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Interactive comment on "Central Himalayan tree-ring isotopes reveal increasing regional heterogeneity and enhancement in ice-mass loss since the 1960s" *by* Nilendu Singh et al.

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General comments: This paper of Singh et al. reconstructed and analyzed the glacier mass balance since 1743 in central Himalaya, using tree ring carbon isotope, it is meaningful for the understanding the glacier variation in Himalaya area. Response: We are thankful to the reviewer for valuable comments and suggestions that improved this manuscript. In this paper, we reconstructed annual variability of four 'benchmark glaciers' of the Uttarakhand Himalaya utilizing tree-ring carbon isotopes of two dominant conifer species growing in the valleys. We also analyzed the variability of tree-ring and ice-core oxygen isotopes on a central Himalayan-scale. Comment: However, the

present version has many problems in the results and structure. One of the most important is the glacier mass balance reconstruction. Firstly, is it available to use tree ring carbon to reconstruct glacier mass? The tree ring carbon is influenced by climate, environment and plant physiological factors, the authors should give reasonable explanation about the mechanisms. Response: In this revised version, we improved this manuscript in light of the reviewer's comments. Here we would like to mention that tree-ring carbon isotopes are strong predictors of local ecohydrology, while δ18O retain physical climatic signals that are essentially coherent over a large region. Studies are available that reconstructed glacier mass balance based on tree-ring carbon isotopes of zonal dominant conifers growing in the glacier valleys. Even seasonal mass balance reconstructions have been attempted utilizing tree-ring parameters and period of growth. Recently, Zhang et al. (2019) reconstructed mass balance of TS. Tuyuksuyskiy glacier in the Tianshan Mountains utilizing the strong link between δ13C variability and growing season temperatures, and the premise that climate is a bridge that indirectly connects mass balance of a glacier with tree growth.

Prevailing climate controls the amount of snow accumulation and ablation, which determine the retreat or advancement of a glacier. Similarly, tree growth (and δ13C composition) is a result of an integrated response to climate. Thus, trees growing in the valleys and glacier mass balance respond to the same climatic forcing. The variability of the 13C/12C ratio (δ13C composition) in tree-ring cellulose is mainly controlled by photosynthesis and stomatal conductance. At dry sites, these processes depend mostly on relative humidity and soil moisture availability, whereas at moist sites the C-isotope ratio reflects the variability of radiation and temperature. Dendroglaciological and paleoclimate studies from the warm-moist, monsoon-dominated Himalaya suggest that temperature changes are the prime factor for glacier fluctuations rather than changes in precipitation. C-isotope ratios in tree-rings of evergreen conifers growing in energy-limited valley environment strongly reflect the temperature as well as some measure of water availability (Figure S3). Therefore, in these environments the factors that influence photosynthesis are strongly correlated with δ13C of tree-rings.

Vegetation growth in the Himalaya is known to be primarily regulated by temperature. Therefore, mass balance reconstruction of valley glaciers based on tree-ring δ13C assumes significance, particularly in the warm-moist valley environment where coupling between carbon and water cycle is strong (Singh et al., 2014). Moreover, given strong land-atmosphere interaction (Singh et al., 2019; Tuinenburg et. al., 2012), ecohydrological memory (Chauhan and Ghosh, 2020), and vegetation-regulated moisture recycling (Keys et al., 2016), tree-ring δ13C is a strong proxy to study local valley-scale climate. In addition, remarkably high interspecies and spatiotemporal coherence observed between tree-ring δ13C and δ18O probably indicate a high ecophysiological-ecohydological coupling, particularly for the studied region (Figure 3b), increasing the reliability of the reconstruction. To conclude, in humid environments, the δ13C composition of tree-rings is determined by the photosynthesis rate, which in turn depends upon temperature. Higher growing season temperatures stimulate photosynthesis rates. This facilitates stable isotope fractionation process, resulting in decreased intercellular CO2 concentration and fractionation against the heavier 13C isotope, which leads to increased higher δ13C. Thus, climate (temperature) is a bridge that indirectly connects the mass balance of a glacier with tree-ring C isotope ratios. Hence, the mass balance can be reconstructed using stable carbon isotope chronologies from trees growing in the proximity of the glacier.

