We greatly appreciate the two helpful reviews, and have used the comments to improve the manuscript. Below, we provide a detailed response to the reviewer comments, outlining how we have revised the manuscript. We have responded to each comment (except for some very minor ones regarding typos), with the referee comments in blue italics and our responses in normal text.

Referee 1

The short communication introduces a workflow to process multi-temporal data for accurate change detection although no GCPs are available. Thereby, images from multiple survey campaigns are processed at once. Afterwards, the orientated images of the individual surveys are split to retrieve the corresponding point clouds of each campaign for change detection. The idea is simple but very effective. The manuscript is well-structured and easy to follow. The results are presented comprehensively and support the introduced method. However, some issues remain regarding the explanation of the approach (especially terminology) that should be addressed in a revised manuscript. Furthermore, the authors should consider the Time-SIFT publication by Feurer & Vinatier (2018) because it describes a similar approach more detailed for applications to archival imagery. Please, see below for some detailed comments.

Thanks a lot for pointing us towards the Feurer and Vinatier paper. We had not seen this, and it is indeed quite similar to our approach. It is a little bit of a relief to see that we are not the only ones to have thought of this nontraditional approach. We have added it to our discussion of previous work and have specified that our proposed method is a generalization of this one.

P1L23: It is not clear what the authors refer to with camera optical parameters. Are these the interior orientation parameters. If yes, it should be mentioned that the GCPs are also used to refine the parameters of the exterior orientation besides the interior parameters.

Yes, this was unclear. We restated that GCPs are used to georeference the model and to improve the calculation of both camera interior parameters and camera positions and orientations.

P1L29: It might be better to refer to dGNSS instead of dGPS as also other satellites can be used for geo-referencing.

Good point, this was changed.

P2L33-35: Are these control points tie points or ground control points? If they are GCPs, where does the reliable/accurate 3D information come from? And if they are tie points, I would avoid the term control points.

Peppa et al., 2019 refer to them as pseudo-GCPs. We will use that instead of the term control points.

P3L65-71: This paragraph seems to be a little bit off-topic if it is left as it is. A better explanation why these challenges are displayed should be provided. For instance, why is the changing appearance of the cliff relevant? Does that potentially impact feature detection and matching? Furthermore, a final statement might improve that paragraph, as well, highlighting that this study at the cliff is a very suitable study to demonstrate the usability/necessity/benefits of the authors' approach. Although, this intention is probably meant in the paragraph it might be suitable to mention this explicitly.

Good point. We have removed the part about the changing appearance, as it's not really relevant.We now explicitly state that these challenges are the reason why this is a good test case.

P3 chapter Methods: I would suggest to include sub-headings for data acquisition and co-alignment processing to improve the readability.

These have been added.

P3L75-76: Did the authors also consider check points as an independent reference of the reconstruction accuracy? With 14 and 12 GCPs this should be possible.

We did not do this, as we rely on the accuracy study in Cook, 2017, which was conducted at the same site using the same control points, to estimate uncertainties (as stated in the text).

P3L94: I thought, only the Mavic Pro was used for data acquisition (but also a Phantom is mentioned here)?

The Phantom 3 was used for the Daan River surveys (this was mentioned in line 73).

P4L97: What is the unit for the reconstruction uncertainty? According to Agisoft, the reconstruction uncertainty somehow relates to the base-height ratio. But how is the reconstruction uncertainty calculated?

This value has no unit, as it is the ratio between the variation in the direction of maximum variation and the variation in the direction of minimum variation. We are reporting the parameters used in Photoscan for completeness, not because they are particularly important for the method. For the case of surveys with a lot of oblique photos, we have found that filtering by reconstruction uncertainty is the best way to remove tie points that are clearly erroneous. Other users may clean and optimize the survey differently; it doesn't really matter in terms of the co-alignment method. Because this is not a particularly important step, we don't think it's necessary to give an introduction to how Photoscan calculates it.

P4L98: How is the adaptive camera model fitting working? What is the difference to the approach without adaptive fitting?

As with the comment above, we are not sure that this manuscript is the place to explain the details of Photoscan's methods.

P4L99: The fine registration in CloudCompare is done via ICP (iterative closest point) fitting. Maybe, it might be preferable to state the actual performed algorithm rather than the tool name.

This was changed.

P4L105: The alignment optimization is actually also a bundle adjustment, however considering some refined parameter settings and/or referencing information. Thus, this might be rephrased to avoid confusion of the reader.

This was rephrased to: "the point detection and matching, initial bundle adjustment, and optimization"

P4L116-118: Is it possible to express these differences between both change maps in numbers, e.g. considering the average of deviations between both maps? This question would also be relevant for the

Rügen analysis. Furthermore, did the authors also check accuracies at check points? They might be helpful to assess how well changes are detectable with the reference in general.

We can provide the average change for each map, but we feel that the histograms shown in the figures are more informative. One issue is that some of the differences calculated are real, so a smaller average difference does not necessarily mean a better result. Unfortunately, we cannot directly compare the two Daan River change maps because the models without GCPs are warped relative to the models with GCPs, so the change maps don't align with each other.

For Rügen, as mentioned in the text, we have no independently measured check points. If we had the ability to have such points, then we would also be able to use GCPs and wouldn't have the need for this workflow. At the Daan River site, we rely on the accuracy study in Cook, 2017, which was conducted at the same site using the same control points, to estimate uncertainties.

P4L124-125: However, this depends on how the models are aligned. If GCPs or stable areas are used, I am not certain if this statement still holds. Of course, if ICP is used than these distortions can lead to difficulties in the alignment (depending on how strong these distortions are).

If alignment involves just rotation and transformation, then distortions will prevent good alignment of the whole model no matter what method is used. Perhaps alignment is not the best term to use here, as we are talking about only transformation and rotation of dense point clouds or meshes; we can see how this can be confused with camera alignment. We have substituted co-registration for alignment.

P5L128-129: I am not sure if I understand that sentence correctly. Changes between 1 and 2 m are common at the observed cliff on Rügen? Thus, the noise in the data is higher than the common changes at the cliff?

We have rephrased this to: "Throughout the model area, up 1-2 meters of change are erroneously detected in many stable areas, indicating that real changes of this magnitude would be below the level of detection. For the Rügen study area, this level of detection would preclude the use of UAV surveys to monitor small cliff failures."

L123-129: Maybe the entire paragraph can be rewritten to improve clarity regarding model related distortions and issues due to alignment approaches.

Hopefully this will be more clear by using "co-registration" rather than "alignment." But basically, if models are distorted relative to each other, then they will not perfectly fit together no matter what method you use, but you might fit them together badly in different ways.

P5L130-131: Maybe it is worth to extent the explanation that the simultaneous alignment of all campaigns leads to the circumstance that the highly spatially correlated errors (James et al., 2017), which also depend on the image observations (i.e. tie points), are potentially situated at the same locations in the individual models (because image orientation across surveys are constrained to the same tie-points) and therefore mitigated during point cloud differencing.

Yes, this is exactly what we are trying to convey – that the models contain errors, but they are consistent across the different surveys, so they don't influence the change detection. We have rephrased as: "When the cameras from multiple surveys are co-aligned, the resulting point clouds still contain distortions, but if the procedure is successful, they have been fit to a common geometry and the distortions are consistent between the models. As a result, these errors do not influence comparisons between the models, comparative accuracy is much higher and robust change detection can be performed."

P5L153: I would not state that edges are the issue but rather areas outside the tie point region.

In these surveys, it does seem to be more an issue of edges, as the extents of the dense and sparse clouds are the same. The points near the edge are generally only seen on two or three photos, and they are only seen on the same edge of these photos, so they are less well-constrained (compared to points which are visible on many photos and which are located at a range of positions on different photos).

