Reviewer # 2

Comment # 2.1

Pirk and others explore the response of a Norwegian alpine tundra ecosystem to a year with anomalously late snowmelt. The Introduction bounced around a bit between different topics including carbon flux, plant succession, global change, hydrology, remote sensing, and more. All of these things are interconnected of course, and the Introduction was very nicely cited, but the topics could be linked more clearly to point toward the particular topic of this study. As a consequence it wasn't entirely clear why the landsat, sentinel, and modis observations were used when modis measures more frequently at coarser scales and landsat and sentinel measure less frequently at finer scales, and how these observations fit together. Was MODIS for historical melt out dates and how were melt out dates characterized for the 16 day landsat overpass? The results are interesting but I had a difficult time understanding how everything fit together.

Reply:

We would like to thank the reviewer for the constructive and helpful comments. We acknowledge that the different topics introduced in the Introduction should be better linked to improve the logical flow in our study. We propose to implement changes as outlined in Comment #2.3 below as well as in Comment #1.2 by Reviewer 1.

Regarding remote sensing, we use merged and gap-filled Sentinel-2 and Landsat 8 imagery in the period 09.2018-09.2021 to retrieve high resolution daily FSCA and NDVI. There retrievals are used as predictors in the flux gap-filling and to analyze spatial patterns including the link to ecosystem type (Figure 2). Note that the 16-day Landsat imagery was never used in isolation, but was instead combined with Sentinel-2 imagery using Gaussian process regression resulting in merged FSCA and NDVI products. Longer-term but coarser scale MODIS imagery is used to retrieve FSCA over two decades, from which we estimate the melt-out date of the seasonal snowpack for each water year in the period 2001-2021 for the area around the Finse flux tower. These melt out dates are used to help contextualize the snow cover dynamics in the three water years 2019-2021 in terms of the longer term snow climatology around Finse (Figure 3). The quality of the MODIS data is also briefly evaluated using the higher resolution satellite imagery as a reference. This has now been clarified in the new subsection "Satellite remote sensing" as follows.

Changes:

High resolution satellite-based daily fractional snow covered area (FSCA) and Normalized Difference Vegetation Index (NDVI) estimates are employed both as predictors in the flux gap-filling (Section 2.5) as well as to analyze the spatio-temporal links between snow melt-out and the presence of ecosystem types based on in-situ vegetation mapping (Section 2.6). These estimates were obtained by merging and temporally gap-filling retrievals from multisensor multispectral satellite imagery covering the 3×3 km^2 area around the Finse flux tower at a ground sampling distance of 10 m. For this purpose, we combine surface reflectance imagery (i.e., level 2 products) from both the twin Sentinel-2 satellites and the Landsat 8 satellite in the following six wavelength bands: blue ($\simeq 0.49$ µm), green ($\simeq 0.55$ µm), red ($\simeq 0.65$ µm), near-infrared ($\simeq 0.85$ µm), shortwave infrared 1 ($\simeq 1.6$ µm), and shortwave infrared 2 ($\simeq 2.1$ µm). The data were obtained from Google Earth Engine (7), which is a cloud-based platform that harvests these open datasets from the original data sources, namely Copernicus (Sentinel-2) and USGS (Landsat 8). The FSCA is retrieved using the spectral unmixing approach described in (8). The NDVI, which is commonly used as a proxy for surface greenness, leaf area, and vegetation development, is calculated according to its standard definition (9). To avoid artifacts in the satellite-based surface reflectance data that can occur due to clouds, we manually selected cloud-free scenes. This selection provided a total of 93 Sentinel-2 scenes and 20 Landsat 8 scenes for the entire study period, resulting in an average of around four cloud-free scenes per month. Note that Landsat 8 imagery, which has a slightly coarser (30 m) native resolution, was only used for days where no 10 m Sentinel-2 imagery was available. The combined stack of cloud-free retrievals of FSCA and NDVI were interpolated in time, independently for each pixel using Gaussian process regression (10) with an exponential kernel and automatic relevance detection. Snow melt-out date was determined for each pixel as the first day with FSCA below 0.25.

Lower resolution satellite imagery with a longer temporal extent is used to build a multi-decadal climatology of the melt-out date of the seasonal snow cover around Finse that can help contextualize the melt out-dates during the study period (2019-2021). For this purpose, we use daily Normalized Difference Snow Index estimates from the MODerate resolution Imaging Spectroradiometer (MODIS) at 500 m spatial resolution to retrieve the FSCA based on a linear relationship (11) for all water years (September-August) from 2001 to 2021. MODIS is an optical satellite-based sensor currently onboard two polar-orbiting satellites, namely Terra and Aqua. These measurements from the MODIS sensors include gaps mainly due to cloud cover. By merging two MODIS-based snow products from Terra (MOD10A1; 12) and Aqua (MYD10A1; 13), we are reducing these gaps for a given day. Subsequently, a temporal cloud gap-filling algorithm following (14) is applied to this merged product to obtain gap-free daily FSCA estimates. For each pixel, snow melt-out dates are determined as the last day in a water year with FSCA greater than 0.25 during a period with at least five consecutive snow cover days. We averaged these estimates from the four closest MODIS pixels to the Finse tower to determine the snow melt-out dates at our site. To estimate the exceedance probability of the late snow melt-out in 2020, and to identify whether or not this year was an extreme year, we fit a beta distribution—a commonly used distribution with two shape parameters (α and β) for double-bounded random variables—to the melt-out dates from the MODIS dataset with the maximum likelihood method. Using gamma, logit-normal, and Generalized Extreme Value distributions for the fit to the melt-out dates only has minimal influence on the resulting exceedance probability.

