We sincerely thank Alexander Raphael Groos for this thorough assessment of our manuscript. We appreciate the positive evaluation of the relevance of the work. We thank the reviewer for the constructive suggestions for improvement, particularly regarding the need to more clearly define the aims of the study, emphasise the added value and limitations of the approach, and strengthen the broader conclusions across the case studies. We appreciate the complementary perspective to Referee 1 and the detailed feedback provided and agree that the feedback will improve the manuscript.

In the following, all reviewer comments are reproduced and addressed. Our responses are provided in blue for clarity.

RC2: 'Comment on egusphere-2025-6432', Alexander Raphael Groos, 16 Feb 2026

This is a review of the manuscript by Maschler et al., entitled "Automated UAV systems for geohazard monitoring: case studies from the Supphellebreen icefall (Norway), the Skjøld instability (Norway), and the Blatten landslide (Switzerland)", submitted for publication in NHESS. The authors present the application of a commercial dock-based Unoccupied Aircraft System (UAS), together with a new integrated data processing pipeline, for persistent geohazard monitoring in mountainous terrain, in the context of three different case studies. Once installed, state-of-the-art dock-based UASs facilitate quasi-autonomous photogrammetric surveys (and other types of measurements) on demand or at regular intervals, even beyond visual line of sight. Hence, they have great potential to complement ground-based and spaceborne systems for geohazard monitoring and risk assessment, especially in complex alpine terrain. Dock-based UASs might be of particular interest in cases where, for example, the study area is difficult to access, located within a risk zone, or beyond visual line of sight, and where frequent measurements or long-term monitoring are necessary. However, dock-based UASs come with certain practical limitations, as they are relatively costly (compared to conventional campaign-based UAV surveys), require a stable power supply, and must conform to regulatory and legislative frameworks, which may prevent timely installation and operation. The manuscript is easy to read and fits the scope of NHESS. I acknowledge the effort the authors put into the setup of the dock-based system, the data collection, and the development of the data processing pipeline. However, I fully agree with the other reviewer that a major revision is necessary to specify the aim of the study, emphasise the added value and limitations of the presented monitoring approach, and outline which broader conclusions can be drawn from the three different case studies.

I have attempted to complement Reviewer 1's report, though some overlap is inevitable given the shared main concerns.

General comments

1. **Specify the main aim of the study** (see also Review 1) in the abstract and in the last paragraph of the introduction. Briefly discuss the benefits and limitations of different geohazard monitoring techniques (e.g. ground-based, spaceborne, airborne, conventional campaign-based UAV surveys) in the introduction, and emphasise in which cases a dock-based UAS might be a game changer (e.g. financially, technically, practically, research-wise) and in which situations multi-temporal UAV surveys

would simply do the job. The study of Walter et al. (2022) provides a nice example of a dock-based UAS for repeated catchment-wide mapping of sediment dynamics and the monitoring of a debris flow torrent in alpine terrain. You cite their paper, but you could outline in more detail how your monitoring approach adds and relates to their and other studies.

We agree with the comments and will define the main aim of this study more clearly and will make efforts to better position it within the broader context of geohazard monitoring approaches. In the revised manuscript, we will clarify the primary aim both in the abstract and in the final paragraph of the introduction. In addition, we will expand the introduction to briefly discuss the benefits and limitations of different monitoring techniques. This allows us to more clearly position dock-based UAS within the existing methodological landscape. We further emphasise the specific situations in which dock-based UAV systems provide clear advantages, such as in hazardous or inaccessible terrain, under the need for high temporal resolution. At the same time, we acknowledge scenarios where conventional multi-temporal UAV surveys may be sufficient and more cost-effective.

We will more explicitly state and differentiate how our study relates to and extends previous work such as Walter et al. (2022). In particular, we will emphasise that our contribution goes beyond repeated elevation change mapping by demonstrating a broader applicability across different geohazard contexts, including glaciers, complex slope instabilities, and post-disaster landscapes, with a stronger focus on the derivation and analysis of surface displacements.

