Response to Reviewer #2

In this paper, the authors examine the spatiotemporal variability of the snow phenology over the Tibetan Plateau, based on MODIS satellite observations. The period covers 2002 to 2021.

The study focuses on snow onset, snow end date and snow cover days. It relies on an improved MODIS dataset, filled for temporal and spatial data gaps. Governing factors, which can have both direct and indirect effects on the snow phenology through the interplay of the different variables are extracted by a Structure Model. It is found that the meterorological factors (temperature, precipitation) play the leading roles. However, the relative importance of temperature and precipitation shifts with elevation.

The study is detailed and comprehensive, and the article clearly written. It should prove a valuable to understand the snow cover variability over the Tibetan Plateau. I recommend the paper for publication provided the three main comments (essentially, discussion points) are addressed.

Response: We appreciate your valuable suggestions and comments, which have contributed to substantial improvement of the manuscript. As suggested, we have particularly improved the manuscript in the discussion section, where we discussed more detail about the effect of black carbon on snow cover, time-dependency of meteorological factors, and the complex relationship between elevation and longitude on snow cover. Detailed responses to each of the comments are provided below.

Main comments:

Comment 1:
It is a bit surprising that the "darkening of the snow" plays such a minor role, given the attention given to this issue in recent years. [e.g., W. Lau et al, Atmosphere 2018, 9(11),https://doi.org/10.3390/atmos9110438]. Are the findings consistent with earlier studies about this point? Is the global BC emission dataset really relevant here since it is mostly the BC transported and deposited on the Tibetan Plateau that would matter? Is the AOD dataset of sufficient quality and resolution over the area of interest?

Response: We agree that the global black carbon emission dataset we previously utilized focuses on the emission of black carbon (Xu et al, 2021), which may be not suitable for representing the transportation and deposition of black carbon on the Tibetan Plateau. The AOD data we previously used measures the aggregate concentration of atmospheric particulate matter, but fails to differentiate black carbon from other particulate components, such as PM2.5 or PM10 (Bai et al., 2022). Therefore, our previous analysis that relied on the global black carbon emission dataset and AOD may exhibit certain biases.

Previous research has mainly relied on numerical simulations from climate models to investigate the effect of black carbon on snow cover on the TP, such as RegCM4.3 (Ji et al., 2015) and GEOS-5 (Lau et al., 2018, reference mentioned by referee). Furthermore, analysis of back trajectory methods also serves as a vital approach to understanding the significance of black carbon on snow cover (Zhang et al., 2018). However, these methods do not generate a black carbon dataset that can be directly utilized as input for structural equation model. To our knowledge, the MERRA-2 reanalysis dataset is the most widely used black carbon concentrations product (Chen et al., 2023; Xu et al., 2020). Its spatial resolution (0.5° × 0.625°, approximately 50 km × 60 km) renders it more appropriate for large-scale investigations (such as Arctic or China), which is not suitable for the Tibetan Plateau. In our latest revision, we have removed the experimental section about black carbon and AOD, and have added the following content to the *Discussion 5.3*:

Atmospheric pollutants, especially those referred to as light-absorbing aerosols, such as black carbon, brown carbon and dust, can warm the atmosphere (Kang et al., 2019; Ji et al., 2015). After being deposited onto snowpack, these light-absorbing particles can reduce the surface albedos of snowpack and promote its melting (Zhang et al., 2018; Lau et al., 2018). Despite the potential importance of these factors to the SP of TP, they were not analyzed in this study due to limited data availability of these factors over extended spatial and temporal scales. Developing high-resolution, spatiotemporal continuous datasets for these factors will be useful in future efforts to comprehensively quantify the response of SP to changing climate conditions.

References:

Bai, K., Li, K., Ma, M., Li, K., Li, Z., Guo, J., Chang, N.-B., Tan, Z., and Han, D.: LGHAP: the Long-term Gap-free High-resolution Air Pollutant concentration dataset, derived via tensor-flow-based multimodal data fusion, Earth System Science Data, 14, 907-927, https://doi.org/10.5194/essd-14-907-2022, 2022.

Chen, X., Kang, S., Yang, J., and Hu, Y.: Contributions of biomass burning in 2019 and 2020 to Arctic black carbon and its transport pathways, Atmospheric Research, 296, https://doi.org/10.1016/j.atmosres.2023.107069, 2023.

