Reply to reviewer

Review of HESS 2024-110

Observation-driven model for calculating water harvesting potential from advective fog in (semi-)arid coastal regions. By Felipe Lobos-Roco, Jordi Vilà-Guerau de Arellano, and Camilo del Río.

We appreciate the Reviewer's comments, suggestions, and alternative analysis, which have enabled us to improve our model formulation and, consequently, the manuscript. We have accepted all the Reviewers' comments, corrections, and suggestions, resulting in significant changes to the manuscript. Below, in blue font, you will find our responses to each comment, correction, and suggestion. We have also included the line numbers where changes were made in the revised version of the manuscript (Revised_manuscript.pdf).

General comments.

Estimating water harvesting potential from advective fog in (semi-)arid coastal regions is an important subject and well worth the effort of developing and evaluating a model. I do however have serious reservations about the building blocks in the model, both Appendix A and Section 2.1.2. In the fog collector model, the variable definitions are not clear and, as I see it, mixing ratios would better that specific humidity in this context. For the cloud base and related parameters it seems extremely optimistic to determine cloud base from near surface (1.5 m?) measurements of T and q at two stations and used to infer the vertical gradients. In the end a factor 0.5 is applied to the results (line 219).

I would like to see the model details cleaned up and more clearly explained

We have accepted most of the Reviewer's comments and alternative analysis for improving the model formulation, including detailed explanations of each variable, unit, and dimension. These revisions have resulted in major changes to the manuscript, particularly in Section 2 (model formulation and evaluation), Figure 1, Section 2.1, Section 2.1.2, Figure 2, Section 2.1.4, Figure 5, Figure 7, and Figure 8.

The main modifications involved the model formulation and assumptions. The primary difference in the revised model formulation is the inflow and outflow fog water, now expressed in terms of the mixing ratio r. This is thoroughly explained in Section 2. Additionally, Appendix A has been removed, and a new Figure 1 with updated definitions has been included. The variable 'q_h' has been replaced by "W_h", which denotes water harvesting. Finally, the variable liquid water content (q_l) has been replaced with the adiabatic liquid mixing ratio (r_l), clearly defined as g of liquid water per kg of dry air. We have also rechecked the calculations for the adiabatic liquid mixing ratio, which are now more physically consistent and overestimate by 28% (0.2 g m^{-3}) when compared to the cloud radar. Despite the our estimations of r_l are slightly higher than cloud radar observations (Fig. 5a and b), now they are more consistent and does not include any correction factor.

The new model formulation, included between lines 72 and 115 of the revised manuscript, reads as follows:

"The AMARU aims to estimate the liquid water content of Sc clouds and the potential for fog harvesting. Our goal is to formulate a model that can use the available routine meteorological data in an area with significant ocean-land contrasts and very complex topography. Figure 1 illustrates the physical assumptions and processes along with the respective variables and units. The model relies on an adaptation of the mass conservation equation. The sequence of physical mechanisms involved is as follows: during a fog event, a certain amount of liquid water (W_h) is retained from the total fog inflow when passing through a passive collector. We assume that the harvested fog water results from the difference between fog inflow (F_{in}) and outflow (F_{out}) in g kg^{-1} m s^{-1}. This equation reads as follows:

$$W_h \cong F_{in} - F_{out} \qquad (1)$$

Here, fog inflow and outflow are described as:

$$F_{in} = r_l \, u_x \qquad (2)$$

$$F_{out} = F_{in}(1 - \eta) \qquad (3)$$

where r_l is the liquid water mixing ratio, defined as the amount of liquid water (m_l in Fig.1) per unit mass of dry air (m_d) that contains it, expressed in g of water per kg of dry air. To calculate the inflow we use u_x, which represents the perpendicular wind speed (m s^{-1}) relative to the collector. The term η is a dimensionless ration representing the collector efficiency. This coefficient is described as:

$$\eta = \frac{W_h}{F_{in}} \qquad (4)$$

where η corresponds to the percentage of water harvested over the total water that can potentially pass through the collector (details in Section 2.2). Reordering the terms, we express Equation (1) in net terms as:

$$W_h = r_l \, u_x \, \eta \qquad (5)$$

The W_h units are then g kg^{-1} m s^{-1}. However, for operationalization, the units of W_h are converted in L m^{-2}s^{-1} (equivalent to mm) once grams are transformed to liters and dry air density (kg m^{-3}) is included as:

$$W_h = r_l \, \rho_a \, u_x \, \eta \qquad (6)$$

Finally, W_h is integrated over a period as:

$$\overline{W}^{\Delta t}{}_h = \int_{t0}^{t1} W_h \, \partial t \ , \qquad (7)$$

where t_0 and t_1 correspond to the initial and ending time intervals. The model has three main assumptions described as follows: (1) F_{in} > F_{out}; (2) since the model aims to reproduce advective fog collection, it is assumed that condensation only occurs in the atmosphere under the conditions r_l = r_v - r_s; (3) the mixing ratio (r_v) being two orders of magnitude higher than r_l, is nearly conserved.

