Roof-integrated dew water harvesting in Combarbalá, Chile

Danilo Carvajal, Jean-Gabriel Minonzio, Elvira Casanga, Jorge Muñoz, Alvaro Aracena, Sonia Montecinos and Daniel Beysens

ABSTRACT

Dew harvesting can be a supplementary source of freshwater in semiarid and arid areas. Several experiments on small-scale dew condensers (usually of 1 m^2) have been carried out in many places in the world; however, few experiments have been conducted on large-scale collectors integrated into buildings. This work aims to assess one year of dew water harvesting in Combarbalá (Chile) using a painted galvanised steel roof as collecting surface. The roof (36 m^2) was coated with a high-infrared-emissivity paint containing aluminosilicate minerals (OPUR, France). Dew measurements were conducted daily from September 2014 to August 2015. The dew yield and its relationship with meteorological variables were analysed. The results show that despite the low nocturnal relative humidity throughout the year (average: 48%), dew collection occurred on 56.1% of the recorded days. The daily average collection rate was 1.9 L d^{-1}, with a maximum of 15 L d^{-1}. The maximum daily dew yield is correlated strongly with relative humidity and correlated weakly with air temperature and wind speed. Considering the same rooftop can collect dew and rain, it was estimated that over one year dew water could contribute to roughly 8.2% of the total water collected, considering both sources.

Key words | atmospheric water, dew collection, radiative cooling, water resources

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INTRODUCTION

The availability of freshwater has become a serious problem in arid and semiarid areas of the world. This phenomenon has been aggravated by population growth and industrial activities (UNDP 2006). As a consequence, various technologies have been developed to obtain freshwater from unconventional sources, such as seawater and brackish

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water desalination (Greenlee *et al.* 2009), wastewater reuse, and water from the atmosphere, as in the case of rain, fog, and dew harvesting (Shanyengana *et al.* 2003; Beysens *et al.* 2005; Ghaffarianhoseini *et al.* 2016; Fernandez *et al.* 2018). The steady increase in energy costs in recent decades (IEA 2017) has had a particularly negative impact on intensive energy-demanding processes, such as reverse osmosis and thermal desalination (Semiat 2008). In contrast, the capture of fog, a technology that does not require additional energy, has been quite successful in mountainous coastal arid areas (e.g. Chile, California, Morocco, South Africa), islands (e.g. Canary Islands) and inland sites (e.g. Guatemala, Tanzania) (Correggiari *et al.* 2017). Rainwater harvesting has also been successfully applied in countries such as Australia, the United Kingdom and the United States (Campisano *et al.* 2017), despite the requirement of a high storage capacity, particularly in places where rainfall is infrequent and highly seasonal.

Dew harvesting has attracted great interest because, it does not require additional energy (it is a passive system), and the resulting water may require little or no processing to be used as drinking water or in agriculture (Lekouch *et al.* 2011; Tomaszkiewicz *et al.* 2017). This technology is robust, decentralised and requires low investment and maintenance costs; however, the production of water through this medium is relatively low in terms of water yields per square metre of collection surface (typically a few 0.1 L $m^{-2}\,d^{-1}$ with peaks at 0.5–0.7 L $m^{-2}\,d^{-1}$). Therefore, increasing efforts in technological development have been carried out by several research groups around the world to improve the efficiency of these systems and to elucidate the underlying physical and chemical phenomenology (Monteith & Unsworth 1990; Nilsson 1996; Muselli *et al.* 2006a; Sharan *et al.* 2007; Muselli *et al.* 2009; Beysens *et al.* 2013). Highly promising results have been obtained, as well as – in some cases – lower costs compared with bottled water production (Sharan *et al.* 2011).

Some investigations included the chemical and biological analyses of dew water, showing that dew characteristics can be significantly different depending on the local conditions (presence of aerosols, dust, water-soluble gases and microorganisms) (Beysens *et al.* 2006a; Lekouch *et al.* 2011). A low content of harmful bacteria was reported by Lekouch *et al.* (2011) in Morocco and Sharan *et al.* (2017) in India; however, if the use of dew water is for drinking purposes, a light sterilizing treatment (e.g. chlorination) has been recommended (Beysens *et al.* 2006b; Muselli *et al.* 2006b). The evaluation of potential uses of dew must consider its chemical–biological analysis to define whether the raw water requires treatment. The possible uses of dew are as follows: drinking water for human consumption, irrigation of crops, livestock feeding, recovery of native flora and fauna, and household water savings (e.g. toilet flushing, laundry and garden irrigation), among others. For instance, dew water has been successfully used as drinking water in India (Sharan *et al.* 2017).

The process of condensation of water vapour into liquid by radiative cooling occurs when a solid or liquid surface radiates heat to the sky, causing its temperature to become lower than the dew point of the water vapour contained in the surrounding air. This condition usually occurs during cool nights with high relative humidity, low cloud cover and moderate or low wind speeds. Once the condensation process occurs, the liquid water may be collected through natural drainage on an inclined surface (by gravity) and then stored in tanks. Two important design factors of these systems are that the collecting surface must have a high emissivity and low thermal mass, as both characteristics permit the heat lost through long-wavelength infrared radiation between the surface and the sky to be greater than the heat gained by conduction and convection from the surrounding air and soil. This constant loss of energy sustains the condensation process when the surface temperature is below the dew point temperature (Beysens 2016). Surface characteristics (e.g. wettability) have an important effect in dew heterogeneous nucleation, growth, coalescence and draining (Beysens 1995; Maestre-Valero *et al.* 2015; Gerasopoulos *et al.* 2018). To reduce air heat exchange, thermal insulation below the condenser is usually used (Nilsson 1996; Muselli *et al.* 2006a). To maximise radiative cooling, a wide sky view (open area) is required. To date, the maximum daily dew yield was obtained in Israel at 0.6 L $m^{-2}\,d^{-1}$ (Berkowicz *et al.* 2004). This figure is quite close to the theoretical maximum amount of 0.8 L $m^{-2}\,d^{-1}$, a number based on various regions' available cooling power (25–100 W m^{-2}) with respect to the latent heat of condensation (2.26 kJ g^{-1}) (Monteith & Unsworth 1990). A diagram showing the factors affecting the dew yields and water quality of a passive dew condenser is presented in Figure 1. The factors have been classified into four groups: (1) condenser design and materiality, (2) position and local environment, (3) weather conditions, and (4) air chemistry and physics. A more detailed description of the factors affecting passive dew collection is presented in Khalil *et al.* (2015).

Atmospheric water condensers have been used for a long time, including by alchemists (see e.g. the Mutus Liber 1677). Zibold (1905) in Ukraine set up the first documented massive condenser (Mylymuk-Melnytchouk & Beysens 2016). However, from the viewpoint of phenomenological knowledge and technological developments, most progress was made in the last 25 years (Khalil *et al.* 2015; Tomaszkiewicz *et al.* 2015; Gerasopoulos *et al.* 2018). Most dew experiments have been carried out using small and flat collecting surfaces (usually around 1 m^2). A few researchers have considered the use of household rooftops as condensing surfaces (Mileta *et al.* 2006; Beysens *et al.* 2007; Sharan *et al.* 2007; Clus *et al.* 2013). This line of research, using dew condensers integrated into rooftops, represents a promising alternative direction. With small modifications, existing roofs can be used as dew condensers, a process that does not require additional land area. Furthermore, existing rain gutters and piping can be used for dew collection. In many countries like Chile, galvanized steel roofing is widely used in household construction as it is a low-cost material that can be used for making dew condensers.

