The brief communication by Brun et al. (2022) "*Everest South Col Glacier did not thin during the last three decades*" presents measurements of the mass change of Everest South Col Glacier between 1984 and 2017 from differencing of digital elevation models, and compares these to results from a set of sensitivity experiments using the COSIPY and CROCUS models. The manuscript is written in response to a paper by Potocki et al. (2022) which calculated mass loss from this glacier of 1.5 m w.e. a^{-1} from analysis of an ice core and the COSIPY model. The Brun et al. (2022) study finds that mass change for this glacier is within uncertainty of zero. Everest South Col Glacier is a small (0.2 km^2) ice mass at 8,020 m a.s.l. on the southern side of Sagarmatha, located above the headwall of Khumbu Glacier and on the climbing route for this mountain from the south. While it is rare that so much effort is dedicated to determining the mass change of such a minor glacier, the location at extremely high elevation is used to justify the attempt with the implication that if glaciers are losing mass at present at the highest elevations in the Himalaya, then widespread mass loss is expected at all elevations.

In the first part of my review, I make several major comments and some minor (editorial) comments on the work by Brun et al. (2022) which I request that the authors address in revising their manuscript. In the second part of the review and because this work is a response to a previous study, I compared and evaluated the results of both papers. The authors of Potocki et al. (2022) wrote a response to Brun et al. (2022) in this discussion, led by the second author rather than the more junior first author, which I discuss in the second part of my review and refer to as Mayewski et al. TCD.

Review of Brun et al., 2022: Major comments

<u>1. Glacier mass change data</u>. Brun et al. first present an analysis of DEM data to demonstrate that no mass loss has occurred from Everest South Col Glacier between 1984 and 2017 CE. This method is well established and has been thoroughly tested for glaciers in this location, notably in the recent paper by King et al. (2020) of which one of the co-authors of Petocki et al. (2022), Alexander Tait, is also an author and therefore aware of the method. It would have been justified to end the paper after these analyses, as the results are convincing and of greater value than the modelling for the reasons outlined below.

These results could be described in more detail to make this section more accessible to a wider audience. Mayewski et al. TCD have interpreted areas of negative surface elevation change in the upper accumulation area of Khumbu Glacier as mass loss indicative of glacier wide mass balance rather than redistribution of mass within the glacier.

<u>2. Surface energy-mass balance modelling</u>. Calculating the surface energy balance of a glacier in this setting is extremely challenging, as extreme winds strongly affect the accumulation and removal of snow from the glacier surface, melt processes are dominated by sublimation, and the influence of the Indian Summer Monsoon on glacier mass balance is unknown at these elevations. I consider this glacier an unsuitable candidate for any surface energy-mass balance modelling study unless a model was developed specifically for this location and constrained by detailed and representative atmospheric and glaciological data (i.e., collected at the site of this glacier over several years, rather than using empirically derived values from other settings).

Brun et al. (2022) have taken a pragmatic approach by reproducing the COSIPY model parameterisation used by Potocki et al. (2022) in a sensitivity test that considers a graduated mass balance parameterisation of the same model and a comparison with results from a snow model, CROCUS. Their results demonstrate that the simulated glacier mass change is sensitive to the model time step used, and that there are large uncertainties associated with such calculations. The model results are useful as a comparison with the approach of Potocki et al. (2022), but I suggest that the modelling work from both papers is phrased more cautiously; as potentially useful to identify where the largest uncertainties arise in estimating the mass balance of South Col Glacier, but unlikely to accurately represent glacier change.

Brun et al. (2022) also used a snow deposition model to quantify the impacts of wind on snow accumulation at this glacier and determine when the ice surface is free of snow and hence may melt. These results are compared with satellite imagery and show good agreement. This model application is more valuable than COSIPY for investigating South Col Glacier, but still contains large uncertainties. As discussed below, these results illustrate the limitations of the interpretation of the ice core data by Potocki et al. (2022).

<u>3. Description of glacier geometry</u>. I find it strange that Brun et al. (2022) assign an ablation area to South Col Glacier in Figure A6 and would expect emergence of ice to be minimal for this glacier as they predict. As discussed below, this interpretation seems rather strange based on the glacier's elevation relative to the local ELA. I suggest revising this figure and reframing the interpretation of the glacier as an accumulation area only.

Review of Brun et al., 2022: Minor comments

Line 1 and 8: Is the glacier "iconic"? It's very high, but otherwise I suggest it is not widely known.

L9: remove "large" as this is relative to the glacier in question; "…glaciers thin at rates often exceeding…".

L14 and elsewhere: check use of compound adjectives; hyphenation is not used with an adverb (ending in "-ly").

L24: "challenge of conducting scientific…"

L28: worth noting here that the South Col AWS recorded only about five months of data (May–end summer 2019). An earlier AWS at this location installed by the Ev-K2-CNR project measured three years of discontinuous data that did represent the entire annual cycle and could be of use if further field data are required.

Comparison of the results and conclusions of Brun et al. (2022) with those of Potocki et al. (2022), in consideration of the response by Potocki et al. in TCD.

