasted trends in temperature and relative humidity were then obtained from gridded climatological data under low and high emissions scenarios at selected locations. These trends were applied to the baseline modeling to estimate future outlook of dew yields across the basin. The study predicted dew harvesting may decline (up to 27%) during the dry season; yet the rate of decrease was found to be less than the projected decrease in precipitation (up to 40%; EEA, 2015) during the same period in the Mediterranean region.

The proposed methodology possesses inherent weaknesses which can be potentially resolved with the next generation of gridded climatological data. Ideally, an ensemble of gridded data would be utilized for both baseline and future scenarios. It is imperative that data is of sufficient temporal scale to model dew yield because dew is dependent upon nightly minimum temperature and maximum relative humidity. Nocturnal wind velocity and particularly cloud cover is also necessary at a fine temporal scale because conditions can differ from the day (Warren et al., 2007). From this data, dew yield can subsequently be estimated for each grid location and can be compared to the results obtained in this study.

CHAPTER 5

DEW AS AN ADAPTATION MEASURE TO SUPPLEMENT WATER DEMAND FOR REFORESTATION AND AGRICULTURE

Non-conventional water resources have emerged as means to meet or supplement irrigation demand for reforestation and agriculture in water scarce regions. Dew water is among those resources that have received little attention. In this paper, we compare water demands to measured dew volumes to assess the feasibility of irrigation from dew harvesting. We estimate water demands of selected trees seedlings using ET-based modeling, while corresponding dew volumes were experimentally measured during the dry season. Field data collected from dew condensers showed average nightly dew yield of 0.13 L m^{-2} of condensing surface, with a maximum yield of 0.46 L m^{-2} d^{-1}. Dew events generally occur more frequently than precipitation events, with an estimated 43% of nights producing dew condensate during the dry season (April-October). The experimental results showed that above average nightly dew yields (> 0.2 L m^{-2} d^{-1}) can have a significant impact upon diurnal soil moisture (> 3%). We demonstrate that harvesting and storing dew using reasonable condensing areas (~2 m^2) can be sufficient to irrigate tree seedlings, typically requiring ~4.5 L $seedling^{-1}$ every 30-40 days, thus providing a feasible option mitigating tree mortality during droughts or in arid or semi-arid regions.

5.1. Introduction

Dew represents a small, yet significant, component of the water budget in terrestrial ecosystems. For example, dew often serves as the primary water resource for biological soil crusts (Kidron et al., 2002; Pan and Wang 2014), lichens (Kidron and Termina, 2013; del Prado and Sancho, 2007), and small shrubs (Pan et al., 2010; Pan and Wang, 2014) in desert environments. In addition, leaf pubescence (hairs), often encountered within plants in arid environments, can promote dew formation, prevent dew evaporation, and reduce transpiration (Konrad et al., 2015). Dew may also help initiate plant photosynthesis (Kidron et al., 2002; del Prado and Sancho, 2007) and reproduction (Kidron et al., 2002). In other ecosystems, evapotranspiration can exceed precipitation and irrigation concluding that dew uptake compensates for the additional demand (Fritschen and Doraiswamy, 1973; Glenn et al., 1996; Malek et al., 1999). Hunt et al. (2008) reported that dew and fog affect crop evapotranspiration based on measurements using lysimeters and Moratiel et al. (2013) suggested a simple method to correct soil moisture based on dew, fog, and mist effects. Note however that dew rarely forms upon bare soil (Agam and Berliner, 2004); instead diurnal changes in soil moisture content are attributed to absorption of water vapor (Ninari and Berliner, 2002; Agam and Berliner, 2004).

Furthermore, dew has reportedly exhibited some potential for irrigation. Early work by Alnaser and Barakat (2000) suggested coupling passive dew harvesting with a drip irrigation system in Bahrain. Similarly, Chen and Cai (2012) proposed an irrigation system in China using atmospheric water harvesting.. A single-wall polypropylene tree shelter in Spain demonstrated the effectiveness of dew harvesting which resulted in an increase in soil moisture content (del Campo et al., 2006). Most recently, a large conical dew-harvesting prototype (~49 m^2)

implemented in West Africa was reported to collect up to 0.43 L m^{-2} d^{-1} which provided 43% of water requirements for maize (Gabin, 2015).

While much efforts have been devoted towards the exploitation of non-conventional water resources for reforestation and crop irrigation (Djuma et al., 2014), data on the use of irrigation water harvested from the atmosphere in the form of dew remains limited. In this study, we conduct a feasibility assessment to evaluate the potential for utilizing harvested dew to offset part of the water demands of selected trees seedlings for use in reforestation and agricultural applications.

5.2. Methodology

5.2.1. Study area

Experimental work was conducted during 2014 in the village of Beiteddine, Lebanon, which is located at 920 msl along the mountain chain overlooking the eastern Mediterranean (Figure 5.1). The site was selected based on superior dew yield measured in the 2013 season (Chapter 3). The climate is semi-arid with a prolonged dry season during warm months (April-October), followed by a wet period (November-March). Meteorological conditions for the 2014 growing season are presented in Table 5.1.

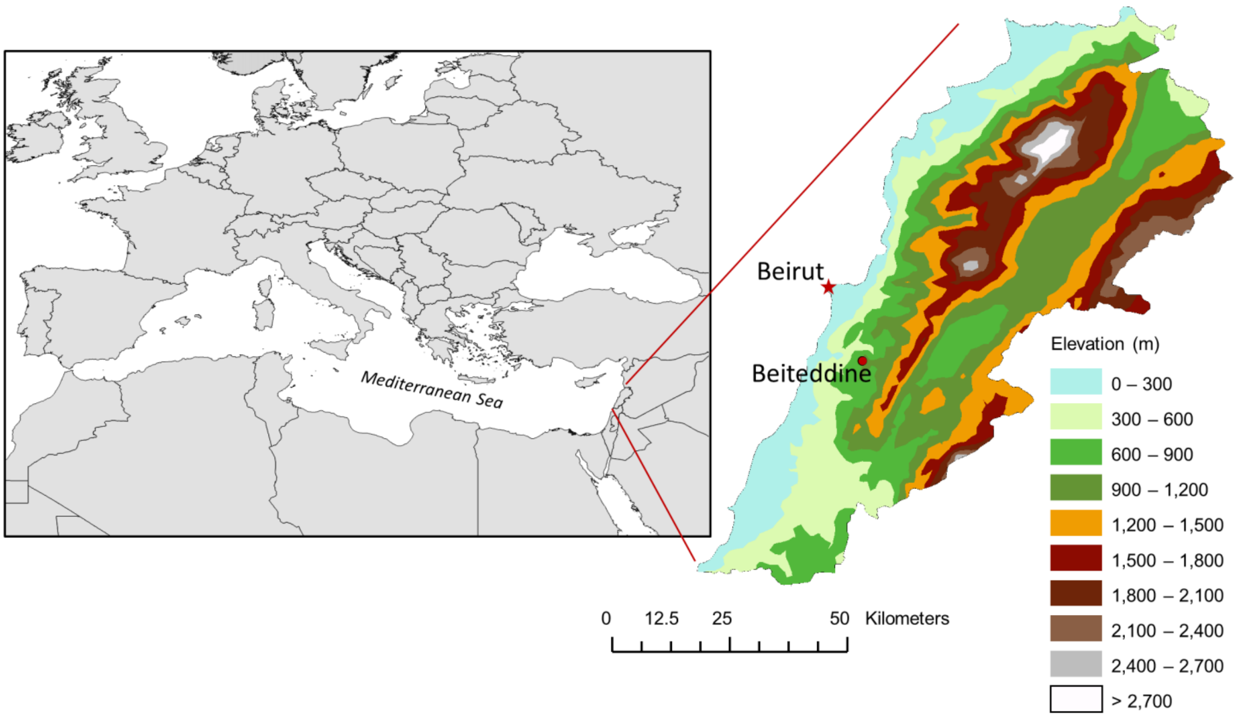

Figure 5.1. Study area

Table 5.1. Meteorological data for study area (2014)

