We would like to thank Anonymous Referee #3 for an excellent and detailed review. It is obvious they have spent considerable time on this review and have provided us with many important revisions and suggested improvements. This will undoubtedly improve the quality of our manuscript and the ATES system, and we will endeavour to implement as many of these suggestions as possible into a revision.

Our responses are highlighted in red below:

ATES Paper Peer Review – Anonymous Referee #3 – 10 July 2024

The paper "The Avalanche Terrain Exposure Scale (ATES) v.2" by Statham and Campbell offers a valuable overview of the developments and applications of the ATES, focusing on the latest advancements. It presents ATES v.2 and the changes from ATES v.1, including applications to routes and areas. The paper effectively introduces ATES and its purpose, emphasizing the classification and communication of avalanche terrain exposure. The main updates from v.1 to v.2 are highlighted (5 classes instead of 3, removal of glaciation as a classification criterion) and the motivation behind the updates seems well argumented. By providing background information on the technical model and the communication model(s) the manuscript is of interest to a wide target-audience ranging from avalanche professionals and educators to individuals working or recreating in potential avalanche terrain.

However, the main intention of the paper is partly unclear, which may cause potential readers to get lost between the general ATES review and the focus on developments specific to ATES v.2. While the historical evolution and widespread application of ATES are emphasized, it would be beneficial to also briefly discuss the similarities and differences to other (automated) avalanche terrain classification schemes (e.g. Harvey et al., 2018; Schmudlach and Köhler, 2016) and their reception by the target audience. To gain better insight into the ATES methodology, the systematic combination of terrain parameters to produce a rating is discussed in detail, but it would also be helpful to provide more guidance on how these parameters could be or are assessed.

1. We will expand the Background section of this manuscript to include descriptions of the work of Harvey et al., (2018) and Schmudlach and Köhler (2016) to develop other avalanche terrain classification schemes. It was on oversight not to include this in the original manuscript.

Based on this and similar feedback from Reviewer #2, we will improve our introduction of the ATES Technical Model (Section 4.2) to more clearly describe the assessment criteria and the process for combining them to determine the ATES rating.

We will list the eight terrain factors to make it more obvious what is being assessed:

1. Exposure
2. Slope angle and forest density
3. Slope shape
4. Terrain traps
5. Frequency-magnitude
6. Starting zone size and density
7. Runout zone characteristics
8. Route options

In section 5.2 Assessment Methods, we will then describe a four-step process to determine the rating, where each of the terrain factors is assessed against the five ATES categories (Class 0-4) and then combined in the following way:

1st Assess each terrain factor independently and determine its rating level
2nd Determine which ***default*** categories are met. This determines the minimum rating level
3rd Compare each of the remaining terrain factors to the minimum rating level or higher
4th For any categories higher than the minimum rating level, determine if this should outweigh the minimum rating level. This determines the ATES rating level.

We will also revise Section 5.2 Assessment methods, to describe the importance of considering the Communication models (Tables 1 and 2) in the assessment process. The Communication models are the message that the receiver gets, thus it is essential that the outcome of the assessment process described above (using the Technical model) aligns with the Communication model. Thus, the final step after determining ATES ratings with the Technical model, is to compare the ratings with the Communication model to ensure it is coherent.

Once the ATES rating has been determined using the Technical model and ensuring it aligns with the Communication model, field checking where possible and peer review are the final steps before publishing ratings.

The paper devotes considerable attention to the communication model and potential (risk management) applications, but the description of the updated technical model (thresholds, description) sometimes lacks consistency. One general point needing clarification in a revised version is the terminology. Specifically, the term “exposure” seems to be used inconsistently or with different meanings. On one hand, terrain exposure (potential vs. actual) towards avalanches is a crucial part of the terrain classification, while on the other hand, temporal exposure (of the element at risk) is used in terms of ATES as a risk management tool.