Very few dew studies have been carried out in Chile. For example, Rubio *et al.* (2002) chemically analysed dew and rain in the city of Santiago in order to determine the effect of nitrite in the early morning, when photochemical smog begins. They reported an average dew yield of 0.127 L m^{-2} d^{-1} based on a 1 m^2 PTFE surface. Balocchi & Hevia (2003) carried out modelling and experimental validation for a 1 m^2 dew condenser installed in Santiago. They estimated dew yields of 0.06 L m^{-2} d^{-1}, which was quite similar to the experimental values (0.05 L m^{-2} d^{-1}). Based on an energy balance model, Kalthoff *et al.* (2006) estimated nocturnal dew deposition in the Elqui Valley. The results showed that the annual nocturnal dew deposition was about 5–10 L m^{-2} yr^{-1}.

This work aims to assess one year of dew water harvesting in Combarbalá, Chile, using a 36 m^2 galvanized steel roof tilted 15°. This system was integrated into a household as a collection surface. In order to increase dew yields, the roof was coated with a high-emissivity paint containing alumino-silicate minerals (OPUR 2017). Dew water yields were recorded daily between September 2014 and August 2015 at the El Chañar site (commune of Combarbalá), located in the semiarid zone of northern Chile. We selected Combarbalá

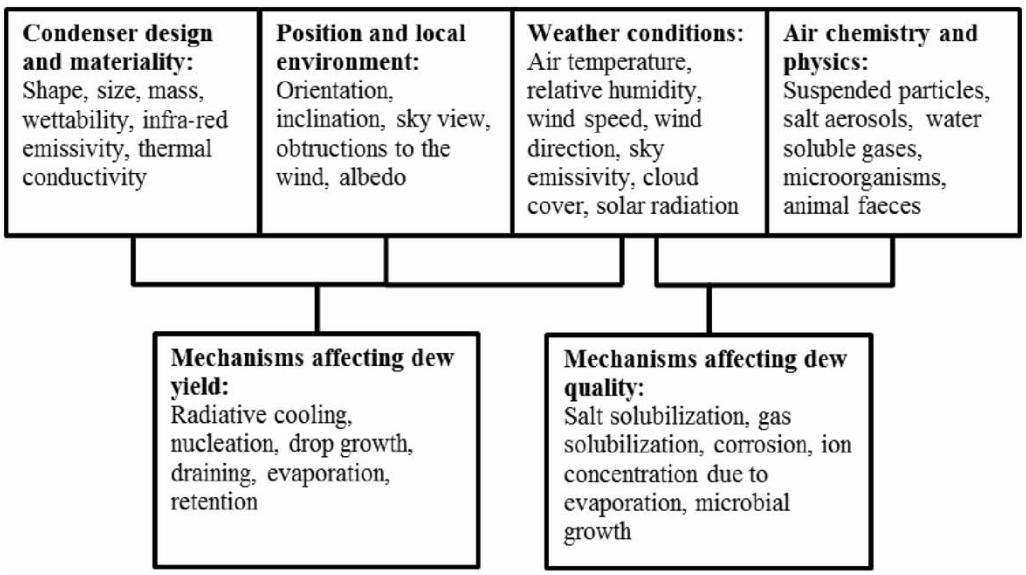

Figure 1 | Diagram of the factors affecting dew yields and water quality of a passive dew condenser.

for two reasons. First, it is representative of the temperate steppe climate in Chile, covering more than half (roughly 20,000 km^2) of the Coquimbo region. Second, such research is particularly important in this area, which is suffering from a quickening process of desertification (UNCCD 2015).

BACKGROUND

Site description

The studied site (El Chañar) is located north-west of Combarbalá city (923 m asl, latitude 31° 7′57.54″S, longitude 71° 7′53.26″W). It lies 50 km away from the Pacific Ocean in the semiarid region of Coquimbo, Chile (see Figure 2). According to the Köppen–Geiger climatic classification, the studied area is BSks, a temperate steppe climate, with winter rain as precipitation (GORE Coquimbo 2017). The average annual rainfall is about 202.4 mm, with a standard deviation of 146.6 mm; this rainfall is concentrated between May and August (austral winter) (DGA 2017; DMC 2017). Rain precipitation is erratic and affected by El Niño – Southern Oscillation (ENSO). Researchers have reported increased winter precipitation during El Niño episodes (Montecinos & Aceituno 2003). The average temperature is 17.3°C, with January being the warmest month (average: 21.6°C) and July being the coldest (average: 12.9°C) (DGA 2017). The average relative humidity is 42%, with a standard deviation of 18%. The relative humidity is higher in January (average: 48.3%) and lower in June (average 33.7%). The average wind speed (measured at 2.5 m agl) is 1.8 m s^{-1}, higher in November (average: 2.0 m s^{-1}) and lower in May–July (average 1.4 m s^{-1}) (CEAZA 2017). The wind direction is characterized by different day–night cycles with prevailing winds from the NW during the day and SE during the

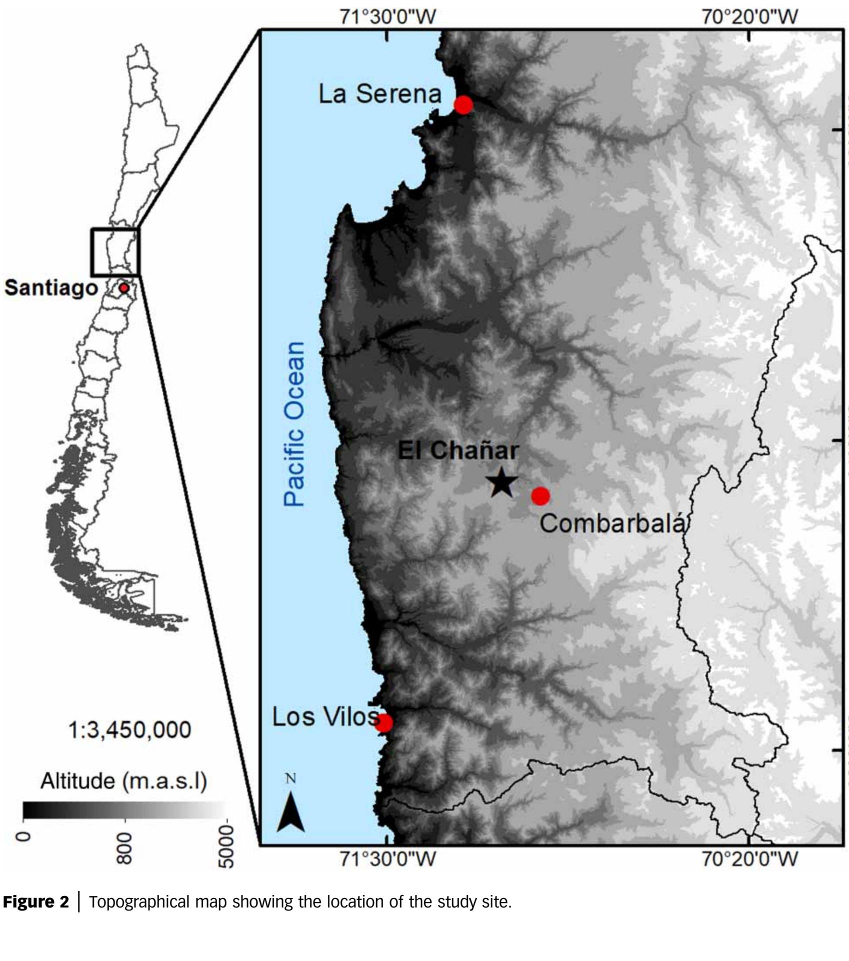

Figure 2 | Topographical map showing the location of the study site.

night. The annual pan evaporation is 1,988.4 mm (CEAZA 2017; DMC 2017).