2. The **motivation for the selection of the three** specific study sites is vague. What were the criteria for the selection? The apparent link between the case studies is the different geohazards (glacier lake outburst flood, rockfall, ice-rock-debris avalanche), but a bit more context on the magnitude and impact of previous glacier lake outburst floods at Supphellebreen and the rockfall activity at Skjøld would be helpful to understand how critical continuous monitoring at these sites is. Moreover, please also be more specific about how the frequent UAV surveys aided “ongoing hazard assessment and response efforts” in Blatten. It seems that operational monitoring with the dock-based UAS was not possible in Norway because of aviation safety regulations. Did you try to obtain permission for operational use, or was the test setup planned as such right from the beginning (see general comments below)? Please clearly state the aim and purpose of each case study and explain how they complement each other and contribute to the overall aim of the manuscript.

We thank the reviewer for this helpful comment. We will clarify the motivation and selection criteria for the three study sites and more clearly state the aim of each case study. In the revised manuscript, we will add context on the relevance and impact of the geohazards at both the Supphellebreen and Skjøld case study sites and better explain how the UAV data supported the hazard assessment in Blatten. We will clarify the regulatory constraints while keeping this discussion concise, as these aspects are site- and country-specific and not the main focus of this study. As noted in the methodology, for the setup in Norway all flights were conducted under supervision by a pilot and observer on site. Finally, we will explain how the three case studies complement each other and contribute to the overall aim of the paper.

3. Since this manuscript may become a basic reference for future studies dealing with autonomous UAV surveys in complex terrain, careful use of terminology is essential. I am wondering why the authors refrained from using or discussing the adjective **"autonomous"** and instead use the description "automated UAV systems" when referring to their dock-based UAS. An "automated UAV system", as stated in the title, could be any (off-the-shelf or customised) UAV that follows a pre-determined flight route and is only controlled by a pilot in the case of unforeseen events. However, from my point of view, the manuscript focuses on something different: the application of an autonomous UAS in alpine terrain, although full operation might not (yet) be possible in all cases due to regulatory and legal frameworks. Careful differentiation between automated, automatic, and autonomous UAVs is important, as different operational restrictions may apply (see e.g. https://www.easa.europa.eu/en/faq/116449). In this context, I would appreciate it if the authors could provide additional information on how much human intervention was necessary during the surveys and subsequent data processing. For example, was a remote pilot in a control room mandatory for continuous flight monitoring at Blatten? Was the data processing initiated automatically after upload from the dock, or was this done manually?

Thank you for this thoughtful and important comment. We agree that a careful and consistent use of terminology is essential. The choice of the term "automated UAV system" was discussed extensively among the authors and with colleagues in the field. We opted for "automated" rather than "autonomous" because the presented system combines automated and partially autonomous components but does not yet operate as a fully autonomous system. For example, flight execution and the data processing workflow are automated, while higher-level decision-making is made by humans such as flight route AOI selection, remote flight monitoring, etc. The system does not independently interpret results or trigger actions such as warnings or interventions. Parts of the UAVs safety features, such as the return to home and obstacle avoidance can be done by the UAV autonomously.

While previous studies (e.g. Walter et al., 2022) use the term "autonomous," we consider "automated" to be a more precise description of the current level of system capability. To avoid ambiguity, we will clarify this distinction in the introduction and explicitly define how the terms "automated," "automatic," and "autonomous" are used in this study.

We will also expand the manuscript by providing a description of the level of human involvement in both the acquisition and processing of data, including regulatory constraints and the degree of automation in the workflow.

4. Since the authors identified current **regulatory frameworks** as one of the main barriers to the (operational) application of autonomous and beyond visual line of sight (BVLOS) flights, the legal requirements and undertaken administrative steps should be briefly discussed for each site and outlined in more detail in the general discussion section.

We thank the reviewer for this helpful and relevant comment. We agree that regulatory aspects play an important role in the operational use of dock-based UAV systems. In the revised manuscript, we will briefly summarise the key legal requirements and administrative steps for each study site and expand the discussion of regulatory constraints in the general discussion section. At the same time, we will keep this discussion concise, as regulations are highly site- and country-specific and subject to change. Our aim is to highlight the broader implications and practical relevance for the scientific community and operational monitoring, rather than to provide a detailed legal review.

