Response to Reviewer

Dear Dr. Robinson,

We are honored by your interest in our work and greatly appreciate your constructive suggestions. Your insights have significantly contributed to improving our work. Following is our response to your question in detail.

Main comments:

The authors introduce a method of defining start dates, end dates, and durations of snow cover over Northern Hemisphere lands that differs from fixed definitions for these variables. This reviewer is left with considerable uncertainties as to how the author's dynamic method is any more useful than the fixed method. One major concern has to do with the use of microwave derived snow depth data to "drive" this approach. Many uncertainties remain to this day regarding the accuracy of this spectral region to accurately estimate depth. This can especially be true at shallow depths, with wet snow, and with deep snow that may have ice lenses, depth hoar, etc. within the pack. Unless the authors can explain how these issues do not impact their dynamic phenology method, I would place greater faith in the IMS and SCF estimates. This brings into question just how specific one can get with timing using an 8-day window for the SCF. Not that the IMS is a full-hemisphere daily evaluation of snow cover given persistent cloud cover that may mask surface conditions for multiple days. These issues are mainly more challenging in the fall for all sources, in part due to greater cloudiness then than in the spring melt season. Also, due to shallower depths, potential wet conditions, and ephemeral snow cover that can be found everywhere during seasonal snow onset (not that it doesn't exist throughout the season at lower elevation, low-mid latitude regions. Also, the challenges of using microwave data to map snow cover over the Tibetan Plateau has long been recognized, in part, as the authors suggest, due to its shallow depth (over non-mountainous areas) and ephemeral nature.

I will go no further with this evaluation as I see earlier reviewers have posted excellent comments regarding manuscript specifics, to which I agree. At this point, I will conclude that while the manuscript addresses an interesting topic and employs the key snow cover extent data products at regional to continental scales (IMS and MODIS), I am not convinced that the SD data and the subsequent conclusions built upon it are fully supported.

Response:

Thank you for your question. Our responses to your questions and comments are listed below.

(1) The first question is about how the dynamic threshold method is more useful than the fixed threshold method. In this study, we do not explicitly quantify bias due to the

lack of direct observational data on snow phenology. We also agree that the data have a great impact on the identification of snow phenology. Given the uncertainties in snow data and the absence of snow phenology references, we focus on the limitations of the existing methods and try to improve the extraction of snow phenology in principle.

We all know that snow at high latitudes differs greatly from snow at low latitudes, and snow changes greatly on a time scale as the climatic context changes. The potential implication of using a fixed threshold is to treat all snow as the same, and the choice of a fixed threshold value is too subjective. We think that when snowfall can be steadily converted into snow on the ground, it means the onset of the snow season. It is the inflection point where we look for a change in the state of the snow curve. For example, an inflection point where the snow curve changes from a smooth change to a rapid increase, which means that snow starts to accumulate and the snow season arrives. Therefore, although we do not have observed snow phenology data for validation, the dynamic threshold approach is more reasonable in principle because this approach can take into account the spatial and temporal variability of snow.

(2) The second question is the choice to use snow depth as the driving data for the dynamic thresholding method. As you say, passive microwave remote sensing still faces considerable uncertainties in accurately estimating snow depth.

This technique detects snow cover based on the volume scattering properties of snow particles. The brightness temperature emitted from the surface propagates through the snowpack and undergoes scattering. Uncertainties in passive microwave remote sensing come from a number of sources, such as ground temperature, snow characteristics, and terrain. Under dry snow conditions, the accuracy of passive microwave retrievals improves as snow depth increases. Studies have shown that microwave retrievals tend to underestimate snow extent during autumn and early winter due to the weak scattering signal from shallow and intermittent snow cover. By mid-winter and spring, the error will be relatively small (Armstrong & Brodzik, 2001; Savoie et al., 2009). Notably, the Tibetan Plateau (TP) represents a unique exception within the Northern Hemisphere, where microwave-based retrievals tend to systematically overestimate snow-covered areas (Frei et al., 2012; Dai et al., 2017). This regional variation highlights the challenges associated with microwave remote sensing of snow, especially in shallow snow areas. On the other hand, in addition to the characteristic of shallowness, you also mention the temporal discontinuity of snow on the Tibetan plateau. Recent studies have shown an average of 14 snow cover events per year in the TP and long periods without snow cover (Li et al., 2022; Wang et al., 2024). All these reasons make TP one of the most difficult areas for passive microwave remote sensing inversion accuracy. Therefore, we will next explore the availability of passive microwave remote sensing snow depth data using TP as the study area.