Month	T_{min} (°C)	T_{max} (°C)	$T_{average}$ (°C)	*RH (%)*	*Wind* ($m\ s^{-1}$)	*Rain (mm)*
March	8.3	17.6	12.7	64	0.5	119.3
April	11.1	21.3	16.3	55	0.4	20.4
May	13.6	23.6	18.4	61	0.3	30.7
June	16.5	26.6	21.2	64	0.3	1.1
July	17.9	27.7	22.6	69	0.2	0.0
August	18.9	28.5	23.3	71	0.1	0.0
September	16.1	25.5	20.3	76	0.2	12.0
October	13.5	22.3	17.2	72	0.2	17.1

5.2.2. Dew measurement

One planar dew condenser (1 m^2) was installed with a condensing surface made from polyethylene foil embedded with TiO_2 and $BaSO_4$ microspheres (PETB), specifically manufactured for dew harvesting (Nilsson et al. 1994; Nilsson 1996) and currently manufactured by the International Organization for Dew Utilization (www.opur.u-bordeaux.fr) (Figure 5.2). The condenser was located 1 m above ground and was shielded from terrestrial radiation by 30 mm thick Styrofoam. The condenser was oriented in the same direction as the dominant nocturnal wind at that location and was tilted 30^0 to the horizontal (Beysens et al., 2003). A weather station was co-located with the condenser measuring several parameters at 5-minute intervals including wind speed and direction, relative humidity, air temperature, rainfall, and dew yield. The wind speed anemometer was installed at the same height as the condenser (1 m). Dew yield was continually measured using a tipping bucket rainfall gauge. Every bucket tip is 4.5 ml; thus error is approximately $\pm$ 0.0045 mm on the 1 m^2 condenser. Nightly dew was collected without scraping during the 2014 dry season (April-October). No dew was collected in other months when rainfall is expected to exceed dew yield. Nocturnal weather conditions were averaged from 21:00pm-05:00am and total dew yield was reported based on results from the previous night. Equipment maintenance and data download were conducted monthly.

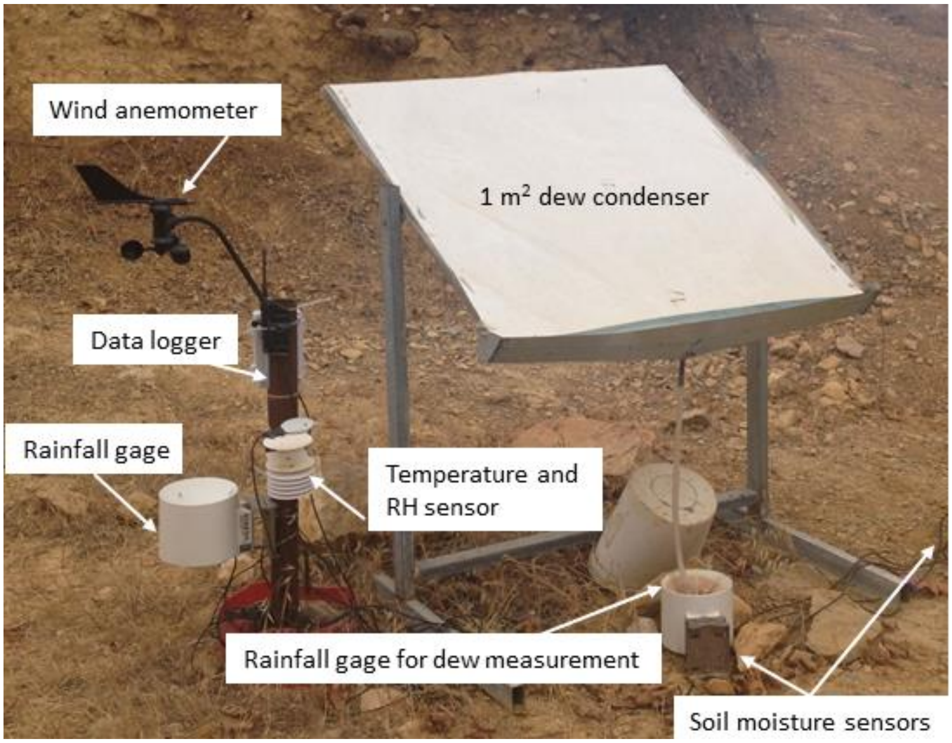

Figure 5.2. Dew condenser and instrumentation

5.2.3. Soil Moisture

The soils in the region are classified as Calcarao-Hortic Anthrosols (Darwish, 2006). At the experimental site, the soil is sandy clay loam with an estimated wilting point and field capacity of 16 and 36%, respectively for similar soil textures (Campbell, 1985). Soil moisture sensors were placed below the rain gauge measuring dew as well as 3 m away from the condenser at a depth of 5 and 15 cm to measure volumetric water content (VWC) for with dew (WD) and without dew (WOD) conditions and to assess the change in VWC from dew harvesting and natural diurnal changes. Comparison between WD and WOD conditions were evaluated on a diurnal basis, whereby the VWC for WD conditions was recalibrated each day at

16:00 pm to match the VWC for WOD conditions to eliminate other effects and measure the net effect of change in soil moisture from dew condensation, as well as assessing the cumulative change (without daily recalibration).

5.2.4. Estimation of dew yield

In case of missing data, dew yield was estimated using Beysens (2016) model (Equation 5.1) after its validation with measured data at the same location assuming a planar surface with an emissivity of 1 (Chapter 4).

$$\frac{dh}{dt} = \begin{cases} \Big\{0.37 \times [1 + 0.204323H - 0.0238893H^2 \\ \quad - (18.0132 - 1.04963H + 0.21891H^2) \\ \quad \times 10^{-3}T_d] \times \left(1 - \frac{N}{8}\right)\left[\exp\left(-\left(\frac{u}{4.4}\right)^{20}\right)\right]\Big\} \\ \quad + [b(T_d - T_a)] & \text{if } \frac{dh}{dt} > 0 \\ 0 & \text{if } \frac{dh}{dt} \leq 0 \end{cases} \quad (5.1)$$

where H is site elevation (km), T_d and T_a are dew point and air temperatures (°C), respectively, N is cloud cover (oktas), u is wind velocity (m s^{-1}), and b is the enveloping slope for $(T_d - T_a)$ versus dew yield. Due to nightly fluctuations in meteorological conditions, Equation (5.1) was applied incrementally every nocturnal hour, assuming the average night duration is 12 hours for the entire simulation period, to obtain cumulative nightly dew yield.