The predominant vegetation in the region is steppe and xeromorphic, adapted to dryness. Plant development mainly depends on winter precipitation. Sclerophyllous arboreal vegetation presents hard leaves, providing strong resistance during dry periods (GORE Coquimbo 2017). Currently, the Combarbalá commune and the Coquimbo region in general suffer from severe water scarcity and desertification due to climatic factors (a long-term decrease in precipitation) and human activities (inadequate farming practices, overgrazing, and deforestation) (Cámara de Diputados Chile 2012). The commune experienced a prolonged drought between 2003 and 2014, with a 34.3% decrease in the amount of rainfall (27.6% if we extend the period to 2003–2016). Within this period, the lowest recorded rainfall occurred in 2014 with 47.9 mm (DGA 2017). The commune of Combarbalá has 12,800 inhabitants, about 50% of whom receive water from tanker trucks (BCN 2013). The trucks transport the water from a potable water plant (run by the Aguas del Valle company) that extracts water from the Combarbalá river in the town of Ramadilla Alto, located south-east of the city of Combarbalá. The frequency of delivery is one to three times a week depending on availability. The commune's main economic activities by labour force are the following: agriculture and livestock (27.7%), commerce (21.2%), mining (15%), and construction (4.2%) (BCN 2011). As a consequence of water scarcity, livestock producers have faced great hardship. For instance, there has been a high mortality rate for goats, an important livestock in the area that contributes to the local economy.

Roof characteristics

The building's roofing is of the gable variety with one side oriented to the south-east and the other to the north-west. Each side of the roof has an area of 36 m^2 and is covered with corrugated galvanized steel sheets. These sheets have been painted with an oil-based paint mixed with a high-infrared-emissivity additive based on 0.2–2 μm aluminasilicate powder (15% by weight), provided by OPUR (France). Both halves are pitched at 15° and insulated underneath with 50 mm polystyrene foam to minimize conductive and convective heating from inside the house and soil. Collection gutters and storage tanks were installed on both sides. Note that a corrugated sheet increases the slope locally, thus improving drop collection by gravity. For dew yield measurements, only the SE-oriented roof side was used because the NW-oriented roof was structurally modified during the studied period, affecting thermal insulation and size. As a result, it was not comparable with the SE-oriented side. Figure 3 shows a schematic sketch and photographs of the roof side of the home used for collecting dew.

METHODS

In order to measure dew water volume (h), we installed a graduated bottle of 20 L capacity (graduation lines: every 0.5 L) connected to the collection system. The water produced was driven by gravity from the corrugated sheet to the bottle. Dew measurements were carried out between 18 November 2013 and 20 November 2015. Within that period, 3 September 2014 to 31 August 2015 presented the highest availability of data, therefore it was selected for the analysis. The measurements of the dew produced were carried out daily at 08:00 local time (LT, GMT 04:00). These measurements were made early in the morning at 08:00 LT because dew events occur during the night; in addition, we sought to minimize evaporation after sunrise. The water measurements correspond to the accumulated volume in the container without scraping the collecting surface.

Cloud cover was registered daily by observations *in situ* at 08:00. Measurements of air temperature, relative humidity, wind direction and speed, and rainfall were obtained from a meteorological station managed by the Centro de Estudios Avanzados en Zonas Áridas CEAZA. Located 14.6 km SW (301°) from the study site, the Cruz del Sur Observatory (coordinates: 31° 12′ 2.03″S, 71° 0′2.85″ W) registers air temperature (T_a) and relative humidity (RH) data (Vaisala HMP155); wind speed (U_2) and direction (U_d) at 2 m agl (RM Young 5103); and rainfall (PR) (Texas Instruments TR-525M rain gauge). All sensors are operated at a sampling period of 5 s, and the data are averaged and stored every 5 min.

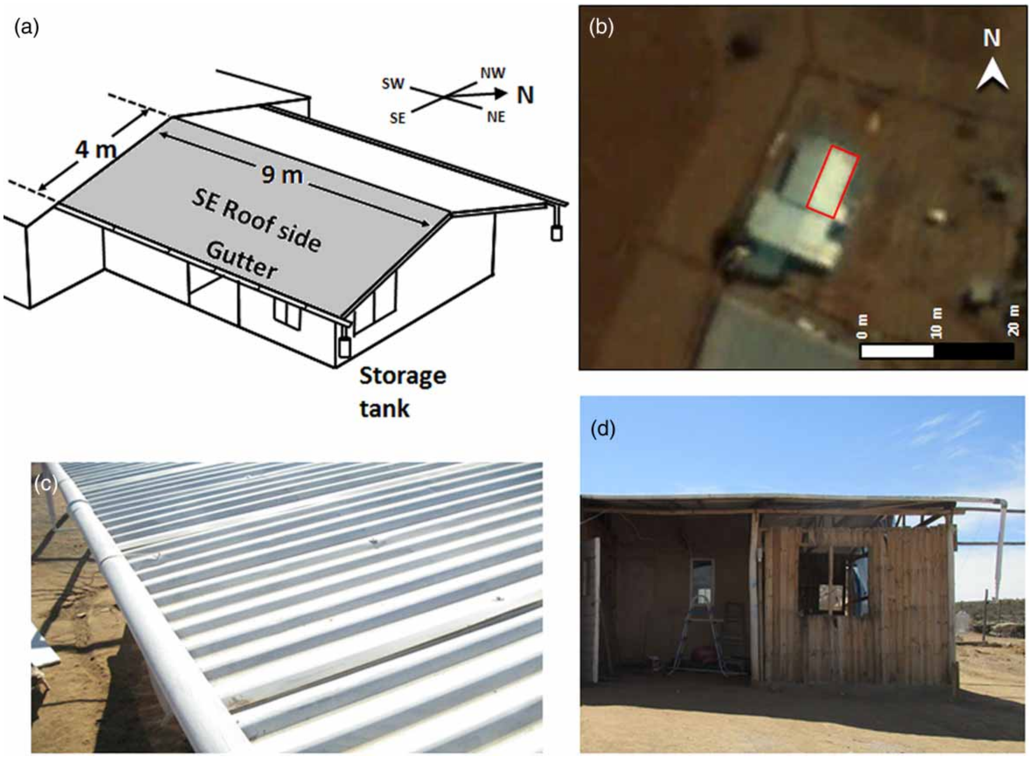

Figure 3 | (a) Schematic sketch of the household with a modified rooftop for dew collection; (b) satellite image of the study site (Google Earth 2018); (c) photograph of the roof; and (d) photograph of the south-eastern façade.

In addition to dew, the roof can collect rain and fog; thus, in order to distinguish the type of event, we used the following criteria for classification: (a) rain event – when rain precipitation is above 0 mm; (b) fog event – when dew-point depression (DPD) is below 0.5°C (Hiatt *et al.* 2012; Meunier & Beysens 2016; Montecinos *et al.* 2018); and (c) dew event – no observed rainfall, the dew yield is above zero and DPD is above 0.5°C. Dew events often occur during the night; at the study site, they happen most frequently between 21:00 and 6:00 local time; therefore, the meteorological data were analysed over that same time period. Because the exact durations of dew events are not known, data analysis employed the average values of meteorological variables during the mentioned time interval. The duration of dew events is always under 24 hours owing to the interruption of passive cooling caused by solar radiation. In addition, we sought to make the timescale between the different kinds of events uniform. As such, these measurements were normalized using a one-day basis. For example, four consecutive days of rain corresponds to four rain events.

