Response to Reviewer #1’s comments

General comments

This manuscript considers the exchange between water molecules between the firn and the atmosphere, and the impact it can induce on the change of isotopic composition in extremely low accumulation regions of Antarctica. Using the results from Dome C as an analogue for Dome A is a clever strategy that can yield promising results to how to explain the impact of surface processes on the future Dome A ice core. The study takes into account the variations of stability of the atmosphere with systematic calculations of the Richardson number and developed three case studies associated with two sets of summer conditions (clear sky and cloud), and one set of winter conditions.

While the authors used a rather classical set of equations to evaluate the isotopic exchanges during sublimation and condensation, it seems not pertinent here, as it ignores major contributors to the boundary layer processes and only consider the system as a closed box without exchange with the free atmosphere. As a result, the results do not match the observations that were made for the surface snow isotopic composition at Dome C, even though, it is supposed to be the case study used to parametrise the model.

I suggest profound modifications to the model, which take into account exchanges between the atmospheric boundary layer and the free atmosphere on top of the surface processes, and which would match the surface snow changes, at least in order of magnitude, before considering the manuscript for publication.

Response: We greatly appreciate the reviewer's insightful comment on the physical mechanism of our model. We agree that realistically exchanges between the atmospheric boundary layer and the free troposphere on top of the surface processes should be considered. It was our originally plan that we wanted to explicitly focused on how much changes on snow isotopes can be induced by processes at the air-snow interface alone. This may not reflect the real changes but can reveal the most potential effects associated with the processes at the air-snow interface. Thanks to the reviewer’s suggestion, that we realized that it might be better to include the free troposphere which will make the result more comparable with the observations. Therefore, in the revised manuscript, we included the mass exchange between the boundary layer and the free troposphere by adding a third box as illustrated in the revised Figure 1. The calculations and equations were also changed to reflect the modifications to the physical mechanisms in the model. But we wanted to note that, with including the effects of exchanges between the boundary layer and free troposphere, the main conclusion of the manuscript doesn’t change (the magnitude of modeled changes are affected but still in the same direction).

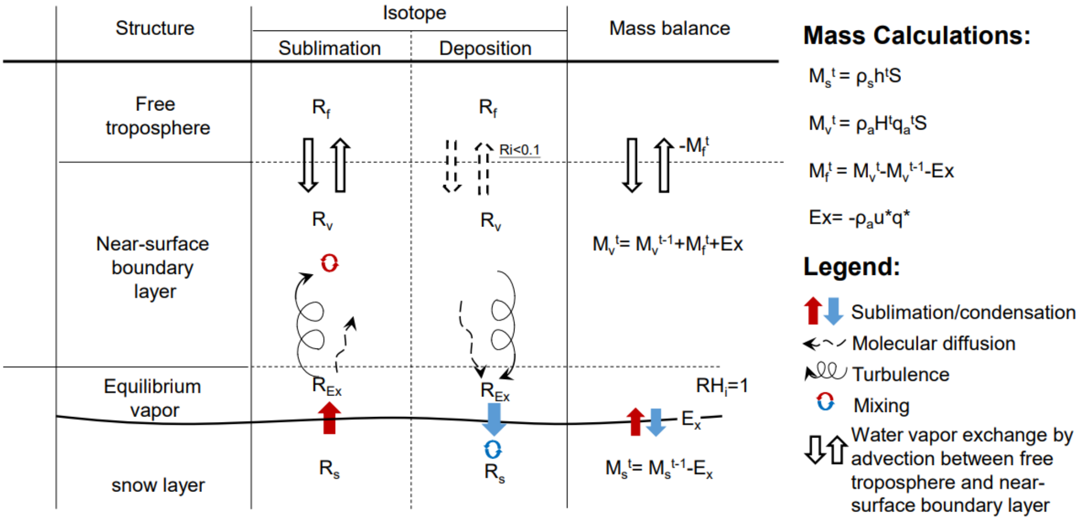

Figure 1: Schematic diagram of the box model used in this study (Revised version).