P6L160-163: Maybe this statement should be separated more clearly from the previous because another aspect is discussed. The first aspect is referring to too strong changes of the surface and therefore failing to find matches and the second refers to changes of the entire surface but remaining a general similar appearance and thus falsely retrieving matches.

We have clarified this and modified this paragraph to:

"In order to get a successful alignment, tie points linking the photos from different surveys must be detected, and false matches must be avoided. If the appearance of the area changes too much between surveys or if too much of the area of interest has changed, sufficient tie points may not be generated, as described above. Therefore, well-distributed stable areas with a consistent appearance are required for successful alignment. In the examples presented here, we did not observe any false matches, as surface changes were always accompanied by changes in appearance, preventing the detection of matches in unstable areas. In settings with large-scale surface deformation, such as a slow moving landslide or deep seated gravitational slope deformation, this may not be the case, and it is possible that points may be matched in unstable areas. In such settings, care should be taken to evaluate the reliability of the common tie points."

P6L164: What do the authors refer to when they are talking about scaling between numbers of photos?

This refers to the nonlinear increase in processing time when more photos are added – doubling the photos will more than double the time required for point matching and camera alignment. We have modified to "Due to non-linear scaling between the number of photos and the processing time"

P6L164-168: I have a little bit difficulty to understand that sentence. Do the authors mean that with each new campaign all the campaigns have to be re-processed?

Yes, this is what we mean. Any previous campaigns that you would like to compare to the new campaign must be reprocessed.

P6L168-169: Might it not be possible to only compare from one survey to the next to avoid increasing the processing time with each new survey, although this might be less favorable for error propagation? Maybe it might worth testing in a future study how well campaign to campaign processing performs compared to reprocessing everything.

Of course, and this is what we typically do with the Rügen surveys. But this means that for four surveys A, B, C, and D, you will need to do all of the processing three times – A+B, B+C, and C+D. So if it takes 10 hours to generate the dense cloud for survey A, you will have to do that twice. And you can't compare A vs. C or B vs. D. Basically, the issue is that when you conduct a new survey, you can't re-use any of the models you have previously generated to compare with it. This is quite different from the typical workflow, where you create a "final" model that can be compared to any future models. This paragraph has been modified to: "For a single pair of surveys, the co-alignment workflow has a limited impact on processing time. Due to non-linear scaling between the number of photos and the processing time, performing the point matching and camera alignment step once with n photos will take longer than performing it twice with n/2 photos, but this effect will be relatively minor until the number of photos becomes large. The more significant impact on processing time comes from the requirement that for each survey set to be compared, the entire chain of processing from point matching to dense cloud construction must be redone. This can greatly increase the total processing time for large sets of surveys. For example, for a set of four surveys, A, B, C, and D, a series of pairwise processing and comparison (A-B, B-C, C-D) would require the point matching and camera alignment step to be performed three times and would require the construction of six dense clouds (surveys B and C would each have two dense clouds). This processing time can be reduced by applying the method to larger sets of surveys. We have simultaneously co-aligned photographs from up to 4 different epochs to obtain a set of mutually comparable point clouds from 2017-2018 (Figure 6). In some cases, an unsuccessful alignment of two surveys can be improved by adding a third survey. For example, if changes in surface appearance (lighting, shadows) or in camera obliquity prevent the detection of sufficient common tie points between the original two surveys, a third survey that generates enough common tie points with each of the original two can lead to successful alignment of all three surveys. However, despite the possibilities for batch processing, the fundamental drawback of this method is that it does not result in a definitive model for a given survey period - models that were constructed based on co-alignment of one set of surveys cannot be re-used for comparison to an additional survey."

P6L177-178: Maybe the combination of both is most suitable (e.g. as discussed by Feurer & Vinatier, 2018). Align all campaigns in one workflow (this might also improve general model accuracy as more image observations will be available) and scale/georeference the whole project with GCPs (from just one campaign).

This is a great suggestion, thanks. We have added a sentence about this, with credit to Feurer and Vinatier.

Referee 2

This is an interesting study on the possibility of improving the comparative accuracy of multiple surveys by co-processing the image sets when stable areas can be found and matched in a particular area. Rather than the workflow itself (which is hardly a proper workflow but just a modification of the standard SfM pipeline), I found the greatest merit of this work drawing the attention to this co-alignment possibility, that in many cases my be discarded or overlooked and can help to improve the quality of the results. My main comments to this work are the following (please check the annotated pdf for specific comments throughout the manuscript): 1. I would strongly suggest to include in the manuscript title the *main limitation of the workflow. i.e. the presence of stable areas. The authors have acknowledged this in the limitations and conclusions sections and should be specified in the title since is a major requirement. 2. The authors are too focused on the geomorphological settings (cliffs, rivers and such), which is not bad, but a relevant part of the SfM community works on more artificial environments such as agricultural settings where hardly stable areas can be found. How applicable would be the co-aligment in these cases? A quick literature review could give the authors a general view of the types of scenarios in which the SfM approaches are being applied and maybe they could comment in more detail to what extent their method is feasible to be applied.*

The limitations of the method are made quite clear in the manuscript; we disagree that it's necessary to include mention of stable areas in the title and feel that it would make the title long, awkward, and too detailed. We added a sentence to the abstract specifying that the method relies of the presence of stable areas: "The method is based on the automated detection of common tie points in stable portions of the survey area."

The goal of this manuscript to introduce a solution for people working in environments where ground control is impossible or very difficult to obtain. Thus, we are not focused on places like agricultural settings or other artificial environments, as traditional methods work just fine in these areas. Plus, since we have no experience with or data from such areas, we have no idea how well the method will perform. It may be that peripheral stable infrastructure such as buildings, roads, fences, etc. may provide sufficient common tie points, and maybe not. It may also vary depending on the location. We hope that people working in different settings can give it a try and evaluate whether it works for their particular area.

Número: 5 Autor: Asunto: Resaltado Fecha: 17/07/2019 7:31:01 1. Please justify the selection of these two study areas 2. Rephrase the sentence to be shorter and better structured

We have rephrased this sentence to: "Here, we introduce a simple workflow involving the co-alignment of photographs from different surveys; our method is similar to that of Feurer and Vinatier (2018), but uses no GCPs and is generalized to any set of repeat SfM surveys. Using data from two contrasting study areas: a bedrock gorge in Taiwan and a steep cliff coast in northern Germany, we demonstrate that we can achieve high comparative survey accuracy and low limits of change detection using a low-cost off the shelf UAV without ground control points."

The appropriateness of the study areas are justified in the area descriptions below; we don't think this level of detail is needed in the introduction.

Número: 6 Autor: Asunto: Resaltado Fecha: 17/07/2019 7:30:56 Include company and country or reference.

Agisoft is the company, so that is already there. We have never seen the country listed in other publications that use Photoscan. We did neglect to provide the version number, so we have added this.

Número: 8 Autor: Asunto: Resaltado Fecha: 17/07/2019 7:38:04 No information of this study area has been included as a figure. Please provide a map and picture if appropriate, similarly to the Rugen site.

We felt that this information wasn't necessary, as it is available in a previous publication and isn't critical for interpreting the results.

Número: 9 Autor: Asunto: Resaltado Fecha: 17/07/2019 7:33:21 Autor: Asunto: Nota adhesiva Fecha: 17/07/2019 7:33:40 Why not describing this first, being the primary area?