In order to compare wind speed, we relied on the literature regarding dew collection; wind speed measured at 10 m agl (U_{10}) was estimated from the data obtained at 2 m agl using the well known expression provided by Pal Arya (1988):

$$U_{10} = \frac{U_2 \ln(10/Z_c)}{ln(2/Z_c)} \tag{1}$$

Here, z_c corresponds to the ground roughness length, which equals 0.1 m, corresponding to an open landscape obstacle of height H, separated by at least $15H$ (Sharan *et al.* 2007). Table 1 summarizes the data used in this work.

RESULTS AND DISCUSSION

Meteorological data

Table 2 presents monthly averaged (Avg) meteorological data and standard deviations (SD) based on nights (21:00

Table 1 | Summary of the data used in this study and their sources

Variable	Method/ Instrument	Sampling	Location	Source
h	Manual	Daily, 8AM	El Chañar	[A]
N	Observation	Daily, 8AM	El Chañar	[A]
T_a	Vaisala HMP155	5 min	Observatorio Cruz del Sur	[B]
RH	Vaisala HMP155	5 min	Observatorio Cruz del Sur	[B]
U_2, U_d	RM Young 5103	5 min	Observatorio Cruz del Sur	[B]
PR	Texas Instr. TR-525 M	5 min	Observatorio Cruz del Sur	[B]

[A] Measurement carried out by the authors.
[B] Centro de Estudios Avanzados en Zonas Áridas.

to 06:00) during the study period. For the entire period, the average relative humidity was 48% with a standard deviation of 18.2%. As the table illustrates, RH at night is higher in the months of September, January, February, March, and August. Lower RH occurred in June and July. For the entire period, the average air temperature (T_a) was 15.2°C with a standard deviation of 3.1°C. The average nightly temperature tends to increase in spring, reaching its peak during summer (~17.8°C) before decreasing in autumn and reaching its minimum in winter (~10.9°C). The maximum observed air temperatures occurred in January, February, and March while the minimum temperatures appeared in September, July, and August. As for cloud cover, the yearly average was 2.3 oktas with a standard deviation of 2.9 oktas. The months of greatest cloud cover were September, July, and August, coinciding with the austral winter (rainy season). Meanwhile, the least cloud cover was observed in December, January, and March, corresponding to the summer (dry season). In terms of wind direction, the nocturnal wind predominantly comes from the south-east throughout the year. By contrast, the daytime wind typically comes from the opposite direction, the north-west. The day/night change of wind direction relates to thermally driven circulations associated with surface heating/cooling and topography. In general, the wind regime changes between 17:00 and 23:00 and between 06:00 and 11:00 (CEAZA 2017). The nocturnal wind speed is distributed relatively evenly throughout the year with speeds mostly between 1 and 2 m s^{-1}, with a small decrease during the summer months and an increase in spring; in both cases, daily peaks remain below 4 m s^{-1}. As a final measure, Table 2 presents rainfall, which was concentrated in autumn and winter months, particularly March (42.5 mm), July (46.6 mm), and August (123.5 mm).

Table 2 | Nightly monthly averaged meteorological data for the study area (from 21:00 to 06:00)

	RH (%)		T_a (°C)		U_{10} (m)		U_d (°)		N (okta)		PR (mm)
Month	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Accum
Sep-14	57.7	22.2	10.9	3.7	1.7	0.5	157	44	3.4	3.2	11
Oct-14	45.8	20.0	15.3	3.3	1.5	0.4	164	64	2.1	2.6	1.5
Nov-14	41.9	16.6	15.4	2.2	1.4	0.3	162	64	1.6	2.8	1.1
Dec-14	49.1	16.7	16.0	2.5	1.3	0.3	153	56	1.4	2.8	0
Jan-15	57.5	13.0	17.8	2.2	1.2	0.2	154	54	1.2	2.8	0
Feb-15	59.8	11.1	17.1	2.3	1.2	0.3	160	59	2.4	2.9	0
Mar-15	58.3	12.9	17.7	2.1	1.4	0.7	163	47	1.1	2.3	42.5
Apr-15	49.2	20.3	16.9	3.0	1.5	0.4	160	48	1.9	3.3	0
May-15	40.1	18.6	15.0	3.2	1.5	0.6	158	39	2.1	3.1	0.7
Jun-15	22.2	15.8	15.5	3.8	1.7	0.3	151	64	1.5	2.5	0
Jul-15	38.8	21.4	12.4	3.9	1.7	0.5	158	58	3.5	3.5	46.6
Aug-15	55.1	30.1	12.1	5.1	2.5	2.1	145	52	5.6	3.1	123.5

Definition of parameters: see text.

Dew yields

Table 3 shows the monthly daily average dew yields, maximum daily dew yields, and SD. To facilitate comparison with the literature, we present dew yields as average daily values using one square metre as a basis. The study included 189 days, of which 106 corresponded to dew events (56.1%), 11 to rain events (5.8%), and 1 to a fog event (0.005%). Discarding days with fog and rain events, the average dew yield was 0.053 L m^{-2} d^{-1} with a standard deviation of 0.075 L m^{-2} d^{-1} (note that for this calculation, those days for which $h = 0$ were included). Considering the whole roof side (36 m^2), the average collected dew water was 1.9 L d^{-1} with a standard deviation of 2.7 L d^{-1}. Obtained in September 2014, the maximum dew yield was 0.417 L m^{-2} d^{-1}. This amount, considering the whole roof side, corresponded to 15 L d^{-1}.

It is not possible to analyse the data on a monthly basis for the entire period due to the lack of information, particularly from May to July 2015. However, it is possible to compare the dry (summer) and humid (winter) seasons. Dew yield in summer averaged 0.030 L m^{-2} d^{-1} with a standard deviation of 0.023 L m^{-2} d^{-1}. Winter dew yield averaged 0.096 L m^{-2} d^{-1} with a standard deviation of 0.105 L m^{-2} d^{-1}. Average dew yield in winter is roughly three times higher than that observed in summer. The highest dew yield (0.417 L m^{-2} d^{-1}) was obtained in winter (4 September 2014). By comparison, the maximum dew yield in summer was 0.083 L m^{-2} d^{-1} (17 January 2015). The percentage of dew events was 72.9% in summer and 67.6% in winter. There is not a noticeable difference between summer and winter in terms of the proportion of dew events; therefore, most of the difference observed between average dew yields in the two seasons results from variations in the daily dew yields. This finding is explainable, in part because more days with high relative humidity occur in winter (26.9% of the days had $RH >$ 70%) compared with summer (14.3% of the days had $RH >$ 70%). A similar pattern appears when only dew events are considered; for winter, 23.5% of the days show a $RH >$ 70%, and in summer, 10.4% of the days exhibit an $RH >$ 70%.

Table 3 | Monthly daily average dew yields, maximum daily dew yields, and standard deviations

Month	Number of study days	Number of dew events	Avg. dew yield (Lm^{-2} d^{-1})	Max. dew yield (Lm^{-2} d^{-1})	SD. dew yield (Lm^{-2} d^{-1})
Sep-14	25	13	0.094	0.417	0.116
Oct-14	29	7	0.034	0.278	0.074
Nov-14	17	3	0.008	0.056	0.018
Dec-14	21	8	0.034	0.222	0.060
Jan-15	21	15	0.033	0.083	0.024
Feb-15	10	10	0.038	0.056	0.014
Mar-15	18	15	0.033	0.083	0.024
Apr-15	21	19	0.102	0.278	0.083
May-15	9	8	0.056	0.178	0.049
Jun-15	3	3	0.130	0.222	0.079
Jul-15	4	4	0.132	0.278	0.099
Aug-15	11	1	0.052	0.167	0.054

Figure 4 shows monthly daily average dew yields, monthly rainfall and meteorological data averaged from 21:00 to 06:00. Omitting meteorological data for which daily dew yield was missing, the figure demonstrates that the average dew yield is higher in winter than in summer, and the monthly average relative humidity is higher during summer; however, as previously pointed out, summer had a lower proportion of high humidity days ($RH >$ 70%) compared with winter. As expected, the air temperature increased during the summer and decreased during the winter; meanwhile, cloud cover increased during the rainy season. The lower dew yields during the summer, as compared to winter, might relate to the low number of high relative humidity days and the increase in air temperature. These trends increased dew point depression, thus reducing the cooling energy available for condensing water vapour.