2. Thank you for highlighting this and we will review the entire paper for consistency in the use of the term “exposure”. Specifically, in Section 4.2.1 Exposure, we will clarify the meaning of temporal exposure in the ATES model in the following way:

The assessment of ATES ratings considers temporal exposure in terms of “for how long” an element-at-risk is exposed, and the rating is dependent upon this. For example, being exposed to an avalanche path for 10 minutes presents a higher severity than being exposed to the same path for only 1 minute. The terminology *minimal, brief, intermittent, long, frequent* and *sustained* used in Tables 2 and 3 refers the length of time one should expect to be exposed to a piece of terrain.

The application (use) of ATES by the receiver considers temporal exposure in terms of “when” the different classes of terrain are within a risk threshold, and “when” they are not. This is independent of the element-at-risk and is a type of dynamic, avalanche risk assessment which requires combining the ATES rating (static) with avalanche hazard assessment (dynamic). For example, when the hazard is *Low*, then *Complex terrain* may be appropriate; alternatively, when the hazard is *High*, then *Complex terrain* may be inappropriate and *Simple terrain* the better choice. We will ensure that a revised manuscript addresses the dynamic nature of avalanche risk.

Additionally, the interplay between avalanche size and frequency could be discussed more in depth, including the limitations of a static representation of a dynamic problem (how the maps are connected to different avalanche hazard/problems/size scenarios).

3. We will address this in Section 4.2.5 Frequency and magnitude. Lines 280-283 touch on the interplay between avalanche size and frequency, and we will expand this section to explain the relationship between the two in more detail.

We agree that this manuscript should improve its description of static versus dynamic hazard models. This deserves an additional section either within, or following the Background section. Here we will describe both the limitations and the benefits of a static model and compare this with the dynamic hazard model. Importantly, static terrain maps are a foundation of dynamic hazard maps; an underlying DEM or even ATES map is necessary to combine with a dynamically modelled or remotely sensed snowpack to develop dynamic avalanche hazard maps. The whole point of ATES is to provide a static terrain exposure model with ordinal categories (Tables 1 and 2) that can be easily interpreted for public recreation and workplace avalanche safety.

Overall, the paper is timely, fits the target audience, and fills a gap in peer-reviewed literature on avalanche terrain classification schemes. Many recent scientific publications have been based on ideas developed by the authors over the past 20 years and as such a peer-reviewed reference to ATES is certainly of interest to the community. However, figures, captions, and referencing leave some room for improvement. Please refer to the specific line-by-line comments for more information.

Specific line by line comments

p.1 Abstract: The abstract is (nearly) identical to the one in the corresponding extended abstract in the ISSW23 proceedings. Please compare with the abstract in the corresponding ISSW proceedings and revise accordingly. Two main questions appear in the abstract but also throughout the paper (see comments above):

l. 7-8: Are ATES ratings only independent of daily hazard conditions or also independent of the (temporal) exposure of the element at risk?

4. The use of ATES ratings as a tool for risk management is independent of the temporal exposure of the element-at-risk; a rating of Class 2 is valid regardless of whether the element-at-risk is exposed or not. However, the assessment of an ATES rating is dependent on the temporal exposure of the element-at-risk; the longer it takes to cross an avalanche path, the higher the exposure will be, and this should be reflected in the rating. We will clarify this in Section 4.2.1 Exposure.

l. 13-14: Is ATES actually risk management tool or is ATES a tool for risk management (comparable to what slope maps are for classical risk reduction methods)?

5. Subtle, but we appreciate the clarification in language and will change this accordingly.

p.2 l.19-23: Briefly explain the difference between hazard and risk, noting that hazard, vulnerability, and exposure are all key factors. Describe how these concepts are related to ATES and how exposure is defined within this context.

6. This is an important baseline, and we will describe the risk framework that ATES fits within (Statham, 2008; Statham et al., 2018) which will establish a reference point to define exposure within ATES.

p.2 l.30: Providing a more in-depth review of different applications of ATES, including manual and automated approaches, and applications in different regions would be interesting. Also an overview of different (spatial) application scales (location, size, etc.) could be of interest to the readers.

