Author Response:

We appreciate the constructive review and comments by Dr. Alvaro Ayala. We agree with the major comments and we will introduce changes in the manuscript to address the reviewer's concerns. Also, we will clarify and correct the manuscript considering most of the specific comments and suggested Figure editions. We think that these changes will improve the manuscript. Here, we provide a brief point-by-point response (in bold) to the general and specific comments and concerns by Dr. Ayala:

PAPER SUMMARY AND RECOMMENDATION

Bravo et al. analyse the impact of an unseasonal atmospheric river (AR) on the annual mass balance of Olivares Alfa Glacier, subtropical Andes of Chile. The AR occurred at the end of January 2021and resulted in a strong precipitation event over central Chile, which is very rare to occur during the austral summer. The authors conducted their analyses using remote sensing products, meteorological observations, and energy and mass balance models. They found that the event produced an accumulation of 164 mm w.e. (measured near the glacier tongue) and lowered the 0°C isotherm from typical summer elevations of 4000-4500 m a.s.l. to 3000-3500 m a.s.l., as well as lowering the snowline elevation to about 2500 m a.s.l. Glacier mass and energy balance modelling shows that the annual mass balance of Olivares Alfa Glacier was close to neutral as a consequence of the AR. Synthetic simulations indicate that without the event the annual balance of Olivares Alfa would have been very negative (between -0.5 and -2.5 m w.e., approximately).

The topic of the article is novel and appropriate for The Cryosphere. The analyses seem adequate, and the main message is interesting and useful for future studies. I suggest that the authors add a few more analyses and clarifications to make the article ready for publication.

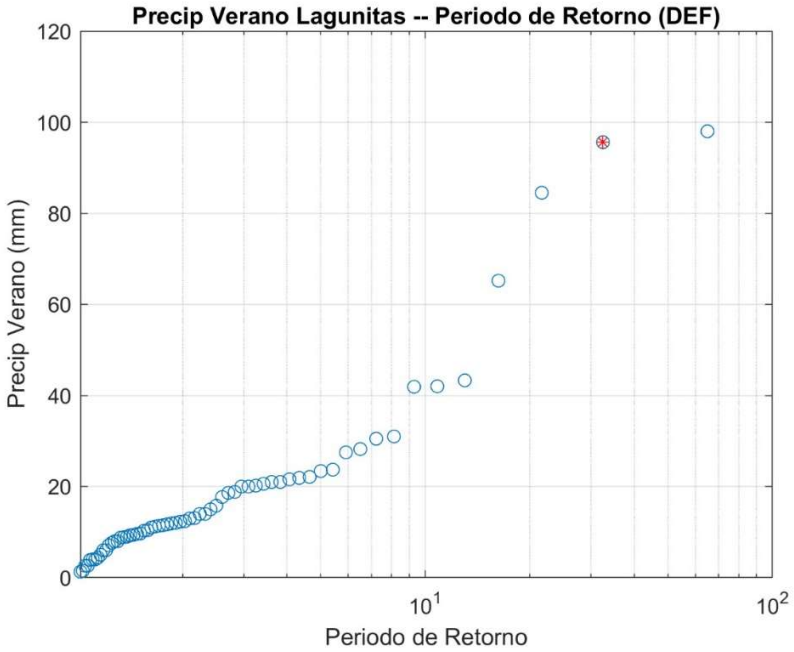
MAJOR COMMENTS

1. How rare was this event on glaciers?

I agree with the main comment of reviewer 1. I understand that Valuenzuela et al. (2022) showed a detailed analysis on a regional scale, but it would be useful to know how often such an accumulation event occurs on glaciers in the study area. Can you add some more analysis in this direction? Calculate a return period from Lagunitas data? Or maybe add data from ERA5 and El Yeso meteorological station?

We thank the reviewer for this suggestion in line with a Major comment of Reviewer 1. We will add an analysis to emphasise the extraordinary occurrence of this event and its accumulation. For one side, we will use ERA5 to extend the catalogue of the Atmospheric Rivers in summer to demonstrate the historic low occurrence of this synoptic feature. Also, we will add an analysis to show how the precipitation rate was also extraordinary for summer. In this case, we will use available data observed at Lagunitas weather station. This station, although located at a lower elevation (2765 m a.s.l.), shows one of the longest precipitation records so that we can put this event in the context of an observed precipitation climatology. We previously performed this analysis (see Figure attached, in Spanish) but we didn't include it in the manuscript. We will do it in the potential new draft. Events with almost 100 mm in Lagunitas occur

between 35 to 65 years. In the figure, the red asterisk is the January 2021 event and the analysed period is 1960-2024.