5. The advantages of the presented geohazard monitoring approach are mentioned at several locations in the manuscript, which is fine, but the manuscript would benefit if the **limitations and challenges** were discussed equally thoroughly. The following aspects, for example, would be worth addressing: current regulations and required permits for autonomous and BVLOS flights (potential conflicts with on-demand operations), safety measures, power supply of the dock-based UAS, data transfer, and UAS maintenance, especially in remote mountain areas.

We thank the reviewer for this suggestion. We agree and will add a dedicated subsection to the discussion, where we address limitations and challenges, including current regulations and required permits for autonomous and BVLOS flights, potential conflicts with on-demand operations, safety measures, power supply, data transfer, and system maintenance, particularly in remote mountain areas.

6. Always **define acronyms before** using them for the first time (e.g. GNSS, InSAR, RTK, PPK, GCP, NVE, SORA, NTRIP, AOI, FH2), even if they are widely used, and keep their number to a minimum so that non-experts can also follow the manuscript easily.

We will make sure to define all acronyms at their first occurrence in the manuscript.

7. Are there any restrictions or why are the **code and data not published** along with the manuscript? That is against common practice. Please have a look at the NHESS Data policy: https://www.natural-hazards-and-earth-system-sciences.net/policies/data_policy.html

We thank the referee for highlighting this important point. We fully agree with the NHESS data policy and the importance of open and reproducible research. We will publish the codes and data in the DataverseNO repository and make them openly accessible along with the final manuscript.

Specific comments

Line 1-3: I suggest rephrasing the title. Consider including “autonomous” and/or “dock-based” as well as “mountainous/alpine/complex terrain”. It is probably not necessary to mention the three study sites explicitly. In any case, I would replace “landslide” with “rock-ice avalanche”.

We will reconsider changing the title

Line 15-29: Specify the aim of the study, explain the motivation for selecting the three specific study sites, and briefly discuss both the potential and the limitations of the presented monitoring approach.

We will clearly state the aim, motivation for site selection, and briefly outline both benefits and limitations in the abstract.

Line 35: “develop into multi-hazard cascades” → Please specify what you mean or provide an example.

We will clarify this statement and include a concrete example.

Line 37-38: “Monitoring is often the only way to predict hazardous events” → Please modify this statement, as modelling and knowledge from previous events are also important.

We agree and will revise this statement to also acknowledge modelling and prior knowledge.

Line 43: “To overcome these challenges” → Perhaps rather compare ground-based (stationary) and mobile measurement techniques, as differential GNSS, photogrammetry, LiDAR, etc. can be deployed within both ground-based systems and UAV/airborne systems.

We will rephrase this section to better distinguish between stationary and mobile measurement approaches.

Line 47: “Yet, conventional UAV surveys remain largely manual and campaign-based, which is often limiting their frequency” → I disagree. Conventional UAV surveys are usually campaign-based, yes, but not necessarily performed manually. Comprehensive surveys are usually performed using automatic UAVs. Please be careful with the terminology (see general comment).

We will refine the wording to more accurately describe automated flight planning in conventional UAV surveys. Here, we used “manual” to refer to the need for on-site deployment of the UAV (e.g. setup, unfolding, battery changes) prior to executing an otherwise automated mission, and we will clarify this distinction in the manuscript.

Line 49-50: “as they reduce the need for human intervention” → Please specify what you mean by “human intervention”. On-site visits might be limited to installation and maintenance of the system, but a remote pilot is usually required for flight monitoring and safety reasons.

We will specify that this refers primarily to reduced on-site presence, while remote supervision remains necessary.

Line 52: Please be more precise. The paper by Walter et al. (2022) deals with monitoring sediment dynamics in the context of debris flow torrents, so it also has a geohazard focus, similar to this study.

Line 55: “systematic field evaluation of a drone dock-based automated UAV system” → Please clarify what you mean by “systematic evaluation”. Outline how it adds to or relates to the above-mentioned study by Walter et al. (2022).

We will more explicitly clarify and differentiate how our study relates to and extends previous work such as Walter et al. (2022). In particular, we will emphasise that our contribution goes beyond repeated elevation change mapping by demonstrating a broader applicability across different geohazard contexts, including glaciers, complex slope instabilities, and post-disaster landscapes, with a stronger focus on the derivation and analysis of surface displacements.