5.2.5. Evapotranspiration modeling

Irrigation demand is invariably based on evapotranspiration (ET) which considers soil evaporation jointly with plant transpiration. It can be estimated using a soil water balance Equation (5.2) which considers ET, precipitation (P), surface runoff (R), change in soil moisture (ΔS), capillary rise (U), and deep percolation (D). In most cases, U, R, and D are negligible due to controlled irrigation.

$$I = ET_c - P - \Delta S - U + R + D \tag{5.2}$$

The FAO-56 crop coefficient method (Allen et al., 1998) is most commonly used to estimate ET as expressed in the Penman-Monteith Equation (5.3) that provides a reference (ET_0), based on grass and local climatic conditions. Meteorological data at the study area was used to calculate ET_0. Crop evapotranspiration (ET_c) is then estimated by multiplying ET_0 by a coefficient, K_c, (Equation 5.4) which is affected by crop species and height, albedo of the crop-soil surface, and leaf and stomata properties:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{5.3}$$

$$ET_c = K_c \times ET_0 \tag{5.4}$$

where R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), which is considered negligible for a 24-hour period, T is the mean daily air temperature (°C),u_2 is wind speed (m s^{-1}), $(e_s - e_a)$ is the vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa $°C^{-1}$), and γ is the psychrometric constant (kPa $°C^{-1}$).

5.2.5.1. <u>Reforestation irrigation</u>

Because FAO-56 has limited guidance for natural landscapes, evapotranspiration for trees and shrubs was estimated using the Water Use Classifications of Landscape Species (WUCOLS) method (Costello and Jones, 1994 and 2014), which was developed for landscapes in California. This practical approach based on the FAO-56 crop coefficient method, replaces K_c with a landscape plant coefficient (K_L) which is divided into a species factor (K_s), a density factor (K_c), and a microclimate factor (K_m), to calculate landscape evapotranspiration (ET_L) (Equation 5.5):

$$ET_L = K_L ET_0 = (K_s \times K_d \times K_m) ET_0 \tag{5.5}$$

Seedlings of four different landscape tree species indigenous to the eastern Mediterranean, were evaluated: Aleppo pine (*Pinus halepensis*), Italian stone pine (*Pinus pinea*), Italian cyprus (*Cupressus sempervirens*), and cedar (*Cedrus libani*). Additionally, immature native orchards were also assessed including olive (*Olea europaea*), carob (*Ceratonia siliqua*), and grape (*Vitis vinifera*). The species factor (K_s) depends upon the specific plant type and water requirements based on six differing mesoclimates in California and can range from < 0.10 to 0.90. Much of California is within a Mediterranean climate (Köppen climate classification: Csa) and thus can be reasonably applied for this study. More specifically, the study area is located within a region comparable to Region 3 (south coastal) in California. Resultant water demand is low ($0.1 \leq K_s \leq 0.3$) for studied species in similar climatic regions, with the exception of *V. vinifera*, which has a moderate water demand ($0.4 \leq K_s \leq 0.6$). The density factor (K_d) accounts for differences in vegetation density, which is affected by leaf area and species diversification and values range from 0.5 to 1.3. Immature plants, such as tree seedlings, are assigned lower values and thus K_d = 0.5 was assumed for all studied species Lastly, the microclimate factor (K_m) considers the local environment whether trees are planted in an open-field setting or an urbanized environment. Natural environments, are assumed to have an average microclimate factor (K_m = 1.0) which assumed for this study's species as well. Because the coefficients are equal for all species examined, they were collectively evaluated as tree seedlings, with the exception of *Vitis vinifera*. The WUCOLS method has been criticized for being ad hoc (Snyder et al., 2015), as coefficients are based on field observations rather than in situ measurements and calculations like crop coefficients in FAO 56, but the method is simple in the absence of detailed data (particularly for tree seedlings) and has been adopted to estimate irrigation demand in Mediterranean climates (Salvador et al., 2011; Nouri et al., 2013; e Silva et al., 2014; Parés-Franzi et al., 2006).

In the absence of precipitation, the tree seedling survival rate can improve if irrigated with a water pulse of 4.5 L seedling^{-1} every 30-40 days (Estrela et al., 2009; Valiente et al., 2011). Based on this irrigation treatment and the estimated tree seedling evapotranspiration, the number of seedlings which receive irrigation solely from harvested dew can be evaluated (assuming a condenser area of 2 m^2). The proposed irrigation system can comprise a condenser placed at a higher elevation than the reforestation plot to exploit pressure head (Figure 5.3). Harvested dew is collected into a storage tank fitted with a system of hoses for subsequent point irrigation at tree/plant stem.

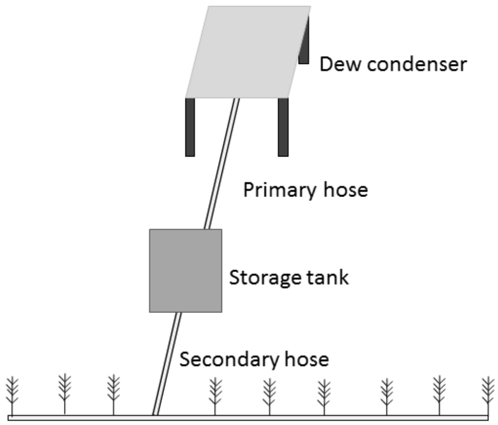

Figure 5.3. Irrigation system layout based on a dew condenser for a reforestation plot

5.2.5.2. Crop irrigation

The feasibility to use dew for crop irrigation was also evaluated based on ET estimation for selected crops using the dual crop coefficient method, which divides K into two components: a basal crop coefficient for transpiration (K_{cb}) and an evaporation coefficient (K_e) (Equation 5.6):

$$ET_c = (K_{cb} + K_e)ET_0 \tag{5.6}$$

Due to limited data in the literature, basal crop coefficients were obtained from Allen et al. (1998) which are based on field and laboratory studies. The K_{cb} curve is divided into 4 stages: initial growth, crop development, mid-season, and late season. The initial stage ranges from germination to 10% ground cover ($K_{cb\ ini}$) with a value of 0.15 for most crops. The coefficient linearly increases during the development stage (10% to effective full cover) to a plateau during the mid-season (effective full cover to maturity) when crops reach maximum transpiration ($K_{cb\ mid}$). Then finally, the curve linearly decreases to the end of harvest or dormancy ($K_{cb\ end}$). Both $K_{cb\ mid}$ and $K_{cb\ end}$ are adjusted to local meteorological conditions (Allen et al., 1998). Five differing small crops (Table 5.2), which are typically grown in the region during the dry season, were selected to estimate ET_c. The crop calendar was estimated based on data obtained in Greece (Tsanis et al., 1996).

