We would like to thank Stephan Harvey for his excellent review, which will result in important improvements to this manuscript. His experience with avalanche terrain, mapping and routefinding is clear and we sincerely appreciate his effort to improve our manuscript. Our responses are numbered and shown in red text below.

ATES Paper Peer Review – Stephan Harvey – 06 July 2024

General comments

The paper outlines the changes to the ATES terrain assessment based on the experience of the last 20 years. The main improvements are as follows:

a) additional classes 0 and 4,

b) exclusion of glaciers and

c) two types of definition (communication model and technical model).

The paper explains the ATES scale and how the classes are defined in a simple and comprehensible manner. The general outcome is not new.

The communication model provides a straightforward description of the scale, which helps less experienced people to recognise avalanche terrain. However, experience is required to understand the definition. E.g. Challenging: " With careful route finding, options exist to reduce or eliminate exposure".

The parameters "exposure" and "frequency magnitude" are subjective. I question whether "frequency magnitude" is a useful way to classify ATES. If the terrain characteristics are optimal for avalanches at a specific starting zone, then avalanches can occur if the snowpack is unstable. The question of frequency is more relevant when assessing objects with observed records. A remote starting zone with no records from past avalanches is not necessarily less complex than a starting zone were records are available.

1. We agree with the reviewer that if terrain characteristics are optimal for avalanches at a specific starting zone, then avalanches can occur if the snowpack is unstable. We also agree that the presence or absence or records does not change the complexity of the terrain; regardless of whether records exist or not, avalanche frequency is an important contributor to terrain severity and avalanche risk.

The point is that not all starting zones are created equally, and when the snow is unstable, certain terrain characteristics will produce avalanches more frequently in predictable locations than others. For example, a 40-degree, leeward slope that is reliably windloaded following every storm can be expected to release avalanches more frequently than a 25-degree, wind sheltered slope below treeline.

Certainly, avalanche frequency can be assessed with much higher reliability on avalanche paths with observed records. But only a small portion of backcountry avalanche paths have observed records. Many (most) known patterns of backcountry avalanche activity in specific locations result from informal, repeated field observations over many years. For example, the avalanche path “Frequent Flyer” in the backcountry of Rogers Pass, Canada, has no formal records, however it is known to release early in most storms and reliably produces several avalanches across the trail every winter.

This kind of information (formal or informal) is critical and has a direct influence the severity and hazardousness of the terrain. Terrain that produces avalanches frequently is more severe than terrain that produces avalanches infrequently. This is one of the most important drivers of terrain severity and is why ATES uses defaults to add weight to the avalanche frequency-magnitude categories.

Avalanche frequency is also crucial for how ATES handles terrain in dry snow climates, where there is usually little or no snow (no hazard), but occasionally a snowpack will develop and create an avalanche hazard (i.e.: every few years). In this case, even if the terrain is steep and complicated, if it is dry then there is no avalanche hazard, and an ATES rating must reflect that. This can be achieved by estimating avalanche frequency.

This is mostly a subjective category, with the rare exception of areas with long-term records. Table 7 is an example of commonly used categories of avalanche frequency in Canada. Despite similar tables being in widespread use in Canada, these appear to be mainly in consulting reports with no well-established references (that we could find). One of our objectives is to introduce such a table into the literature, as this method is widely used for terrain and avalanche hazard assessments (e.g.: CAA 2016; Jamieson 2018).

The authors say that the ATES rating is subjective and that some criteria require experience and local knowledge to be properly assessed. This leads to different assessments both for manually and automatic mapping.

2. Yes ATES v.2 is a mostly subjective terrain assessment method that is applied to trails, routes and climbs (guidebook style) as well as mapped. We have described this subjectivity in several spots in the manuscript (Lines 442-443 and 488-495) and encourage collaboration, field checking and peer review in order to check biases and improve consistency on the ratings. AutoATES removes these biases and provides consistent results, but AutoATES lacks the local knowledge of routes and avalanche frequency, so is crucially aided by expert knowledge at the smaller scales. Sykes et al., (2024) directly addresses the differences between human mapping and AutoATES and Figure 12 shows the validation of AutoATES against human mapping.

As some parameters of the technical model describe frequencies, this is only suitable for classifying an area or a route as a whole. It is not possible to assess individual cruxes or objects using some of the assessment criteria. E.g. "many very large starting zones", "some open slopes > 35°", "options exist to avoid avalanche path".

3. We agree with the reviewer that some of the ATES v.2 criteria do not perform well at the terrain feature or slope scale, and that some of the assessment criteria require multiple slopes or avalanche paths to fully assess. Not all of the ATES criteria are available to be assessed for each situation, usually depending on the scale of the assessment. It was an oversight to not describe this, and we will ensure this is made clear in both Section 5.1 Spatial Scale and Section 5.2 Assessment Methods.

The possibilities of high-resolution terrain models and avalanche dynamics models to describe the runout, such as used in the Swiss avalanche terrain maps, are not mentioned. Furthermore, the different approach to classifying avalanche terrain is not mentioned, for example, "classified avalanche terrain, CAT" (e.g. in Introduction).

4. Agreed. This was an oversight as we have spent considerable time reviewing the work of Harvey et al., (2018). We will improve this manuscript's description of static versus dynamic hazard models as well as describe the Swiss CAT system. We will expand on this following Line 29 where the concept of the static model is introduced, and we will describe two key references regarding static and dynamic hazard maps (Harvey et al., 2018, Schmudlach and Köhler, 2016).