Major Comments:

1) *The box model developed by the authors was parametrised against vapour measurements obtained at Dome C, in order to compensate for lack of measurements at Dome A. The outputs of the model predict changes of vapour isotopic composition that seem realistic, but it is not the case for the changes of snow isotopic composition for which the variations are extremely small (less than 0.02‰) while the observed changes are around 2‰ during a typical night (Casado et al., 2018). The relative changes of snow and vapour isotopic compositions during a typical clear sky night were modelled in this manuscript, and suggested that a closed box model (which is de facto what the authors have implemented since no exchanges between the free atmosphere and the boundary layer are taken into account) is not realistic for this type of event.*

Response: Thanks for pointing out this. Indeed in the original model framework, the modeled results on snow isotopic changes cannot match the observations. In the revised manuscript, this is addressed by including the effect of exchanges between boundary and free troposphere. In particular, the new results indicate that simulated changes in snow isotopic composition are significantly larger (i.e., ~ 0.02‰ for δ^{18}O) than the original model (i.e., ~ 0.02‰ for δ^{18}O) at Dome C. Especially, for the case the reviewer mentioned, i.e., a typical night with a frost event on 6-7th January 2015, the diurnal changes of newly simulated results between the maximum and minimum can reach 2‰ for snow δ^{18}O (as demonstrated in Figure 2). This magnitude is in line with the observations for snow isotopes from Casado et al. (2018) which is ~ 2‰.

In the revised manuscript, we have re-run all simulations under Dome C conditions and three different cases at Dome A using the adjusted model. The simulated results within a 24-hour period were displayed in Figures 3-6 of the revised manuscript.

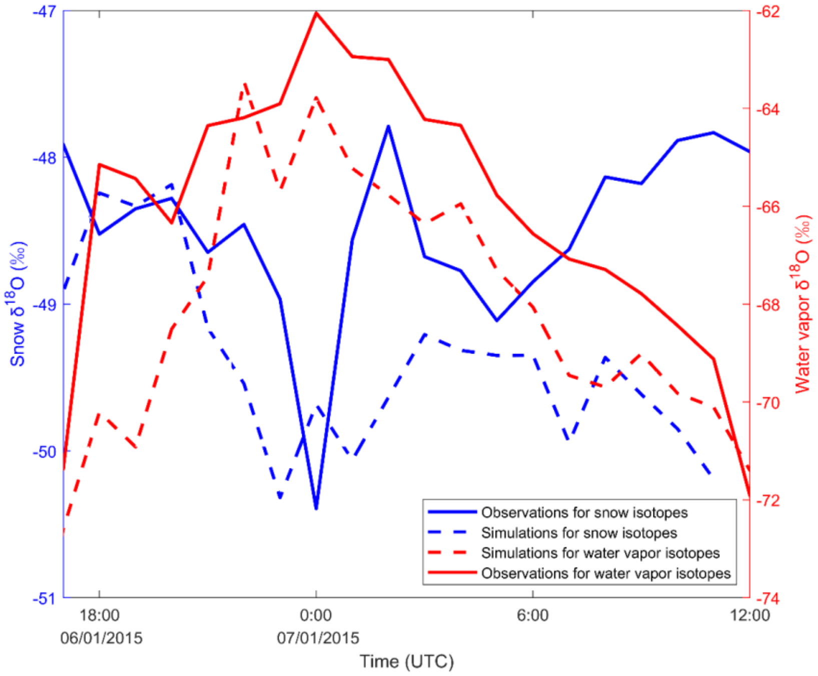

Figure 2: The changes of snow isotopes and water isotopic composition in the near surface atmospheric layer in Jan 6-7th, 2015 at Dome C

2) *Another aspect that suggests that exchanges between the boundary layer and the free atmosphere must happen is the Richardson number. Indeed, for negative Richardson numbers, the atmosphere must be quite convective, which suggest that the boundary layer exchanges with both the surface snow and the free atmosphere.*

The atmosphere is qualified as stable for any positive Richardson number, yet, it seems that some studies suggest that some amount of mixing remains quite strong for 0 < Ri < 0.1 (Zilitinkevich et al., 2007) . This could be discussed.

Response: Thanks for this valuable suggestion. In our original simulations, we assumed that unstable conditions for atmosphere stability only existed under negative Richardson numbers. Based on this assumption, we considered how mixing between the boundary layer, surface snow, and the free troposphere can affect the water vapor isotopic composition in the near-surface atmospheric layer and snow isotopes during the warming phase with negative Richardson numbers. However, as pointed by the reviewer that Zilitinkevich et al. (2008) suggested mixing can occur under positive Richardson numbers as well. If this is true, our original simulations for the water vapor isotopic composition in the near-surface atmospheric layer may be underestimated in the cooling phase.