2. Mechanisms that explain the mass balance change

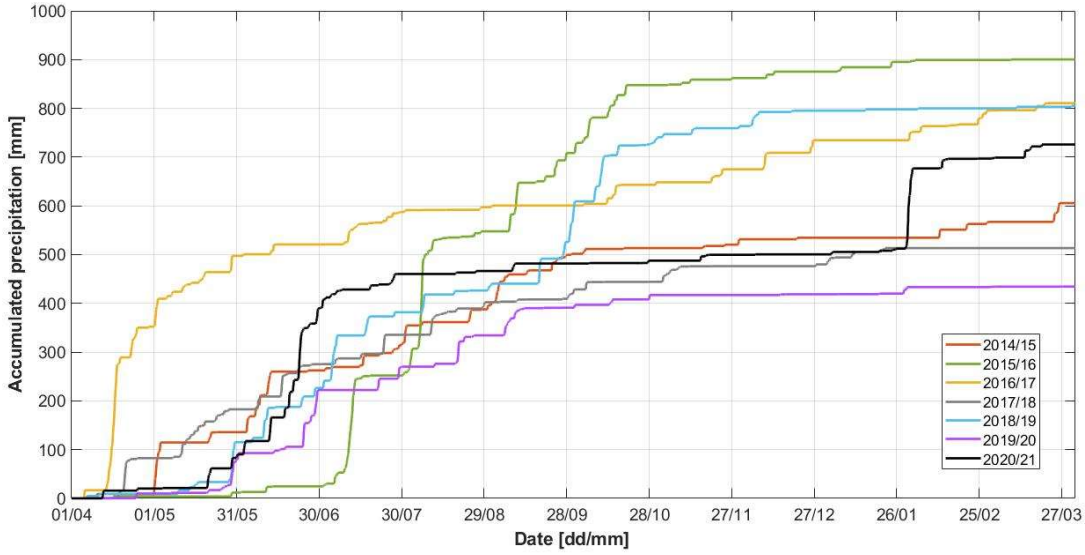
The authors state that "… the impact is not solely from the event itself. Feedback mechanisms related to snow accumulation also impact the mass balance. After the event, ablation diminished due to reduced surface temperatures and increased albedo, which lowered net shortwave radiation, which is the main source of energy for melting during summer" (lines 438-440). So, which was more important? It would be good to answer this question very clearly in the abstract and conclusions. I see that the total snow accumulation at the location of AWS was 164 mm w.e. (Fig. 5) and that the expected ablation without the event ranges between -500 to -2500 m w.e. (Fig. 8). Can you conclude that the main effect of the event was to change the energy balance rather than the mass gain during the event? If this is the case, I think it could be stated more clearly.

I have other suggestions along these lines that could help to understand the effect of the storm on the glacier energy and mass balance.

- Figure 6: Can you add two more panels showing i) albedo and ii) surface temperature? It would be interesting to know for how long the albedo remained high.
- Satellite images: Can you show satellite images to better understand how the AR affected the glacier surface during the rest of the summer? For example, I can see from a Sentinel image of 09.03.2021 that the glacier was already quite dark on that date, but a few days later, a small snowfall brought the albedo back to high values again. So, maybe there were other snowfalls that contributed to keeping the mass balance neutral by increasing the albedo?

Checking the albedo outputs of COSIPY, we agree that the post-event feedback is not directly related to the event. As is parametrized, the albedo reduces quickly,

which seems to agree with Reviewer's comments on the satellite images. The low ablation rate in the last two months of the hydrological year seems to be related with two smaller events of snow accumulation in February and March and also to relatively lower air temperature on these months (Fig. S4). The magnitude of these events is not unusual in summer (see Figure below), but it forced a similar impact on the albedo. With this in mind, we will change our statement, and concentrate on the importance of the 164 mm w.e. is quite extraordinary for the date if compared with previous years (e.g. Lagunitas precipitation data) and this was due to the AR. Also, we mentioned that the albedo parametrization is a source of uncertainty (L312-317), to be consistent we will not discuss in detail the post-event albedo. However, we will add in the discussion section that the two accumulation events impacted, reducing the ablation. Just briefly, both, albedo and surface temperature during February are lower than the previous years for the same month, but we recognize this is not solely by the AR event but also for other events. An analysis using satellite images is beyond the scope of this work.