Ji, Z., Kang, S., Cong, Z., Zhang, Q., Yao, T.: Simulation of carbonaceous aerosols over the third pole and adjacent regions: distribution, transportation, deposition, and climatic effects, Climate Dynamics, 45 (9), 2831–2846, https://doi.org/10.1007/s00382-015-2509-1, 2015.

Lau, W. and Kim, K.-M.: Impact of Snow Darkening by Deposition of Light-Absorbing Aerosols on Snow Cover in the Himalayas–Tibetan Plateau and Influence on the Asian Summer Monsoon: A Possible Mechanism for the Blanford Hypothesis, Atmosphere, 9, https://doi.org/10.1007/10.3390/atmos9110438, 2018.

Xu, X., Yang, X., Zhu, B., Tang, Z., Wu, H., and Xie, L.: Characteristics of MERRA-2 black carbon variation in east China during 2000–2016, Atmospheric Environment, 222, https://doi.org/10.1016/j.atmosenv.2019.117140, 2020.

Xu, H., Ren, Y., Zhang, W., Meng, W., Yun, X., Yu, X., Li, J., Zhang, Y., Shen, G., Ma, J., Li, B., Cheng, H., Wang, X., Wan, Y., and Tao, S.: Updated global black carbon emissions from 1960 to

2017: improvements, trends, and drivers, Environment Science Technology, 55, 7869-7879, https://doi.org/10.1021/acs.est.1c03117, 2021.

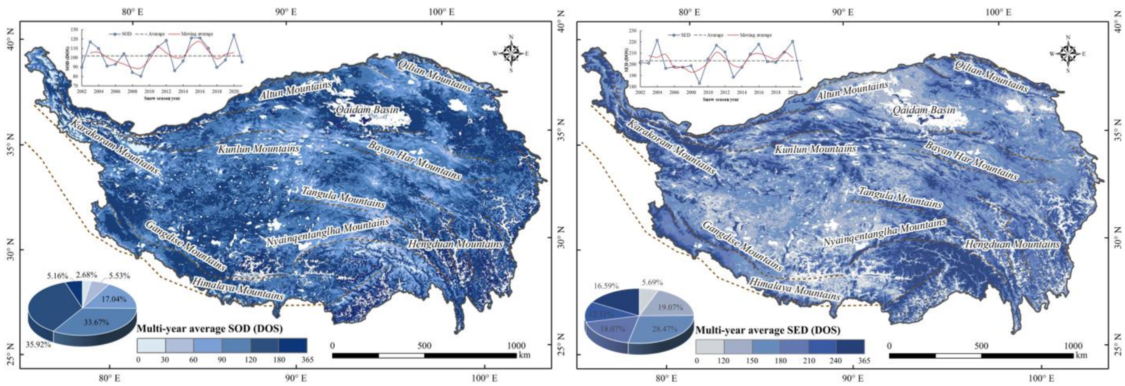
Zhang, Y., Kang, S., Sprenger, M., Cong, Z., Gao, T., Li, C., Tao, S., Li, X., Zhong, X., Xu, M., Meng, W., Neupane, B., Qin, X., and Sillanpää, M.: Black carbon and mineral dust in snow cover on the Tibetan Plateau, The Cryosphere, 12, 413-431, https://doi.org/10.5194/tc-12-413-2018, 2018.

Comment 2:

The precipitation data is at high spatial resolution, which was deemed important and explaining differences with respect to earlier studies. Yet, the precipitation data consists of monthly means. Is this sufficient to elicit the daily snow evolution required to estimate snow onset and end dates? Is there daily precipitation dataset that the authors could have used and could they test if it affect the results?

Response: Given the large spatial extent of the Tibetan Plateau, there exists a significant time span encompassing both the snow onset date and snow end date, with snow onset date mainly occurring from September to December and snow end date ranging from February to August (Figure 1). This indicates that daily precipitation corresponding to snow onset/end date likewise crosses this identical temporal ranges. However, time series of precipitation often reveal natural periodicity and continuity, suggesting a time-dependent correlation in precipitation. Taking the example of snow onset date, starting from September 1st (as winter approaches), the precipitation exhibits a decreasing trend over time, indicating a negative temporal correlation (Hu et al., 2021). However, we found that the daily precipitation also exhibits a negative correlation ($R = –0.20$) with snow onset date using a daily meteorological dataset with 3 km resolution (Figure 2a). Ignoring the time dependence of precipitation data may lead to an overestimation of the negative impact of precipitation on snow onset date.