Comment: Secondly, the record of glacier mass balance in only 23 years, also with a few years gap, it is too short and lead to a very low degree of freedom, and then the correlation coefficients between tree ring carbon and glacier mass balance are not so high. Therefore, I deeply doubt the statistics of the reconstruction. Response: Thank you for your concern. We admit that due to inclement weather conditions, difficult terrain, and consequent logistic-infrastructural reasons, the longest available record of glacier mass balance is maximum upto 23 years for the Uttarakhand Himalaya. However, to overcome the limitation of short glacier mass balance data, we used the well-established and robust statistical leave-one-out cross-validation method (Michaelsen, 1987). This statistical approach has often been applied under similar

limitations of short calibration data length in dendroclimatic studies, including the Himalayan region (Shah et al., 2013; Shekhar et al., 2017; Yadav and Bhutiyani, 2013, Duan et al., 2013; Zhang et al., 2019). The leave-one-out method (Michaelsen, 1987) fits a regression model to all the data except for a single point, and then makes a prediction at that point. The estimates for every data point form a modelled time series, which is compared with the actual values. Our mass balance reconstruction captured robust significant verification statistics (Table S3, Figure S4), thereby validating the regression model. In addition, our mass balance reconstruction passed other verification statistics. Particularly, the sign-test and the root mean square error (RMSE) have been widely used as a validation parameter for the reliability of climate reconstructions (Cook and Kairiukstis 1990). We recorded a small RMSE value (0.166), indicating a small error in the reconstructed values. The low Durbin-Watson coefficient (1.21), and the F-test value (12.37) in the verification also indicate the significance of the regression model. The positive values of reduction of error (RE) and coefficient of efficiency (CE) underpins significant skills in the reconstruction and acceptable model performance (Cook et al. 1999) (Table S3). Comment: I think the authors should firstly determine the dominant factor of glacier mass, temperature or precipitation in which season? After that, clarify the influence factor of tree ring carbon. Only make these explicit can discuss if tree ring carbon is available to reconstruct glacier mass. Response: We appreciate the reviewer's suggestions. Dendroglaciological and paleoclimate studies from the region suggest that temperature change is the prime factor for glacier fluctuations on a decadal timescale rather than changes in precipitation. In the present study, correlation analysis with CRU temperature data indicate a high coherence with mass balance dynamics ($r = -0.78$, $P < 0.001$). In contrast, correlation with gridded precipitation including that of northern India and ISM rainfall indicate a low association (Figure 3a). While the response function analyses (Figure S3) indicate that tree-ring δ13C composition is primarily influenced by temperature. Thus, our analyses indicate that temperature is a main governing parameter of glacier mass balance and tree-ring δ13C composition in the region. Comment: Besides, the studied glacier type is not obvious, the authors should give the monthly ice mass, as well as the percentage of summer rainfall and winter snowfall. Response: Thank you for your comment. The glacier type and its geomorphological characteristics including hypsometric curves have been detailed in section 2.2. The studied glacier belongs to land-terminated valley-type glaciers of simple configuration and hypsometry, which are most suitable to infer paleoclimatic information and are therefore designated by workers as ’benchmark glaciers’ of the humid central Himalaya. As mentioned previously, due to obvious logistical reasons, no data on monthly ice mass values for the Himalayan glaciers are available. Based on the analyses of available meteorological records, we indicated that warm-wet summer months receive about 80% of the mean annual precipitation, while winter snowfall contributes the rest. This observation is supported by many previous studies. Special comments: Comment: Introduction: in the fifth paragraph of this section, you present that tree ring width, you should give some investigation that why tree ring oxygen and carbon could record the information of glacier mass balance. To my knowledge, the climate signal recorded in tree ring carbon isotope is more complicated. Response: We appreciate the reviewer’s comment. As suggested, we have now incorporated (Lines: 82-86) the linking mechanism and the basic premise explaining why tree-ring carbon isotope ratios could record the information of glacier mass balance. Comment: Line 174: Do you mean the two conifer trees contain winter-time climate record? what is the growth period of the two conifer trees and the deciduous trees? Response: Early wood accounts for most of the whole ring in coniferous species and mainly carries a climate signal of the previous autumn or winter and early-spring seasons (Zeng et al., 2017). Conifer trees mostly use the snowmelt water of the previous winter for wood formation in the early growing season. The two conifer species are evergreen, while growth of the deciduous trees occurs between April and September in the Himalaya. Comment: Line 181: the amount of cellulose is too much, why? Response: The amount of cellulose utilized for IRMS analyses is per common isotope-dendrochronological procedure. Comment: Line 165-173: this paragraph should be removed, it should be given in Results section. Response: Thank you for