We use the Daan case as a kind of proof of concept, where we apply the method to a more traditional type of survey in an area where traditional methods are possible, so we present it first. We describe it first because we present it first in the results. We consider Rügen to be the primary area, as it is the setting where traditional methods can't be used and our co-registration workflow is really necessary to get useful change detection results.

This was made after or before the fine registration and M3C2 algorithm?

This was done after the M3C2 calculations – the steps were done in the order that they are presented in the text. We have clarified this.

Número: 2 Autor: Asunto: Resaltado Fecha: 17/07/2019 7:47:23 Can you provide the results when both surveys are processed independently (no co-alignment)?

We have added this result to figure 3.

Página: 5 Número: 1 Autor: Asunto: Resaltado Fecha: 17/07/2019 7:56:33 I recommend discussing in more detail each of the results in Fig. 5 and 6.

We are not sure what additional detail is expected. To discuss the patterns of cliff collapse and retreat on Rügen is far beyond the scope of this manuscript, particularly since it is a short communication and not a full research paper.

Número: 2 Autor: Asunto: Resaltado Fecha: 17/07/2019 8:00:42 This table must be improved: using capital letters at the beginning of the column titles, better structure, etc... The references to the study sites are confusing, please include always the main name of the site and then the particular name of the area. Why not being consistent with Daan river results first and then Rugen? It is confusing.

We have reorganized the table and clarified the study site names.

The examples provided by the authors are typically focused on geomorphological settings which include stable areas. What about other scenarios such as agricultural settings where SfM is being frequently used? I would recommend revising other settings in literature where UAV SfM is being extensively used and comment the feasibility of the workflow accordingly.

As we say above, we don't have the data or experience to evaluate the feasibility of the approach in such settings, and it may vary depending on the details of the agricultural setting and the surveys. Such a discussion would only be speculation, which we don't feel is very useful. We are open about what is required to make the approach work, and we hope that readers can evaluate their own areas on the basis of that.

Número: 2 Autor: Asunto: Resaltado Fecha: 17/07/2019 8:03:23 What does this mean? Different surveys may have different target accuracies depending on the aims of the study

Survey-grade accuracy is a term that is commonly used in the surveying community and typically refers to accuracy on the order of cm or better. We have rephrased to "GCP-constrained georeferencing is preferable to the co-alignment workflow if accuracy on the order of cm or better is desired."

Short Communication: A simple workflow for robust low-cost UAV-derived change detection without ground control points

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Abstract. High quality 3D point clouds generated from repeat camera-equipped unmanned aerial vehicle (UAV) surveys are increasingly being used to investigate landscape changes and geomorphic processes. Point cloud quality can be expressed as accuracy in a comparative (i.e., from survey to survey) and absolute (between survey and an external reference system) sense. Here we present a simple workflow for calculating pairs or sets of point clouds with a high comparative accuracy, without the need for ground control points or a ~~dGPS equipped UAV.~~dGNSS equipped UAV. The method is based on the automated detection of common tie points in stable portions of the survey area. We demonstrate the efficacy of the new approach using a consumer-grade UAV in two contrasting landscapes: the coastal cliffs on the Island of Rügen, Germany, and the tectonically active Daan River gorge in Taiwan. Compared to a standard approach using ground control points, our workflow results in a nearly identical distribution of measured changes. Compared to a standard approach without ground control, our workflow reduces the level of change detection from several meters to 10-15 cm. This approach enables robust change detection using UAVs in settings where ground control is not ~~possible~~feasible.

1 Introduction

Camera-equipped unmanned aerial vehicles (UAVs) and Structure from Motion (SfM) methods are increasingly being utilized as a low-cost method to conduct repeat topographic surveys in order to measure geomorphic change (Fonstad et al., 2013; Eltner et al., 2016; Anderson et al., 2019). To obtain high quality 3D models using SfM, precisely located ground control points (GCPs) are typically used (James and Robson, 2014; Carrivick et al., 2016) to both georeference the model and to improve the calculation of camera ~~optical~~interior parameters and camera positions and orientations. This requires either the deployment of GCP targets prior to UAV flights or the identification of existing natural or artificial features that can be used as targets. In either case, the locations of the GCPs must be precisely measured, typically using a differential ~~GPS (dGPS~~GNSS (dGNSS) or total station (James et al., 2017).

In the absence of GCPs, models can also be created using direct georeferencing, which requires GPS locations of the camera positions (Carbonneau and Dietrich, 2017). For highly accurate results, this relies on having very accurate camera locations, typically by using a UAV equipped with ~~dGPS~~dGNSS (Turner et al., 2013; Hugenholtz et al., 2016). Direct georeferencing performed using only the GPS positions recorded by consumer-grade drones can lead to models that contain a range of errors and distortions (Carbonneau and Dietrich, 2016; James et al., 2017). Model errors can also be reduced by complementing nadir surveys with oblique images in a convergent geometry (James and Robson, 2014), but this is typically recommended in conjunction with GCPs or ~~dGPS~~dGNSS based direct georeferencing. Peppa et al (2018) presented a method for automatically generating ~~control points~~pseudo-GCPs in stable areas using DEM curvature and openness, but this relies on using surface texture to estimate stability, which may not be reasonable in all settings. In addition, the generation of DEMs may not be appropriate for all terrain types, such as overhanging cliffs. Feurer and Vinatier (2018) introduce a method to process sets of archival aerial photographs in the same SfM block to achieve accurate change detection with only a small set of poorly constrained GCPs (accuracy ~20 m) for scaling and georeferencing.

When considering accuracy in relation to change detection, we distinguish two different types~~—~~: the real accuracy of an individual model and the comparative accuracy of a pair of models. Real accuracy includes both relative and absolute accuracy, or the internal accuracy (distortion) of the model and the accuracy of the scaling and georeferencing of the model. We use the term comparative accuracy to describe the accuracy of the change measured between model pairs, or to what degree the models are consistent with each other. High real accuracy should lead to high comparative accuracy, and is the most desirable outcome, but it may be possible to achieve high comparative accuracy for model pairs with low real accuracy. For example, if two models are subjected to the same incorrect transformation or rescaling, their real accuracy will be affected while their comparative accuracy remains unchanged.

While high real accuracy is desirable, some settings of interest for change detection preclude the deployment or measurement of GCPs, and ~~dGPS~~dGNSS-equipped UAVs may be prohibitively expensive. Therefore, an alternative method for achieving high comparative accuracy of survey pairs could open up new types of settings to event monitoring using low-cost UAVs. Here, we introduce a simple workflow involving the co-alignment of photographs from different surveys~~, present~~; our method is similar to that of Feurer and Vinatier (2018), but is generalized to any set of repeat SfM surveys and requires no GCPs. Using data from two contrasting study areas: a bedrock gorge in Taiwan and a steep cliff coast in northern Germany, ~~and~~we demonstrate that we can achieve high comparative survey accuracy and low limits of change detection using a low-cost off the shelf UAV without ground control points. Our workflow is extremely simple, can be performed entirely ~~in~~with the software Agisoft Photoscan~~,~~ Pro (now called Metashape Pro), and could be made fully automated.

2 Study area

We first present data from the Daan River, a bedrock gorge in Taiwan. In this system, the river experiences large changes between survey periods, while the surrounding area has variable degrees of vegetation cover and remains stable aside from vegetation growth. The gorge also experiences localized erosion of its steep to vertical walls. An extensive description and analysis of survey accuracy in this setting can be found in Cook (2017~~).~~), who estimates a level of detection of 10-30 cm (depending on surface characteristics) for GCP-constrained surveys. Because we have ground control information for these surveys, we can compare GCP-constrained changes to changes measured using our workflow without GCPs.