Relative humidity

Figure 5 shows the relationship between relative humidity and daily dew yields for the period under study. The figure demonstrates that there is a minimum threshold for dew formation of approximately 25% relative humidity. 90% of the days with non-zero dew yield had RH between 40.2% and 96.4%. The figure illustrates that maximum dew yield increases along with rising relative humidity. A dotted line

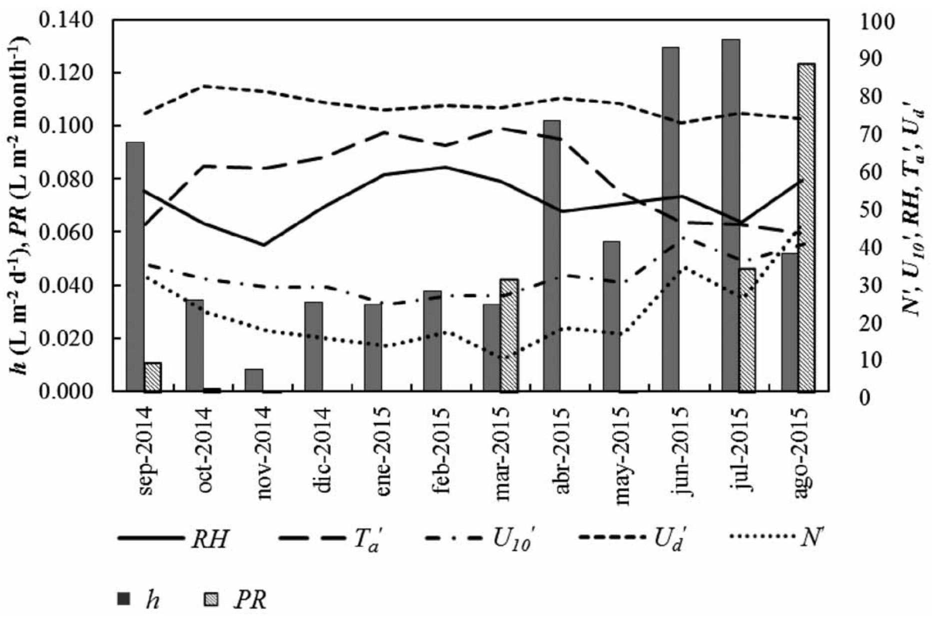

Figure 4 | Monthly daily average dew yields, monthly rainfall, and meteorological data (from 21:00 to 06:00). Meteorological data were normalized as follows: $N' = 10\ N$, $U_{10}' = 20\ U_{10}$, $T_a' = 4\ T_a$, $U_d' = U_d/2$. Meteorological data for which daily dew yield was missing were omitted.

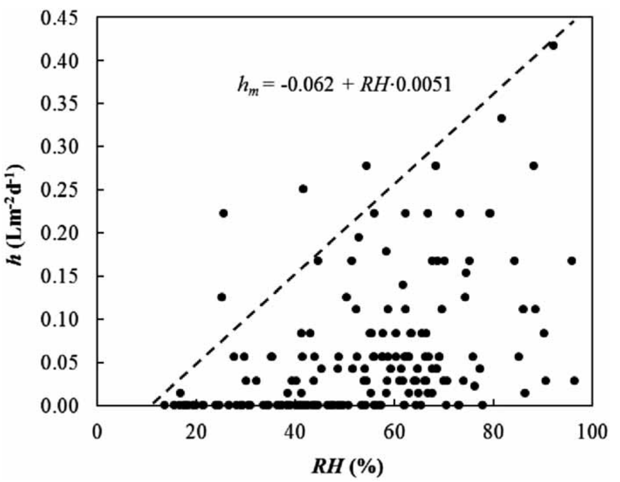

Figure 5 | Daily dew yields versus relative humidity averaged during the night (21:00 to 06:00).

covers the region where most (96.4%) dew events occurred. The line corresponds to the following equation:

$$h_m = -0.062 + 0.0051 \times RH \tag{2}$$

Here, h_m corresponds to the maximum potential daily dew yield ($\mathrm{L\,m^{-2}\,d^{-1}}$) at a given daily average relative humidity (%). Similar patterns have been observed during various meteorological conditions around the globe (Nilsson 1996; Sharan *et al.* 2007; Maestre-Valero *et al.* 2011; Lekouch *et al.* 2012; Meunier & Beysens 2016). However, the intercept and slope of the line defining maximum potential dew yield with respect to *RH* varies depending on the condenser design/materiality and position/local environment, and other weather conditions. In many studies, the minimum *RH* for dew formation varies between 40 and 70%. By comparison, in our study, we report dew formation for a minimum *RH* of around of 25%. The study site has a very low relative humidity year round owing to its distance from the ocean and the influence of the nearby 'Cordillera de la Costa', a coastal mountain range that serves as a barrier to the Pacific Ocean's humid winds. Notwithstanding these very dry conditions, the study area presents a relatively high number of dew events, which could be related to the atmosphere's high infrared transmittance and low wind speed.

Air temperature

Figure 6 shows the relationship between ambient temperature and dew yield, making possible the observation that

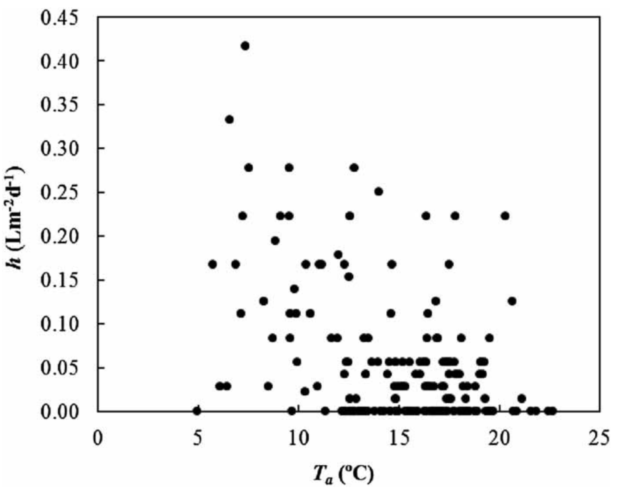

Figure 6 | Daily dew yields versus air temperature averaged during the night (21:00 to 06:00).

dew events occur for a wide range of temperatures between 6 and 21 °C. Maximum values for dew yields relate to lower temperatures, primarily because relative humidity depends on ambient temperature; a lower temperature leads to a higher relative humidity when absolute humidity is constant. As indicated above, higher relative humidity goes hand in hand with higher maximum dew yield.

Cloud cover

Figure 7 shows cloud cover versus daily dew yields. Dew events are concentrated between 0 and 2 oktas, and 8 oktas. From a theoretical point of view, lower cloud cover should promote greater dew yield because the atmosphere becomes more transparent for the long-wave infrared radiation emitted by the condenser. The literature has reported decreasing maximum dew yields with increasing cloud cover (Lekouch *et al.* 2012; Meunier & Beysens 2016). Some studies (Muselli *et al.* 2002, 2006) have reported the same tendency for a range of 1–8 oktas, but these reports also indicated lower dew yields for $N = 0$ (clear sky); in such cases, the researchers hypothesized that a clearer sky might lead to drier air (low relative humidity). For the recorded data in this work, there is no clear relationship between cloud cover and dew yields. For most data with dew yields above zero, the oktas equal 0, 2 or 8. Further, the maximum dew yield observed was for $N = 8$ (overcast sky). On the other hand, our data do not point to a clear relationship between cloud cover and relative humidity (not shown). This finding may relate to the change of wind regime after sunrise, which is usually between 06:00 and 11:00. Because dew events usually occur between 21:00 and 06:00, it is not possible to ascertain whether or not cloudiness at 08:00 is truly representative of night cloudiness, particularly for this study site.