In fact, temperature is also time-dependent and provides a more intuitive understanding. Theoretically, colder temperatures are associated with earlier snow onset date, suggesting a positive correlation between temperature and snow onset date. However, our experiment based on the daily temperature corresponding to snow onset date shows a negative correlation ($R= –0.27$, Figure 2b). Temperature consistently decreases from September 1st onwards, displaying a negative correlation with time. Consequently, the actual effect of temperature on snow onset date may be obscured by its time dependence.



(a) Snow onset date (b) Snow end date

Figure1: The spatial pattern of the multiyear averaged (a) Snow onset date, (b) snow end date on the TP from 2002 to 2022.

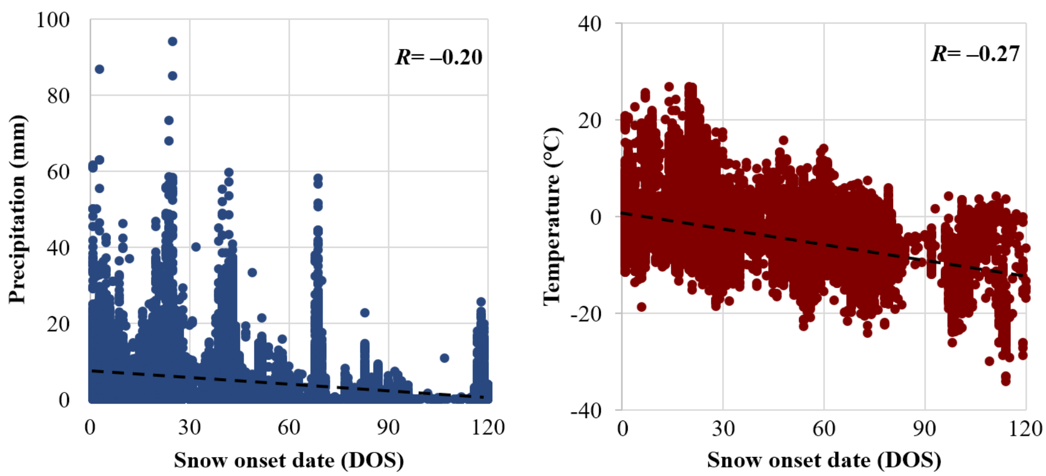


Figure 2: Scatter plot of snow onset date and precipitation (a), and temperature (b). DOS represents the day of the snow season, DOS 1 is equivalent to September 1.

Referred to literature on snow phenology (Chen et al., 2018; Ma et al., 2023), we defined the snow accumulation period (from September 1 to February 28/29) and the snow melting season (from March 1 to August 31), and calculate the average temperature and total precipitation for these two time periods, respectively. The average temperature and total precipitation from the snow accumulation season were used to analyze their impact on snow onset date. Similarly, the average temperature and total precipitation during the snow melting season were used to examine their influence on snow end date. The purpose of this is to address the time-dependence of meteorological factors by representing the general climatic conditions during the seasons of snow accumulation and melting. In the future, we intend to explore more methods to effectively isolate the time-dependency of meteorological factors.

References:

Chen, X., Long, D., Liang, S., He, L., Zeng, C., Hao, X., and Hong, Y.: Developing a composite daily snow cover extent record over the Tibetan Plateau from 1981 to 2016 using multisource data, Remote Sensing of Environment, 215, 284-299, https://doi.org/10.1016/j.rse.2018.06.021, 2018.
Hu, W., Yao, J., He, Q., Chen, J.: Elevation-Dependent Trends in Precipitation Observed over and around the Tibetan Plateau from 1971 to 2017, Water, 13 (20), 2848. https://doi.org/10.3390/w13202848, 2021.
Ma, Q., Keyimu, M., Li, X., Wu, S., Zeng, F., and Lin, L.: Climate and elevation control snow depth and snow phenology on the Tibetan Plateau, Journal of Hydrology, 617, https://doi.org/10.1016/j.jhydrol.2022.128938, 2023.