We use the observational snow depth dataset of the Tibetan Plateau from the National Tibetan Plateau Data Center as a benchmark to validate passive microwave remote sensing snow depth data. There are a total of 102 meteorological stations within the study area, with 99 stations remaining after eliminating three stations with a high number of missing measurements. The time period covers 1961 to 2013, and we select hydrologic years 2001 to 2013 for this study. The hydrological year is defined as the period from September 1 to the following August 31.

To explore the continuity of different snow conditions on the Tibetan Plateau, we select the 30 meteorological stations with the greatest maximum snow depth to represent the deep snow and the 30 stations with the lowest maximum snow depth to represent the shallow snow. The maximum snow depth at deep snow stations is about 12 cm, and the maximum snow depth at shallow snow stations is about 3 cm. Next, we compare the maximum number of consecutive days for shallow snow and deep snow. As we expected, the maximum number of consecutive days for deep snow is longer than for shallow snow. The maximum number of consecutive days for deep snow is centered on 4 days, while for shallow snow, it is only 1 day. Such a short succession of days reflects the instability of snow on the Tibetan Plateau, which increases the difficulty of passive microwave remote sensing inversion.

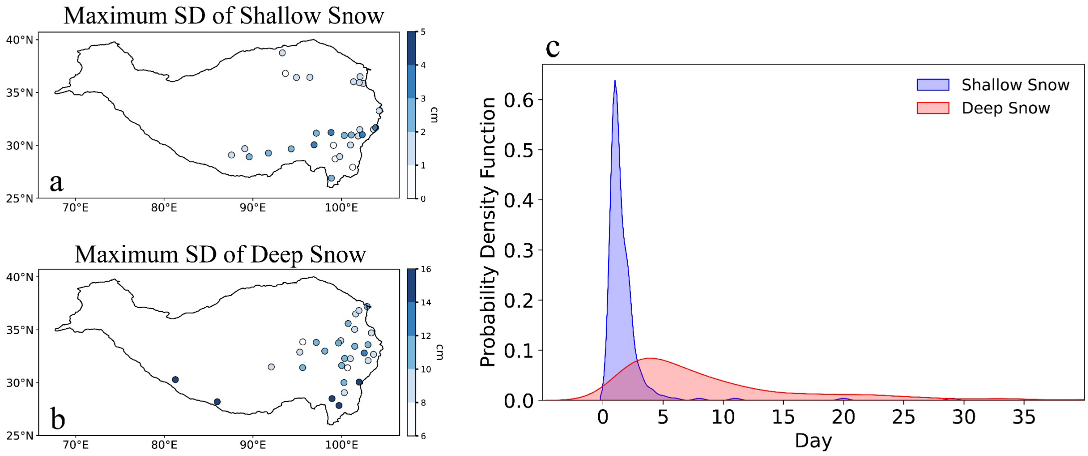

Figure R1. Spatial distribution of maximum snow depth at 30 meteorological stations of (a) shallow snow and (b) deep snow. (c) The probability distribution function for the maximum number of consecutive days of snow depth at shallow and deep snow weather stations. The blue line represents shallow snow, and the red line represents deep snow.

To compare passive microwave remote sensing data with in situ observations, we select the nearest grid point based on the latitude and longitude of each meteorological station. Spatial maps of multi-year average snow depths show that passive microwave remote sensing snow depths are greater than observed data. Passive microwave remote sensing of snow depth captures the inter-annual variability of the observed data, but suffers from systematic bias and greater fluctuations in observations. The passive microwave remote sensing data do not capture these small fluctuations. It is worth noting that the small number of meteorological stations in TP and the fact that they are mainly located in valleys at lower altitudes and on leeward slopes may make the observations not entirely accurate either.