3. Hypothetical scenario (“no event”)

This is a very interesting and useful exercise, but the description provided by the authors is very brief. What were the main assumptions made? What were the time series of precipitation, temperature and the other variables that you used? The same as those recorded, except for precipitation? Is surface albedo calculated by the model? How low would have been the glacier albedo without the event?

Figure 8: Can you add a panel showing the albedo in the actual and hypothetical scenario? What was the effect of the small events after the AR on surface albedo?

The approach here was statistical, using the time series of the mass balance of similar behaviour years (L190-195). Therefore, no time series of air temperature and other meteorological variables. We decided on this approach because we discarded the influence of the rest of the variables during the event such as incoming shortwave and longwave radiations, wind speed, relative humidity, atmospheric

pressure and air temperature. Following also comment of Reviewer 1 we will add more details to clarify this approach. We will provide more details about this procedure as follows: "The mass balance time series from previous years were decomposed to extract the trend for each year (Box et al., 2015). Then, the 2020-2021 mass balance series was detrended, and the average, maximum, and minimum trends derived from previous years, in terms of the final mass balance result, were applied to the analysed hydrological year."

MINOR COMMENTS

Title: I think that the title is not fully accurate. "Glacier accumulation" is not the most common term. Maybe change to "snow accumulation", "glacier mass accumulation", "glacier snow accumulation" or "glacier mass gain"? E.g. "Unseasonal atmospheric river drives anomalous summer snow accumulation on glaciers of the subtropical Andes".

Thank you for your suggestion. We will modify the title.

Data availability: Are the meteorological data going to be available?

In the short-term, by request.

21: "… led to substantial snow accumulation on the Maipo River glaciers, confirmed by the post-event snowline …" I don't think that the low snowline confirms a substantial snow accumulation, because a cold event with low precipitation can also produce a low snowline.

We agree, we will change to: "… led to substantial snow accumulation on the Maipo River glaciers and post-event snowline observed at …"

58-62: Can you briefly explain how an AR could produce more melt? Is it because it rains on the glaciers? I thought that an AR was always associated with a precipitation event.

AR originate in the intertropical zone. Therefore, both, water vapour and high temperature are transported poleward by the AR, are transferring to the glacier as energy available for melt. According to Kropač et al. (2021), this is through longwave radiation and strong turbulent heat fluxes. Rain heat flux also plays a role in fuelling melt.

112: The 70% number is originally from a DGA report, maybe check if there is a more recent number? Maybe Álvarez-Garretón or CR2 have calculated a more updated number in recent years.

We will update this. Although is not the same, we agree that is more relevant to mention that 60% of the water of the basin is used in the agricultural sector and 35% is for drinking water and sanitation.

122: I'm not sure if "two accumulation zones" is technically correct. Maybe say that the accumulation zone is divided in two valleys or cirques.

We agree.

159: Can you show the sensors along the Olivares Basin on a map?

We will add the location of the air temperature sensor in the new map of Figure 1.

181: Can you briefly explain how the model distributes meteorological variables? Precipitation, winds? How is snow and ice albedo calculated by the model? What value did you use for ice albedo? From observations or the literature?

These steps are explained in the paper by Sauter et al. (2020). Briefly, the model used lapse rates for air temperature, and relative humidity. The barometric formula for atmospheric pressure and modelling approaches for shortwave and longwave radiation. Wind speed is constant. For albedo, the Oerlemans and Knap (1998) approach is used, assuming theoretical values of 0.3 for ice and 0.85 for fresh snow.