To test the relationship between mixing occurrence conditions and Richardson numbers, we ran simulations for Dome C taking into account mixing when Ri<0 and Ri<0.1. As shown in Figure 3, the case with Ri<0 (Case II) indeed underestimates the water vapor isotopic composition in the near-surface atmospheric layer during the cooling time. Based on this comparison, in the revised manuscript, we incorporated mixing into the modeling once Ri<0.1 (Case I) in addition to the original consideration with Ri<0. Discussion on taking into account Ri<0.1 was added in supplementary information (Text S3) of the revised manuscript, and in the main text all results were updated with consideration of the mixing when Ri<0.1.

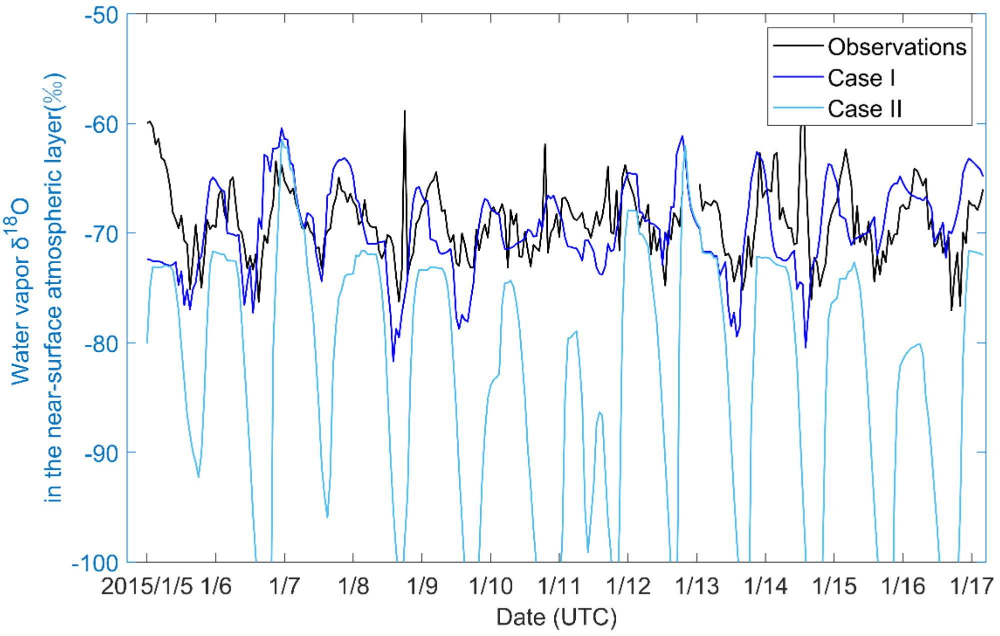

Figure 3: The comparison of water vapor isotopic composition between the simulated and observed changes at Dome C. Two simulated cases are presented here to discuss the occurrence condition of mixing. In case I, the mixing is assumed to only happen when Ri<0 in the cooling phase, while case II also considers the occurrence of mixing when Ri<0.1 in the cooling phase.

3) *Some limited vapour data exist at Dome A (Liu et al., 2022). While these data might be difficult to compare to your results, in particular consider how high the d-excess is, which could be associated with calibration issues, it should be discussed.*

Response: Thanks for this suggestions. Actually before finalizing the manuscript, we have discussed with the leading author of the Liu et al. (2022) study, but we noted that due to the harsh environment, direct observations of water vapor as the Liu et al did is difficult and the calibration can induce large issues. In addition, their measured sites are actually not exact the same at Dome A (~100 km away). In the end we didn’t choose to compare this dataset. But since the reviewer asked, in the revised manuscript, we compared our simulations at Dome A with the data of water vapor δ^{18}O, δD, and d-excess from Liu et al. (2022). We found that both our simulations and observations exhibit diurnal patterns, with high values occurring during the warming phase (daytime) and low values during the cooling phase (nighttime). However, we note that the magnitude of the observed diurnal changes in water vapor δ^{18}O and d-excess at sites near Dome A are very large, over 40‰ and 200‰, respectively. This could be due to calibration drift caused by the extremely cold and dry conditions during the measurements at the nearest Dome A site.

