Spatial and Temporal Investigation of Dew Potential based on Long-Term Model Simulations in Iran

Atashi et al.

S.1. Detailed Model description

The original model setup included phase change between water vapor and liquid (i.e. vapor-to-liquid; condensation) as well as solid (i.e. vapor-to-solid; desublimation). The model assumes condensation on a condenser surface, which is horizontally aligned sheet of a suitable material such as low-density polyethylene (LDPE) or polymethylmethacrylate (PMMA). The condenser sheet is also assumed to be at 2 meters from the ground and thermally insulated from the ground. In the model, only dew is considered whereas precipitation and fog were not accounted.

The model describes the dew formation on a flat surface (i.e. condenser) and it is based on the mass and heat balance equation

$$\frac{dT_c}{dt}(C_c m_c + C_w m_w + C_i m_i) = P_{rad} + P_{cond} + P_{conv} + P_{lat}, \quad (1)$$

where dT_c/dt is the change rate in the condenser temperature. C_c, C_w, and C_i are the specific heat capacities of the condenser, water, and ice; respectively. Here, m_c, m_w, and m_i are the masses of the condenser, water, and ice; respectively. The right-hand side includes the heat exchange involved in the process: P_{rad} is the incoming and outgoing radiation, P_{cond} is the conductive heat exchange between the condenser surface and the ground, P_{conv} is the convective heat exchange, and P_{lat} is the latent heat released by the condensation or desublimation of water. This equation was solved by using a fourth- order Runge-Kutta with 10 s time-step. All terms and nomenclature are described in more details in Tables S1 and S2.

The model was setup so that it assumes similar conditions for the phase-change of pre-existing water or ice on the condenser sheet. For instance, if the water on the condenser is in liquid phase (i.e. $m_w > 0$) and the condenser temperature $T_c < 0$ °C, then the sheet is losing energy (i.e. the right-hand side of Equation (1) is negative). In that case, instead of solving Equation (1), T_c is assumed to be constant and the lost mass from the liquid phase of water is transferred to the cumulated mass of ice; i.e. the water is transformed from liquid phase to solid phase. Consequently, Equation (1) is replaced by

$$L_{wi}\frac{dm_w}{dt} = P_{rad} + P_{conv} + P_{lat}, \quad (2)$$

where L_{wi} is the latent heat of fusion. If the water on the condenser is in solid phase (i.e. $m_i > 0$) and the condenser temperature $T_c > 0$ °C, a similar equation is assumed for the change rate of ice mass (m_i).

Note that Equation (2) is not related to the condensation of water; it only describes the phase change of the already condensed water or ice on the condenser. For the water condensation rate, which is assumed independent of Equation (2), the mass-balance equation is then assumed as

$$\frac{dm}{dt} = \max\left[\ 0\ ,\ S_c k\left(P_{sat}(T_d) - P_c(T_c)\right)\right], \quad (3)$$

where m represents either the mass of ice (m_i) or water (m_w) depending on weather T_c is below or above 0 °C. $P_{sat}(T_d)$ is the saturation pressure at the dew point temperature and $P_c(T_c)$ is the vapor pressure over the condenser sheet. $k = h / L_{vw}\gamma = 0.622h / C_a p$ is the mass transfer coefficient, where L_{vw} is the specific latent heat of water vaporization, γ is the psychrometric constant, C_a is the specific heat capacity of air, and p is the atmospheric air pressure. Here, $h = 5.9 + 4.1\ u\ (511 + 294) / (511 + T_a)$ is the heat transfer coefficient, where u and T_a are the prevailing horizontal wind speed and the ambient temperature at 2 meters from the ground.

In practice, the wettability of the surface affects the vapor pressure P_c directly above it. In other words, P_c is lower over a wet surface; and thus, condensation may take place even if $T_c > T_d$. It is also assumed that the processes included in Equation (3) undergo irreversible condensation; i.e. there is no evaporation or sublimation during daytime even if $T_c > T_a$. Furthermore, the model simulation resets the cumulative values for water and ice condensation at noon and takes the preceding maximum value of $m_w + m_i$ as the representative daily yield. This way, the model simulation replicates the daily manual dew water collection of the condensed water around sunrise; i.e. after which T_c is often above the dew point temperature.

Table S1: Description of the dew formation model by listing the terms in Eq. (1).