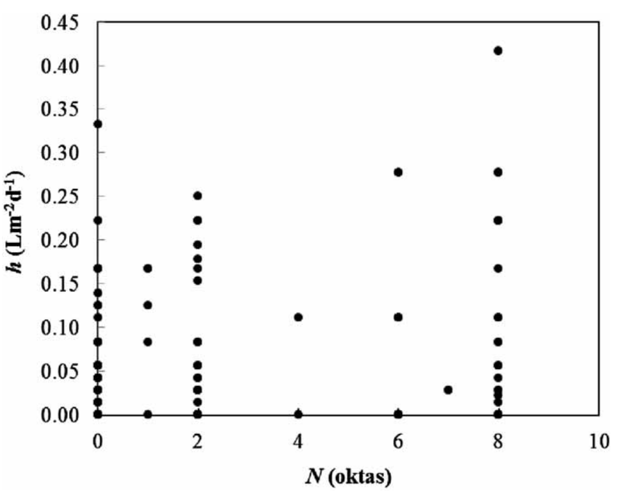

Figure 7 | Daily dew yields versus cloud cover recorded at 08:00.

Cloud cover is one of the main factors affecting the formation of dew and is one of the most difficult variables to measure. Generally, cloud cover is measured by visual observations during the day, as is usual at airports. Accurate measurement of cloud cover at night is very expensive, requiring an infrared all-sky camera or analysis of high-resolution infrared cloud-cover images from satellites, which was beyond the scope of this study.

Wind speed

Figure 8 shows daily wind speed at 10 m agl (U_{10}) (averaged overnight) versus daily dew yields. For 99.5% of the analysed days, U_{10} was between 0.7 and 2.7 m s^{-1}. Discarding those data with $h = 0$ L m^{-2} d^{-1}, the range is almost the same (0.8 to 2.7 m s^{-1}). One outlier event was registered ($U_{10} = 5.6$ m s^{-1}; $h = 0.056$ L m^{-2} d^{-1}); this value was considered an outlier because it differed by five SD from the average value (1.56 m s^{-1}), which means that we do not know whether this value is correct or erroneous. Figure 8 shows that there is no clear relationship between wind

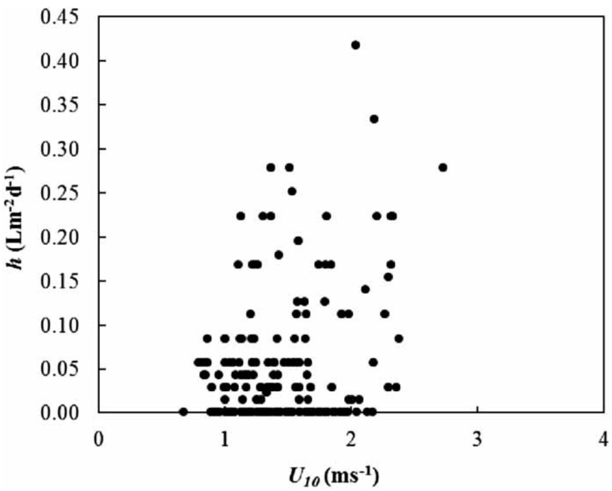

Figure 8 | Daily dew yields versus wind speed at 10 m agl averaged during the night (21:00 to 06:00). Outliers ($U_{10} > 3.5$ m s^{-1}) were not plotted.

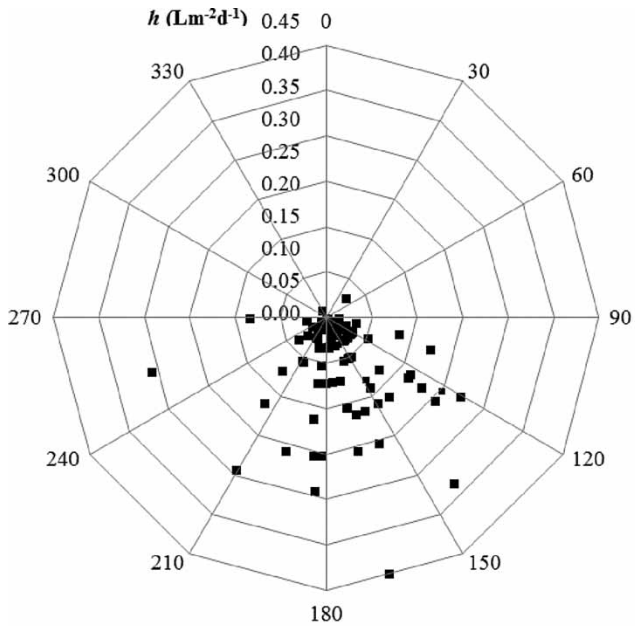

Figure 9 | Daily dew yields versus wind direction averaged during the night (21:00 to 6:00); north: 0°; east: 90°; south: 180°; west: 270°.

speed and dew yield. According to the literature, most dew events occur for $U_{10} < 4.4$ m s^{-1} because higher wind speeds increase convective heat transfer to the condenser's surface to the extent that it can detain dew formation (Beysens *et al.* 2003; Beysens 2016). In our study, in 99.1% of the dew events, the average wind speeds were below 4.4 m s^{-1}.

Wind direction

Figure 9 shows daily dew yields in relation to average wind direction at night. In general, dew was observed to form for directions between 90° and 240°, with maximum dew yield for a wind direction of 166.3° (south by east). The collecting surface had a south-east orientation, and the nocturnal wind commonly reached near perpendicular to the vertical projection of the roof face. Because wind speed was generally of low intensity (<4.4 m s^{-1}), the fact that the roof face commonly received winds from the south-west, south and south-east should not appreciably affect dew yields. Additionally, the change in wind regime in the morning (usually after 06:00) should not affect dew yields because wind speed after sunrise was often below 4 m s^{-1}.

Dew point temperature and air temperature

From a theoretical perspective, the highest dew yields occur when dew point temperature (T_d) is close to air temperature (Beysens 2016). In this case, most of the cooling energy is used for condensation. For values of $T_d - T_a < 0$°C, dew yields are lower, as part of the cooling energy is used to reduce the temperature of the condenser to the dew point temperature. It should be noted that for values $T_d - T_a > -0.5$°C ($DPD < 0.5$°C), fog occurrence is common, which was considered in this work to distinguish fog and dew events. Figure 10 shows daily dew yields versus $T_d - T_a$ averaged overnight values for the study site. A dotted line encloses the region where most (94.6%) of the dew events were observed. The line corresponds to the following equation:

$$h_t = -0.383 + 0.017(T_d - T_a) \quad (3)$$

where h_t corresponds to the maximum potential daily dew yield for a given value of $T_d - T_a$. The literature indicates that, in general, the threshold for dew formation falls within the range of -11 C $< T_d - T_a < -3$°C, and the slope of Equation (3) commonly lies between 0.035 and 0.089 L m^{-2} d^{-1} °C^{-1} (Sharan *et al.* 2007; Clus *et al.* 2008; Maestre-Valero *et al.* 2011; Lekouch *et al.* 2012; Beysens 2016; Meunier & Beysens 2016). In the present study, the threshold for $T_d - T_a$ was approximately -22.4°C, and the slope was