7. We will provide descriptions with references for interesting examples of manual versus automated approaches, different regional applications (.g.: Canada and Europe) and different recreational applications (skiing versus climbing).

p.2 l.40: Correct "Larson" to "Larsen." (generally check correct spelling and formatting of references in the manuscript) Yes

p.2 l.41: Insert a comma in "(Klassen, 2012)" and specify if this refers to ATES v.2 or ATES in general. Yes

p.2 l.48: Include both recreationists and professionals in the discussion.

8. We agree that terrain rating systems play an essential role for both recreationists and professionals and are directly relevant to both communities. But here we used the term "recreational" not to define the audience (recreationist or professional) but to define the

activity. Climbing, hiking, skiing and mountain biking are recreational activities, regardless of whether one is an amateur or a professional in their field and we intend this to mean that terrain rating systems are useful for recreational activities.

p.2 l.58-60: Expand on why quantitative methods become impractical in this context (due to the highly mobile element at risk). Clarify the impact and exposure-based approaches within ATES (see comments above on exposure).

9. We will improve our description of why quantitative methods become impractical (reviewer #1 has asked the same thing) when the element-at-risk is highly mobile. As described above, we will clarify temporal exposure in the context of both ATES, and exposure-based systems.

p.3 l.64: Clarify what is meant by "river ratings".

10. Penniman and Boisselle (1996) refer to the "river rating" system and show it in their Table 5 with no citation, but they mean the International Scale of River Difficulty (American Whitewater, 2024). We will change our manuscript to read ""… and modelled after river ratings, which describe the level of difficulty and the consequence of a rapid" and we will add a reference.

p.3 l.70: Reformulate the sentence for clarity. Yes.

p.3 l.76: Question the certainty that avalanches do not occur in class 0 terrain; suggest it may be very unlikely instead (compare table 2 "small sluffs").

11. This has been a challenge with defining Class 0 terrain, and we agree with the reviewer that there is a conflict with Table 2 where small sluffs and spindrift are possible in Class 0 (for ice climbing terrain). Any small snow slope can produce a small sluff, the key is that in Class 0 terrain it should be of no consequence.

We will change Line 76 to say: "the zoning model also introduced Class 0 (non-avalanche terrain), an essential rating level in any avalanche terrain classification system that shows where avalanches with consequence do not occur."

We will also modify Table 3, Class 0, Frequency-magnitude to say "***Never > size 1***".

Class 0 is presented as an optional terrain class, due to its need for a high degree of certainty. If the assessor remains uncertain, then Class 1 should be used. This is described on Lines 97-99.

p.8 l.173: Discuss how the ATES scenario (potential maximum avalanche size, expected average avalanche size, etc.) is implicitly considered when developing a spatial and temporal exposure rating. So any individual trying to come up with a spatial and temporal exposure rating for a certain location (for both ATESlinear and ATESspatial) must implicitly have some sort of "Avalanche Scenario" in mind (i.e. at least potential avalanche sizes, which are to some extent related to expected avalanche frequencies).

12. Maximum avalanche size and typical avalanche size are related directly to avalanche frequency-magnitude. Generally, it is expected that as the average frequency decreases down slope into the track and runout zone, the average magnitude increases (CAA 2016b). This is a key consideration when determining a rating, but doing this requires a route, or location (spatial exposure) to assess. Thus, these considerations apply to ATES linear, where the exposure is known but not directly to ATES spatial, with its "potential exposure". We address this in our revision of Section 4.2.5 Frequency and magnitude.

p.10 l. 191 ff. @Forest effects on avalanche formation:

The first argument you introduce in the discussion of forest effects is the mechanical anchoring of the snowcover in dense forest stands. However, this effect might be secondary to modification of snowpack structure by influencing wind re-distribution and micro-climatic conditions in forest stands. You also state that ATES uses a simplified model of the involved processes; maybe you can expand on which forest effects are included in your assessment and which are neglected (e.g. do you mainly consider forest effects on avalanche formation, or do you also consider potential forest effects on avalanche runout behavior?).

13. This is a good point as we have given a general explanation of forest effects but will be important to show the ATES forest density parameter considers primarily of the anchoring effects of the forest; snowpack modification is a secondary consideration. We will clarify this. ATES does not explicitly consider the forest effects on avalanche runout behaviour except that dendrochronology is an important input to avalanche frequency and thus is considered in this way.