In Equation (6), r_l and η depend on location and condensation processes. Regarding location, r_l varies in height (the vertical dimension of the model) and depends on the conditions of the marine Sc cloud over the ocean and its interaction with the topography. The second term, η is related to cloud microphysics and the design and material properties of the collector. To delve into the details of r_l and η, we break down the analysis of Equation (6) into two parts: the thermodynamic and water potential modules. In addition, we introduce a third module for representing the model's horizontal spatial variability of W_h trough spatial interpolation creating a fog harvesting potential map."

Regarding the cloud base, we understand the Reviewer's concerns about its estimation. However, we have thoroughly evaluated this estimation. To achieve this, we compared independent cloud base measurements from ground-based experiments (Fig. 4) and the observations obtained by a cloud radar (Fig. 5a and b) against our cloud base estimations. The comparison shows a high degree of agreement (Figures 4a and 4b, line 206), with errors ranging between 10 and 50 m. To clarify this, we have revised the manuscript to include detailed explanations of our calculation methods and the variables involved. We have also made some corrections to Equation (8) and Figure 2. These modifications, included between lines 171 and 183, are as follows:

"The second approach considers two physical processes involved in the Sc-to-fog transition: environmental mixing and topographic uplifting. Firstly, to represent the mixing with the environment experienced by an air parcel during adiabatic ascent, and based on Lobos-Roco et al. (2018), we combined the meteorological conditions measured at both transect stations (z_1, z_2) using a mixing parameter m as follows:

$$\varphi^{p}_{(z)} = (1 - m\frac{z}{z_{LCL}})\varphi^{s} + (1 - m\frac{z}{z_{LCL}})\varphi^{ML} \qquad (8)$$

Where φ is a scalar for potential temperature (θ) or specific humidity (q), super script p represents the state of the air parcel, s indicates the conditions at the lowest station used (z_1), ML refers to mixed-layer, which is an average of conditions observed at the two stations, m is the mixing parameter ranging from 0 (no mixing) to 1 (maximum mixing), and z_{LCL} is the height at which LCL is reached. Secondly, to account for the inland effect (observed at z_2 station), LCL is calculated iteratively using an averaged θ and q (φ^{ML}) from z_1 and z_2. This φ^{ML} and LCL are used in Equation 8 to estimate the air parcel state $\varphi^{p}_{(z)}$, which is then used to calculate a new LCL. This calculation is repeated several times, with φ^{ML} being re-averaged with the conditions at station z_2 in each iteration. This repetitive calculation ensures that the inland conditions (z_2) in the MBL's state are accurately represented. Our estimations show that the appropriate number of iterations is related to the distance in km between z_1 and z_2,. For example, if z_1 and z_2 are separated by 5 km, we iterate five times."

Detailed comments

line 75: "total specific humidity (q)". Maybe make it clear that this is mass of water vapor + droplets + (if present) ice/Total mass of a parcel, and presumably in kg/kg. Many authors will use q as a symbol for mixing ratio which in the atmospheric context of mass of water/mass of dry air.

We agree with the Reviewer's comment., Please find our answer in the general comment section.

line 79: Equation (1) appears to be dimensionally incorrect unless q h is defined as a time integral of q with units like kgs/kg? Give a clear definition of "fog harvesting capacity, qh". Same with q in and qout - are these amounts the inflow and outflow specific humidities. Same concerns in Appendix A

line 83: qin , qout and q h appear to have same dimensions?

We agree with the Reviewer's comment, Please find our answer at the general comment section.

line 83: Assuming qs(in) ≃ qs(out) implies no temperature change including any release of latent heat due to water vapor condensation on the grid. Will that be true? The rationale used, "given that ql is by two orders of magnitude lower than qs", is invalid. What matters is the size of ql relative to any change in qs!

line 89, 90 and Appendix A: Figure1 is useful, and makes it clear that qh is NOT a specific humidity. Better to use a different symbol, and specify the units (maybe in kg rather than L/m 2). See notes at end.

We agree with the Reviewer's comment. Please find our answer at the general comment section, where we clarified our assumptions (line 104) and units (line 81,90, 99).

line 122: How close to the shore is Diego Aracena airport?

Diego Aracena Airport is very close to the shore, situated 0.42 km away and at an elevation of 48 m ASL. We have included this information in line 143 of the revised manuscript.

Figure 3: Points 10,11,12 seem to be missing. Negative correlations?

Yes, they are slightly to the left and behind the Y-axis line of the plot , indicating a negative correlation. We have added a short explanation about this negative correlation in the caption of Figure 3 as follows:

"Note that numbers 11 and 12 have a slightly negative correlation, placing behind the line and to the left of the Y-axis."

lines 134-139: I found this confusing. What time of day are the fog situations we are looking at? Earlier in the paper, sea breezes are cited as the cause of the flow from the ocean, so daytime, while here I am not sure. Does "stratified" mean stably stratified? Over water in the marine boundary layer solar radiation has only a small impact on sea surface temperature.

