Reply to reviewer#2

HESS submission by Roco et al

This work uses a simple 1D advective fog model based on various assumptions for a given budget equation. It is claim that using satellite observations, model results and observations from MWR and adiabatic method are comparable, and they are very close to each other for annual representation. The work claims results can also be used for climatic fog research.

We appreciate the reviewer's comments, and based on them, we have introduced modifications to the model formulation and explanation of assumptions. Our model reproduces fog harvesting volumes using standard fog collectors. To this end, we have two goals: (1) to understand which processes govern the fog physics in the Atacama region; and (2) to optimize the use of routine meteorological data collected in regions with complex terrain to calculate water estimations. For goal 1, the main assumption is the simplification of microphysical processes. Here, we are aware that such processes are essential in the transition of low marine clouds and land fog formation. However, to justify these simplification, we have used two meteorological stations over a topographic transect facing the ocean to estimate the adiabatic liquid water mixing ratio (all or nothing) and its potential harvesting. In that respect, we would like to stress that the model has been systematically evaluated with the available observations, obtaining a reliable comparison. This comparison proves that, despite the model's simplicity, it reproduces the main characteristics of the fog over land physics in terms of fog frequency, its relation to the cloud base and top height, liquid water mixing ratio, and water harvesting.

Following the reviewer's comments, we have revised the entire model formulation, emphasizing on explaining the model assumptions. Regarding the model limitations, we have now discussed in more depth in section 4 and conclusions the purpose of the model. We place emphasis in describing the key role played by the available routine meteorological data to justify assumptions and to evaluate the mode. This last part is completed with a discussion on the model limitations and potential model improvements. In addition, we have added the suggestions and references provided by the reviewer in the introduction. Below, in blue font, you will find our responses to each comment. We have also included the line numbers where changes were made in the revised version of the manuscript (Revised_manuscript.pdf).

Based on my review, there are several errors existing in their work.

- This starts with equations and follows up with results. For example, mass balance equation is wrong, and assumptions are not presented or mentioned properly. What are they?

Based on comments provided by reviewers #1 and #2, we have introduced major changes in model formulation, including detailed explanations of each variable, unit, and dimension. In addition, we have elaborated more on the physical implications of the model assumptions. 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 changes in section 2 relating to formulation and assumptions are as follows:

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 changed with the adiabatic liquid mixing ratio (r_l), clearly defined as grams of liquid water per kilograms of dry air. We have also double checked the calculations for the adiabatic liquid mixing ratio to improve on the evaluation of the fog harvesting model. The new calculations are now more physically consistent and overestimate by 28% (0.2 g m^{-3}) when compared to the cloud radar. Despite our estimations of r_l are higher than cloud radar observations (Fig. 5a and b), now they are more physical consistent since we can omit the correction factor included in the first version of the manuscript.

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

“The AMARU aims to estimate in a simple way the adiabatic liquid water content of Sc clouds and the potential for fog harvesting. Our goal is to design a model that use the available routine meteorological observations in an area with significant ocean-land contrasts and very complex topography. Figure 1 shows the physical assumptions and processes along with the respective variables and units. The model is derived from the mass conservation equation. The sequence of physical mechanisms are: (i) 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:

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

(ii) Fog inflow and outflow are described as fluxes of the mixing ratio:

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

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

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 grams of water per kilograms of dry air. To calculate the inflow we use u_x, which represents the perpendicular (mean ± std) wind speed (m s^{-1}) relative to the collector. (iii) 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 (calculation 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, in giving the final output, we convert 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 times. 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. To estimate this variable using routine data, we assume that water vapor condenses once it reaches the thermodynamic conditions to reach saturation, This assumption implies that we do not take microphysical properties such droplet size, nucleation or droplet concentration into the calculations. The second term, η groups cloud microphysics, the collector design, and its material properties. To delve into the detailed calculation of r_l and η, we break down the analysis of Equation (6) into two parts: the thermodynamic and water potential modules (section 2.1 and 2.2). 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."

- Introduction is given in a large parag that doesn't focus on fog physics/dynamics etc at all. There are several works on marine fog (Gultepe et al 2021 BLM; 2019 Marine fog review; Fernando et al 2021) that are not mentioned. Characteristics of LWC, Nd, and DSD are provided in these works.