Line 86: “These three locations, chosen for their contrasting mass-movement characteristics and monitoring challenges” → Please state this already in the introduction and explain in what sense the mass-movement characteristics and monitoring challenges differ.

We will introduce and explain this earlier in the introduction.

Line 97: You state that no previous studies exist, but below you cite several studies with respect to Supphellebreen. Please clarify.

We will clarify and correct this statement that no previous studies exist in context of assessing of the glacier dynamics, and ice velocities.

Line 98: “Temporal (diurnal and seasonal) variations...” → How do you know this? Please provide supporting evidence or a reference.

We will provide a reference for this statement.

Line 103: This information is needed right from the beginning to understand the motivation for selecting this site. What were the characteristics, magnitudes, and impacts of previous GLOFs?

We will add background on magnitude and impacts to better motivate site selection.

Line 105: I think the reference “Breien, 2008” is missing in the bibliography. Please check.

Thank you for pointing out, it is missing in the references, and we will add it in the revised mission.

Line 120: How do you know this? Can you provide an appropriate reference? A bit more background on the geology would be helpful. How exceptional or critical is this site risk-wise, considering the presumably large number of slope instabilities in Norway?

We will provide additional context; the site is currently under investigation and not risk classified yet.

Line 131: “that partially impacted local infrastructure” → To what extent? Please be more specific.

We will specify the extent of the impact.

Line 150: It is unclear at this stage whether you are using a ready-to-operate commercial system or presenting a newly developed dock-based UAS. Clearly state which individual components (hardware and software) were implemented and which were newly developed.

We will improve that section. The dock & drone is a commercial system.

Line 163: Can you provide a rough cost estimate for the dock and UAS?

We can provide a rough cost estimate; however, these values are highly region-specific, subject to change.

Line 164-165: Some information on the power supply and consumption would be helpful.

We will include preliminary information on power requirements and system setup. However, more detailed investigations are needed to assess deployment in remote environments, particularly for solar-powered system configurations.

Line 178-180: I assume the flights were conducted autonomously and BVLOS (and above 120 m), so a Specific Operation Risk Assessment (SORA) was necessary (https://www.easa.europa.eu/en/domains/drones-air-mobility/operating-drone/specific-category-civil-drones/specific-operations-risk-assessment-sora). Can you provide information on the legal requirements and how a permit was obtained within such a short time?

Thank you for this important comment. The flights were conducted on behalf of the Regional Command Staff and under subcontract to the Cantonal Police of Valais. As such, the operations fall under the Swiss state aviation framework. This allows certain extensions of the operational conditions defined in the SORA for dock-based operations. We will clarify this regulatory context and its implications in the revised manuscript.

Line 201: Is the data processing initiated automatically after upload, or is this done manually? (see general comment)

We will clarify which steps are automated and which require manual input.

Line 205-206: Could you explain why you use two different photogrammetry software packages (DJI Terra and OpenDroneMap) to create the point clouds, orthophotos, and digital elevation models? I am not familiar with DJI Terra, but in OpenDroneMap there are many processing options. Please specify whether default settings or any specific settings were applied. You refer to the ODM GitHub repository as a reference, so I assume the access date should be 2025 and not 2020. Two other suitable references are Toffanin (2019), a user guide from the core developer, and Groos et al. (2019), the first case study using OpenDroneMap for UAV-based photogrammetry in alpine terrain.

We will justify the use of both tools, specify processing settings, and add and update references.

Line 238/250: Please describe your observations here and leave the conclusions for the discussion section.

We will make sure to separate observations more clearly from interpretation.

Line 240-248: "Monitoring of the icefall at Supphellebreen" → The accuracy and level of detail of the velocity and surface change products are impressive, but it is unclear how these observations are linked to the UAV-based monitoring and risk assessment of GLOFs at this site, which was reported earlier in the manuscript as a motivation for this study.

We will strengthen the connection between UAV observations and GLOF-related monitoring objectives.

Line 250-260: Given the number of flights at this site (n = 7), what is the added value of the dock-based system here?

The number of flights was reduced after initial results indicated very small displacements (~5 cm over a two-week interval), close to the level of detection. Nevertheless, we believe this test site provides important value, as it represents a different process type, exhibits smaller magnitudes of displacement compared to the other study sites, and highlights specific challenges for unstable slope monitoring. It therefore offers useful insights into current limitations (small displacements & for our setup with photogrammetric mapping, vegetation) and potential areas for methodological improvement.