The primary study area is located in Jasmund National Park on the island of Rügen, Germany, where steep to overhanging coastal cliffs up to 118 m high are eroding rapidly (Schulz, 1998) (Figure 1). Our study area comprises about 7 km of coastline, from the Königsstuhl in the north to the town of Sassnitz in the south. The cliffs, composed of chalk and glacial till, experience frequent rockfalls and collapses during the winter months. During our study period from 2017-2019, these failures varied in size from a few m^3 to about 4000 m^3. While rockfalls are relatively common, they affect a small proportion of the total cliff area, and the rest of the cliff face remains stable, with no discernable internal deformation.

This cliff coast presents a challenging environment for UAV-based surveying. The cliff sections are out of bounds, access to the base of the cliffs is limited and can be dangerous, the forest above the cliffs limits both ground visibility and the communication range of the UAV, and strong winds are common. ~~The appearance of the cliff can also change throughout the year, as the till layers become much darker relative to the chalk when they are wet.~~ In addition, the coast is a long linear feature that precludes complicated flight patterns, and flying close to the cliff is restricted to protect peregrine falcons nesting there. However, because cliff collapses can represent a significant hazard to National Park visitors, there is a strong interest in a rapid and easy to implement method of monitoring cliff activity. This combination of characteristics makes the cliff a good location for demonstrating the applicability of our workflow, as it is a setting in which conventional methods are unsatisfactory.

3 Methods

3.1 Data acquisition

Daan River surveys were flown with a Phantom 3 Advanced UAV using flight planning software, yielding grids of nadir photographs from 35-60 m above ground level. Here, we marked ground control points with spray paint and measured their locations using a dGPS with 1-2 cm accuracy. We compare subsets of surveys conducted in May 2017 and Jan 2018, which used 14 and 12 ground control points and 197 and 298 photographs, respectively.

Rügen surveys were conducted by manually flying a DJI Mavic Pro UAV from three to seven locations along the top of the cliff (depending on wind conditions and the impact of foliage on the UAV communication range). Photos were taken every 3 seconds, and typically two passes were made for each cliff section – one at lower altitude with the camera more oblique, and one at higher altitude with the camera more nadir (Figure 1). Typically, the camera pitch was 40 to 80 degrees from nadir and flight elevations ranged from 30 to 150 m above sea level, depending on the height of the cliff. In order to ensure adequate coverage, the UAV was positioned so that each photo included the full vertical extent of the cliff. As a result, the distance between the UAV and the cliff varied depending on the cliff height. Flight heights and distances from the cliff also had to be adjusted to weather conditions such as wind speed and sun glare. Each flight took 20-30 minutes, so the full 7 km stretch of cliff could be surveyed in a few hours. Each survey contained 1000-2000 photographs. We also conducted several partial surveys that covered smaller segments of the cliff coast during the winter of 2017-2018. We have no ground control points for the surveys. The base of the cliff can only be accessed in a few locations, and National Park regulations prohibit employees or associates from working along the cliff base. Deploying ground control points only on the cliff top would result in a linear array of points, a geometry that can lead to large errors.

3.2 Data Processing

SfM processing was done using Agisoft Photoscan Pro~~.~~ (v. 1.4.2). In order to decrease processing time, the 7 km long Rügen study area was separated into five overlapping segments. In this paper, we will show data from just two of these segments~~.~~ – the Kieler Bach and Königsstuhl sections.

As a control, we processed the data using a standard Agisoft workflow in which each survey is processed separately. For the Daan example, we used the GCP information to georeference each survey. For the Rügen surveys, the only georeferencing information was provided by the photo GPS tags created by the DJI Mavic Pro or Phantom 3. Because the elevation data reported by these UAVs often contain systematic offsets, we used the known elevations of the launch points to correct the elevations of the cameras for each flight. Photos were aligned (using high quality and 40,000 and 4000 key and tie point limits, respectively), tie points with reconstruction uncertainty greater than 50 were removed, and the alignment was optimized (using adaptive camera model fitting). Dense clouds were calculated using medium quality and aggressive depth filtering, exported into CloudCompare (CloudCompare 2.10.1, 2019), and ~~aligned~~co-registered using ~~the fine registration tool~~iterative closest point fitting. Then the M3C2 algorithm (Lague et al., 2013) was used to compare point clouds from successive surveys, using a projection diameter of 0.5 m, normal scales from 0.5 m to 4.5 m by 1 m steps, and core point spacing of 0.25 m. We then trimmed areas of vegetation using standard deviation and point density filters (Cook, 2017).

We then tested a workflow, which we term co-alignment, that involves processing survey pairs together (Figure 2). To do this, we imported the photographs from two different surveys into a single chunk in Photoscan and performed the point detection and matching, initial bundle adjustment, and ~~alignment~~ optimization steps on the combined set of photographs, using the same parameters as above. We created different camera calibration groups for each survey, so the calculated camera calibration parameters can differ between surveys. If there is sufficient similarity in the photographs between the two survey periods, key points can be matched between photos from different surveys and common tie points will be generated. After the alignment and optimization steps were finished, we separated the photos from the different surveys by creating two duplicates of the original chunk and removing photos as needed, thus preserving the sparse clouds, position information, and the camera calibrations. We then calculated dense clouds for each survey period and compared the resulting point clouds using M3C2 in CloudCompare, with the same parameters listed above.

4 Results and discussion

The Daan River surveys enable us to compare the effectiveness of the co-alignment workflow without GCPs to a traditional workflow using GCPs. We find that the co-alignment workflow results in a change map and ~~histogram~~density curve that are almost identical to those produced using the GCPs (Figure 3). The only apparent differences between the two change maps occur on the upper edge of the area, where the photograph coverage becomes marginal and errors occur in both the GCP-constrained and co-aligned comparisons. This provides evidence that co-alignment can be used for change detection with a level of detection comparable to that of a survey grade GCP-constrained pair of models.

For the Rügen data, we assessed the comparative accuracy of the resulting model pairs based on the measured change in stable areas of the cliff. Areas of poor fit can be distinguished from areas of real change by the spatial pattern of the differences, the sharpness of the boundary, and by visual inspection of the before and after photographs (Figure 1, 4-6).

Using the standard workflow, the point clouds from successive surveys each contain distinct errors and distortions. Because the error in each cloud is independent of the other cloud, the point clouds are distorted relative to each other and typically cannot be ~~aligned~~co-registered well, resulting in large errors in the change detection. The error varies throughout the model area, depending on the distortion of the individual models. The spatial pattern of error will also depend on the method used to ~~align~~co-register the two point clouds. For the example shown in Figure 4, erroneous changes of up to 5 m are measured on the edges of the models and of up to 2.5 m in the center. ~~Areas with 1-2 m of measured change are common, so real changes on the order of a few meters will not be detected in this comparison.~~ Throughout the model area, up to 1-2 meters of change are erroneously detected in many stable areas, indicating that real changes of this magnitude would be below the level of detection. For the Rügen study area, this level of detection would preclude the use of UAV surveys to monitor small cliff failures.

When the cameras from multiple surveys are co-aligned, the resulting point clouds still contain distortions, but if the procedure is successful, they have been fit to a common geometry~~, so~~ and the distortions are consistent between the models. As a result, these errors do not influence comparisons between the models, comparative accuracy is much higher and robust change detection can be performed. We find that the measured change in stable areas is substantially less than in the control case, and therefore smaller amounts of real change can be detected (Figure 4). For the examples shown here, the level of detection has been reduced from several meters to as low as 15-20 cm. Small cliff failures, bands of more diffusive erosion at the base of the cliff, and even the growth of individual bushes can be reliably detected (Figures 4-6).