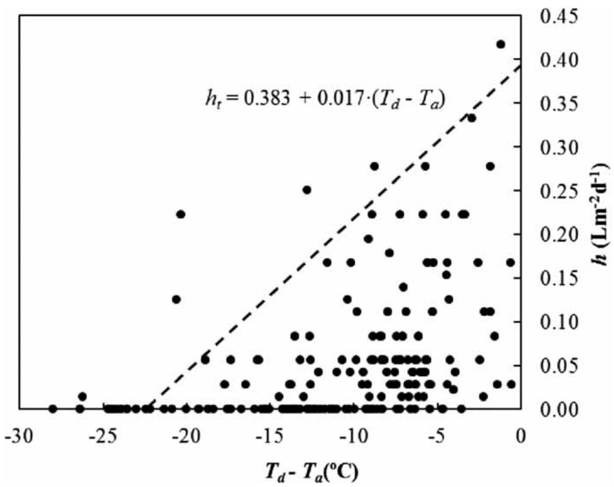

Figure 10 | Daily dew yields versus $T_d - T_a$ averaged during the night (21:00 to 6:00).

$0.017\ L\ m^{-2}\ d^{-1}\ {}^{\circ}C^{-1}$. Aside from the fact that dew experiments might differ in terms of condenser characteristics and local topography (affecting the parameters of Equation (3)), two aspects of meteorological conditions might also explain the difference: this region's very high atmospheric transmissivity (low cloudiness with little presence of aerosols during the year) and low wind speed at night (CEAZA 2017; EOSDIS 2017). Both of these characteristics should increase condenser cooling power, so increasing the range of *RH* at which dew could occur.

Potential yearly dew yield

The absence of some data means that it is impossible to know exactly the total amount of dew collected over one year in the study area. However, it is possible to estimate this amount, as this study recorded data for 189 days in a single year, across all seasons. In a typical year, with annual rainfall of 202.4 mm (DGA 2017), dew events of 56.1% and an average dew yield of $0.053\ L\ m^{-2}\ d^{-1}$ (see dew yields section), and excluding the contribution of fog (1–2 days per year), it can be estimated that a roof with the characteristics and area specified here ($36\ m^2$) would collect 647 L of dew and 6,922 L of rain per year. This calculation was based on an assumed 23 rainy days per year (CEAZA 2017) and a run-off coefficient of 0.95 (tilted steel sheet) (Novak *et al.* 2014). Based on the total (dew + rain), dew can be said to contribute 8.2%.

Combarbalá has an average 1.8 inhabitants per household (INE 2011; BCN 2013). Although there is no available information about average roof area by household for this community or for others in Chile, satellite images (Google Earth 2018) allow us to estimate an average roof area of $134\ m^2$ based on 100 households near the study area. Gable-type roofing made from galvanized corrugated steel sheets is widely used in the area. Currently (2018), two adults live in the analysed house which has a total roof area of $140\ m^2$ (including inhabited rooms and an adjacent open barn), which can be considered representative of this community. The World Health Organization (WHO 2017) Guidelines for Drinking-Water Quality recommend an intake of 1.4 litres per day for an adult female and 2 litres per day for an adult male; for a household comprising two adults (one female and one male), the yearly drinking water requirement would be 1,241 litres. Given that the rooftop can potentially collect $0.053\ L\ m^{-2}\ d^{-1}$ of dew; the entire household could collect 2,708 litres per year, representing more than twice the drinking water requirement. If we include rainfall in the calculation, the total (dew + rain) would be 29,627 litres per year.

As was mentioned in the introduction, rainwater harvesting has been successfully applied in several countries, however, in places where rainfall is infrequent and highly seasonal (as the semi-arid region of Chile) and a high storage capacity is required, thus increasing costs. In contrast, dew is a much more frequent phenomenon and requires low storage capacity. Dew and rainwater harvesting are complementary; however, more knowledge (e.g. daily water demand and water quality) is required for a further technical–economic analysis.

Limitations of the study

For the purposes of this study, nightly averaged data (21:00–06:00) were used. The selected time interval was based on the literature (Sharan *et al.* 2011; Lekouch *et al.* 2012; Maestre-Valero *et al.* 2015) and on observations *in situ*. As no hourly data for dew collection were available, it was not possible to establish a period based on empirical data. However, a comparative study using different time intervals (05:00–06:00, 00:00–06:00 and 21:00–00:06) obtained similar results. The interval 21:00–00:06 was selected as a better match with observations conducted by the authors at the study site. Seasonal variations in sunrise and sunset did not influence the results, as the period 21:00–06:00 always falls within the night throughout the year. It is important to highlight that after sunrise the roof can continue to drain water for a time before evaporation occurs due to solar radiation. This time interval may be of the order of minutes if nothing is obstructing direct solar radiation, or of several hours if the sky is overcast and wind speed is low.

Following dew events, some water droplets remain attached owing to the forces of adhesion between water and surface. In the present study, remaining (stagnant) water was not scraped and measured because of the difficulty of carrying out such a procedure every day. According to the literature, the remaining water may amount to anything between 15% and 33% (Muselli *et al.* 2002; Maestre-Valero *et al.* 2011). In the present case, it was also observed that some water remained stagnant in the gutter after dew events and then evaporated during the day. We did not measure this water loss, again because of the difficulty of such a procedure. For both roof and gutter, the amount of water remaining will depend on surface characteristics, inclination and the presence of dust and organic debris. We believe that water losses due to stagnation may be important in the long term, especially in semi-arid and other areas where the accumulation of dust and debris on roofs could increases water retention. This issue has not yet been fully addressed and requires further investigation.

Other possible water losses that were not observed here but seem important for projects involving roof-integrated dew collectors include leaks in gutters and downpipes, and dripping losses that occur when the wind speed is sufficiently high to divert water droplets out of the collection gutter. These problems are easily addressed by means of a well-designed condenser-draining system and periodic inspection and maintenance. Tilted galvanized steel roofing has a high run-off coefficient (above 0.95), but arriving at a more precise value would require measurement both under controlled conditions in the laboratory and under field conditions.

The presence of radiation fog was observed at the study site by the first author during several visits between 2015 and 2017, mostly in the early morning and after sunset. Radiation fog occurs when the ground loses heat through radiative cooling. As air temperature decreases, relative humidity increases to saturation point, which is a condition for fog formation. This can be a negative factor for dew generation because it reduces sky transmissivity, so reducing the cooling power of the condenser. Because radiation fog generally occurs at reduced wind speeds (Cereceda *et al.* 2002), it cannot be measured by conventional means such as standard fog collectors. Instead, a fog spectrometer is required for *in situ* quantitative characterization while an infrared all-sky camera or satellite (i.e. GOES) image analysis can provide qualitative information (Underwood *et al.* 2004). Quantitative and/or qualitative analysis of fog was beyond the scope of the present study.

The present study does not include a theoretical analysis for the development of mathematical models or validation of an existing model. Any theoretical study would have to take account of the timescale of dew formation and draining, as well as the most important variables affecting dew yield, such as wind speed. It would also be necessary to identify and, if possible, to measure fog events; a standard fog collector and/or satellite imagery would be useful for that purpose. *In situ* measurement of meteorological variables would also be necessary in order to reduce the uncertainty caused by using data from a meteorological station several kilometres away from the study area, as was the case for the present study. It is also important to note that the lack of data (48.2%) prevented deeper analysis of daily, monthly and seasonal variations for a mathematical model that may be applicable to other condensers/conditions. Nevertheless, the empirical data on the amount of dew water collected by a roof at the study site over a significant period of time provide important information on dew formation and its general relationship to key meteorological variables. This information is of great relevance for future studies of dew collection and for the scientific community and society in implementing scientific and/or community projects.