Therefore, in Section 4 of the revised manuscript, we only qualitative compare and discuss the similarities and/or differences between simulations and observations, without delving into quantitative details.

4) *Considering how fundamental these changes are, an updated version of the manuscript could have completely different conclusions.*

Response: We really appreciate the reviewer's comments. By including the effect of exchanges between boundary and free troposphere, the modeled results indeed differ a lot compared to the original model. However, the modeled changes in snow and vapor isotopes are still in the same direction (the magnitude or absolute values differ), and the main conclusion stays the same as that the air-snow exchange would lead to diurnal variations in atmospheric water vapor δ^{18}O and δD by 4.75±2.15 ‰ and 28.79±19.06 ‰ under summer clear-sky conditions at Dome A, with corresponding diurnal variations in surface snow δ^{18}O and δD by 0.81±0.24 ‰ and 1.64±2.71 ‰, respectively. These values become smaller compared to those in the previous simulations. After 24-hour simulation, snow water isotopes were enriched under clear-sky conditions. However, there is no or very little enrichment for snow water isotopes under cloudy conditions, which is different with the previous simulations. Under winter conditions at Dome A, the model still indicates the diurnal change in atmospheric and surface snow water isotopes are not significant, but the model predicts more or less depletions in snow δ^{18}O and δD in the period of 24-hour simulation, opposite to the results under summer clear-sky conditions. This suggests that the air-snow vapor exchange tends to enlarge snow water isotope seasonality.

Supplementary response

The revised figures in the main text are as follows:

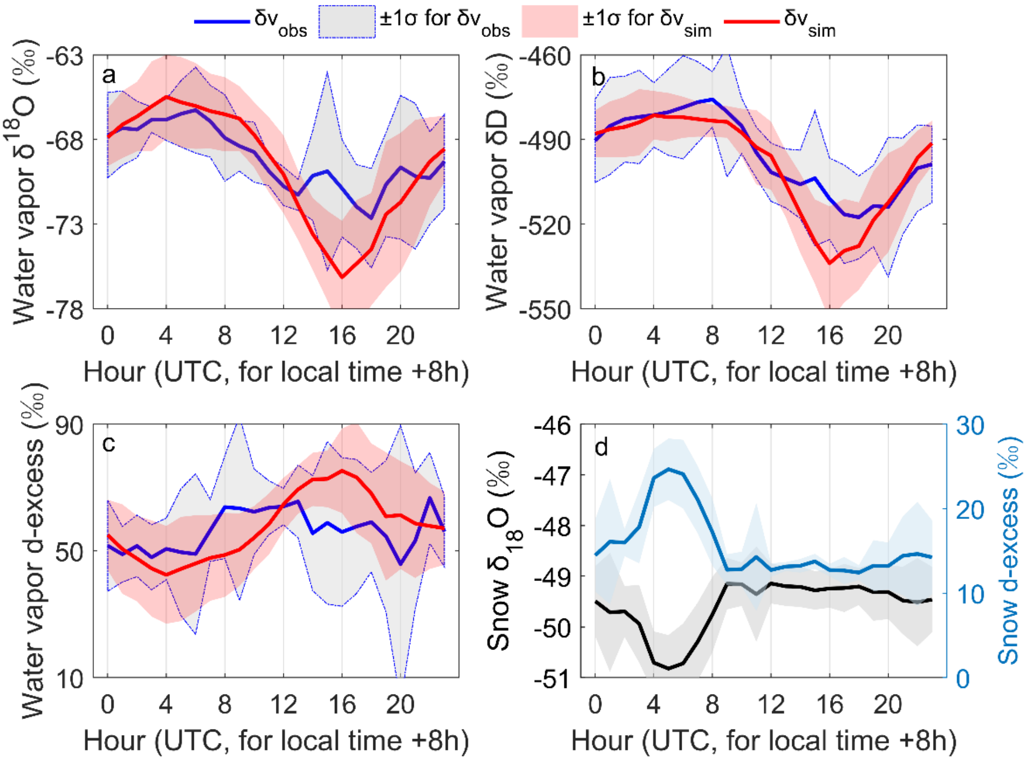

Figure 3: Model simulated diurnal variations of water vapor and snow isotopic compositions at Dome C along with the observations. (a) water vapor $\delta^{18}O$, (b) water vapor δD, (c) water vapor d-excess and (d) snow isotopes. In panels (a)-(c), blue solid line represents the observations of water vapor isotopic composition (δv_{obs}) with the light grey shaded area as the uncertainties (±1σ). The red solid line and the light red shaded area depicts the modeled variations of water isotopic composition (δv_{sim}) and correspondingly uncertainties (±1σ). In panel (d), the diurnal variations of modeled snow $\delta^{18}O$ and d-excess are shown as the black solid line and light blue solid line, respectively. Their uncertainties are also displayed with shaded areas like δv_{obs} and δv_{sim} in first three panels. The method for uncertainties estimation can be seen in SI (Texts S2).

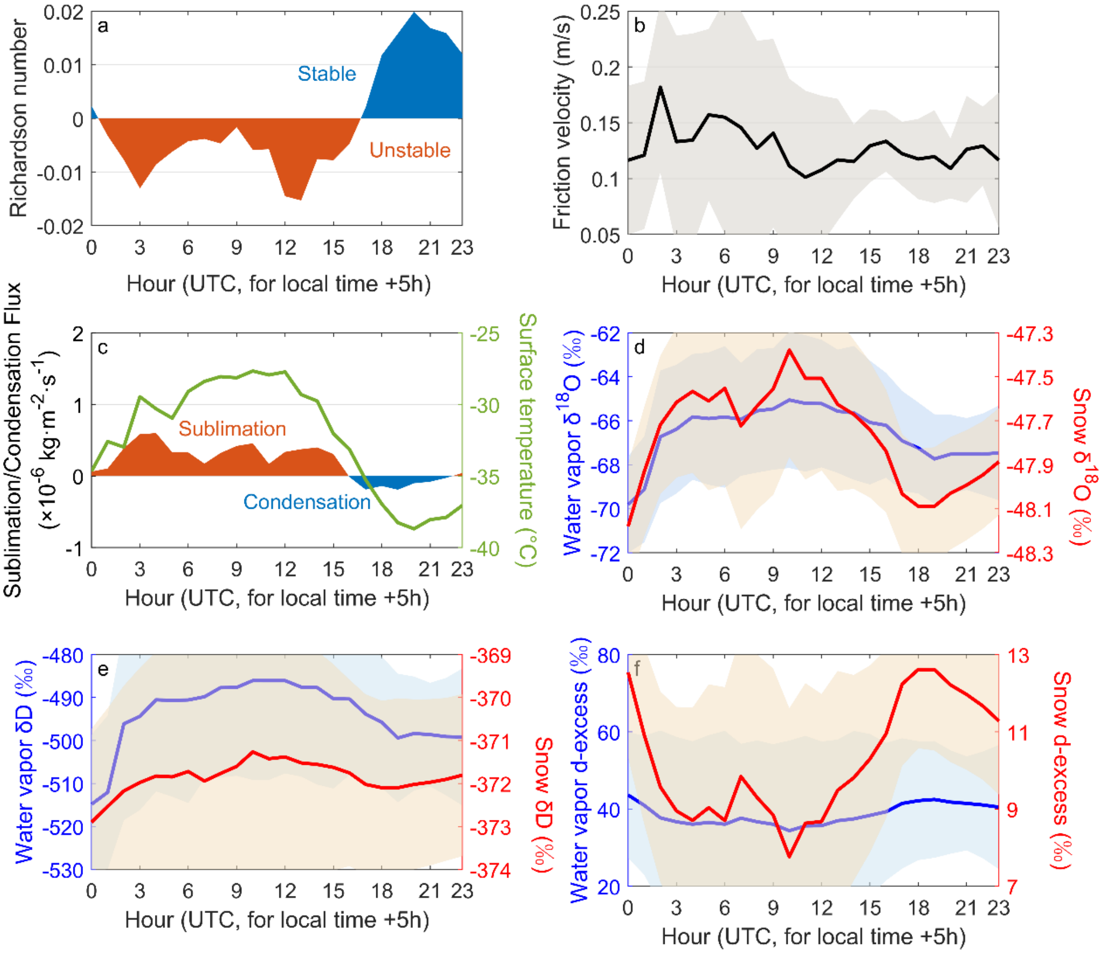

Figure 4: The simulated hourly mean vapor exchange flux and variations in atmospheric water vapor and snow isotopes under summer clear-sky conditions at Dome A: (a) Richardson number, (b) friction velocity, (c) vapor exchange flux, (d) snow and water vapor δ^{18}O, (e) snow and water vapor δD, (f) snow and water vapor d-excess. The uncertainties for each variable are displayed by shaded area in each subpanel.