A key question addressed by both papers is; what is the duration of snow cover on the glacier surface? This would indicate when the bare ice surface is exposed to incoming solar radiation and ice melt could occur. However, the occurrence of seasonal melt does not imply net annual mass loss. Determining mass change over a representative timescale of several decades requires observations of longer-term change as provided by both papers.

In the case of both papers, I consider that the COSIPY model is unsuitable for application to South Col Glacier and the associated uncertainties render the results insignificant. My group's ongoing work applied COSIPY to Khumbu Glacier including the area occupied by South Col Glacier (https://doi.org/10.5194/egusphere-egu21-8663). COSIPY was forced by downscaled CORDEX RCM outputs and constrained by AWS data including the five months of data from the Nat Geo South Col AWS (Matthews et al., 2020). In each simulation, the net annual mass balance at the location of South Col Glacier was strongly positive (>7 m w.e. a^{-1}). We can debate the strengths and limitation of any of these model parameterisations but any existing glacier surface energy-mass balance model is unlikely to be suitable for South Col Glacier due to the significant differences in the processes that control mass balance at 8,000 m a.s.l. compared to glaciers for which these models were developed at lower elevations where the mass balance is better understood by established glaciological theory. The different datasets used by each study (e.g., DEMs of difference/an ice core) are more important indicators of glacier mass change.

More important than debating the parameterisation of models that are likely not meaningful, we should consider the glaciological context of South Col Glacier. The elevation of the glacier is about 2,000 m above the equilibrium line altitude (ELA) for this region, determined for Khumbu Glacier as about 6,000–6,400 m a.s.l. (Rowan et al., 2015; 2021). While glaciers usually melt during the ablation season due to warm air temperatures and high incoming solar radiation, this does not equate to mass loss year-on-year. It is difficult to see why a glacier 2,000 m above the local ELA would have a net annual negative mass balance. Mayewski et al. TCD refute the suggestion by Brun et al. (2022) that their core is collected from the glacier ablation area. As the entire glacier is located well above the local ELA, the entire glacier should be "accumulation area" and therefore as a small cold-based glacier, the mass of South Col Glacier is likely to remain stable over decadal timescales.

Mayewski et al. TCD refer to the glacier as have a stagnant area. This term is used to describe the tongues of debris-covered glaciers such as Khumbu Glacier where the velocity of ice flow has declined rapidly as the glacier has lost mass in recent decades. The term is not accurately applied by Mayewski et al. TCD in context of South Col Glacier, which has not undergone a change in glacier dynamics but instead has a typical (slow, deformation only) flow regime as a cold-based glacier.

As referenced by Mayewski et al. TCD, Figure 1 of Brun et al. (2022) shows areas of negative surface elevation change in the upper accumulation area of Khumbu Glacier. These bands are often interspersed with bands of positive surface elevation change, and I would interpret that they are evidence of large avalanches onto and within the glacier, and opening or closing of crevasses close to the bergschrund. Again, it is the net annual mass balance over a representative period of years (i.e., the integration of these features across the entire glacier) that tells us if the glacier is losing mass. These features in the DEMs of difference are not evidence of glacier mass loss but represent mass redistribution within the glacier. The mass gain of >7m a–1 predicted by our COSIPY simulations of South Col Glacier indicate the source of these avalanches—75% of accumulation to Khumbu Glacier and neighbouring valley glaciers occurs by avalanching of snow from the steep slopes, in some cases initiated by wind erosion of snow at the ridge crests (Benn and Lehmkuhl, 2000).

Potocki et al. (2022) interpret their ice core as representing the accumulation area of the glacier and the age of the ice collected near the glacier surface (0.1–0.7 m core depth) is about 2,000 years old ("1966 ± 179 years ago"). This period is then multiplied by the annual layer thickness for the entire core (27 mm w.e. a^{-1}) to estimate mass loss (apparently without any correction from water equivalent to ice thickness accounting for ice density?). This calculation assumes that the age of the ice at the glacier surface is the same as at the depth measured in the core and that the annual layer thickness is consistent throughout. From their Supplementary Information, it appears that annual layers were only measured in a 0.1 m section of the core at about 6 m depth. The representativeness of these values is determined by comparison with a core from East Rongbuk Glacier at 6,518 m (Kaspari et al., 2009). However, the annual layer thickness at South Col Glacier could be much thinner if wind erosion is accounted for. The snow deposition model results from Brun et al. (2022) suggest that at South Col Glacier nearly all precipitation can be eroded from the glacier surface by wind, which would not be the case at East Rongbuk Glacier or Khumbu Glacier where the majority of accumulation is sourced from avalanching. It is therefore possible that since the Sol Col Glacier last expanded and formed the moraines identified by Petocki et al. (2022) that most or all of the annual snow accumulation is scoured off by wind and that the exposed ice surface represents the last period when the glacier expanded. These moraines are undated at South Col Glacier, but there are three possible equivalent ice-marginal moraine ages at Khumbu Glacier dated to 1.3 ± 0.1 ka, 0.9 ± 02 ka and 0.6 ± 0.16 ka (Hornsey et al., 2022).