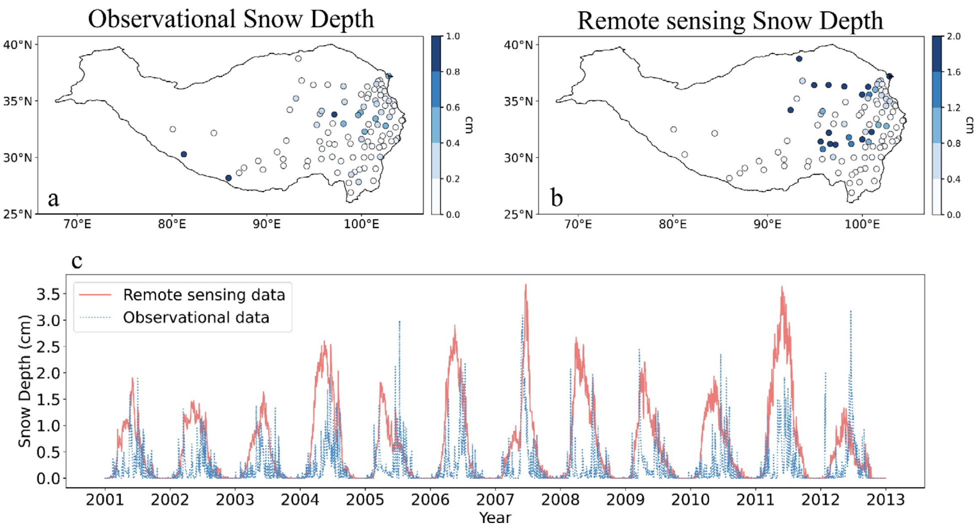

Figure R2. Spatial distribution of average snow depth at 99 sites of (a) observational data, (b) passive microwave remote sensing data. (c)Interannual fluctuations in snow depth for hydrologic years 2001-2013. The solid blue line represents observed snow depth data, and the dashed red line represents passive microwave remote sensing snow depth data.

We further analyze the snow phenology results of passive microwave remote sensing snow depth in comparison with the observed data. First, we use the traditional fixed threshold method for snow phenology extraction. Snow cover duration (SCD) from observed data is generally less than 20 days, with a maximum of 62 days. Passive microwave remote sensing data, because of its large bias, reaches the threshold more often, and the extracted SCD is naturally longer. Twenty-two of these stations have SCDs greater than 70 days. For the snow cover onset day (SCOD) and the snow cover end day (SCED), more stations in the observed data do not extract the SCOD and SCED because it is more difficult to meet the requirement of 5 consecutive days. The SCOD of observational data is generally later than the SCOD of passive microwave remote sensing data, while SCED is the opposite.