Lines 134-13 explain the relationship between MBL regimes and fog formation. We have based and connected our discussion to the findings of Lobos-Roco et al. (2018). In short, when we discuss the MBL, we refer to the conditions observed at the coast. This is because our observations (z_1, z_2) are taken over the continent. These observations enable us to quantify the advection of moist air that originates mostly during the day due to the ocean breeze. During the night, fog mostly dissipates as the MBL becomes stably stratified. However, our analysis shows that thermal and moisture vertical gradients follow different patterns. For example, Fig. 3a shows that orange (thermal) and purple (moisture) criteria are not similarly correlated with observations; thermal criteria show better correlations than moisture ones. This is explained by the coast's aridity, which, on the one hand, contributes in changing MBL thermal conditions, for example, stratifying the MBL during the night resulting in low fog frequency. On the other hand, these arid slopes do not contribute to moistening the MBL, with or without fog presence, resulting in low or even negative correlations with the fog frequency.

Yes, it means stably stratified, as opposed to well-mixed. We have enhanced this explanation by adding some key words to improve the text readability in lines 150- 160.

line 143+: 2.1.2 Cloud Base, CB It seems extremely optimistic to determine cloud base from near surface (1.5 m?) measurements of T and q at two stations used to infer the vertical gradients. The explanation is rather vague (Lines 160-170). The interpretation of the results seems rather generous. Is there any chance of some more comparisons with sounding data of some sort?

Unfortunately, no sounding data are available in the nearby area. However, we have contrasted our data with the ground-based observation detailed in Figure 4. For further clarification on our cloud base estimation, please refer to our answer to the general comment above.

line 153: Equation (3) is probably wrong. Equations 3 and 4 in Lobos-Roco et al (2018) make sense, this does not. Also it is not clear to me exactly what subscript 1,2 means, and the iteration process needs more explanation.

We agree with the Reviewer's comment, We have made significant changes in Section 2.1.2. Please refer to our answer to the general comment above.

line 208+: There is a missing) in Eq (7) but it seems reasonable, Thus I was surprised to read (line 219)

that " Our estimations of liquid water content obtained from Equation (7) systematically double the observed values. Consequently, we applied a correction factor of 0.5 to our estimations, as illustrated in Figure 5b. Something is wrong!

We agree with the Reviewer's comment. The ")" was added. Moreover, we have introduced major changes in the model formulation, specifically in Section 2 (lines 72-115) and 2.1 (117-128; 171-190; 242-261).   Please refer to our response to the general comment above for further details.

line 241+: Collection efficiency. Could this be determined in a laboratory wind tunnel study? Here it just looks like model tuning.

The collection efficiency factor is now better described (see our answer to the general comment above). This efficiency was not determined by a wind tunnel. Instead, we have estimated it using fog collector observations at several locations along the Chilean coast, though equation 13 (revised_manuscript). In our model runs, we use an efficiency ranging between 0.22 to 0.25, consistent with values reported in models and in-situ observations by Carvajal et al. (2020), Montecinos et al. (2018) and de Dios Rivera (2011) (lines: 295-300).

Fig 7b: Annual means seem wrong, based on monthly values shown.

We thank the Reviewer for her/his comment. The annual means refers to the averages of monthly daily rates (L m^{-2} day^{-1}). For example, In the hyperarid site (Fig. 7a), monthly daily rates range from ~0 to ~10 L m^{-2} d^{-1}, whit an annual average of 5. With the new model experiments, these values have been revised meticulously. In addition, we have revised the observations used for the model comparison, excluding those with low data quality during several months where the SFC measurements were affected by a broken mesh. These low-quality data were excluded from the new analysis. Consequently, "no data" labels appear in Figures 7b and 7c.

Alternative analysis.

1) Use q, q l , q s as mixing ratios rather than specific humidity - since, with specific humidity, mass of total parcel will change from q in to q out .

Is the assumption that the air is always saturated, so that water vapor mixing ratio $q_v = q_s(T)$, necessary?

Work with fluxes of liquid water, and let $A = dydz$

Flux in, $Fl_{in} = \rho_a uAq_{lin}$; Flux out, $Fl_{out} = \rho_a uAq_{lout}$, both in kg/s,

Then water collection rate, $Q_h = Fl_{in} - Fl_{out} = \eta Adx Fl_{in}$, also in kg/s with η having dimensions m^{-3} . With a different symbol, Q_h , since this is different from other q usage.

This has assumed no vapor-liquid transfers as the parcel goes through the mesh. But is that true? Is there "dew" produced as well as cloud drops captured?

We thank the Reviewer for the alternative analysis, which significantly contributed to improving our model formulation. For further details, please refer to our answer in the general comment section.