Also a discussion of the extent of the spatial evaluation area might be of interest here, since average tree spacing might be substantially different when assessed over different spatial scales/extents (e.g. 10m pixel in GIS or a slope in a manual delineation).

14. Yes and in many cases the average tree spacing itself will determine the spatial extent of different zones for the reason described here. When average tree spacing is substantially different (in steep terrain) and results in a material change to the avalanche exposure, then the polygon boundaries (spatial extent) can represent these differences through zoning. See next comment #15.

How would you e.g. classify the slope depicted in Fig. 3 according to tables 5 and/or 6? Can you comment on how to assess average tree spacing in the scope of practical applications?

15. Figure 3 is part of a helicopter ski run located in the Purcell Mountains of British Columbia, Canada. For the entire area selected, the slope angle in the lower 50% is in the 20°- 30° range and the upper 50% is 30°- 45°, but nothing is steeper than 45° (Figure 3a). According to Table 6, this fits the criteria for Class 3 – Complex Terrain.

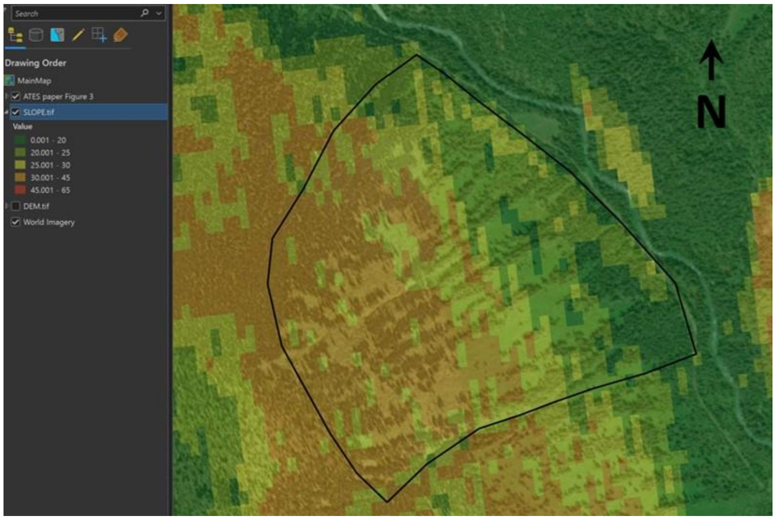

Figure 3a. Slope angle distribution across the area shown in Figure 3.

For the forest density distribution, the main open/gladed area in the middle is 120 stems/ha, slightly < 10 m spacing. The thicker forest around the area boundaries ranges from 209 stems/ha at the top, to 400-600 stems/ha on the northern flank, to 764 stems/ha at the bottom and southeastern corner (Figure 3b). According to Table 5, this is slightly below the threshold for Class 3 – Complex Terrain.

Figure 3b. Forest density distribution across the area shown in Figure 3.

The classification of this slope would depend on the objectives (Lines 390-393). Taken as one large area, the whole slope would be rated Class 3 – Complex Terrain, as the rating will default to the highest level within the area. However, smaller scale zoning would consider the different distributions of forest density and slope angle, resulting in some Class 1 and 2 terrain in the dense and gladed areas. There is perhaps even some Class 0 terrain in the SE corner of the area.

From a practical perspective, average tree spacing is done by estimating the distance between individual stems in various locations, and then applying this to the entire slope to estimate an average value. The largest forest opening on the left side of the figure is 170 meters wide with slopes angles of 30°- 45°, so there is little protection from avalanches in this terrain. It would be possible to sneak through this terrain by following the contiguous strips of dense forest, however this is very close to the large open glades and would require previous, specific knowledge of the ski lines and a high level of skill to avoid the open slopes.

p.11 l.204: Provide more information on the reasons for combining ATES v.1 with the zoning model (such as automatic classification with more objective thresholds).