The increase in comparative accuracy is due to the generation of tie points between photographs from different surveys. These tie points, if they are well distributed, enforce a common geometry between the different surveys. We can evaluate the number of common tie points between surveys by comparing the number of points in each sparse cloud following chunk duplication and photo removal (Figure 2) to the number of points in the sparse cloud generated during the combined alignment. Tie points generated using only photos from survey 1 will be removed when the photos from survey 1 are removed, while tie points generated using photos from both surveys will remain. If common tie points were generated, the two separated sparse clouds have more total points than the original, with the difference being the number of common points (Table 1). Note that this is distinct from the number of matches, as each tie point may be used in multiple matches.

Even when relatively few common tie points are generated, or when they are irregularly distributed, a successful alignment can be achieved. For example, Figure 5 shows a section of the Rügen study area that is heavily vegetated, with only isolated patches of bare cliffs. While no common tie points can be generated in the vegetated areas, as long as there are common tie points distributed throughout the cliff sections, a relatively good comparative accuracy can be achieved, as illustrated for April 2018 – May 2018 (Figure 5B). However, if there are sections of the cliff where no matches can be made, then large comparative errors can result, as is shown in Figure 5C for the survey pair Oct. 2017 – April 2018. This survey pair had both a low number (1355) and percentage (0.4%) of common tie points compared to the April 2018 – May 2018 pair, which had 3402, or 1% common tie points. More importantly, there were no common tie points generated in a ~350 m long stretch at one end of the model, leading to up to 1.5 m of comparative error in this section of the cliff. This illustrates that if common tie points are not distributed through the full extent of the model, edges of the models may not align well. The Daan River example further demonstrates that the distribution of tie points is more important than their number, as good alignment was achieved throughout most of the model despite the generation of only 900 common tie points (0.3% of the total).

4.1 Potential limitations

In order to get a successful alignment, tie points linking the photos from different surveys must be detected., and false matches must be avoided. If the appearance of the area changes too much between surveys or if too much of the area of interest has changed, sufficient tie points may not be generated., as described above. Therefore, well-distributed stable areas with a consistent appearance are required for successful alignment. In the examples presented here, we did not observe any false matches, as surface changes were always accompanied by changes in appearance, preventing the detection of matches in unstable areas. In settings with large-scale surface deformation, such as a slow moving landslide or deep seated gravitational slope deformation, this may not be the case, and it is possible that points may be matched in unstable areas. In such settings, care should be taken to evaluate the reliability of the common tie points.

For a single pair of surveys, the co-alignment workflow has a limited impact on processing time. Due to non-linear scaling between the number of photos and the processing time, performing the point matching and camera alignment step once with n photos will take longer than performing it twice with n/2 photos, but this effect will be relatively minor until the number of photos becomes large. The more significant impact on processing time comes from the requirement that for each survey set to be compared, the entire chain of processing from point matching to dense cloud construction must be redone. Models that were constructed based on one survey pair cannot be re-used for comparison to a third survey. This can greatly increase the total processing time for large sets of surveys. However, weFor example, for a set of four surveys, A, B, C, and D, a series of pairwise processing and comparison (A-B, B-C, C-D) would require the point matching and camera alignment step to be performed three times and would require the construction of six dense clouds (surveys B and C would each have found that it is possible to applytwo dense clouds). This processing time can be reduced by applying the method to more than two larger sets of surveys. We have simultaneously co-aligned photographs from up to 4 different epochs to obtain a set of mutually comparable point clouds from 2017-2018 (Figure 6). In some cases, an unsuccessful alignment of two surveys can be improved by adding a third survey. For example, if changes in surface appearance (lighting, shadows) or in camera obliquity prevent the detection of sufficient common tie points between the original two surveys, a third survey that generates enough common tie points with each of the original two can lead to successful alignment of all three surveys. However, despite the possibilities for batch processing, the fundamental drawback of this method is that it does not result in a definitive model for a given survey period - models that were constructed based on co-alignment of one set of surveys cannot be re-used for comparison to an additional survey.

While this procedure can yield point clouds that are well-aligned relative to each other and can be robustly compared, the real accuracy of the point clouds is not enhanced. The point clouds still contain errors and distortions, and measurements of distance, area, or volume should be interpreted accordingly. In the Daan river case, the point clouds generated without GCPs had a typical doming distortion, with up to 0.75 m of error on the edges of the model (relative to the GCP-constrained cloud). Thus, where ground control is feasible to obtain, GCP-constrained georeferencing is preferable to the co-alignment workflow if ~~survey-grade accuracy is desired.~~ accuracy on the order of cm or better is desired. The combination of co-alignment and GCPs used by Feurer and Vinatier (2018) demonstrates a potential way forward to efficiently obtain both high real and comparative accuracy. If GCPs can be deployed and measured for just one survey, they can be used in conjunction with the co-alignment workflow to refine the model geometry for additional surveys. This could lead to improved real accuracy for all models while significantly reducing the field time needed for repeat surveys.

5 Conclusions

We show that for environments such as coastal cliffs where the use of ground control points is not possible or not feasible, UAV-based change detection can still be performed with a high degree of confidence if there is sufficient stable area between successive surveys. The workflow we present is quite simple and involves performing image matching and bundle adjustment simultaneously on photographs from pairs or sets of different surveys. This technique may be particularly useful for monitoring processes such as rockfalls, which typically involve steep settings that are difficult to access and exhibit discrete regions of change set within large stable areas.

Author contribution. Both authors carried out the field campaigns and designed the project. KLC did the data analysis and wrote the manuscript with input from MD.

Competing interests. The authors declare that they have no conflict of interest.

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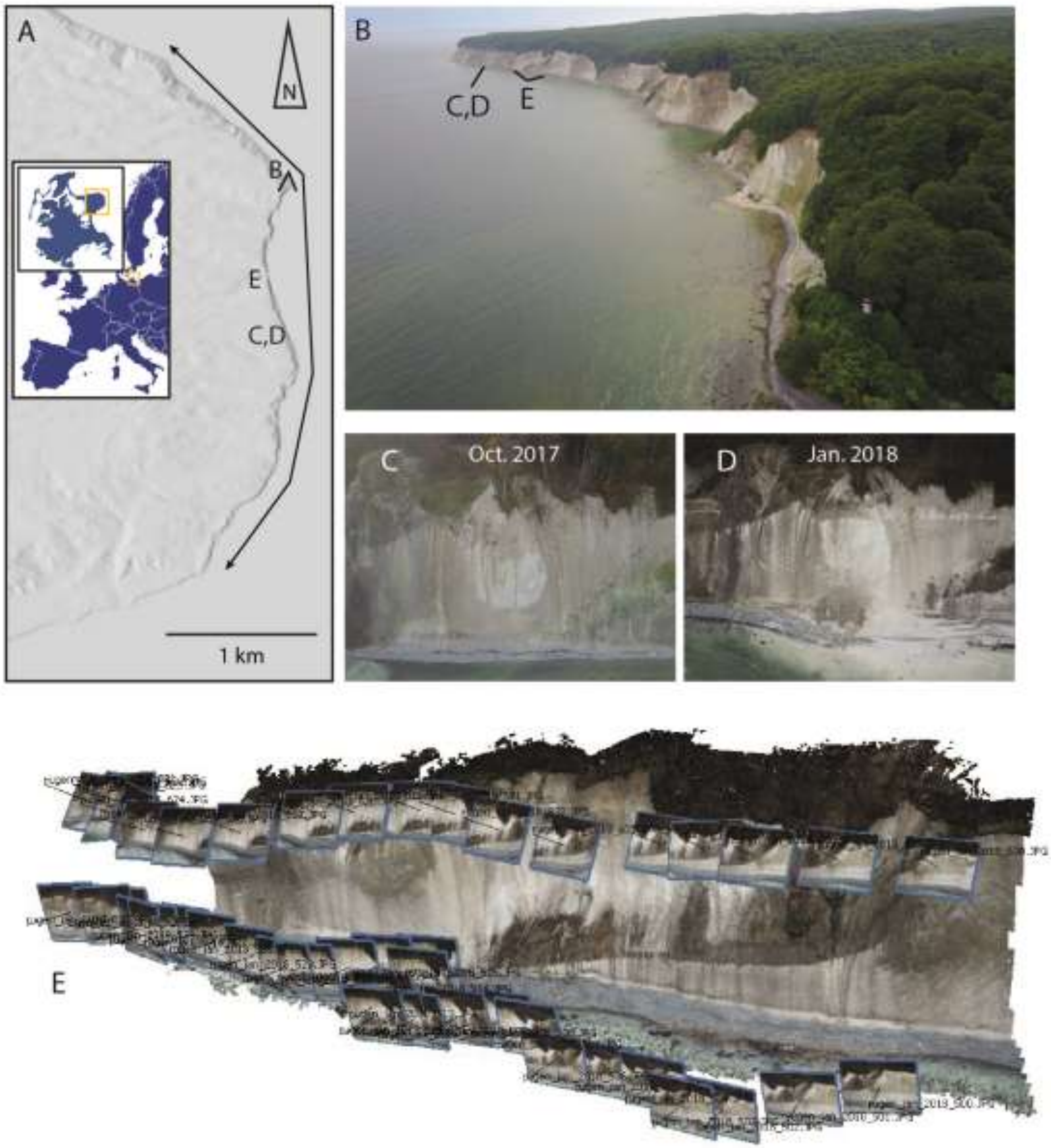