The FSCA dynamics estimated from the MODIS data agrees qualitatively with a visual inspection of daily webcam imagery available at the Finse research station (www.finse.uio.no/news/webcam/). We also evaluated the snow cover duration from the MODIS using the higher resolution (Sentinel-2 and Landsat 8) retrievals as a reference during an overlap period (from 2017 to 2021) and found a close agreement with an root mean square error of 6 days and a correlation coefficient $r = 0.98$ for the 9 km^2 study area.

COMMENT # 2.2

Are fig. 5 c and d on log scales?

Reply:

Yes indeed, the y-axes in these plots are scaled logarithmically. We have clarified this by adding more y-labels to these axes in the revised version of the figure (see Figure R2), and additionally noted this in the figure caption.

COMMENT # 2.3

The eddy covariance measurements were discussed nicely and the gapfilling approach was well suited to the site. All in all with some restructuring and focus on a consistent narrative the manuscript will be publishable as it makes some interesting points.

Reply:

Thanks for this positive evaluation.

We also worked more on the structure of the manuscript. The method subsection on "Satellite remote sensing and synoptic patterns" has now been split into two subsections. The resulting subsection on "Satellite remote sensing" was moved before the subsection on "Flux gap-filling" because two remotely sensed variables are used there. We also added more references between the subsections of our methods to improve the coherence of the manuscript.

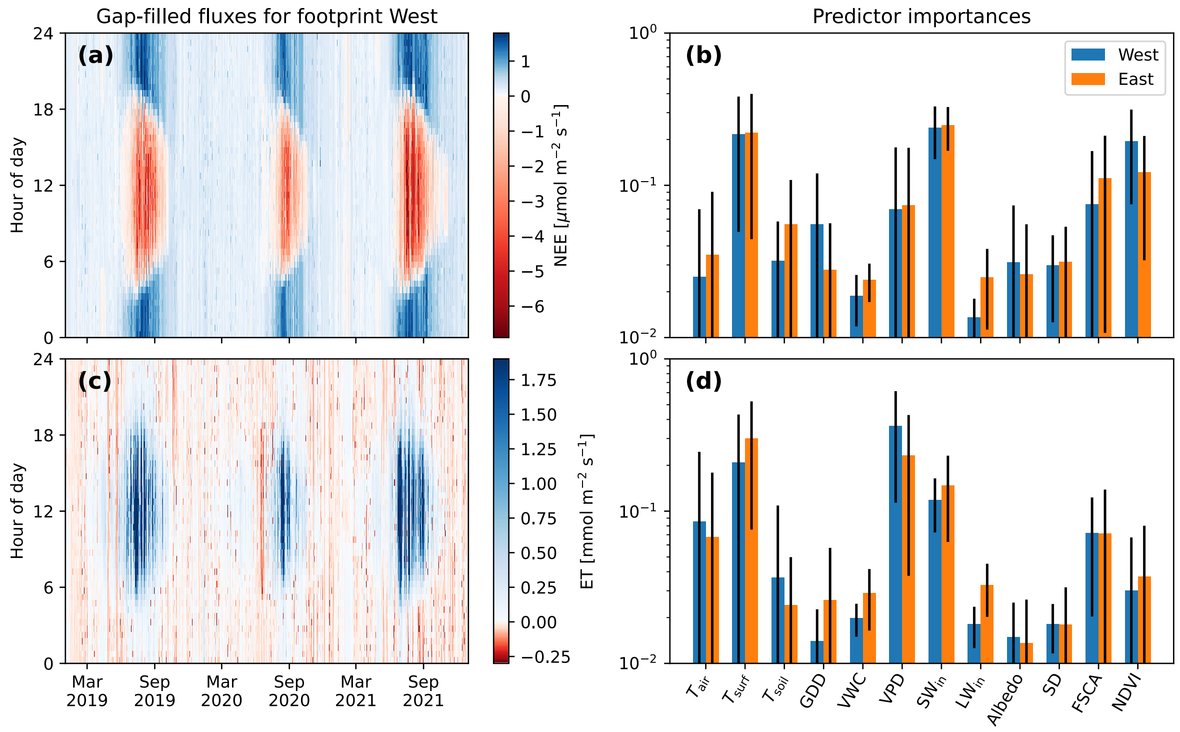

Figure R2: Flux dynamics and drivers. Left: Gap-filled NEE and ET as fingerprint plots for footprint West. Right: Predictor importance of the random forest regression models of both footprint East and West plotted on a logarithmic scale. Black error bars indicate the standard deviation across the 2000 trees in the respective random forests.

To improve the logical flow in the Introduction, we propose to implement the following changes, aiming to highlight the specific topic at the beginning of a few of the paragraphs.

Changes:

Community ecologists have long recognized that plant associations form and thrive in specific ranges of environmental conditions (15; 16). ~~Responses to changes in site conditions depend on complex plantplant interactions, which~~ However, snow-vegetation interactions and the related responses to snow cover changes in high latitude and altitude ecosystems can be highly context-dependent ~~(17; 18)~~(19; 18). (5) and (20) analyzed...

...

~~The widespread greening of mountain slopes, as quantified by the~~ There are a number of indicators for an ecosystem's interaction with the atmosphere that—while related—highlight different aspects of this coupling. The Normalized Difference Vegetation Index (NDVI)~~(9), can~~ , for example, has been used to document widespread greening of mountain slopes (9). Such changes can in turn have profound impacts on the ecosystem's carbon and water balances...

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