In the introduction we keep a balance between the essential physics of the transition marine stratocumulus to land fog over coastal mountains, and the quantification of the water yield. Following this argument, the manuscript describes the marine stratocumulus formation between lines 43-57 as the main mechanism of fog formation. To gain in clarity we have revised the introduction. In short, we have divided the instruction in three parts: 1) problem statement, 2) fog-cloud dynamics and 3) fog collection. In the second part we have focused on fog with similar characteristics as the one studied. Specially, we have introduced the following changes (**lines 50 to 55**), to reinforce the physics and dynamics of fog, including microphysical processes and the suggested references provided by the referee.

"Here, one of the main physical involved in stratocumulus formation is the microphysical properties of cloud droplets, which are linked to cloud optical properties that have important climate effects (Wood, 2012). In the South East Pacific, cloud droplet sizes of 5 to 15 µm are often found, whose concentration is ≤50 cm^{-3} increasing to 200 cm^{-3} along coastal areas of Chile (Painemal et al., 2011). The droplet size and concentration determines the liquid water content (Gultepe et al., 2021), which essentially is the amount of water that can be harvested on land once Sc becomes fog."

- Fog device for LWC is being used since 2006 (Gultepe et al BAMS and others).

We have introduced the fog measurement devices and their respective reference in **line 135**.

- Where is the importance of Nd in the model? Without Nd, how do you get accurate LWC? What is physically missing here? What is the role of Nd in LWC?

As mentioned in our general comment, the model assumes an "all or nothing" formation of liquid mixing ratio. The satisfactory evaluation we show in sections 2.1 and 2.1.4 with the available observations reinforces that this simplistic assumption gives physical consistent estimations in magnitude, height-dependence, and evolution. However, as the referee mentioned, further improvements to the model will aim to increase the complexity of the microphysical mechanism, providing that we have enough observational evidence.

We introduced several changes in Section 4 (**between lines 446 and 451**) by including:

“Firstly, one of the most important variables in the model is the adiabatic liquid water mixing ratio (r_l), which is estimated assuming water vapor is condensed because it reaches saturation. Despite our simplistic approach and reliable results, we know that further model improvements must be made by including essential microphysical processes. Such processes are mean volume diameter, effective size, droplet concentration, and effective droplet size (Gultepe, et al 2021). To account for these processes, comprehensive observations must be performed to get a complete budget equation allowing us to have more realistic modeling.”

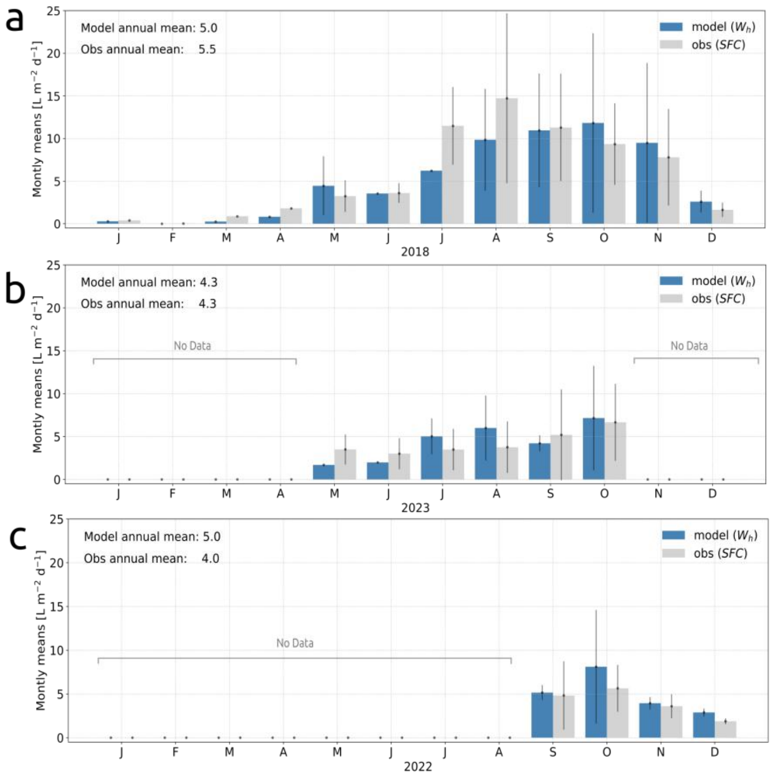
Moreover, conclusions have been restructured including now the just mentioned limitations (See comments below).