16. We agree that this is a gap in the manuscript and our revision will provide a better explanation of why ATES v.1/04 and the ATES Zoning model have been merged, however we will explain this in the Introduction section, approximately near to Line 37. The main reasons were that these two models had different thresholds, assessment criteria and descriptive terminology, and the Zoning Model's more objective approach to slope angle and forest density is an excellent baseline to support the subjective methods of the ATES Technical model.

p.11 l.211: Define "high spots" and "steep, unsupported slopes" for non-expert readers and explain their significance in relation to avalanche exposure (overhead hazard).

Yes.

p.12 l.220 ff.: Clarify the meaning of slope shape classes, as the definitions of classes between "flat" and "cliffy" are less clear. Discuss the slope shape factor's relevance to avalanche triggering and potential avalanche sizes and overhead hazards. All in all slope-shape is probably the least justified of the 8 ATES factors. The area reference remains rather unclear (while parts of a slope can be convex, the whole slope might be convoluted or intricate or cliffy?). The discussion of terrain shape is mainly linked to likelihood of avalanche triggering by limited additional load (e.g. skier-loading) and does not really consider factors such as potential avalanche sizes and overhead hazard?

17. Agreed, slope shape has been a difficult factor to justify and reference properly, but we consider the shape of the terrain to often be a (the) deciding factor when routefinding through avalanche terrain. This is a particularly difficult factor to justify in an objective manner, and its inclusion as an assessment factor is based upon the experience of professional ski and mountain guides.

In our response to Reviewer #2, we agreed that at the slope-scale there are usually more options for a less exposed route in convoluted terrain than in planar terrain; a planar slope has less options for routefinding, while a convoluted slope may provide more options for route selection and minimizing risk.

So it is the routefinding that is more complicated in convoluted terrain, not necessarily the avalanche exposure. Routefinding in planar terrain may be more straightforward, but this comes with a potentially higher degree of avalanche risk, with more widespread crack propagation and less options to reduce risk through route selection. ATES v.1/04 was designed to rate "routes"

(ATES linear), meaning that terrain that is more convoluted in shape with more challenging routefinding in avalanche terrain, receives a higher class of terrain rating.

This is also a scale issue, as some of the ATES v.2 criteria do not perform well at the terrain or slope scale, and some of the assessment criteria require multiple slopes or avalanche paths to fully assess. Assessing the slope shape criteria requires multiple slopes to fully assess properly. We will make this clear in a revised manuscript. When looking at terrain at the larger scales, convoluted terrain shapes are more complex than isolated, single slope shapes that can be navigated around to reduce risk. We propose to reword the description of slope shape accordingly:

Slope shape	Straightforward, flat or undulating terrain	Straightforward undulating terrain	Mostly undulating with isolated slopes of planar, concave or convex shape	Convoluted, with multiple open slopes of intricate and varied terrain shapes	Intricate, often cliffy terrain with couloirs, spines and/or overhung by cornices

However, we recognize that this factor is poorly supported with references and submit that it can be removed with few implications to the ATES method. We propose to keep the inclusion of slope shape in order to highlight its importance as a terrain factor, but we can highlight the lack of objective support and suggest these gaps in can be addressed in future avalanche terrain research.

p.13 @terrainTraps: Consider adding the Harvey et al. (2018) CAT, ATHM reference. Yes.

p.13 l.239, 245: Elaborate on what is meant by "harmless."

18. We will add a second sentence giving and example to provide context.

p.14 @Avalanche Frequency: Suggest a more nuanced formulation regarding the stability of avalanche frequency at a location, considering potential shifts due to climate change and the significance of the observation period.

19. Agreed. We will highlight potential changes to avalanche frequency due to shifts in climate patterns.

p 15. l. 274-276, Tab 8: Is e.g. typical impact pressure not rather a measure of intensity?

20. Yes, "Typical Impact Pressure" aligns with Jackson (2013) who defines intensity as "related to the effects at a specific location or area". However, Table 8 is taken directly from CAA (2016a), and we are reluctant to change an established definition that is the primary reference point for avalanche magnitude in Canada, even though we agree with the reviewer. We will pass this feedback to the CAA's Technical Committee for inclusion in an upcoming update.

p.16, section 4.2.7: Refine the definition of remote triggering. Use clear definitions for runout zones, distinguishing them from the track and relating them to international classification schemes (e.g., zone of origin, transit, deposition, see De Quervain, R et al.: Avalanche atlas , Unesco, Paris, 1981). Yes.

p.16 l.302: Specify whether “The ATES Technical Model” refers to the old or the new model. Yes.

p.17 @route options: Clarify the meaning of “route options” when applied to ATES_spatial as opposed to ATES_linear.