Term	Unit	Description
dT_c/dt	K s^{-1}	Change rate of the condenser temperature
T_c	K	Temperature of the condenser
t	s	Time. Here the time step in the model was 10 s
C_c	J kg^{-1} K^{-1}	Specific heat capacity of the condenser. For low-density polyethylene (LDPE) and polymethylmethacrylate (PMMA) it is 2300 J kg^{-1} k^{-1}
C_i	J kg^{-1} K^{-1}	Specific heat capacity of ice (2110 J kg^{-1} k^{-1})
C_w	J kg^{-1} K^{-1}	Specific heat capacity of water (4181.3 J kg^{-1} k^{-1})
m_c	kg	Mass of the condenser given by $m_c = \rho_c S_c \delta_c$ where ρ_c, S_c, and δ_c are the density (here it is 920 kg m^{-3}), surface area (here it is 1 m^2), and thickness of the condenser (here it is 0.39 mm)
m_i	kg	Mass of ice
m_v	kg	Mass of water, representing the cumulative mass of water that has
P_{rad}	W	Heat exchange due to incoming and outgoing radiation $P_{rad} = (1 - a)S_c R_{sw} + \varepsilon_c S_c R_{lw} - S_c \varepsilon_c \sigma T_c^4$ where a is the condenser short-wave albedo (here it is 0.84), S_c is the condenser surface area (here it is 1 m^2), ε_c is the emissivity of the condenser (here it is 0.94), σ is Stephan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T_c [K] is the temperature of the condenser, and R_{sw} and R_{lw} [W m^{-2}] are the incoming short-wave radiation (i.e. surface solar radiation downwards) and incoming long-wave radiation (i.e. surface thermal radiation downwards)
P_{cond}	W	Conductive heat exchange between the condenser surface and the ground. For simplicity, we assumed that the condenser is perfectly insulated from the ground; i.e. $P_{cond} = 0$
P_{conv}	W	Convective heat exchange $P_{conv} = S_c (T_a - T_c) h$ where S_c is the condenser surface area (here it is 1 m^2), T_a [K] is the ambient temperature at 2 meters from the ground, T_c [K] is the temperature of the condenser, and h [W m^{-2} K^{-1}] is the heat transfer coefficient that is estimated based on a semi-empirical equation (Richards, 2009) $h = 5.9 + 4.1\ WS\ (511 + 294) / (511 + T_a)$ and here WS [m s^{-1}] is the prevailing horizontal wind speed at 2 meters from the ground.
P_{lat}	W	Latent heat released by the condensation or desublimation of water $P_{lat} = \begin{cases} L_{vw} \dfrac{dm_w}{dt} & T_c > 0\,^oC \\ L_{vi} \dfrac{dm_i}{dt} & T_c < 0\,^oC \end{cases}$ where L_{vw} [J kg^{-1}] is the specific latent heat of water vaporization and and L_{vi} [J kg^{-1}] is specific latent heat of water desublimation. Here, dm_w/dt is the change rate of water whereas dm_i/dt is the change rate of ice

Table S2: A list of nomenclature.

Parameter	Unit	Description
α	--	Albedo of condenser sheet
C_a	J kg^{-1} K^{-1}	Specific heat capacity of air
C_c	J kg^{-1} K^{-1}	Specific heat capacity of the condenser
C_i	J kg^{-1} K^{-1}	Specific heat capacity of ice
C_w	J kg^{-1} K^{-1}	Specific heat capacity of water
DP	K	Dew point temperature
h	W K^{-1} m^{-2}	Heat transfer coefficient
k	Per s^{-1}	Mass transfer coefficient
L_{vi}	J kg^{-1}	Specific latent heat of desublimation for water
L_{vw}	J kg^{-1}	Specific latent heat of vaporization for water
L_{wi}	J kg^{-1}	Latent heat of fusion
m_c	kg	Mass of the condenser
m_i	kg	Mass of ice
m_w	kg	Mass of water
p	Pa	Atmospheric air pressure
p_c	Pa	Vapour pressure over condenser
p_{sat}	Pa	Saturation pressure of water
P_{cond}	W	Conductive heat exchange between the condenser surface and the ground
P_{conv}	W	Convective heat exchange
P_{lat}	W	Latent heat released by the condensation or desublimation of water
P_{rad}	W	Heat exchange due to incoming and outgoing radiation
R_{lw}	W m^2	Surface thermal radiation downwards
R_{sw}	W m^2	Surface solar radiation downwards
S_c	m^2	Surface area of condenser
T_a	K	Ambient temperature at 2 meters
T_c	K	Temperature of the condenser
U_{10}	m s^{-1}	Horizontal wind speed component at 10 meters
V_{10}	m s^{-1}	Horizontal wind speed component at 10 meters
WS	m s^{-1}	Prevailing horizontal wind speed at 2 meters
z_0	m	Surface roughness
δ_c	mm	Condenser sheet thickness
ε_c	--	Emissivity of condenser sheet
γ	Pa K^{-1}	Psychrometric constant
σ	W m^{-2} k^{-4}	Stefan-Boltzmann constant