Comment 3:

I am a bit unclear on the longitude dependence of the results is it merely elevation that is folded in this dependency (to explain that different longitudes receive different amount of radiation, precipitation and so forth).

Response: Indeed, the elevation of the TP decreases from west to east, resulting in a correlation between elevation and longitude. We conducted a correlation analysis between these two factors and found a correlation coefficient of 0.532 (Figure 3a). This correlation can cause the effect of longitude on SP folded under the effect of elevation on SP. However, controlling the influence of elevation, we still find the longitudinal dependency of snow cover. Taking the snow cover days as an example, at a fixed elevation (e.g., 5000 m), a correlation still exists between longitude and SCD (R = 0.356, Figure 3b). This implies that longitude could be interacting with additional factors to shape the spatial and temporal distribution of snow cover on the plateau.

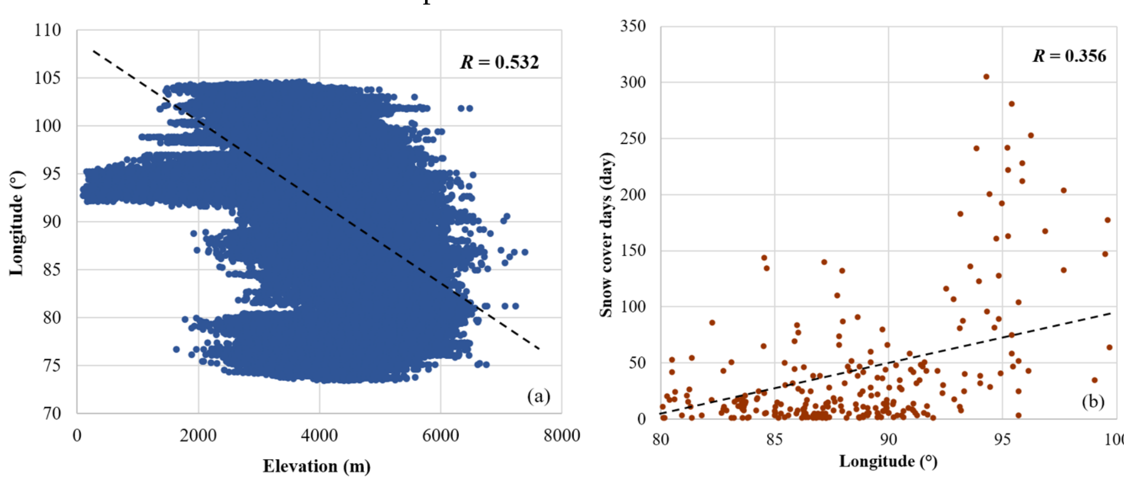


Figure 3: Scatter plot of (a) elvation and longitude, (b) longitude and snow cover days (at a fixed elevation of 5000 m).

Minor comments:

L 162: It is a bit unclear how the number 56 is derived. Number of stations times years with sufficiently long records? Please spell out the details.

Response: Since snow phenology is recorded annually, every station can calculate a valid yearly dataset for validation. However, not every station can extract snow phenology every year due to data gaps or other reasons. Therefore, the total number of records is not 24 stations multiplied by 19 years. Instead, the total number of records was extracted for all valid years for each station. We have added the following sentences in *Section 3.1*:

Stations with fewer than 20 snow-covered days and fewer than 5 consecutive snow-covered days during the snow season were excluded. After applying these criteria, a total of 56 ground-observed SP from 24 stations were used for accuracy validation.

L191: "owing to its valuable for unstable factor weights". Unclear sentence.

Response: For a better understanding, we have revised this sentence as follows:

High multicollinearity between factors may result in inaccurate path coefficient, leading to these factors being misperceived as unimportant or invalid (Hair et al., 2010).

L288: The wording "temperature gradient" is misleading (also caption of Fig 8). It is actually the correlation as a function of temperature that is shown, not the temperature vertical or spatial gradient (which would have different units).

Response: We have revised the word to "Temperature range".

L326 Unclear sentence and wording for "essential": "proved consistently as essential as elevation" (Is that what is meant here?)

Response: What we intend to convey here is that relative importance of temperature and precipitation shifts with elevation. We have also made revisions to this statement in *Section 5.1*:

Overall, we identified that relative importance of temperature and precipitation shifts with elevation.