The dual crop coefficient method also considers soil evaporation that occurs in two stages after a rainfall (or irrigation) event. During the first stage, the soil surface is wet and evaporation occurs at a maximum rate limited solely by the available energy (Allen et al., 2005). The second stage experiences a decline in the evaporation rate, resulting in a decline in K_e. Evaporation ceases when no moisture is available in the soil surface layer. In the absence of irrigation, crops which are planted during dry periods (*e.g.* cucumber and cauliflower, Table 5.2) are immediately subjected to the second stage.

Table 5.2. Crop calendar for selected plants suitable for simple subsistence farming

Crop	*Plant spacing (cm) (Albert, 2015)*	*Row spacing (cm) (Albert, 2015)*	*Plant density (plants m^{-2}) (Albert, 2015)*	*Maximum plant height (m) (Allen et al. 1998)*	*Maximum root depth (m) (Allen et al. 1998)*	*Plant/ start date*	*Crop growth stages (days)*				*Harvest/ end date*
							Initial (I)	*Dev (II)*	*Mid (III)*	*Late (IV)*	
Cucumber	33	92	3	0.3	0.7 – 1.2	15 Apr	20	30	40	15	28 Jul
Tomato	100	100	1	0.6	0.7 - 1.5	20 Mar	30	40	45	25	7 Aug
Cauliflower	49	92	2	0.4	0.4 - 0.7	1 Jun	20	25	20	10	15 Aug
Garlic	9	38	30	0.3	0.3 - 0.5	1 Mar	15	25	65	35	19 Jul
Eggplant	92	92	2	0.8	0.7 - 1.2	1 Apr	30	40	35	20	4 Aug

5.3. Results and Discussion

5.3.1. Experimental and modeled dew yield

Maritime climate and orography facilitate favorable conditions for dew events in the study area due to its windward position (Table 5.3). Decreasing atmospheric pressure due to increasing elevation causes the humid air originating from the sea to expand and cool adiabatically to approach dew point temperature (T_d). During the study period, dew events were frequent (43%) with an average yield of 0.13 L m^{-2} d^{-1}. In later summer (Aug-Sep), events become more regular (>74%) and the average nightly yield is slightly higher (> 0.14 L m^{-2} d^{-1}) resulting in cumulative dew of 5.9 L m^{-2} for the 2 months. The largest dew yield was in October (0.46 L m^{-2} d^{-1}), likely due to the increase in relative humidity and lower temperatures during the transition from the dry to the wet season.

Table 5.3. Dew harvesting experimental data for 2014 dry season

Month	*Number of study nights*	*Number of rain nights*	*Number of dew nights*	*Average dew yield (L m^{-2} d^{-1})*	*Maximum Dew Yield (L m^{-2} d^{-1})*
April	21	6	2 (13%)[a]	0.063	0.086
May	31	4	8 (30%)	0.087	0.153
June	20	3	5 (29%)	0.194	0.315
July	25	0	14 (56%)	0.130	0.275
August	23	0	17 (74%)	0.142	0.311
September	29	4	24 (96%)	0.143	0.342
October	31	15	8 (50%)	0.141	0.459

[a] Frequency of dew nights estimated as number of events compared to the number of study days, not including rain nights

Dew yield and rainfall patterns in study area are depicted in Figure 5.4 where, as mentioned above, missing dew yield data were simulated using Equation (5.1) after optimizing the envelope slope (b) of ($T_d - T_a$) vs dew yield (b = 0.092; R^2 = 0.43) using the field data collected. We observed that Equation (5.1) tends to eliminate higher yields likely due to the temporal scale (hourly) of meteorological data. Note that the small size of dew droplets may keep it pinned to the condenser and thus not harvested at times causing discrepancies between simulated and observed yields.

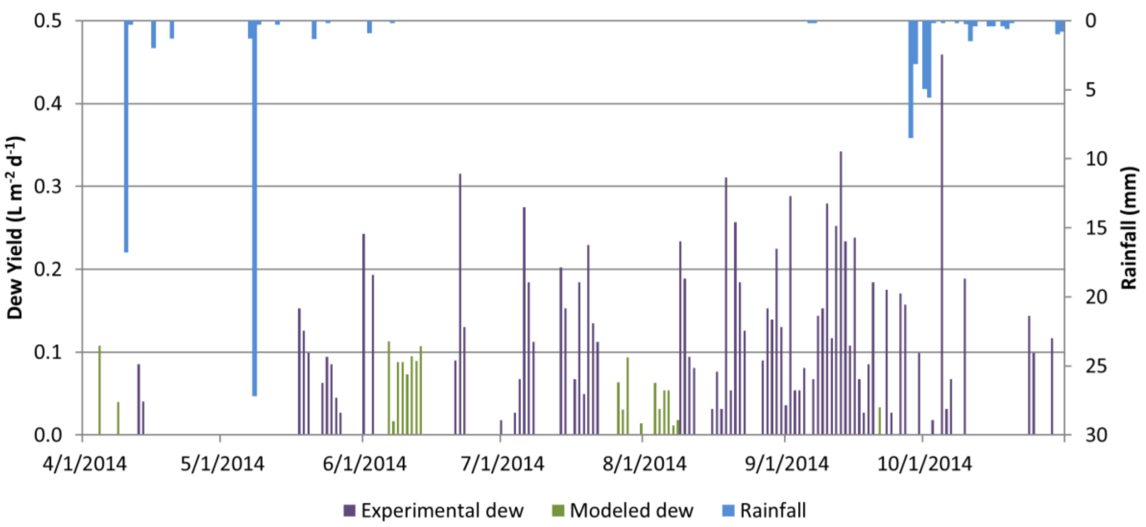

Figure 5.4. Dew yield and rainfall evolution in study area

5.3.2. Dew and soil volumetric water content

Prior to the commencement of dew harvesting, differences in VWC were apparent and are likely due to differing water vapor adsorption rates and shading effects from the condenser for WD conditions (Figure 5.5). Vapor adsorption in bare soil occurs when the relative humidity is high (Agam and Berliner, 2004; Verhoef et al., 2006) and can differ within the same soil even at small distances (~1m) due to varying radiation effects (Verhoef et al., 2006). Figure 5.5 shows the nightly increase in soil volumetric water content (VWC) when comparing WD to WOD conditions at depths of 5 and 15-cm for 6 selected dew events, as other nights behaved similarly. On all nights when dew events occurred (> 0.02 L m^2 d^{-1}), there was a measureable difference in VWC at both 5 and 15-cm depth with an average of 0.9% and 0.6%, respectively. Although statistically significant ($p<0.5$), the effects are considered negligible due to the limited VWC increase. However, dew yield events exceeding 0.2 L m^{-2} d^{-1} resulted in a greater increase (> 3%) in VWC at shallow depths (5 cm) and for higher dew yield (> 0.3 L m^{-2} d^{-1}), the change in VWC is more significant (> 5%). Those incidents constitute 20% of the nights tested from April to October (2014). The VWC decreases rapidly soon after sunrise due to evaporation, particularly during the summer and thus changes in VWC may be reduced due to higher temperatures.