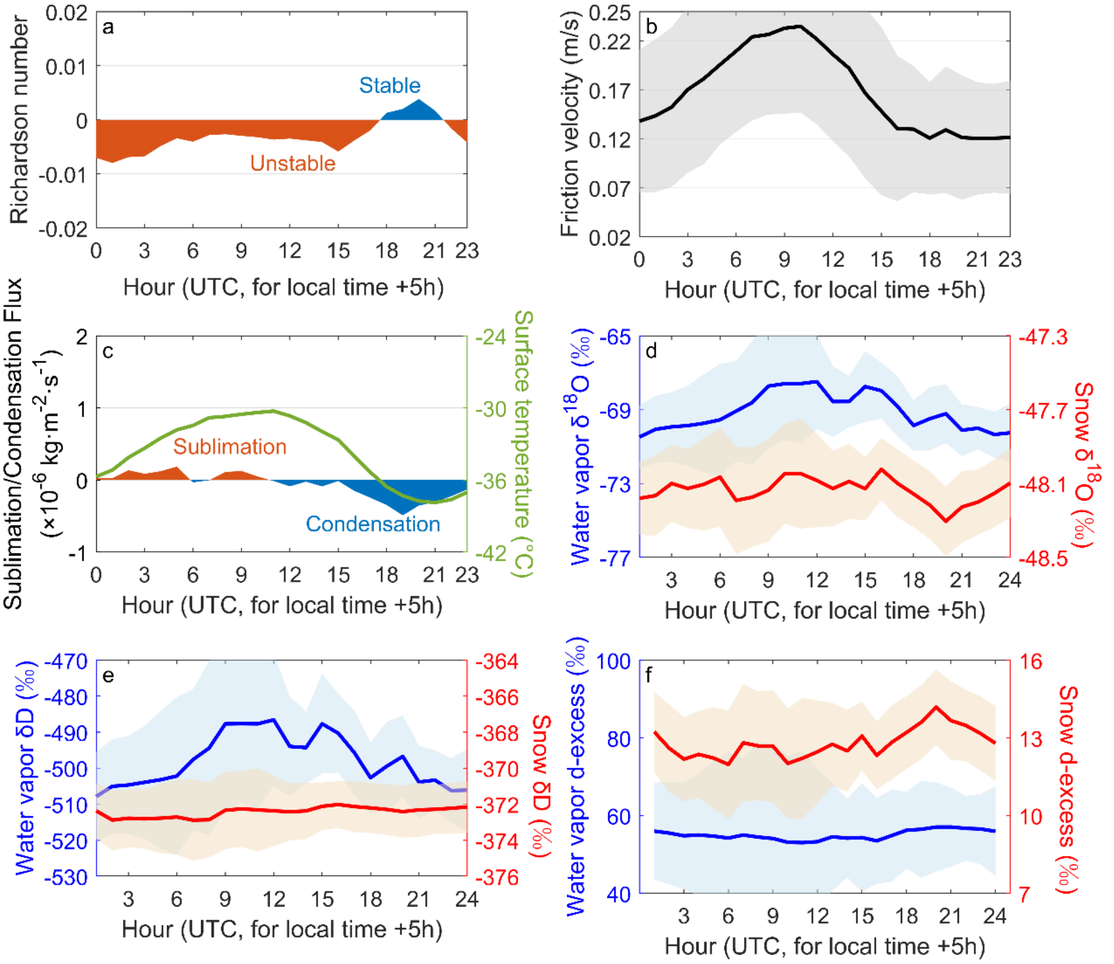

Figure 5: Same to Figure 4 but for Dome A under highly cloudy conditions in summer.