Line 264-265: "The automated monitoring campaign following the rock-ice avalanche event at Blatten highlights the possibilities offered by automated UAV systems in post-disaster response" → Please specify this and provide examples.

We will provide concrete examples of how UAV data supported response efforts.

Line 267: "could only be visited once" → Once during the entire monitoring period?

Yes, once during the entire monitoring period

Line 299: "Automated UAV systems offer a paradigm shift in the monitoring of dynamic geohazard environments" → A paradigm shift in what sense? This is a strong statement and should be supported by sufficient evidence and robust arguments.

Thank you for this comment. By paradigm shift, we refer to the transition from the use of UAVs as tools for primarily campaign-based surveys toward the integration of automated, near-continuous monitoring systems. This enables more frequent, repeatable, and time-critical data acquisition, moving UAVs from episodic mapping tools to potentially components of operational monitoring frameworks.

Line 341: "4D datasets offer a robust foundation for training deep learning models" → Please be more specific or provide an example.

We will provide a concrete example or clarify the statement.

Line 356-358: Is this not a bit too optimistic? During precipitation, strong winds, and ground fog, UAV surveys are usually not feasible or deliver data of reduced quality. Can you quantify the number of days with stratus clouds where the base height is high enough for UAV surveys to be performed safely?

The observation was intended as a general indication rather than a quantified assessment. A detailed quantification would require site-specific analysis of weather data and would be interesting to assess in a future study. At the same time, the UAV system used shows a relatively high tolerance to wind and precipitation, allowing flights close to operational limits. However, under such conditions, data quality may be reduced, which should be systematically assessed in future studies.

Line 357: "low fog" → Do you mean ground fog or stratus clouds (i.e. low-level clouds)?

Low level clouds, we will adjust that.

Line 365: Why a maximum of 120 m above ground level? Do you refer to the maximum flight altitude in the "open" category defined in the EU drone regulation?

The flight height was defined by what was necessary to cover the AOI in reasonable time with the drone chosen and the desired ground sample distance

Line 374: Please provide a rough cost estimate here.

We can provide a rough cost estimate; however, these values are highly region-specific, subject to change.

Line 394: "failure event" → Consider using "rock-ice avalanche" or "rockfall and glacier collapse".

We agree.

Line 397-398: Have autonomous surveys up to 3000 m a.s.l. been performed? Can you explain what "dynamic mission adjustment" meant in practice? Both information should be included in the methods section.

We will clarify and move relevant details to the methods section.

Table 1: Could be moved to the appendix. I think an overview table with key figures regarding the dock and UAV would be more interesting.

Table 2: Maybe add the maximum distance of the UAV from the dock during the surveys.

Figures 1-3: The overview maps (a) are difficult to interpret. Add contour lines or colour by elevation. Maybe highlight the location of critical infrastructure below the monitored sites.

Figure 5: The labels are difficult to read. Please increase the font size. Add a scale bar and a north arrow (if the map is rotated). Are the white spots in (c) snow patches or data gaps?

Figure 6: Change the unit to cm or mm per day. A scale bar and north arrow are missing. It is difficult to recognise the mentioned features in (e) and (f).

Thank you for the comments on the tables and figures. We will improve readability in the revised version, including increasing font sizes and enhancing clarity where necessary. We will also take the specific suggestions of referee 1 into account and revise the figures and tables accordingly.

Technical corrections

None at this stage.

References

Toffanin, P. (2019). OpenDroneMap: The Missing Guide. MasseranoLabs LLC. [https://odmbook.com/]

Groos et al. (2019). The Potential of Low-Cost UAVs and Open-Source Photogrammetry Software for High-Resolution Monitoring of Alpine Glaciers: A Case Study from the Kanderfirn (Swiss Alps), 9(8), 356. https://doi.org/10.3390/geosciences9080356.

Walter et al. (2022). Brief communication: An autonomous UAV for catchment-wide monitoring of a debris flow torrent. NHESS 22, 4011-4018. https://doi.org/10.5194/nhess-22-4011-2022.