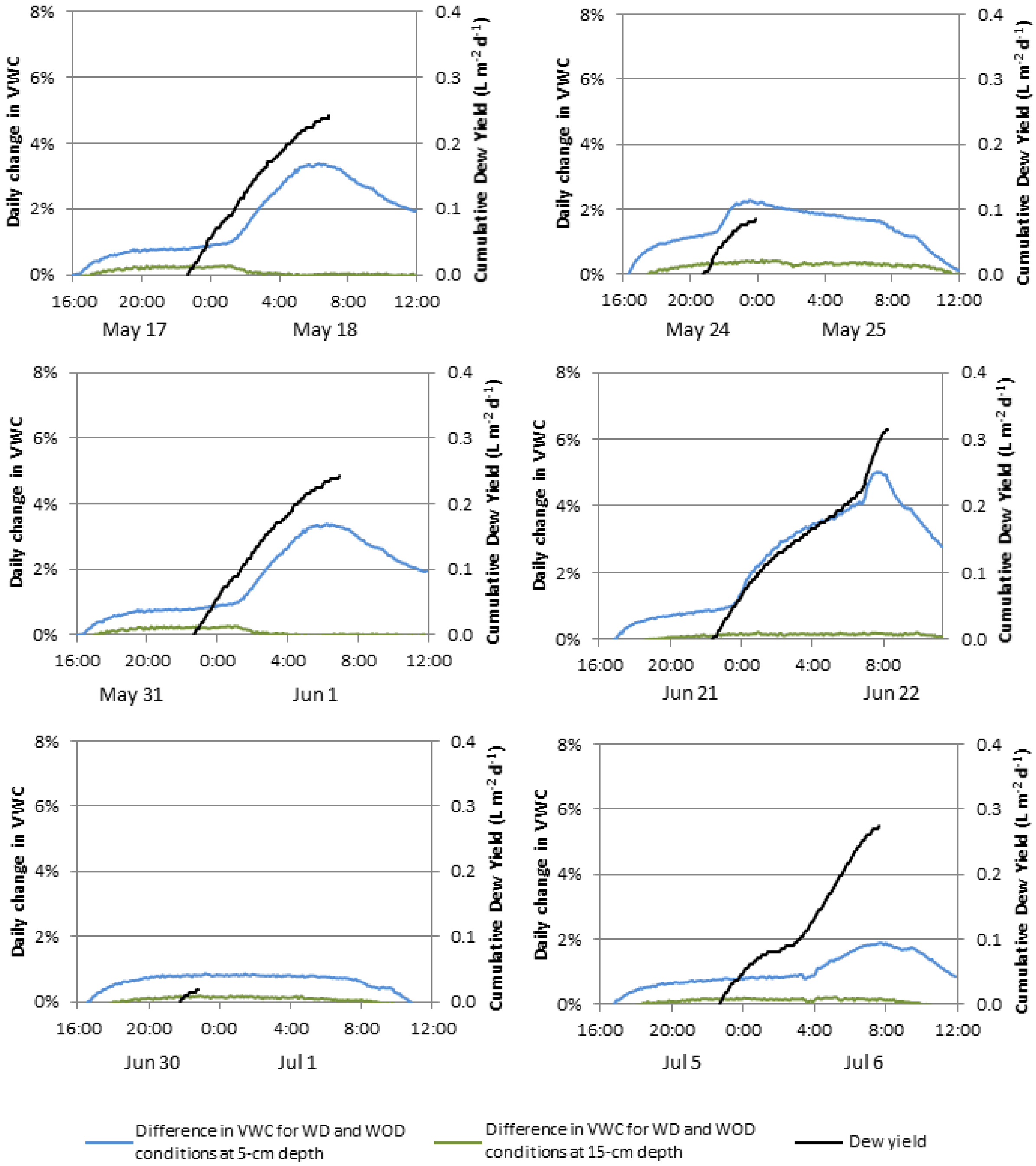

Figure 5.5. Nightly increase in soil volumetric water content (VWC) when comparing with dew (WD) to without dew (WOD) conditions at depths of 5-cm and 15-cm for 6 selected dew events which range in duration and yield from 1.1 hrs and 0.018 L m^{-2} d^{-1} to 9.9 hrs and 0.315 L m^{-2} d^{-1}

Dew irrigation and its impact on VWC are more apparent on a cumulative basis (Figure 5.6) when comparing WD and WOD. In the absence of irrigation (WOD), the VWC is generally below the wilting point (~16%) and thus the soil moisture is not available for plant transpiration. Conversely, at shallow depths (< 5 cm), surface irrigation from frequently occurring dew events can maintain a VWC well above the wilting point with 87% percent of the nights above the wilting point in the WD compared to 10% percent of the nights in the WOD scenario (which actually coincided with a rainfall event). Because the maximum root depth for tree seedlings often exceeds this depth (up to ~1.6 m; Stone and Kalisz, 1991), only the youngest seedlings can potentially benefit from dew applied at the soil surface. Otherwise, a drip emitter can be utilized to apply dew at greater depths to reach the root zone. The effects at 15-cm depth are negligible and the VWC remains below the wilting point for WD conditions. Note that the experimental setup did not include vegetation and the dew condenser provided some shade over the dew-irrigated soil thus resulting in longer moisture content for WD conditions particularly over the May rainfall event.