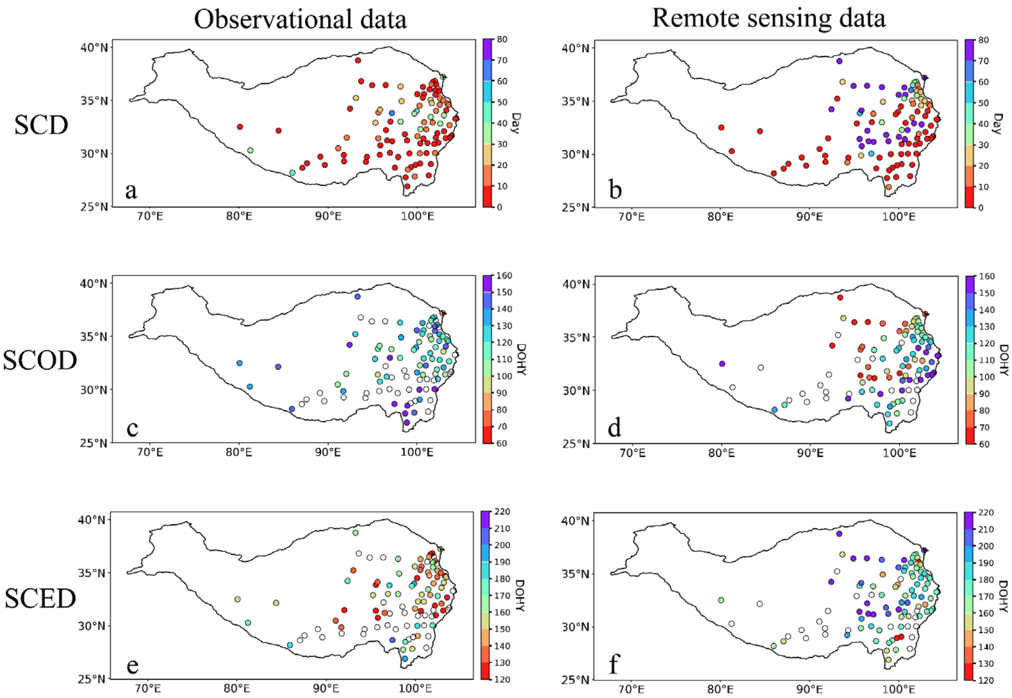

Figure R3. Spatial distribution of average snow cover duration (SCD), snow cover onset day (SCOD), and snow cover end day (SCED) at 99 sites of observational data (a, c, e) and passive microwave remote sensing data (b, d, f) extracted using the fixed threshold method. The unit DOHY stands for day of the hydrological year.

For comparison with the fixed threshold method, we extract SCD, SCOD, and SCED using our proposed 10% dynamic threshold method, showing that the SCD are prolonged for both data sets. The maximum SCD for observed snow depth data is 77 days. A portion of the sites where SCOD and SCED could not be extracted by the fixed threshold method are also able to obtain snow phenology. The traditional 2cm threshold is too high and difficult to reach for most sites at TP, but that doesn't mean that TP doesn't have a snow season. After using the dynamic approach, the thresholds are selected according to the snow conditions at the TP site itself. Therefore, the dynamic thresholding method will extract more realistic and reasonable snow phenology.

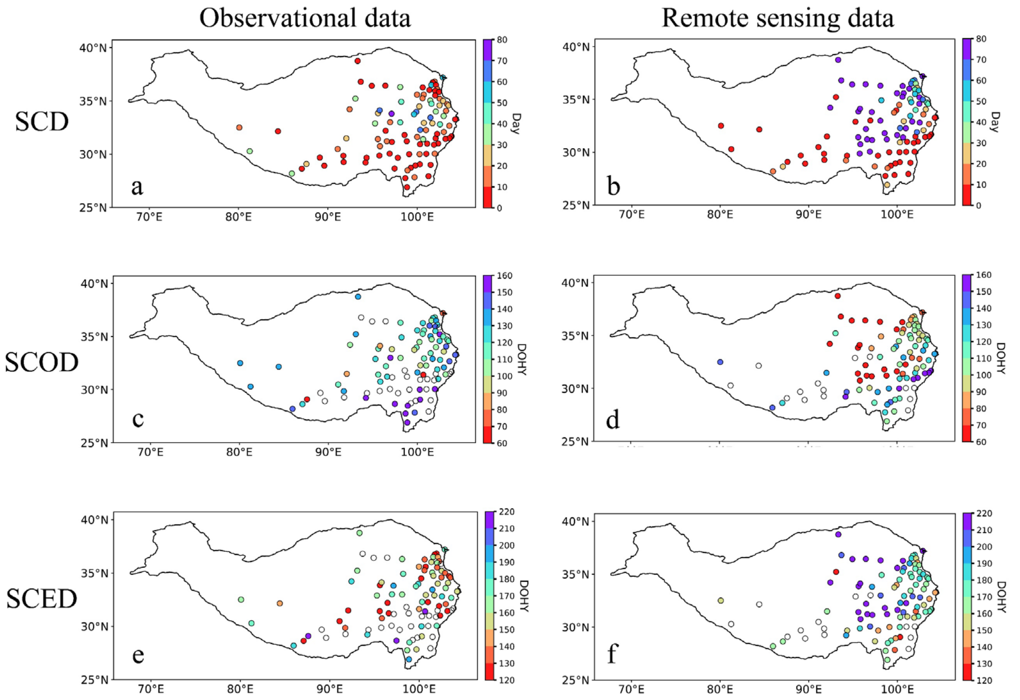

Figure R4. Spatial distribution of average snow cover duration (SCD), snow cover onset day (SCOD), and snow cover end day (SCED) at 99 sites of observational data (a, c, e) and passive microwave remote sensing data (b, d, f) extracted using the dynamic threshold method. The unit DOHY stands for day of the hydrological year.