Although long-term systematic analysis of dew water quality was beyond the scope of this work, we did conduct a chemical analysis of a sample of dew water taken from the study site on 7 August 2014, analysing the following parameters: pH, Total dissolved solids (TDS), Cu^{2+}, Fe (total), Zn^{2+}, Pb^{2+}, Cl^{-} and SO_4^{2-}. Trace elements were analysed at the Chemical Engineering Department of Pontificia

Universidad Católica de Valparaíso, using a flame atomic absorption spectrometer (Thermo Scientific, model M5, USA). TDS was measured by gravimetric analysis, chloride was analysed by titration with silver nitrate, and sulphate was measured by precipitating as barium sulphate. TDS, Cl^- and SO_4^{2-} were analysed at the Laboratory of Analytical Services, Pontificia Universidad Católica de Valparaíso. Table 4 summarizes the results and compares them with the WHO standards for drinking water.

For this dew sample, we can see that all parameters fall within WHO standards for drinking water. However, we cannot conclude that this water is drinkable, as not all WHO parameters were analysed, and a long-term (i.e. one year) sampling campaign would be required to produce a representative description of the chemical and biological load of dew. Atmospheric pollution can affect dew water quality, and some studies have reported that proximity to electric thermal plants (Muselli *et al.* 2002), urban areas (Rubio *et al.* 2002), agricultural fields and motorways (Gałek *et al.* 2016), among other factors, affects dew composition. Major non-anthropogenic sources of aerosols and suspended dust such as oceans and deserts, respectively, can also affect dew water quality (Lekouch *et al.* 2011). In the case of the study site, we would expect any impact of anthropogenic air pollution on dew water to be low, as major sources are some distance away; these include open pit mines (Punitaqui copper and gold mine: 32 km); thermoelectric plants (Punitaqui diesel thermoelectric plant: 32 km); mineral foundries (Ventanas copper smelter: 182 km); main motorways (Ruta 5: 44 km) and urban areas (Combarbalá urban area: 13 km). Given the distance to the Pacific Ocean (49 km), we could also expect a low concentration of ions of marine origin (salt aerosols) in the dew water. Conversely, high deposition of dust was observed on roofs at the study site, therefore we would expect some effect of local soil in the chemical composition of dew. Regarding agriculture and livestock, large producers are far from the study area (15 km). Near the study site, there are very small agriculture and/or poultry producers (mainly for their own consumption and small-scale trade). It is expected that some fine organic debris could be transported by the wind from the production sites, however, more research is necessary to quantify this possible source of contamination.

Table 4 | Chemical analysis of dew collected at the study site in August 2014

Parameter	Dew sample	WHO (2017)
pH	7.48	6.5–8.5[a]
Total dissolved solids (mg/L)	170	<600 mg/L[a]
Cu^{2+} (mg/L)	<0.0385	≤2 mg/L
Fe_{tot} (mg/L)	<0.055	<0.3 mg/L[a]
Zn^{2+} (mg/L)	0.4	≤3 mg/L[a]
Pb^{2+} (mg/L)	<0.055	≤0.01 mg/L
Cl^- (mg/L)	28	<250 mg/L[a]
SO_4^{2-} (mg/L)	50	<500 mg/L[a]

[a]Desirable range. No guideline in the last version of WHO standards.

The effect of roof material on the chemical characteristics of dew water was not analysed here. Among the very few studies that include chemical analyses of dew produced from painted galvanized steel-sheet condensers, Lekouch *et al.* (2011) found a high concentration of Zn^{2+} (around 46 mg L^{-1}). However, as those samples were taken over a period of two months, they cannot be considered representative of a whole year. The more numerous studies of rainwater and its interaction with different roofing materials have shown that roofing materials (especially galvanized steel roofing) have no significant effect on water quality. In fact, steel roofing may reduce microbiological load, as exposure to ultraviolet light and high temperatures during the day effectively disinfect the roof surface (Lee *et al.* 2012).

Atmospheric pressure

Atmospheric pressure (P) influences mass transfer across the air–water interface. At lower atmospheric pressure, more latent heat must be extracted to sustain the condensation process. In Combarbalá, the variation of atmospheric pressure did not exceed 1.9% (17.3 hPa) during the study period, which meant that any effect on the condensation process would be very low, as the difference in latent heat of condensation did not exceed 0.6%. This becomes apparent when dew yields are set against atmospheric pressure (see Figure 11), as no clear patterns are discernible.

The highly scattered data reflect the fact that atmospheric pressure is related to the large-scale circulation of winds, which affects local-scale variables such as wind speed, relative humidity, air temperature and cloud coverage.

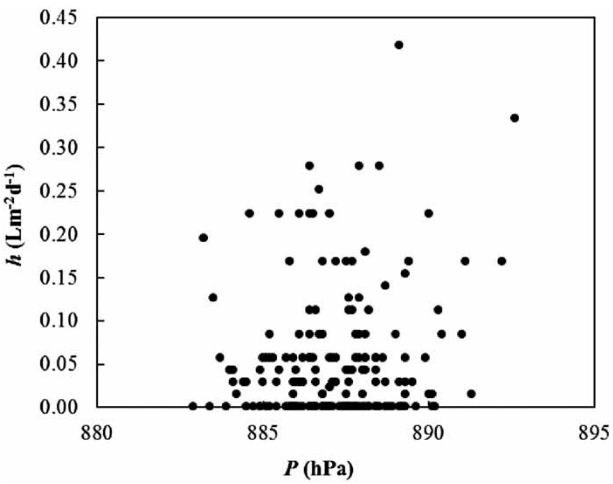

Figure 11 | Daily dew yields versus atmospheric pressure averaged during the night (21:00–6:00). Pressure sensor: Vaisala/PTB110. Location: Observatorio Cruz del Sur, CEAZA.

Improvements to future studies and on-going research

Future studies could usefully include such enhancements as measurement of rooftop surface temperature; continuous measurement of dew yield (e.g. hourly); comparison of dew yields between different roof orientations; *in situ* measurement of all meteorological variables and long-term chemical and biological analyses. These enhancements would facilitate better understanding of system heat balance, contributing to improved thermal design, and better knowledge of water quality enabling identification of further potential uses of dew water. We note that some of these improvements (such as the measurement of the condenser's surface temperature and hourly dew yields) are already being implemented under Fondecyt project 11140863 ('Experimental assessment and predictive modelling of rooftop dew collection for water supply in Chile'), using small-scale (1 m^2) dew condensers.

CONCLUSIONS

Few studies to date have investigated passive collection of dew using building rooftops. The present findings confirm that a 36 m^2 household roof in the semi-arid area of Combarbalá, Chile can serve as a relatively stable source of dew water throughout the year. During the study period, the average daily dew yield was 1.9 L d^{-1}, with a standard deviation of 2.7 L d^{-1}. Maximum dew yield is very strongly related to relative humidity overnight. The minimum relative humidity threshold for dew formation was around 25% relative humidity which could be explained because of the high atmospheric transmissivity and low wind speed. The maximum daily dew yield is correlated strongly with relative humidity and correlated weakly with air temperature and wind speed. It was estimated that the contribution of dew to the total collected water (including rain) is of the order of 8.2%. However, unlike rain, which requires large storage tanks because of its irregular distribution through the year, dew collection is more stable; it therefore requires less storage capacity, and it can be used immediately after being produced. In light of the acute water scarcity problem in the study area, dew represents a promising alternative as a supplementary source of water that can be used for such purposes as human consumption, irrigation of crops, livestock feeding, recovery of native flora and fauna and household water savings, among others.

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