S.2. Meteorological data as input for the model

The model input parameters includes:

- horizontal and vertical wind components (U_{10} and V_{10}) at 2 meters
- surface roughness (z_0)
- ambient temperature and dew point (T_a and D_P) at 2 meters
- short-wave and long-wave surface solar radiation (R_{sw} and R_{lw})

These were obtained from the European Centre for Medium Range Weather Forecast (ECMWF) Interim Reanalysis. ERA-Interim is a reanalysis of the global atmosphere covering the data-rich period since 1979 and continuing in real time [37,38], which has a horizontal resolution of 0.75° (approximately 80 km) and 60 vertical levels. The reanalysis combines available data sources (satellite, radiosondes, air craft, buoy data, stations etc.) into a coherent and balanced form of the atmospheric dynamic and thermodynamic state [39].

The ECMWF data-base is differentiated into three main categories: reanalysis, instantaneous forecast, and accumulated forecast. In our case, U_{10}, V_{10}, T_a, and DP were obtained from the reanalysis fields at 00:00, 06:00, 12:00 and 18:00 UTC whereas at 03:00, 09:00, 15:00 and 21:00 UTC were instantaneous forecasted fields. Both the forecasted and the reanalysis fields provided every 3 hours. According to the ECMWF data-base, the horizontal wind components (U_{10} and V_{10}) are provided at 10 meters. Therefore, the wind speed at 2 meters was calculated by using a logarithmic wind profile

$$WS = \frac{log\left(\frac{2+z_0}{z_0}\right)}{log\left(\frac{10+z_0}{z_0}\right)} \sqrt{\mathrm{U}_{10}^2 + \mathrm{V}_{10}^2}, \tag{4}$$

where z_0 is the surface roughness and U_{10} and V_{10} are the horizontal wind speed components at 10 meters. It is important to understand that Equation (4) is a simple equation that is valid during certain conditions. For instance, in stable conditions (such as at night) Equation (4) overestimates wind speed at 2 meters whereas in unstable conditions equation (4) underestimates the wind speed at 2 meters.

According to the ECMWF data-base, z_0 was obtained as an instantons forecast parameter whereas R_{sw} and R_{lw} were accumulated forecasted fields. The mean R_{sw} and R_{lw} in a time interval is obtained by taking the difference of the accumulated values between the corresponding time steps divided by the time difference in seconds. The result is a mean value for that time interval 00:00 or 12:00. All input parameters had a horizontal resolution 0.25 degree (approximately 30 km).

The model output for dew occurrence is given in liters of water collected on a 1 m^2 condenser sheet (i.e. L/m^2). However, this can be converted to units of mm (i.e. equivalent to rainfall).

S.3. Illustration s for detailed model input and output

Here we selected three examples to illustrate the model input and output parameters. The selected examples were: Bandarabas during 2–6 January 2005 (Figure S1), Ramsar during 1–5 September 2011 (Figure S2), and Tabas during during 12–15 December 2002 (Figure S3). As mentioned in the main part of the manuscript, the selection of these examples was to represent three regions in Iran. As for the time periods, they were based on the model simulation result for maximum yield in that year and season.