Figure 1: A) Location of the Rügen study area, black line shows the studied coast section and the locations of panels B-E are indicated. B) Photo of the cliff coast in May 2018, view looking south. C) and D) before and after photos of a cliff failure. E) Example of survey geometry, with two passes at different altitudes and camera orientations, from Jan. 2018.

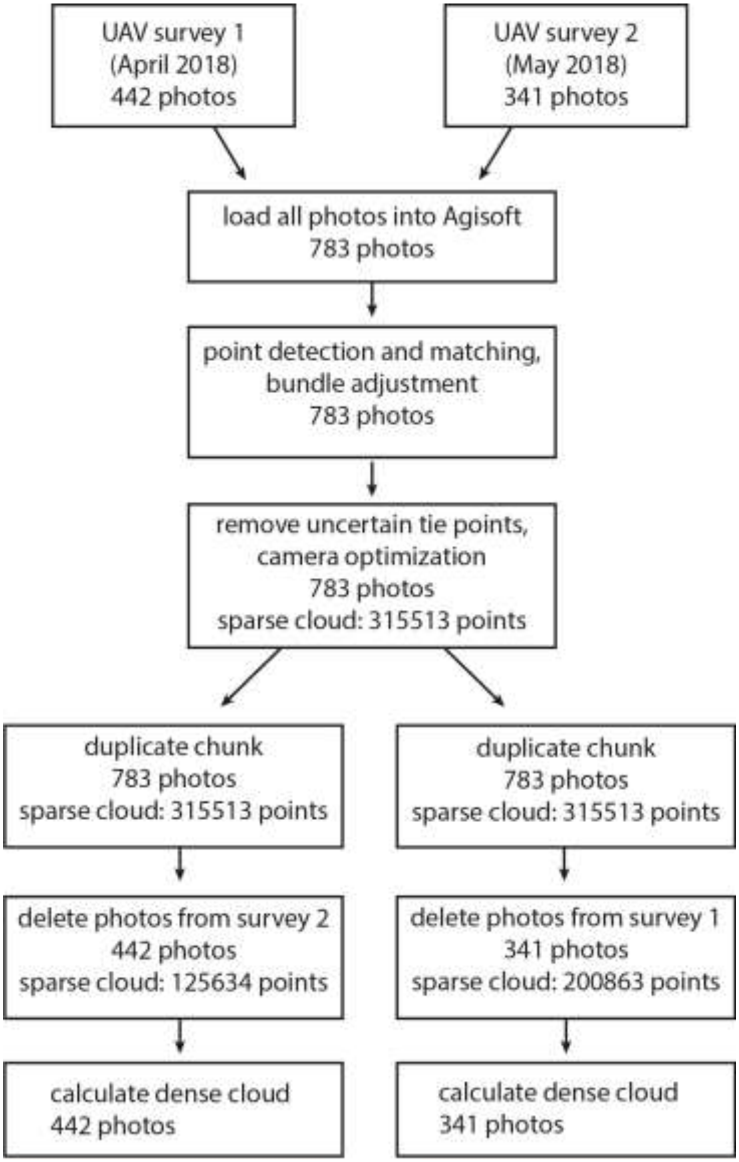
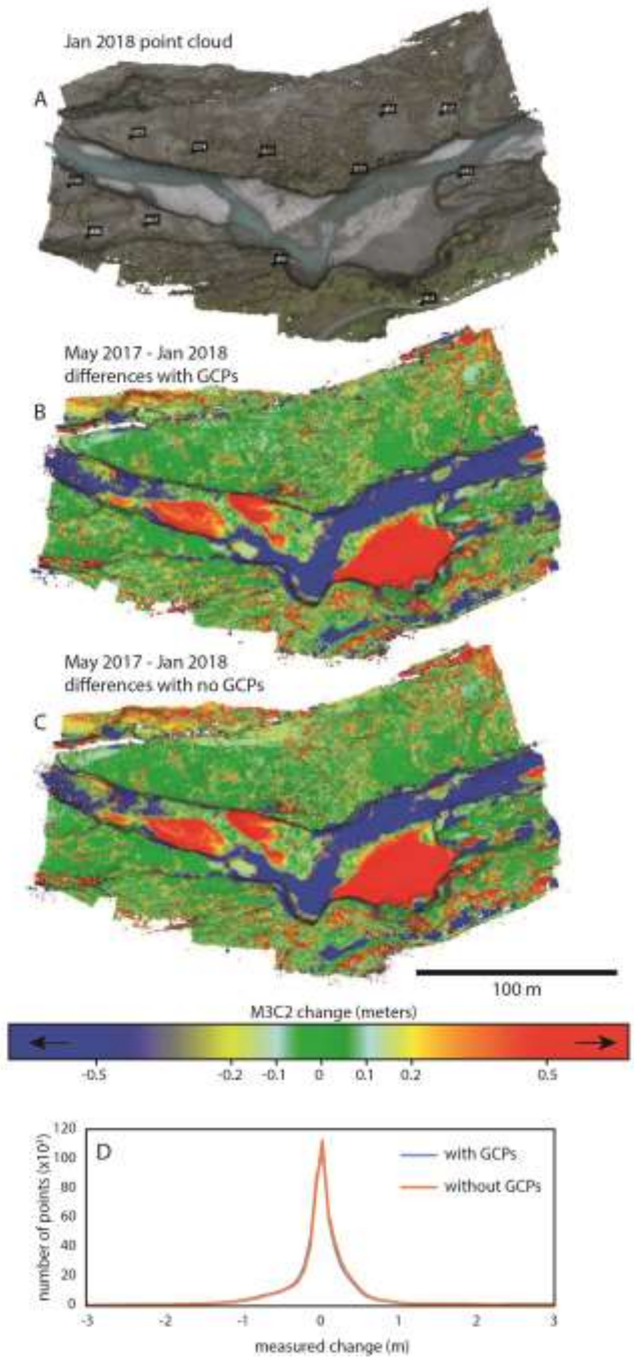


Figure 2: Workflow of the co-alignment processing method, with numbers from the April-May 2018 Rügen comparison for reference.