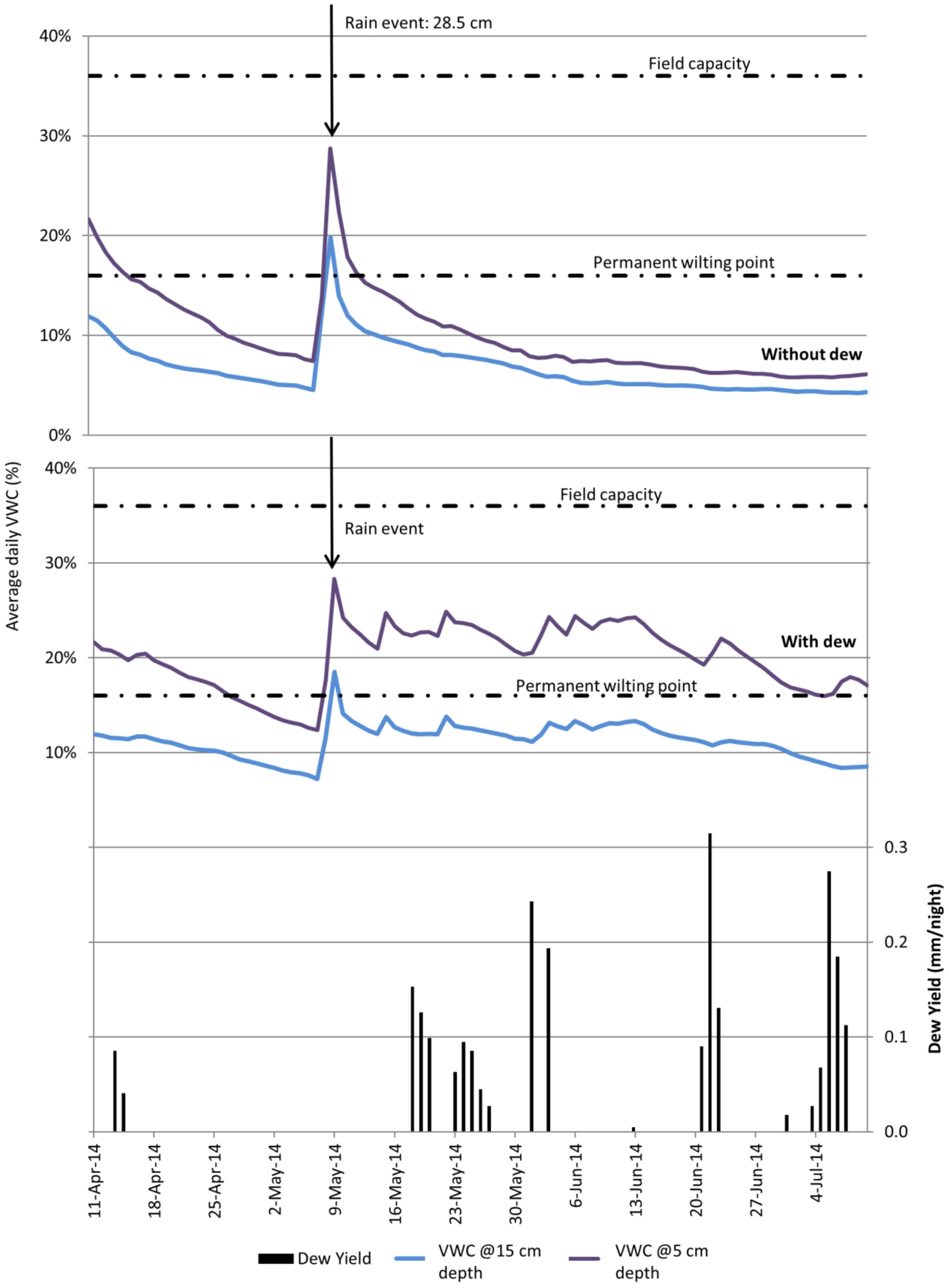

Figure 5.6. Cumulative change in soil moisture content to compare WD and WOD conditions

5.3.3. Reforestation evapotranspiration and irrigation from dew

The estimated ET_0 ranged from 18.5 in early March to 40.9 mm week^{-1} in early July while recognizing that the Penman-Monteith method (Equation 5.2) tends to under-estimate ET_0 (Berengena and Gavilán, 2005). At the beginning (Mar.-May) and end (Sep.-Oct.) of the tree seedling-growing season, precipitation is sufficient to meet water demand based on ET_L (Table 5.4). During the summer, however, seedlings are dependent upon irrigation for survival. Although harvested dew is less than ET_L, tree seedlings (particularly *P. halepensis*) demonstrated moderate drought resistance due to osmotic adjustments (Calamassi et al., 2001) and stomata closure (Klein et al., 2011) and thus periodic water pulses (~30-40 days) are expected to be sufficient to mitigate water stress. Dew from a 2 m^2 condenser is adequate to provide a 4.5 L seedling^{-1} water pulse in June and July. Condenser scale-up coupled with rainwater harvesting could potentially meet water demand for an entire reforestation plot (*i.e.* 100 m^2 condenser for 50 trees). For *V. vinifera* however, the water demand is greater, thus requiring a 5 m^2 condenser per vine rendering dew harvesting for irrigation impractical in this case.

Table 5.4. Evapotranspiration (ET_L) for selected tree seedlings and *V. vinifera* (grape vines) using Equation 5.2, rainfall, and harvested dew based during growing season

Month	*Tree seedling ET_L (mm month^{-1})*	*V. vinifera ET_L (mm month^{-1})*	*Rainfall (mm month^{-1})*	*Harvested dew based on 2 m^2 condenser (L month^{-1})*
March	9.2	22.9	119.3	0.00
April	12.2	30.4	20.4	0.55
May	15.2	37.9	30.7	1.39
June	16.4	41.1	1.1	3.29
July	17.2	42.9	0.0	4.04
August	15.8	39.5	0.0	5.28
September	11.9	29.8	12.0	6.95
October	4.7	11.7	14.1	1.53

5.3.4. Crop evapotranspiration and irrigation from dew

Crop coefficients (K_c) for selected crops were determined based on the dual crop coefficient method (Allen et al., 1998) and compared to experimentally determined K_c values (Table 5.5). Values can differ widely due to varying crop management practices and local climatic conditions. Although FAO-56 has a tendency to underestimate $K_c$values, use of the dual crop coefficient method has demonstrated good reliability in the Mediterranean region when compared to the single coefficient method because evaporation is considered (Lazzara and Rana, 2010).

Table 5.5. Estimated crop coefficients (K_c) to calculate plant evapotranspiration

Plant	*K_c for different growth periods*			*Reference*
	$K_{c\ ini}$	*$K_{c\ mid}$*	*$K_{c\ end}$*	
Cucumber	0.30	0.83	0.59	
Tomato	0.51	0.99	0.60	
Cauliflower	0.15	0.80	0.76	This study
Garlic	0.47	0.84	0.52	
Eggplant	0.46	0.88	0.68	
Cucumber	0.16	1.44	0.59	Blanco et al. (2003)
Tomato	-	0.82	0.45	Amayreh and Al-Abed (2005)
	0.15	1.0	0.9	Hanson and May (2006)
Cauliflower	0.84 (average for entire growth period)			Sahin et al. (2009)
Garlic	-	1.3	0.6	Villalobos et al. (2004)

Based on the aforementioned criteria, the estimated ET_c (Figure 5.7) for selected crops in Beiteddine can range from 261 mm (cauliflower) to 549 mm (tomato) for the respective growing seasons assuming average planting density (Table 5.2). Under full irrigation treatment, the dew water demand (I) is the difference between ET_c and effective rainfall (P) and available VWC. The resultant wetting pattern within the soil can be described as an axially symmetric elliptical shape downwards from the emitter (Haynes, 1985), which can be assumed to have an average diameter of 10 to 60 cm. Because the area of the condenser may be larger than the wetted area, dew effect can be magnified. For example, for the average measured dew yield in Beiteddine (0.129 L m^{-2} d^{-1}), the corresponding equivalent rainfall is 0.46 and 16.4 mm for a 60 and 10 cm diameter area, respectively. Note that although dew can help supplement irrigation demand, in practice it is generally not applied due to the yield amount and competition with irrigable land for condenser placement, even when coupled with a rainwater harvesting system. However, dew irrigation may be utilized in unusual circumstances when conventional methods are unattainable, such as farming at sea.