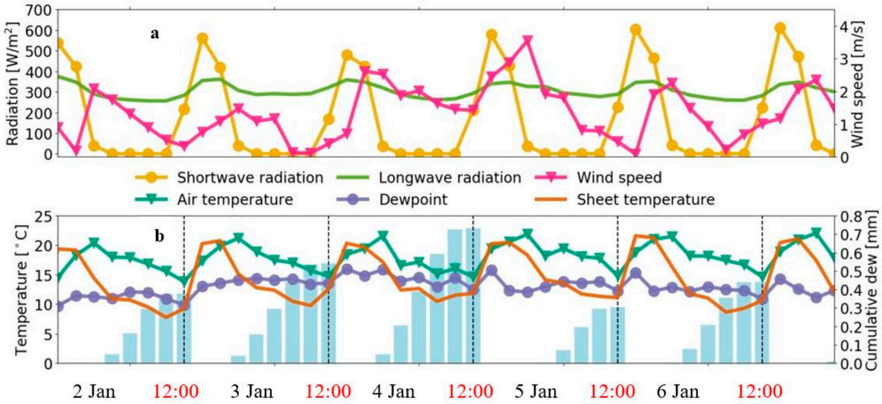

Figure S1: An example model simulation for dew formation during 2-6 January 2005 at Bandarabas, Iran. (a) the short-wave and long-wave radiation (left y-axis) and wind speed (right y-axis) whereas (b) the cumulative dew formation on the condenser (bars linked to the y-axis right axis) and the ambient temperature, dew point, and condenser sheet temperature (left y-axis).

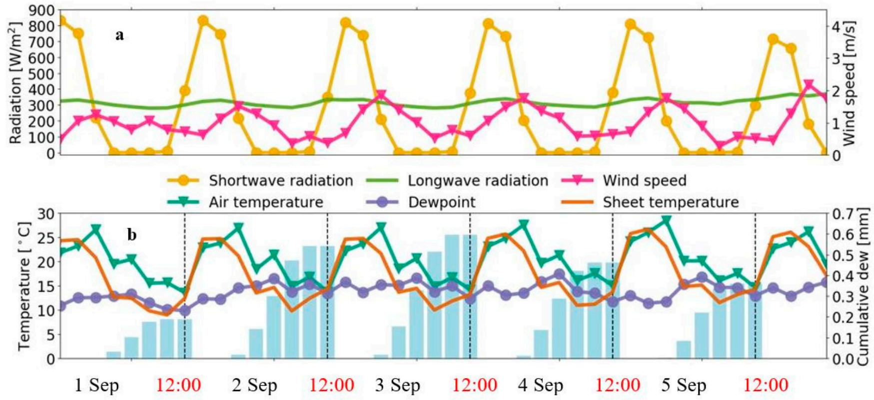

Figure S2: An example model simulation for dew formation during 1-5 September 2011 at Ramsar, Iran. (a) the short-wave and long-wave radiation (left y-axis) and wind speed (right y-axis) whereas (b) the cumulative dew formation on the condenser (bars linked to the y-axis right axis) and the ambient temperature, dew point, and condenser sheet temperature (left y-axis).

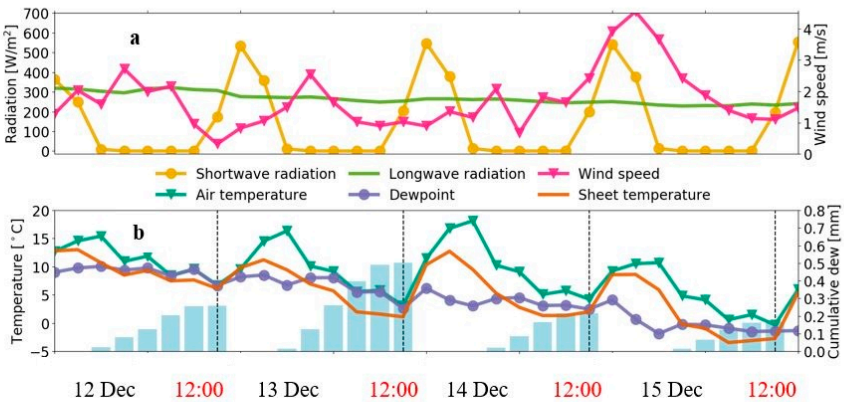

Figure S3: An example model simulation for dew formation during 12-15 December 2002 at Tabas, Iran. (a) the short-wave and long-wave radiation (left y-axis) and wind speed (right y-axis) whereas (b) the cumulative dew formation on the condenser (bars linked to the y-axis right axis) and the ambient temperature, dew point, and condenser sheet temperature (left y-axis).