Interactive comment on "Using GNSS-based vegetation optical depth, tree sway motion, and eddy-covariance to examine evaporation of canopy-intercepted rainfall in a subalpine forest" *by* S. P. Burns et al.

Reply to Referee #3

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The comments by Referee 3 are greatly appreciated. We have listed the comments by Referee 3 below in italics, followed by our responses. We added numbers to each of the specific comments so it is easier to reference the comments by Referee 3. Coauthor Mark Raleigh processed the tree sway frequency data and coauthor Vincent Humphrey processed the GNSS/VOD data. Both of these coauthors have been away from work since the comments by Referee 3 were posted. In order to keep the discussion moving forward and respond in a timely fashion, the lead author has crafted the responses below. We hope the replies are accurate; however, certain comments might need for future revision after consultation with Mark, Vincent, and the other coauthors.

This paper compiles VOD, tree sway frequency, and flux tower data for a subalpine forest. Additional data include output from a land-surface model, and field/sensor data related to air temperature, bole temperature, bole apparent dielectric permittivity, wetness, and precipitation. Together, these data are used to suggest that VOD and tree sway frequency capture signals related to canopy evaporation. These measurements offer unique insight into canopy storage dynamics from completely independent observations. I don't have any major suggestions/comments for the authors. The following suggestions are meant to help the reader understand additional context for the tree sway measurements, interpretation of results, and to facilitate reproducibility/follow up studies.

This is an accurate summary of our manuscript and we appreciate the effort made by Referee 3 in the interpretation of our data/results and to facilitate follow-up studies.

Under the category "Main Comments":

I agree with Referee #2 in that parts of the tree sway methodology can be expanded, even briefly. Suggested expansions:

We reply below to each specific comment.

1. *A) Line 145-146. If possible, include a brief description of the accelerometer methods, even though they are included in Raleigh 2022. Can go in the appendix, along with the other measurement expanded details if authors see fit.*

This is a good idea and we think it's best to put it in the main text rather than the appendix (which doesn't have any information about the tree sway frequency measurements). We used what is described in Raleigh et al. (2022) and modified the text near lines 145-146 to be:

"Processing of the raw tree sway accelerations [$\mathrm{m\,s^{-2}}$] into frequency [Hz] used the method described by Raleigh et al. (2022), except that a 30-minute analysis window was used. A brief summary of the data-processing steps is as follows: (1) spectral analysis of the 12-Hz acceleration data determined a primary frequency of the tree-swaying motion f_{sway} for each 30-min period, (2) a sliding 72-hr mean-filtered f_{sway} time series was calculated, (3) any 30-min f_{sway} outliers relative to the 72-hr mean-filtered data or values with low spectral power (i.e., due to low wind speeds) were removed, and (4) any missing 30-min time periods in the f_{sway} time series were gap-filled using splines. A detailed description of these steps can be found in Sect. 3.2 of Raleigh et al. (2022)."

2. *B) Line 147. Why was a 30-minute window chosen? Were other windows tried but this was the best one for the analysis?*

The short answer is that the eddy-covariance fluxes are calculated over 30-min periods and the US-NR1 site data are typically averaged to 30-min periods for analysis. Depending on the goals of the study, there are situation when examining the high-frequency data is more appropriate (e.g., for spectral analysis). For the US-NR1 site (and many flux sites), 30 minutes is the standard data-sharing and analysis time period. A 30-min period also provides better temporal resolution (compared to hourly periods) when examining the diel cycle. We discuss this in more detail in item #3 of our reply to Referee #2. We did not do a systematic examination of time-window-averaging length for the tree sway data analysis.

3. *C) Line 148. What interpolation and smoothing function(s) were used?*

A MATLAB spline fit of the tree sway freq data was used to gap-fill the low-wind periods. An example is shown in Fig. 4 of Raleigh et al. (2022). We mention the spline interpolation in our modified text (shown in #2 above), but will not go into any more detail within our manuscript. Coauthor Mark Raleigh can provide more specific details about the spline fit after he returns to the office.

4. *D) Line 156-157. How was the value chosen to be 1? Was this done by offsetting the low frequency trend such that the average frequency over the time series was 1? If so, please include this.*

For the detrended tree sway frequency f_d a value of 1 was chosen for two primary reasons: (i) it was not very different than the actual frequency and (ii) it added an "offset" between the detrended and raw data, so that plots (such as Fig. 4) do not have the f_{sway} and f_d data right on top of each other. As you suggested, it was done by removing the low-frequency trend and then adding back in a value of 1. The important take-away message (described on lines 158–159), is that the low-frequency detrending of the tree sway did not significantly impact how diel cycle of tree sway frequency changed with precipitation state (as shown in Fig. 4 and supplemental Fig. S5c).

5. *Similarly, Line 138, can there be a brief inclusion of the data processing for VOD? Even if it is a brief summary, it would be helpful. This can be in the appendix.*

We will include some of the key information about the VOD data processing which is extracted from Humphrey and Frankenberg (2023). We revised the text near line 138 to be:

> "The data processing and calculation of hourly VOD time series followed the procedures in Humphrey and Frankenberg (2023). A brief summary of the VOD data-processing steps is as follows: (1) calculate the GNSS signal attenuation due to the forest by comparing the GNSS signal strength from the forest receiver (gnssB) to the one above the canopy (gnssA), (2) use the signal-strength difference to estimate the forest transmissivity γ, and (3) calculate an initial estimate of VOD from $\mathrm{VOD} = -\ln(\gamma)\cos(\theta)$. Because the GNSS system samples the forest at irregular temporal intervals and angles, the long-term mean as a function of azimuth and elevation angle is used to improve the precision of the hourly measurements (Humphrey and Frankenberg, 2023)."