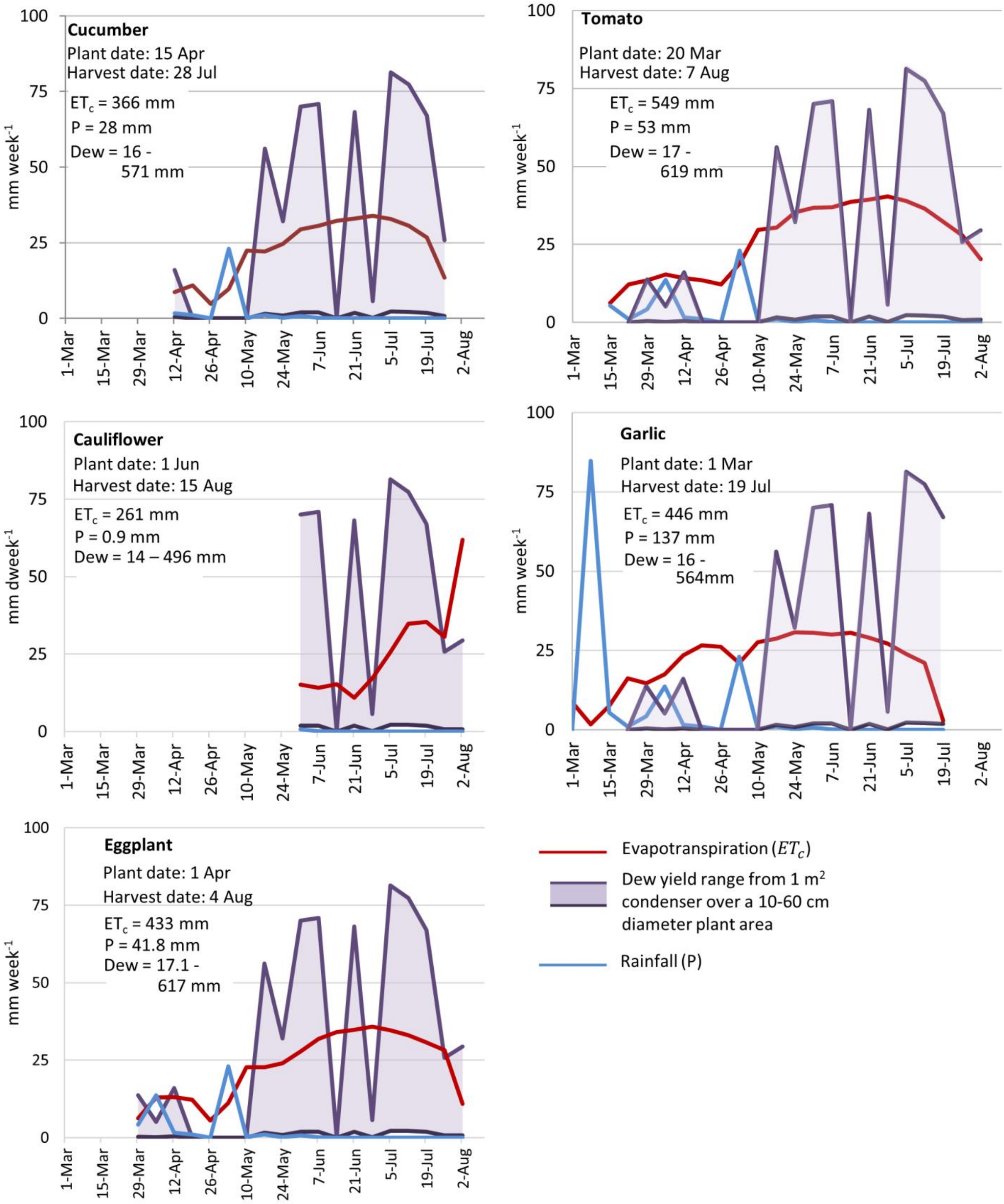

Figure 5.7. Estimated ET_C for selected plants compared to measured dew yield and precipitation during the plants' growth period. Dew harvesting commences on 1 Apr.

5.4. Economic considerations

Financing reforestation efforts takes various forms and comes from different sources. For example, the largest cedar reserve in Lebanon promotes an elective cedar adoption program at 150 USD $tree^{-1}$ and participants receive various benefits including a nameplate. Adopted seedlings are guaranteed to last a minimum of three years and the fund is mostly used to offset the cost of transporting the irrigation water into the forest to irrigate the seedlings (Shouf Biosphere Reserve, 2016). Participant in such funds are aware that the cost is not for water at the source, but for water delivered to the seedlings. In rural Bolivia, a survey was conducted to assess residents' willingness to pay a surcharge on their water tariff to be utilized for watershed restoration including reforestation. Over half of the respondents, with an average household income of 100 USD $month^{-1}$, indicated they would be willing to pay, provided the surcharge was less than 2 USD $month^{-1}$ (Shultz and Soliz, 2007). Other reforestation programs have been financed by grants from conservation organizations (Williams, 1999) or severance taxes (Bullard and Straka, 1988). Reforestation budgets must consider fertilizer, pesticides, protection, irrigation, and the seedlings themselves (Zhou et al., 2007). Using dew harvesting can minimize the irrigation costs, particularly the transportation cost associated with it, and thus the total budget. Moreover, revenue from any crops (*e.g.* olives, carob) can generate a higher rate of return.

Thus, if one considers the cost of treated water without delivery to such off-road locations, a comparison between dew harvesting and other more common water management measures (*e.g.* wastewater treatment and reuse, desalination, dam construction) can show dew harvesting to be less cost effective. For example, wastewater treatment and reuse, which has been used for reforestation in the Mediterranean (Angelakis et al., 1999) has a total annual economic cost of 0.55 USD m^{-3}, not including transportation costs, (for Lebanon, 2007; Aulong et al., 2009), whereas 1 m^3 of dew harvested per year requires a 60 m^2 condenser (assuming conditions described in this study). However, dew harvesting possesses unique advantages which prevail in situations such as reforestation where infrastructure is limited and natural water sources are scarce. Dew harvesting entails low initial investment and maintenance costs and has no energy requirements which prevail in remote areas with limited infrastructure and water availability. Moreover, because systems are stand-alone, water tariffs, pumping over long distances, and water transport via off-road tankers are not applicable. Investment costs include the condenser frame, which can be built using locally available materials, and the condensing surface. Although the condensing foil used in this study (PETB) is costly (~10 USD m^{-2}) and has a limited life span (~18 months) (Chapter 2), it is generally used in research studies and can be substituted with cheaper condensing surfaces. Maestre-Vallero et al. (2011) obtained a 20% increase in dew yield using a low density polyethylene (LDPE) foil commonly used in agricultural applications, which costs ~0.4 – 0.6 USD m^{-2} (Lamont, 2004). Additional studies have tested Teflon, Plexiglass, aluminum, and other surfaces with varying success (Chapter 2). The full installation cost of a larger (850 m^2) dew condenser built in India for drinking water was 3.6 USD m^{-2} which included a specially manufactured UV-stabilized condensing surface, insulation boards, ribbon batons, water conveyance and storage, and a boundary fence. The expected lifespan of the system was 15 years with the exception of the condensing surface (~ 4 years), which entails a replacement cost of 2.5 USD m^{-2} (Sharan et al., 2011). This cost can reduce significantly if cheaper condensing surfaces like LDPE are used.