- See for budget equations given for cirrus clouds in PAAG 1990s Gultepe et al where steady state assumption is assumed to solve hor and ver advections. In addition, what role turbulence, radiation, and vertical advection play role? What happened to these terms?

We would like to answer the referee with a question: Can this budget terms be explicitly and accurately calculated in an area characterized by a strong ocean-land contrast and a very strong slope (1000 meters in the first 5 km)? We agree with the referee that our research should indeed aim to get a complete budget as s/he is mentioning. However, in absence of complete and comprehensive observations in space and in time, or a more explicit simulations using large-eddy simulation accounting with strong height differences, we have opted for a simple conceptual model to attempt to understand the main physics and reproduce the available observations.

- Fig. 7 suggests that there are huge diffs between observed and model simulations per month, how can be annual values get closer so much? Something is wrong.

Regarding Figure 7, we have revised the observations used for the model comparison, as suggested by the first reviewer. Our thorough revision revealed that some observations of sites B (arid) and C (semi-arid), were seriously affected by broken meshes and pipe's obstructions. Therefore, we decided to exclude such months in order to make a fair comparison with modeling results. The new Figure 7, which includes results obtained from the model reformulation and quality-filtered observations, is shown below.



Here, we observe that monthly and annual daily averages modeled collected water in the three sites are in 80% agreement with observations. In addition, the model is able to reproduce the seasonal cycle in magnitude and variability.

- How do you use satellite obs is not clear, how do you get fog LWC/LWP or coverage, no method is given properly.

As explained in section 2.3, the vertical variability of modeled water harvesting (W_h) is spatially extrapolated using as a base map the fog and low cloud (FLC) frequency image obtained through the GOES satellite (Espinoza et al., 2024) and a digital elevation model (DEM). We are not obtaining the liquid water content or liquid water path through the satellite, but using GOES+DEM as a geographical framework for extrapolating the vertical fog harvesting potential (W_h). This simple spatial extrapolation aims to know the horizontal variability that vertical fog harvesting potential might have.

We separate this extrapolation into four steps:

1. Reclassifying DEM grid cells whose height is between the cloud base and cloud top height determined by the model.
2. Reclassifying DEM grid cells with orientation based on main (mean ± std) wind direction observed at the z_2 station.
3. Calculating the FLC frequency using GOES satellite and intersect grid cells obtained in steps 1, 2, and 3.
4. As both the intersect grid cells from the last step and the vertical variability of W_h have a vertical domain (height), we replace the altitude values of the grid cells with W_h values, resulting in a spatial variability of W_h.

To gain clarification in the manuscript, we have introduced several changes in Section 2.3:

"In addition to the thermodynamic module, we propose a spatial module for extrapolating the vertical variability of W_h into a horizontal spatial domain. To do it, we integrate the vertical domain (z) of W_h to an area of optimal fog harvesting potential obtained from a combination of a digital elevation model (DEM) and GOES satellite images. We outline four steps to achieve this spatial variability.

The first step involves reclassifying the DEM grid cells based on the cloud layer height and removing all grid cells below the CB and above the CT elevation. This reclassification ensures that only the elevation range where the Sc cloud could potentially impact the topography is considered. In the second step, we create an aspect image (slope orientation) with the DEM and reclassify the pixels based on the angle range of the main wind direction (mean ± std) when fog is collected (obtained from observations at the z_2 station). The third step involves calculating the fog and low cloud (FLC) frequency using data from the GOES satellite (del Rio et al., 2021; Espinoza et al., 2024). This algorithm continuously calculates the presence and absence of FCL in every GOES grid cell. The third step serves as a geographical framework, delineating the area where fog-cloud interacts with topography. The spatial intersection of the three steps generates optimal areas for fog collection, physically representing the locations where the Sc cloud and its harvesting potential intersect the surface. It is important to note that the values of grid cells in these optimal areas for fog collection represent elevations (m ASL) in areas with high FLC frequency. The final step involves replacing the elevation grid cell values of the optimal fog collection areas with the vertical distribution of potential fog harvesting (W_h). As W_h values are associated with a vertical domain (z), each W_h value can be mapped onto the resulting grid of optimal fog collection areas. The result of this last step yields a spatial distribution of potential fog harvesting."