6. *Table 1. Is it possible to add the original/raw frequency of measurements for each observation?*

We will add additional details to Table 1 (this was also suggested by Reviewer 2). There are two different considerations—one is the raw sampling frequency and the other is the averaging period (over which mean values or fluxes are calculated). In the revised manuscript, we will include both of these in separate columns in Table 1.

7. *Figure 2. Is the accelerometer associated with Pine 3 or Pine 4? Or are the dielectric permittivity sensor on two different trees? Please clarify.*

Good point. The 3-axis accelerometer is on a spruce tree that is very close to the main tower (within about 2 m of the tower) while Pine 3 and Pine 4 are located about 20-30 m southeast of the main tower. To clarify this, we added the approximate location of Pine 3 and Pine 4 in the sensor description on lines 482–483 (Sect A5).

8. *Line 347-349. Is it possible to expand on this (how these empirical relationships might facilitate changes in the land-surface model)? This seems like an important consideration, however there is nuance to it. In particular for tree sway frequency, the tree sway frequency is proportional to the inverse square root of tree mass, so while the frequency is observed to be linear, this does not mean that the tree mass (interception) is changing linearly. However, there is no mention of how tree sway frequency relates to mass in a mathematical form throughout the manuscript. I suggest adding this here and/or earlier on in the manuscript so if improvements on the land-surface model can begin there's the additional context of how physically sway frequency relates to changing tree mass due to interception.*

We are still thinking about this comment. The relationship between tree sway frequency and mass is shown by Eq. (1) in Raleigh et al. (2022). This is an important comment and we need a bit more time to consider what changes to make to the manuscript based on it. A full reply to this comment will be in our final summary of changes to the manuscript.

9. *This is not exceptionally important, and the authors can ignore: I was trying to determine any sort of relative magnitude differences in responses for the precipitation events presented in table 3 and figure 8 (and 9). I tried to find the lowest precipitation event (3.6 mm, solid cyan line) and the highest precipitation value (29 mm, solid red line). I think I found them in the sway frequency plot and they had the lowest and highest range/variability, which was helpful to see that with a first order approximation that the observations aligned with physical interpretations (more precipitation –> more change in tree sway frequency). I couldn't quite find them in the VOD diagram. Highlighting these two events with bolded lines might help the reader understand the relative sensitivity to single events and strengthen the connections observed between precipitation, evaporation, and VOD or sway frequency.*

We like the idea of highlighting the VOD and tree sway lines in Figs 8/9 for the lowest and highest precipitation values. We will try to add this to the revised manuscript. We should point out that Fig. 10b in the discussion manuscript has the information we believe you are trying to extract for VOD. This plot shows the precipitation amount for each storm vs the 4-hour mean VOD value from 4 to 8 hours after the storm stopped (note: we noticed that there is a mistake in the caption of Fig. 10 where the red dots are related to Fig. 9, not Fig. 8). Though only based on 17 points, Fig. 10b gives a rough idea of the relationship higher VOD values occur with higher precipitation amounts (as one would expect). Since we have many years of tree sway data, we could create a similar plot for tree sway that might reveal the pattern more clearly (based on more points). We will try this and report back in our final summary about changes to the manuscript. If this was not the intention of your comment, please clarify.

10. *Are the authors amenable to including in the acknowledgements or in brief 'open science' section in the appendix or supplemental info where the data and code used throughout the manuscript can be found? This would help future studies reproduce these results and follow up studies that are interested in conducting similar experiments elsewhere.*

Thanks for bringing this up. Most of the US-NR1 30-min flux/met data are already available via AmeriFlux (`https://ameriflux.lbl.gov/sites/siteinfo/US-NR1`) which is listed under the "Assets" tab in the discussion paper.

For the final paper, we are planning to create an ESS-DIVE archive for the raw GNSS data, as well as the processed tree sway and flux data, and other data from our manuscript. The planned ESS-DIVE archive will have a format very similar a 2020 ESS-DIVE archive that is listed in the Assets tab:

> Burns, S.P., P.D. Blanken, and R.K. Monson, 2020: *Data, Photographs, Videos, and Information for the Niwot Ridge Subalpine Forest (US-NR1) AmeriFlux site.* AmeriFlux Management Project, ESS-DIVE Dataset,
> `https://doi.org/10.15485/1671825`

The goal is to have the GNSS ESS-DIVE archive created and included in the revised manuscript under the paper Assets tab. We need to have further discussion about including the data-processing code within the ESS-DIVE archive (or perhaps made available elsewhere).

References

Humphrey, V. and Frankenberg, C.: Continuous ground monitoring of vegetation optical depth and water content with GPS signals, Biogeosciences, 20, 1789–1811, doi:10.5194/bg-20-1789-2023, 2023.

Raleigh, M. S., Gutmann, E. D., Van Stan, J. T., Burns, S. P., Blanken, P. D., and Small, E. E.: Challenges and capabilities in estimating snow mass intercepted in conifer canopies with tree sway monitoring, Water Resources Research, 58, doi:10.1029/2021WR030972, 2022.