21. Agree. This was an oversight and will be corrected.

p. 17 l. 320-321: Please check for consistency “Class 1” -> Class 1 Terrain, by checking for uniform usage throughout the text. Yes.

p.18: Consider providing specific color codes (RGB, hex) for clarity, as color descriptions alone can be vague. Yes.

p.19 l.345: Refer to the corresponding figure (Figure 11?) when discussing North American colors. Yes.

p.22 @actual vs. potential exposure: Clarify the difference between actual and potential exposure in the context of ATES, and how avalanche size scenarios play a role in identifying exposed segments. Additionally, (temporal) exposure in terms of avalanche risk may have a different meaning than (spatial) exposure to avalanche terrain (see comment above)?

22. Yes we will clarify the difference between actual and potential exposure and will link this to our improved description of temporal scale (see our response above).

p.22 @spatial scale: Discuss the importance of spatial scale and how well the eight ATES evaluation criteria can be assessed at different spatial scales (i.e. forest densitiy on a synoptic scale might be difficult, …). Yes.

p.23 l.445: Provide a brief explanation of autoATES and related automated criteria and algorithms if it has not been referenced previously.

23. Yes, or we may move this statement (Lines 443-445) to the next Section 5.2.1 AutoATES.

p. 26 l.501: also refer to Larsen et al 2020 who developed autoATES v1 Yes

p.26 l.501: Discuss the limitation of automated algorithms for autoATES due to the ‘subjective’ selection of parameterization.

24. Yes we will add a sentence at the end of the paragraph describing this.

p.26 l.504-505: Potential & true (terrain or spatial) exposure: Please comment on the differences between the types of exposure and double check on the wording throughout the paper. Following your thought “because there is no route” further implies that without an element at risk there is no (temporal) exposure (see comment on “Is ATES a risk management tool or tool for risk management”?).

25. Yes, we will be improving our description of exposure (spatial, temporal, potential, actual) and will check for consistency throughout the manuscript.

p.26 l.506: Highlight the importance of being aware of resolution differences in maps and corresponding uncertainties. Yes.

p.27: Mention additional benefits of ATES compared to classical slope-angle-based terrain-choice strategies, particularly emphasizing the role of overhead hazard and terrain exposure to avalanches (one of the highlights of ATES, which appears to be underrated throughout the paper).

26. Yes, and we will look to improve our descriptions of overhead hazard throughout the manuscript.

Figures

General: Review all figures and their captions. Highlight key features in the images and provide appropriate scales for the maps.

Fig. 1: Describe the blue trails (ATES class 2?) and explain why the white trails are class 0 (due to flat and forested terrain?). Include data sources for trails and maps. Add an overview map for context, orientation (north arrow), and scale (scale bar). Yes.

Fig. 2, 4: Indicate if all displayed terrain is the same class and highlight accordingly.

27. Yes, we can do this also by including a dashed line to indicate the exact route that is referenced.

Fig. 3: Provide more context, such as slope angle, and show how an ATES v2.0 map would look in this area. Highlight different forest densities and slope angles.

28. Yes, this is good feedback as this image provides a good opportunity for this context and explanations. We do not think an ATES map will add value to this figure as the purpose of the image is to show the slope angle and forest parameters rather than the ATES rating itself.

Fig. 5: Highlight the zone of deposition and discuss terrain rating.

29. Yes we will annotate the figure to illustrate features in the terrain shapes.

Fig. 6, 7, 8: Highlight different zones and terrain ratings, particularly areas that might propagate into nearby starting zones. Yes.

Fig. 10: Include overview maps, orientation, and scale. Ensure 10b is not arbitrarily cut off and is easily interpretable without local knowledge; consider redesigning the figure. Yes.

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