- Apply these results for climate is very much simplification, this should be taken out.

We agree with reviewer and we have removed the following sentence in line 475 to 476 (from the original manuscript) from the conclusions:

"Moreover, by using future climate data projections, it becomes feasible to assess how these water resources might respond to climate change. "

And line 477:

"and the study of the climatological evolution of cloud water, among others"

- Conclusions; needs to be collected for a few bullets and explained based on the text, not clearly explained properly.

We agree with the reviewer and following his/her advice we have restructure the conclusion in relevant bullet points focus on:

- Model reliability to reproduce in time and space fog harvesting despite its simple approach and limited data used.
- Model limitations, challenges, and further improvements.
- Potential uses of this model for water planning.

These major changes have been introduced in the conclusion as follow:

"We propose, formulate, and evaluate an observational-driven model, named AMARU, for estimating advective fog water potential harvesting in (semi-)arid regions. This model uses standard and routine meteorological observations to estimate where, when, and how much water can be potentially harvested from fog clouds. The proposed model employs a thermodynamic approach to estimate fog's adiabatic liquid water mixing ratio, incorporating key physical processes associated with the interaction between the stratocumulus cloud and topography. This approach yields vertical profiles of liquid water mixing ratio, from which fog frequency, cloud base, and top can be derived. In addition, by integrating the estimations of liquid water mixing ratio with climatological records of fog harvesting observations, we derive an empirical collector efficiency coefficient to estimate vertical profiles of potential fog harvesting. Finally, combining vertical profiles of fog harvesting potential with satellite products, we introduce a methodology for spatially extrapolating these results, thereby generating fog harvesting potential maps.

Below, we outline the main conclusions of our research.

- Despite the simple approach, this model correctly reproduces essential physical components involved in fog harvesting. Our evaluation with available observations show that model results reproduce: fog frequency (R: 0.95; RMSE: 6%), cloud base and top height (errors <50 m), liquid water content (errors ~0.2 g m^{-3}), and fog collector efficiency (errors ~5%). Overall, fog harvesting observation are satisfactorily reproduce by the model with mean errors of 10% (<1 L m^{-2}).
- The simple approach takes advantage of using routine meteorological data, which is widely available worldwide in areas characterized by land-ocean contrast and complex topography.
- However, the model presents several limitations, whose improvement will depend on comprehensive observations and further research. Between the limitations, microphysics observations of cloud droplet size, concentration, and actual water content must be incorporated to improve the model. Moreover, further research must be done on the empirical coefficient, which is constant in the model. However, our observations suggest a variability which depends mainly on wind speed, but also in the materials. Finally, future research should incorporate accurate vertical profiles of temperature, mixing ratio, and wind speed to corroborate our vertical modeling assumptions.
- Our model offers a versatile approach with multiple applications in massive fog harvesting planning and ecosystem delimitation for conservation purposes, among others. Since fog is a global meteorological phenomenon, this model holds potential for applicability in many coastal (semi-)arid regions, addressing data deficiencies in regions where fog harvesting represents a viable water source.

Finally, we expect this research to yield significant social benefits by providing decision-makers with valuable insights into new water sources, thus aiding in the mitigation of climate change impacts."

- Appendix also has severe issues without providing assumptions. Overall, I cant accept this paper as scientifically meaningful and it needs lots of work to be published.

As mentioned in this point-to-point answer we have attempted to clarify the derivation of the model and explain assumptions (resulting in removing the Appendix). Here, we would like to stress the original aspects of our research: a conceptual model that is able to provide an interpretation of the transition stratocumulus to fog in a very complex topographic area. The possibility to use this model on the interpretation of diurnal variability (height), but also seasonal to yearly variations. Finally, the possibility of using this model as a predictor using routine and standard meteorological variables, either observations or model results.