The 'space-for-time substitution' suggested by Mayewski et al. TCD reasons that because snow melts at Camp 2 in April–May then ice must melt at South Col Glacier in July–August. Their photographs show melt water on the surface of the accumulation area of Khumbu Glacier at Camp 2 (6,464 m a.sl.) on a patch of rock debris. The low albedo of the debris combined with high incoming solar radiation is likely to promote snow melt, but again is not evidence for net annual glacier mass change. The substitution reasoning is not convincing; South Col is up to 20 degrees colder based on the ERA data presented by Mayewski et al. TCD and the incident radiation would presumably be much lower than given here due to monsoon cloud cover. The uncertainties in this estimate of seasonal melt seem similar or greater than those in the COSIPY experiments.

In summary, there are limitations to both the DEM differencing and ice core methods. I am convinced that both papers present their results accurately and have not made errors in their data processing. However, the DEM differencing presented by Brun et al. (2022) quantifies mass change across the glacier over a representative period of several decades. The ice core collected by Potocki et al. (2022) represents only one point on the glacier and is open to an alternative interpretation in context of the erosion of snow by wind from the glacier surface. I suggest that the model results are discounted as indicative of glacier mass balance due to the limitations of simulating this extreme environment without a dedicated model driven by spatially and temporally representative measurements from South Col Glacier. The remaining question is if there is value or feasibility in collecting direct glaciological measurements from South Col Glacier. Installing and managing equipment over a sufficient timescale (>5 years) would be very challenging and expensive. We therefore need to rely on high-quality remotely sensed observations, including those presented by Brun et al. (2022), which in the last 15 years or so have greatly improved understanding of recent glacier change in the Himalaya.

References

Benn DI, Lehmkuhl F. 2000. Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. Quaternary International 65–66 : 15–29. DOI: 10.1016/S1040-6182(99)00034-8

Brun, F., King, O., Réveillet, M., Amory, C., Planchot, A., Berthier, E., Dehecq, A., Bolch, T., Fourteau, K., Brondex, J., Dumont, M., Mayer, C., and Wagnon, P. 2022. Brief communication: Everest South Col Glacier did not thin during the last three decades, The Cryosphere Discussions. [preprint], https://doi.org/10.5194/tc-2022-166.

Hornsey J, Rowan AV, Kirkbride MP, Livingstone SJ, Fabel D, Rodes A, Quincey DJ, Hubbard B, Jomelli V. 2022. Be-10 Dating of Ice-Marginal Moraines in the Khumbu Valley, Nepal, Central Himalaya, Reveals the Response of Monsoon-Influenced Glaciers to Holocene Climate Change. Journal of Geophysical Research: Earth Surface 127 DOI: 10.1029/2022JF006645

Kaspari S, Hooke RLeB, Mayewski PA, Kang S, Hou S, Qin D. 2008. Snow accumulation rate on Qomolangma (Mount Everest), Himalaya: synchroneity with sites across the Tibetan Plateau on 50–100 year timescales. Journal of Glaciology 54 : 343–352. DOI: 10.3189/002214308784886126

King O, Bhattacharya A, Ghuffar S, Tait A, Guilford S, Elmore AC, Bolch T. 2020. Six Decades of Glacier Mass Changes around Mt. Everest Are Revealed by Historical and Contemporary Images. One Earth 3: 608–620. DOI: 10.1016/j.oneear.2020.10.019

Matthews, T., Perry, L. B., Koch, I., Aryal, D., Khadka, A., Shrestha, D., Abernathy, K., Elmore, A. C., Seimon, A., Tait, A., Elvin, S.,Tuladhar, S., Baidya, S. K., Potocki, M., Birkel, S. D., Kang, S., Sherpa, T. C., Gajurel, A., and Mayewski, P. A.: Going to Extremes: Installing the World's Highest Weather Stations on Mount Everest, Bulletin of the American Meteorological Society, 101, E1870–E1890, https://doi.org/10.1175/BAMS-D-19-0198.1, 2020.

Potocki, M., Mayewski, P.A., Matthews, T. et al. Mt. Everest's highest glacier is a sentinel for accelerating ice loss. npj Climate Atmospheric Sciences 5, 7 (2022). https://doi.org/10.1038/s41612-022-00230-0

Rowan AV, Egholm DL, Quincey DJ, Glasser NF. 2015. Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya. Earth and Planetary Science Letters 430 : 427–438. DOI: 10.1016/j.epsl.2015.09.004

Rowan AV, Egholm DL, Quincey DJ, Hubbard B, King O, Miles ES, Miles KE, Hornsey J. 2021. The Role of Differential Ablation and Dynamic Detachment in Driving Accelerating Mass Loss From a Debris-Covered Himalayan Glacier. Journal of Geophysical Research: Earth Surface 126 DOI: 10.1029/2020JF005761

Ann Rowan, University of Bergen, Norway. 10/10/22