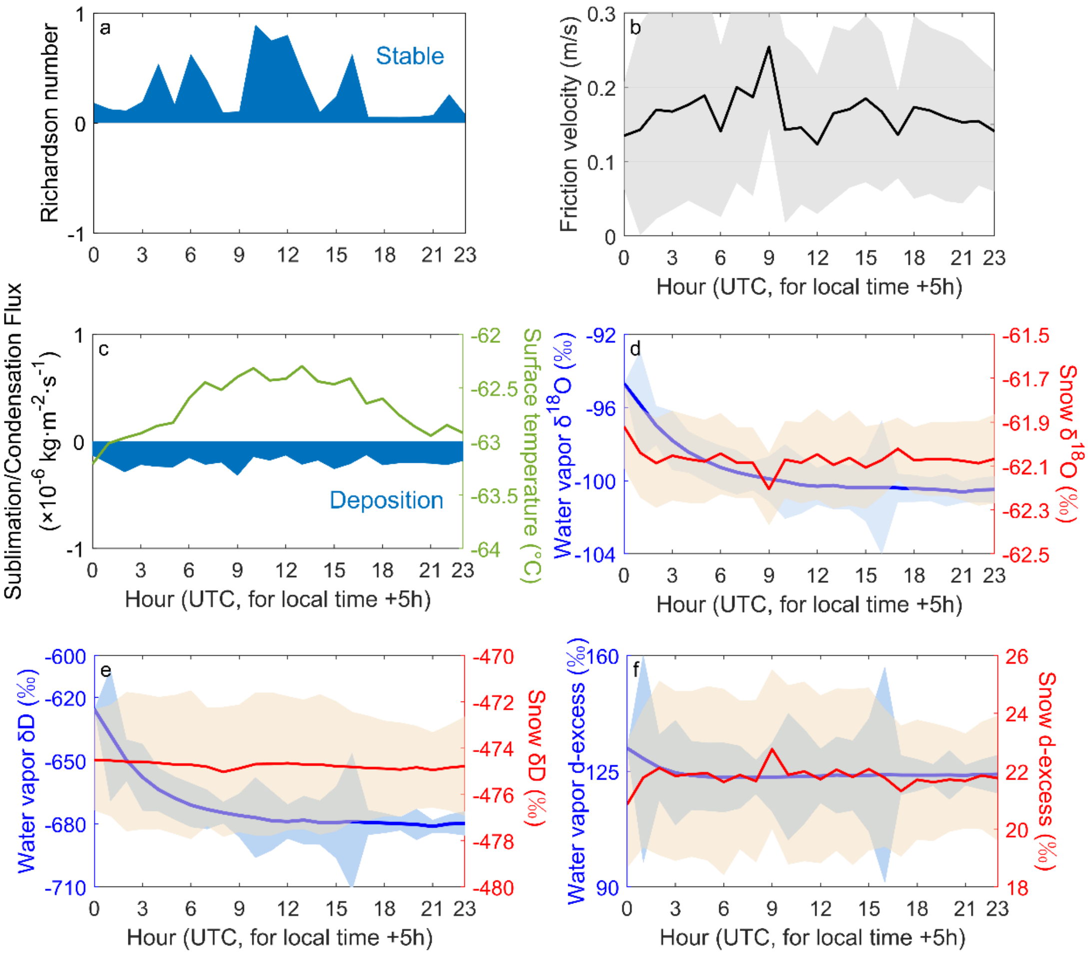

Figure 6: Same to Figure 4 but for Dome A under winter conditions.

End of the responses to Reviewer #1

Reference

Casado, M., Landais, A., Picard, G., Münch, T., Laepple, T., Stenni, B., et al.: Archival processes of the water stable isotope signal in East Antarctic ice cores, The Cryosphere, 12(5), 1745-1766, doi: 10.5194/tc-12-1745-2018, 2018.

Liu J., Du Z., Zhang D., Wang S.: Diagnoses of Antarctic inland water cycle regime: Perspectives from atmospheric water vapor isotope observations along the transect from Zhongshan Station to Dome A, Frontiers in Earth Science, 10, doi: 10.3389/feart.2022.823515, 2022.

Zilitinkevich, S.S., Esau, I.N.: Similarity theory and calculation of turbulent fluxes at the surface for the stably stratified atmospheric boundary layer, Boundary-Layer Meteorology, 125, 193–205, doi: 10.1007/s10546-007-9187-4, 2007.