Jan 2018 point cloud
A
May 2017 - Jan 2018
differences with GCPs
B
May 2017 - Jan 2018
differences with no GCPs
C
100 m
M3C2 change (meters)
-0.5
-0.2
-0.1
0
0.1
0.2
0.5
D
with GCPs
without GCPs
number of points (x10³)
measured change (m)

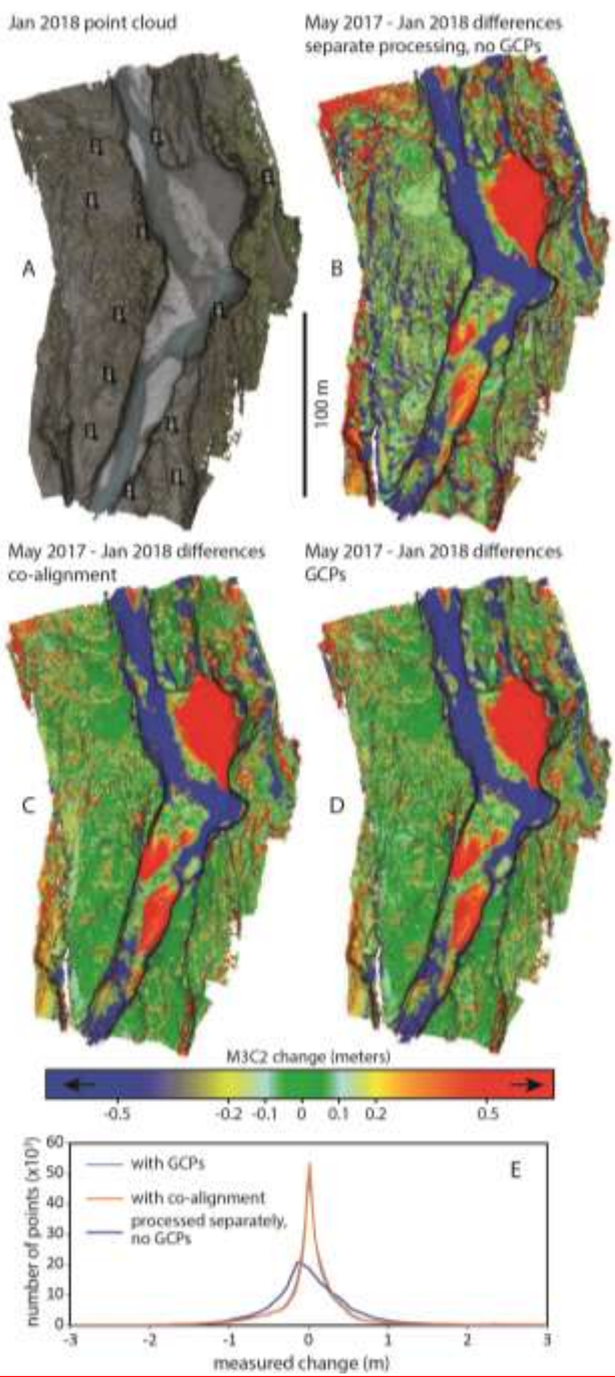


Figure 3: Daan River comparisons. A) Jan. 2018 point cloud with the ground control points shown. B) M3C2 differences between May 2017 and Jan. 2018 point clouds ~~that were~~ processed separately ~~using~~with no GCPs. C) M3C2 differences between May 2017 and Jan. 2018 point clouds processed using the co-alignment workflow. D) ~~Histograms~~M3C2 differences between May 2017 and Jan. 2018 point clouds processed separately using GCPs. E) Density curves of the measured changes shown in B ~~and~~, C, and D.

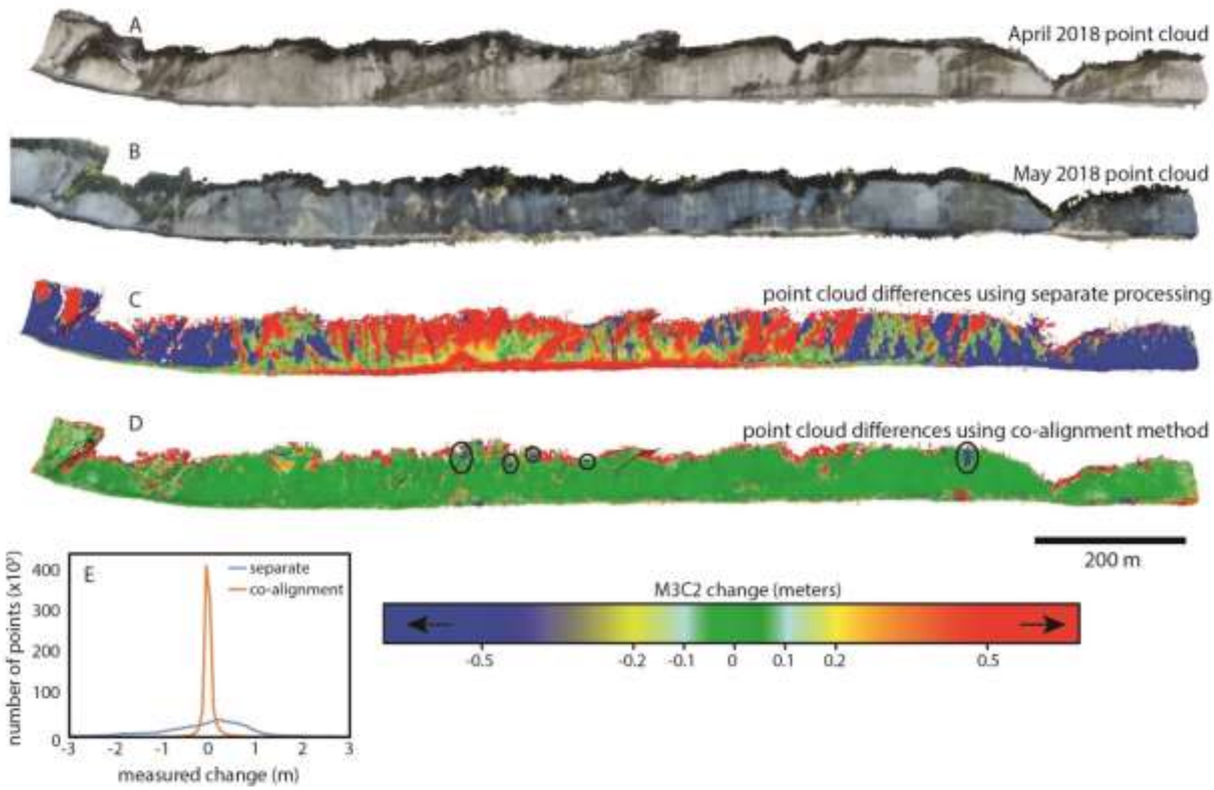


Figure 4: Cloud-cloud differences between the April 2018 and May 2018 surveys in the Kieler Bach section of the coast, calculated using the M3C2 algorithm. A) April 2018 point cloud. B) May 2018 point cloud. C) M3C2 differences between point clouds created using the standard workflow. D) M3C2 differences between point clouds created using the co-alignment workflow. High values of positive change at the top of the cliff are due to leaf growth on the trees. Isolated sections of positive change on the cliff face are also related to growth of bushes and trees. In panel D, several small failure events can be identified on the cliff face (circled). These have been confirmed visually using the before and after photographs. E) ~~Histograms~~Density curves of the measured changes shown in C and D.