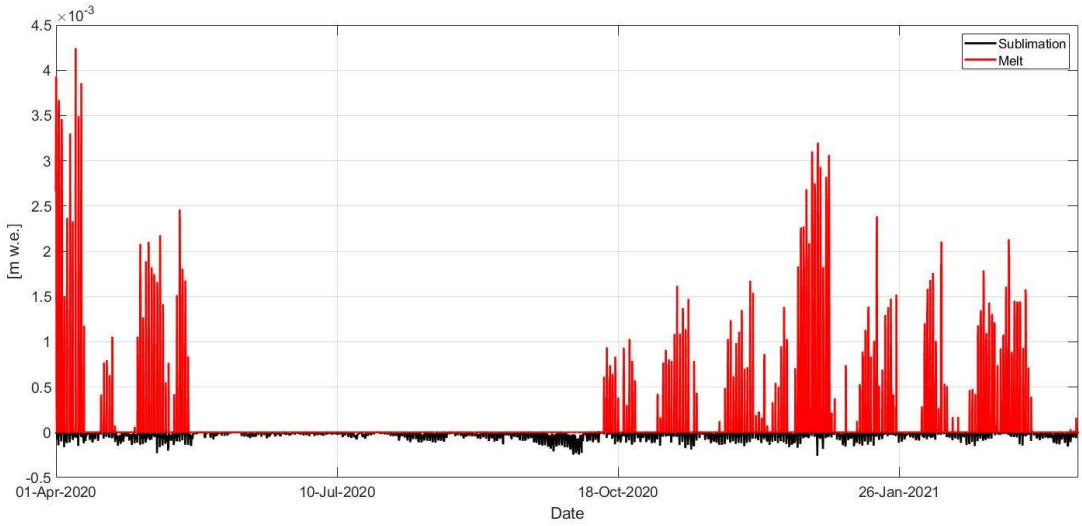
191: “detrending the mass balance time series post-event” This is not clear, how was this procedure? Can you provide more details about this experiment? Did you remove all the summer precipitation? Is albedo adjusted by the model? See my major comment 3.

192: “The behavior from previous similar years … was derived and applied to the detrended 2020/2021 accumulated mass balance time series” I don’t follow the procedure. I thought that the experiment consisted only of running the model without the AR event, but did you use information from other years? See my major comment 3.

191-192: We answered this in the major comment. We hope this clarifies the method. We added a reference.

260: The negative latent heat flux means in this context sublimation, not melt. What happened to the snow deposited by the event? Was it sublimated or melted? Can you provide both amounts? Looking at figure 6, I would say that sublimation dominated over melt after the event.

We will correct this statement; it is not clear. After the event, the snow melted and a small fraction sublimated. The figure below shows that there is sublimation over the hydrological year but the rate is lower than the melt. During the event and in the other summer events, no melt is registered but sublimation continues.



FIGURES

Figure 1: A, please delete the rest of the political boundaries, or explain what they are. The text refers only to the Maipo River Basin.

We will edit this Figure.

Figure 3: Please change the red colour of the ERA5 longwave radiation. It is difficult to distinguish from the black lines. Maybe change this plot from hourly to daily time steps? As it is, the hourly data have a lot of noise.

Following the comment of Reviewer 1, we will move this Figure to the Supplementary section. We will keep the hourly time step because is the time step that we used for feeding the model.

Figure 4: Can you indicate the event period here?

We will add a marker to indicate the period of the event.

Figure 5: -> “Time series of the 0°C isotherm around the event”

We will correct this.

Figure 5: What is AWS DGA? So, you didn’t use the Ta sensors along the valley to calculate the isotherm?

We will change this. We used several air temperature sensors as is described in the manuscript.

Figure 5: The number 164.6 mm w.e. is only given here, and it is quite important. Please mention it also in the text.

Ok, thank for noting this omission. We will introduce this information in the text.

Figure 6: Please see my main comment 2.

Figure 8: Can you add another panel showing accumulation and ablation separately? I think that would be very useful to understand whether the cause of the neutral mass balance was the snow accumulation during the event or its effect on surface albedo.

We will add what the reviewer suggested. Similar to the Figure below.