From the interannual variation in snow phenology, the SCD of passive microwave remote sensing of snow depth is longer than the observed data, the SCOD is earlier, and the SCED is later. Overall, passive microwave retrievals tend to depict an extended snow season. Most discrepancies in snow phenology between the two datasets fall within one month. Additionally, the application of the dynamic threshold method results in a longer snow season for both datasets.

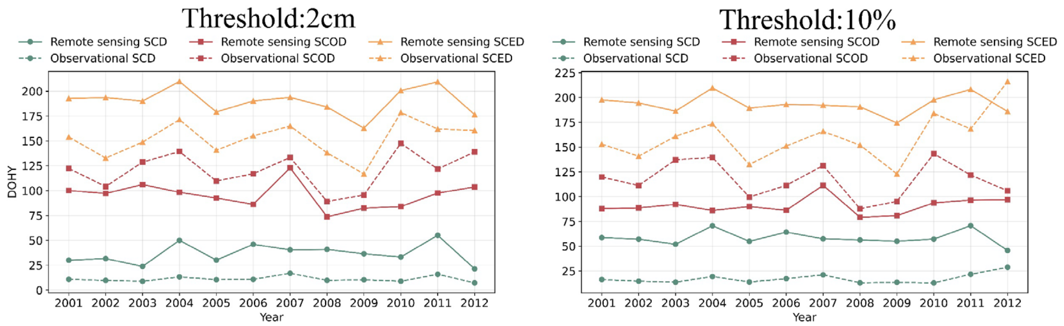

Figure R5. Interannual fluctuations in snow phenology extracted using (a) the fixed threshold method and (b) the dynamic threshold method for hydrologic years 2001-2013. The solid line represents observed snow depth data, and the dashed line represents passive microwave remote sensing snow depth data. Green represents snow cover duration (SCD), red represents snow cover onset day (SCOD), and yellow represents snow cover end day (SCED).

Snow depths from passive microwave remote sensing in TP are generally higher than observed data, leading to some bias in snow phenology as well. However, a major limitation of optical remote sensing is cloud contamination, which obscures snow data on most days during the snow season. To mitigate this issue, 8-day and 16-day composite snow cover products are generated to reduce cloud interference (Hall et al., 2002). And the resolution of 8 days may be too coarse for extracting snow phenology. The IMS is an unchangeable threshold for processed data. Therefore, each type of data has its own advantages and disadvantages, and we originally chose snow depth as the driving data. In order to make the work more complete, we also use the snow cover fraction as the driving data for the dynamic threshold method of snow phenology. Snow cover yielded roughly the same results as SD, and we show the results in the supporting information. For issues and implications arising from passive microwave remote sensing snow depth data, we have added a description in the discussion section of the manuscript.

In summary, we have recognized the impact of data uncertainty on snow phenology identification, and we believe that the spatial and temporal heterogeneity of snow cover needs to be considered. This work is a preliminary exploration of dynamic snow phenology, and we hope to further refine it in future work, including your important suggestions.

Line 449:

Since the accuracy of passive microwave detection increases with snow depth, the passive microwave remote sensing data is more effective for analyzing snow phenology in regions with consistent snow cover (Armstrong & Brodzik, 2001; Savoie et al.,2009). In areas with shallow snow with wet snow, the accuracy of passive microwave remote sensing data is reduced, and snow depth indicator may not accurately capture accumulation and melting processes. In addition, for the transient snow area, the snow depth curve is more volatile, which makes the assumed single-peak structure untenable. After comprehensive consideration, the snow cover area may be a more reliable indicator in such cases. Therefore, we perform another extraction of dynamic snow phenology using the snow cover data, and the results are similar to SD, but with greater differences in TP (see supplement). Regardless of the threshold method, problems with the data itself increase the uncertainty of snow phenology analysis. Therefore, it is necessary to integrate ground observation data with different remote sensing data to form a more comprehensive and accurate snow phenology extraction system.

References:

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