Specific comments

1 Introduction or 2 Background

Mention other automatic approaches, such as "Classified avalanche terrain, CAT" (Harvey et al., 2018), incorporating high-resolution digital terrain models, avalanche data and numerical avalanche dynamic model

5. Agreed. This was an oversight, and we will correct this in either the Introduction or the Background. We have spent considerable time reviewing the work of Harvey et al., (2018) and it was an oversight to not describe this and how static terrain mapping can enable dynamic hazard maps.

3 Principal changes to the Avalanche Terrain Exposure Scale

L80: has ATES Zoning Model been introduced before?

6. Yes, the ATES Zoning Model (Campbell and Gould, 2013) is introduced in the Background (Lines 70-78), but we will also add this to the Introduction following Line 30.

4 Avalanche Terrain Exposure Scale v.2

Tables 1 and 2 : The colours are not ideal:

7. We agree. Line 357-358 describes "further research is necessary to determine a colour standard that achieves the best balance of comprehension, base map visibility and CVD compliance". Engeset et al., (2022) is the only research into ATES colour choices, and their suggestion of black cross-hatching for Complex terrain will obscure the underlying base map.

We included Figure 9 to show a good example of alternative colour choices, and will improve our captioning to suggest the need for future work in this area.

Why is complex black and extreme red. Black is rather used for extreme in hazard rating.

8. ATES in Canada has always been black for Complex terrain, which was originally based upon the North American ski run difficulty system. European use of ATES subsequently changed this to red to align with the European ski run difficulty system. This is described in Lines 343-347. When Extreme (Class 4) terrain was added to ATES v.2, red was chosen to distinguish it from Complex terrain (black).

Black was originally a good choice for Complex terrain, as it was intuitive to skiers as a higher degree of terrain severity, but this was before ATES became a mapped product. Black is not ideal for mapping because it obscures the underlying base map information, and therefore adjusting its opacity is crucial to ensuring ATES maps are useable. This is described on Line 352.

Problem with red/green colour blindness.

9. This is a major challenge, as many warning systems in society (including avalanches) use both green and red. In order to communicate with a diverse audience, including those with Color Vision Deficiency (CVD), ATES uses a combination signal words, numbers and colours (Lines 333-335). This approach provides options for different ways to communicate with different people. To accommodate CVD issues, modern computers, websites and digital products can use colourblind filters which help with deuteranopia, protanopia, and tritanopia. Additionally, we consider the use of a map legend to be crucial. We will expand our description of this issue towards the end of Section 4.3.

L160-167: A bit short and confusing. Maybe pull up as matrix with ATES classes and 8 parameters defining 40 criterias. How are criterias ideally combines to rate ATES? I would like more guidance than in this respect.

10. We agree this is a confusing description of an important section and will revise Section 4.2 to introduce the ATES Technical Model (Table 3) more clearly. 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, peer review is a final step before publishing ratings.

Table 3:

Is “Frequency magnitude” necessary for backcountry ATES rating?

11. Yes, we have addressed this in reply #1.

Convoluted terrain leads to higher ATES rating than planar terrain (terrain shape). This contradicts with route options. In convoluted terrain there often are more options for less exposed route than in planar terrain. Furthermore planar terrain often leads to widespread crack propagation in unstable snowpacks and therefore to larger avalanches.

12. Excellent point and we agree with the reviewer that there are often more options for a less exposed route in convoluted terrain than in planar terrain; on the slope scale, a planar slope has less (no) options for routefinding, while a convoluted slope may provide more options for route selection and minimizing risk.

It is therefore 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 exposure as the reviewer describes, with more widespread crack propagation and less options to reduce risk through route selection.

This is a scale issue, and as described in response #3 above, not all of the ATES v.2 criteria work well for smaller scale (terrain feature, slope) assessments; some criteria require multiple slopes to assess. 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

Difficulty of defining "Exposure" and "Frequency magnitude". Also low frequence can be extreme terrain….

13. Defining exposure is not difficult when assessing a specific route or climb, in which case the exposure is known. For mapped terrain, when no specific route is assessed, we describe this as "potential exposure" on lines 175, 406 and 503. In this case, exposure cannot be defined until a route has been planned through the terrain at which point, the exposure is known and the ATES rating that affects that route can be determined.

Frequency-magnitude has been addressed in reply #1.

L220: Convoluted terrain: What do you want to say in this section?

14. We will revise this paragraph to explain the meaning more clearly.

Convoluted terrain presents a more spatially variable snowpack because the depth and distribution of snow is uneven as a result of wind redistribution through the topography. This uneven snowpack distribution increases spatial variability in the snowpack, resulting in more trigger points and increased uncertainty for snow stability evaluation (Schweizer at al., 2008). Zones of terrain that present mixed shapes of concave, convex and planar (Figure 4) usually present a snowpack with more trigger points than a zones with a smooth, evenly distributed snowpack where the depth and layer distribution is more predictable.

L224: What are propagation spots? Do you mean trigger spots?

15. Yes, we will change this to "trigger points".

L263: What about remote terrain without records? A slope with no records is not inherently less prone to avalanches.

16. Agreed, a slope with no records is not inherently less prone to avalanches. But regardless of whether records exist or not, a slope that avalanches more frequently than others is crucial information related to terrain severity. Determining this is a challenge, as records are rarely available for most backcountry terrain. Historically, avalanche experts have to make their assumptions often on a very weak basis (Maggioni and Gruber, 2003). Statistical methods exist, but these are usually inaccessible for smaller operations where the avalanche frequency of specific terrain and routes is known from experience with the terrain.

In lieu of records, common methods for assessing avalanche frequency include using local observations, knowledge, history and dendrochronology (Carrara, 1979).

References:

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Maggioni, M. and Gruber U.: The influence of topographic parameters on avalanche release dimension and frequency. Cold Reg Sci Technol 37, Issue 3, 407-419, https://doi.org/10.1016/S0165-232X(03)00080-6, 2003.

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