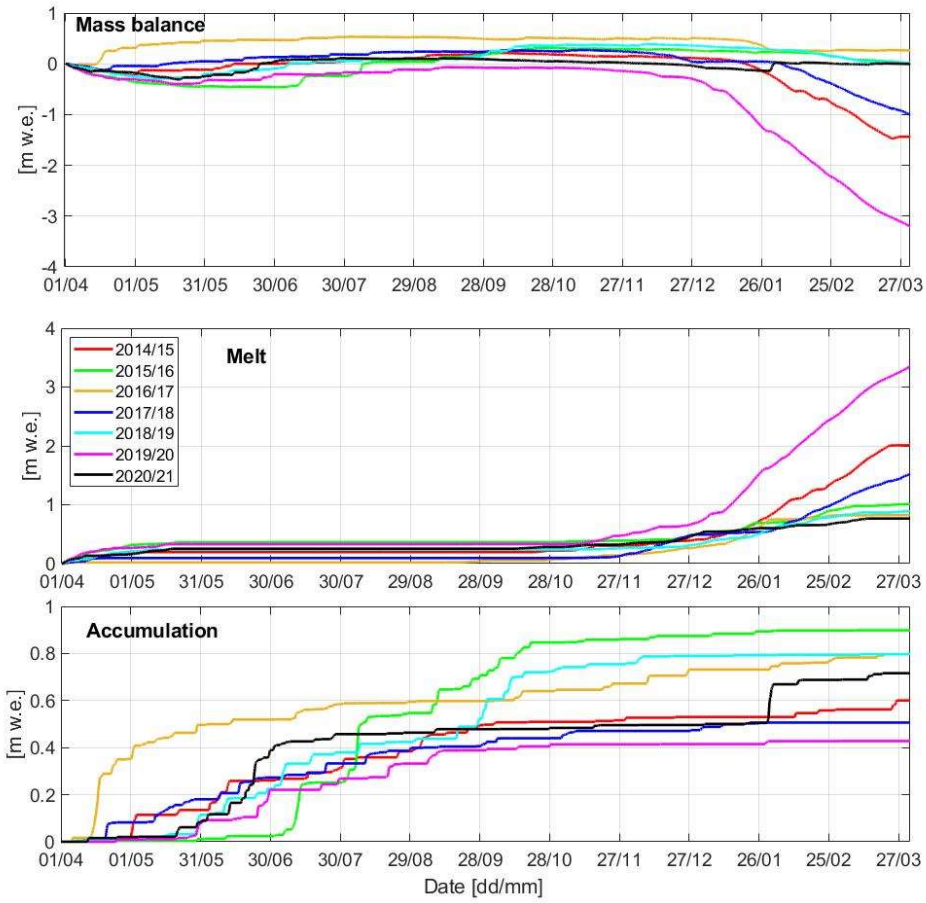


Table 2: Can you add a new column with the average fluxes in the days or weeks after the event? This would make it easier to understand the changes caused by the AR (instead of looking at Figure 6).

We will add a column with the mean values during the event.

SUGGESTED TECHNICAL CORRECTIONS

We are very grateful for the technical corrections by the reviewer. We will introduce all the changes suggested by the Reviewer.

18: add “austral” to “summer”

20: -> “the effects of the AR on the…”

21: Replace “significant” by another term, maybe “massive” or “large”.

25: Introduce the current mega-drought before or maybe just say “a severe drought”. As it is, the sentence assumes that all readers know about the prevailing mega-drought conditions.

35: Delete “during specific periods, such as the hydrological year”

36: -> “there is a typically large interannual variability”

138: -> “strong even for winter events”

150: This sentence is quite orphan. Remove or move to the introduction. Or provide here some more general details.

209: “Pacific coastal grid points” Refer to Figure 2c.

211: Please move “Category 1 being the lowest and …” to line 131 when the categories are first mentioned.

213: -> “by the amount of time” or maybe “duration”

231: “an elevation like January 2021”, which one?

239: “Diurnal cycle” is more precise

250: precise here if the direction of the discrepancy, what is higher and what is lower?

383-385: But this is logical, no? It is the ablation season.

415: “Cortés and Margulis”

425: I think it should be Fig. 4, not 3.

New References

Alvarez-Garreton, C., Boisier, J. P., Garreaud, R., González, J., Rondanelli, R., Gayó, E., and Zambrano-Bigiarini, M.: HESS Opinions: The unsustainable use of groundwater conceals a “Day Zero”, Hydrol. Earth Syst. Sci., 28, 1605–1616, https://doi.org/10.5194/hess-28-1605-2024, 2024.

Box, G. E. P., Jenkins, G. M., Reinsel, G. C., and Ljung. G. M.: Time Series Analysis: Forecasting and Control (5th ed.), Wiley, United States, 720 pp., ISBN 978-1-118-67502-1, 2015