5.5. Concluding Remarks

Trees are beneficial to the environment by providing habitat for flora and fauna, increasing biodiversity, and reducing erosion. However, efforts to reforest landscapes can be threatened by seedling mortality due to water scarcity during periods of drought although irrigation of seedlings is often impractical due to the isolation of forests and lack of infrastructure. Dew harvesting can be an effective method to mitigate seedling mortality because systems are stand-alone, inexpensive, and simple to build. Moreover, systems can be relocated once reforestation plots have been established and have no adverse impact to natural landscapes. Locales with a mid-mountain maritime climate along the Mediterranean exhibited a strong potential for dew harvesting during the dry season because events are frequent (43%) with an average yield of 0.13 L m^{-2} d^{-1} which can have significant impacts on the soil water content. Although such yields are small, they are adequate to irrigate seedlings (assuming a 100 m^2 condenser for 50 tree seedlings) by applying small water pulses at set intervals, particularly when coupled with rainwater harvesting, and can sustain a vital role in conservation efforts.

CHAPTER 6

PERSONAL STATEMENT AND VISION FOR THE FUTURE IN DEW RESEARCH

Dew harvesting is simple is conceptually simple but the physics which enable the process are quite complex. As a result, although dew condensers can easily be constructed at low cost, our understanding of the physical processes entailing radiative cooling and condensation limits dew yield to small volumes. Although these volumes are significant, they render increased utilization of dew difficult. Moreover, because dew is declining in the Mediterranean and perhaps other regions, methods which permit increased yield are imperative.

6.1. Innovative condenser design

The most common condenser design is the planar condenser. As introduced in Chapter 2, some unique condenser geometries have been studied such as an inverted pyramid (Jacobs et al., 2008; Beysens et al., 2013), a funnel (Clus et al., 2009), one resembling an egg carton (Beysens et al., 2013), and one resembling artistically folded paper (origami) (Beysens et al., 2013), or a multi-ridge condenser (Clus et al., 2009), all of which are often designed using Computational Fluid Dynamics software (Clus et al., 2009). Such condensers have attained dew yields up to 150% more than standard planar condensers for larger dew events and 400% more for lesser dew events (Beysens et al., 2013).

Similar unique design prototypes have been introduced into the market such as:

1. the Deep Root Irrigation Precipitation System (DRIPS, 2015) (Figure 6.1a);
2. a combination fog and dew collector using mesh and a laminate (Trotter, 2008) (Figure 6.1b);
3. the Tal-Ya multiridge dew collection system proposed for agricultural applications (Tal-Ya, 2015) (Figure 6.1c);
4. the Warka Water dew and fog tower (Warka Water, 2015) (Figure 6.1d); and
5. the Dew Bank bottle (Yanko Design, 2010) (Figure 6.1e).

To date, no known scientific studies have been conducted on any of these prototypes. Thus resultant yield is unclear. Nevertheless, they have each generated interest in dew harvesting in selected markets and have exhibited strong potential to harvest atmospheric water.

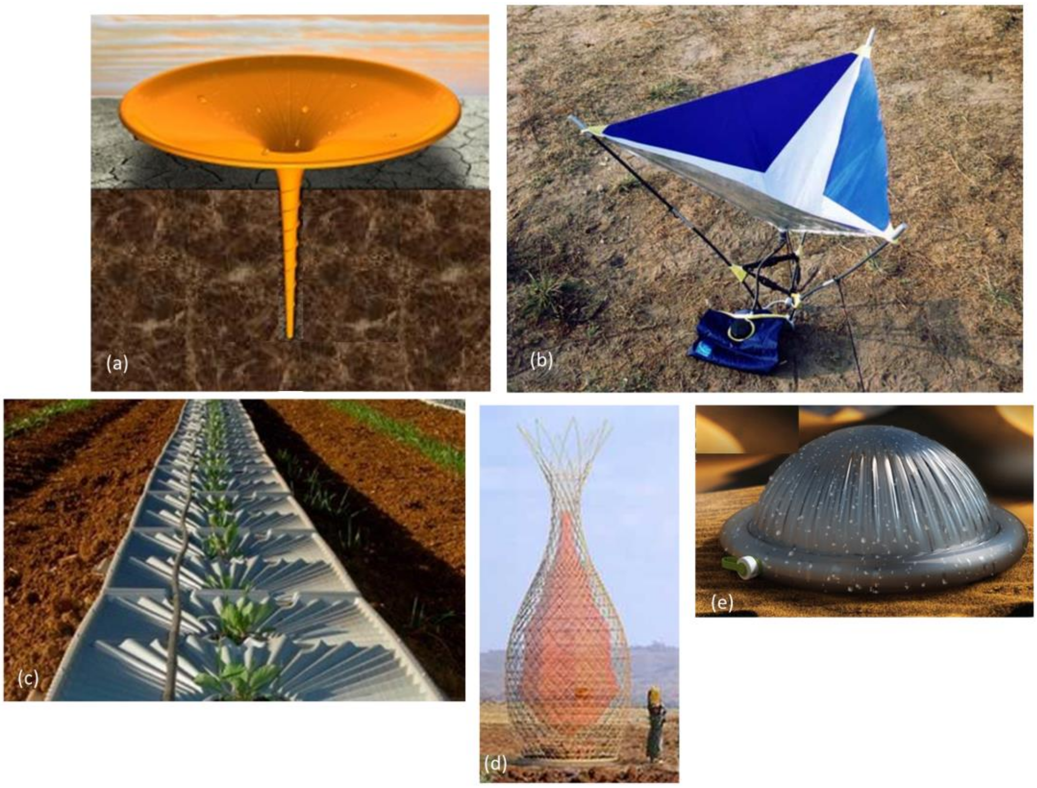

Figure 6.1. Selected dew harvesting prototype designs: (a) Deep Root Irrigation Precipitation System (DRIPS, 2015); (b) fog and dew collector (Trotter, 2008); (c) Tal-Ya (Tal-Ya, 2015); (d) Warka Water (Warka Water, 2015); and (e) Dew Bank (Yanko Design, 2010)

6.2. Active dew harvesting

Most dew harvesting research to date has been devoted solely to passive radiative cooling. Greater dew yield potential can be achieved using active systems. The most common systems entail atmospheric water vapor processing (AWVP) technology which includes surface cooling by heat pumps, water vapor concentration by desiccants, and convection induced, often at high energy cost (Walgren, 2001). Energy costs can be reduced using renewable energy, such as a solar-powered desiccant collector proposed by Gad et al. (2001), which produced 1.5 mm^{-2} d^{-1}. Another system proposed by Guan et al. (2014) used ice bricks to cool condensers with Teflon and aluminum condensing surfaces which resulted in significant increases in dew yield compared to using the condensers without artificial cooling (45% and 150% increase, respectively). Larger potential dew yield can also stimulate expanded interest in dew harvesting.

6.3. Dew measurement and forecasting

Dew is perhaps the sole meteorological phenomenon which is not routinely measured or forecast. This is partly due to lack of a standardized sensor. In addition, properties of any sensor must be calibrated to represent the specific environment in which it represents (Magarey et al., 2005). Therefore, first an acceptable standard to measure dew must be established to enable substantial collection of data.

Secondly, although dew prediction models are continually improving, clearer understanding of dew physics and meteorological processes will facilitate model improvement. Data used to develop the model should be based upon measurements obtained from the standardized dew sensor. This model can then be applied to forecast dew and develop a global atlas, which will ultimately promote the utilization of dew.

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