the suggestion. We modified as suggested. Now lines: 221-263. Comment: Section 3: this section should present the carbon series firstly, and then the correlation analysis, finally the reconstruction. The authors should give the raw and corrected 13C values of the studied five trees, as well as the EPS, Rbar and the number of trees at different period. Response: We modified as suggested (Lines: 221-263). Raw and corrected 13C values of the studied species are presented in Figure S6. Generally, EPS > 0.85 and Rbar statistics are used in tree-ring studies for determining the reliable length of chronologies in dendroclimatology, which commonly lose replication when moving further into the past (Yadav and Bhutiyani, 2013). However, in case of dendro-isotope studies (because of the high coherency of isotope series from individual trees) the common approach is to combine more than 3-4 tree cores over the time, which are sufficient for establishing a reliable tree-ring isotope chronology (Zeng et al., 2017; Singh et al., 2019; Sano et al., 2012, 2013, 2017; Xu et al., 2018). In the present study, we have used a chronology with 5 tree cores over the entire series of respective species (i.e., 1743-2015 in case of Abies and 1920-2015 in Picea). Comment: Line 236-239: the correlation coefficients between 13Cof two PFTs and annual mass balance are not very high, especially in consideration of the low value of degree of freedom (n = 23), so I deeply doubt the reliability of the reconstruction. Response: In paleoclimate reconstructions, more than 35% variance explained in the calibration period is acceptable to tell the past history, although a higher variance explained is preferred (Fritts 1976). In our reconstruction, we achieved 46.5% variance explained during the calibration period, which is quite high and sufficient for a reconstruction. Further, our regression model was rigorously verified with multiple verification statistics (please see Table S3). Detailed statistics, previous studies, and the reliability of reconstruction have been discussed in our response to earlier comments (see Table S3). Comment: Line 250-253: this sentence is obscure, you mentioned that the uncertainty still exists in the reconstruction, how does the 13C and the combination of two conifer species can help to minimize several factors……………? Why? Response: Thank you for pointing to this unclear expression. From these lines (now lines: 257-259), we contend that the short observation period might create a certain level of uncertainty during pre-observation period. The use of highly sensitive isotope chronologies (with respect to tree-ring width) could avoid or minimize uncertainty that arises due to sensitivity issues associated with ring width. Thus, the observed high coherence in the isotope chronologies of two conifer species allowing their combination, could help to minimize the both low and high frequency noise and enhance the climate signal. Comment: Line 262: please give the period of the last glacial advance. Response: Incorporated in the text as suggested (Line: 272). Comment: Tree ring 13C is affected not only by climate variation, but also the plant physiology and ecological factors, such as the photosynthesis, respiration, soil etc. in term of this, may be tree ring oxygen isotope is better for the reconstruction. Response: The sensitivity of tree-ring δ13C to climate is strictly controlled by the environmental conditions impacting tree physiology. Tree-ring δ13C composition is mainly controlled by photosynthesis and stomatal conductance. At warm-moist sites such as in the Himalaya, the C-isotope ratio should reflect the variability of irradiance and temperature. In contrast, tree-ring δ18O consistently reflects variations of the source water δ18O under humid conditions. Further, leaf-water enrichment occurring during transpiration usually modifies the oxygen signal contained in the source water. Therefore, we found a strong correlation with atmospheric moisture content, while no relation was observed with the glacier mass balance. Comment: You should give sufficient discussion on the impact factors of tree ring carbon isotope, the physical mechanisms between tree ring 13C and glacier mass balance must be discussed, the basis of the statistical correlation between them is not persuasive. Response: Thank you for your suggestions. We discussed this point as suggested in response to an earlier comment, while we also have introduced (Lines: 82-86) the linking mechanism and the basic premise why tree-ring carbon isotopes can record information on glacier mass balance. Comment: Line 370: please give the reference. Response: Reference added as suggested (Line: 380). Comment: Line 376-377: please give the reference. Response: Incorporated as suggested (Line: 387). Comment: Table S1: The first order autocorrelation is very high, why? Response: The high autocorrelation suggests the presence of carbon carry-over effects and a memory effect. Comment: Section 3.3: this section is too complicated and have no focus. Response: In this section utilizing six tree-ring δ18O chronologies from the central Himalaya, we discussed the mechanisms of increasing climate heterogeneity since the mid-twentieth century between the western (WCH) and eastern (ECH) parts of the central Himalaya. This section discussed that temperature is the prime climatic factor that influences the behavior of mass balance at interannual to multi-decadal time scales. We further discussed the implications of large-scale changes in atmospheric circulation on cryospheric mass balance in the central Himalaya. We showed that over the WCH (compared to ECH), the westerlies and the Arabian Sea branch of ISM has a significant impact on annual mass balance behavior. Using spectral wavelet coherence analyses, we show a lack of strong coherence in the high frequency bands between mass balance dynamics and SST indices (ENSO Modoki, IOD and PDO). We feel that this information is relevant in the context of the major aims of the paper. Comment: Line 236-240: what is the relationship between 13C of both evergreen conifer species, from Figure S6, the difference between two series is obvious, I don't think it is available to combine the two series. Response: Both conifer species (Abies pindrow and Picea smithiana) revealed a high inter annual correlation (r = 0.84, P < 0.001; please see Table S1 and S4), a basis to merge both chronologies together. In doing so, we strengthen the common (climatic) signal in the final isotope chronology and dampen possible species-specific individual physiological reactions to local factors. Additionally, the mean difference (‰ between the two conifer species is only 0.53 ‰ $whereasthemeandifferencebetweenconiferanddeciduousspeciesis1.6 - -2.2\ (TableS1andS4).Reference : Chauhan, T., andGhosh, S., 2020.Partitioningofmemory$

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