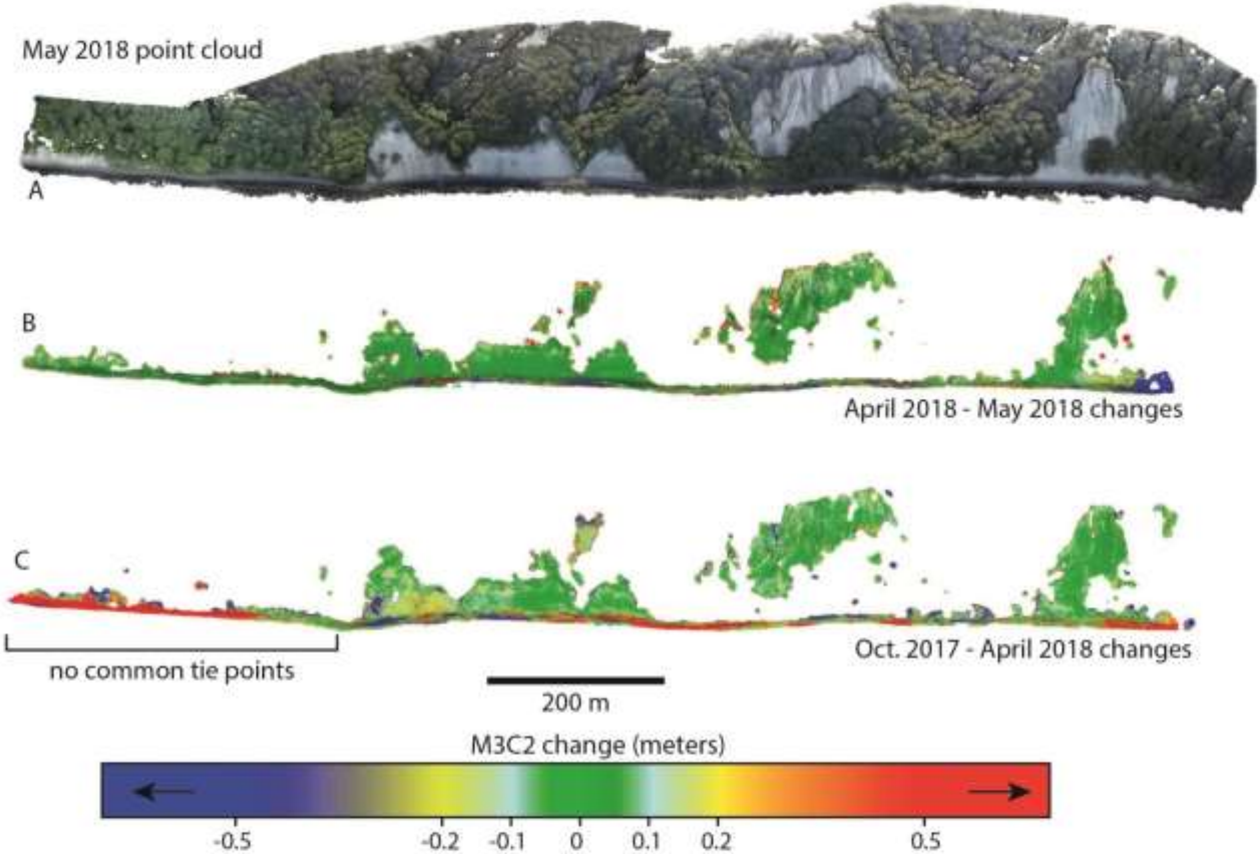
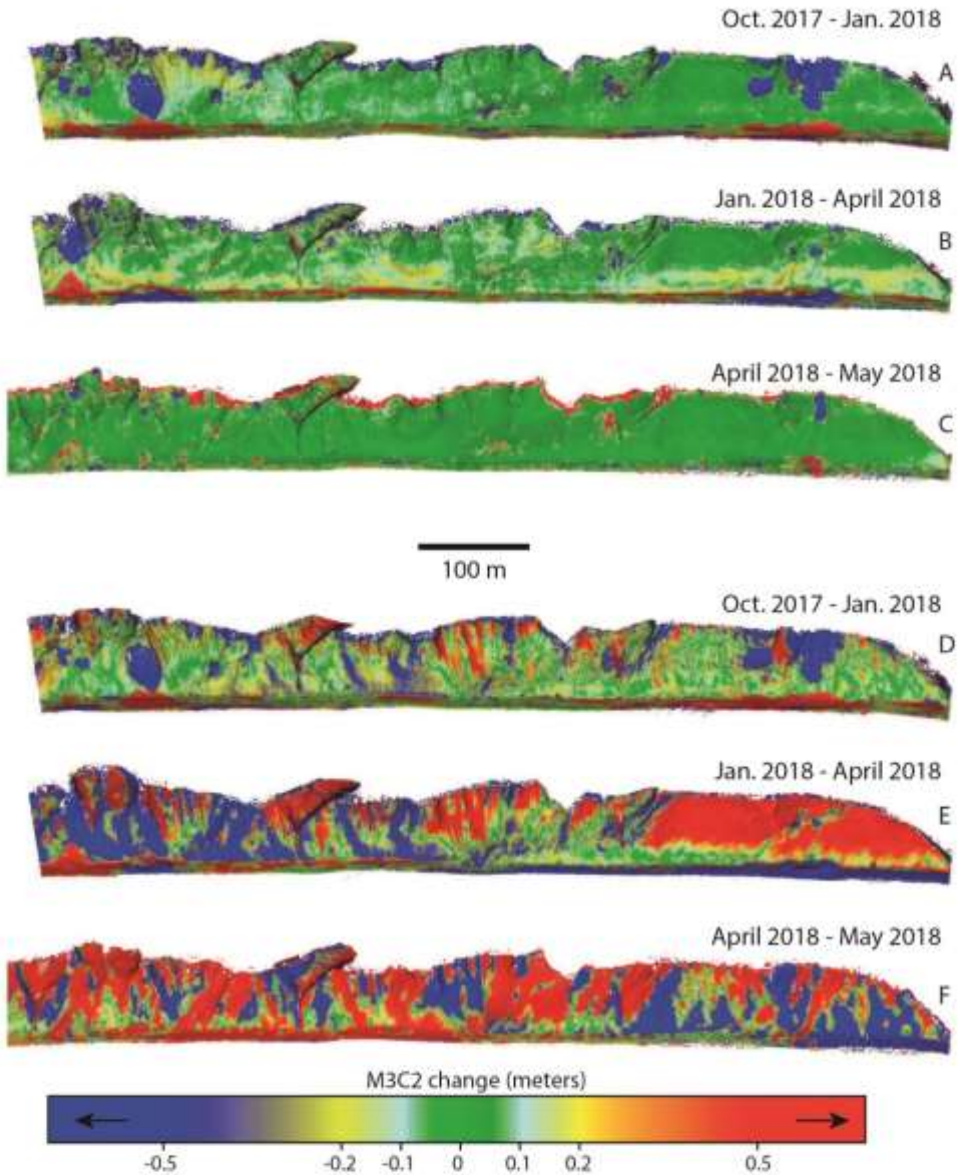


Figure 5: Cloud-cloud differences in the heavily vegetated Königsstuhl section of the coast. A) May 2018 point cloud showing the extent of the vegetation. B) M3C2 differences between April 2018 and May 2018 point clouds. The vegetation has been removed using standard deviation and point density filters. Leaf growth results in very high measured changes in the vegetated areas, so only the bedrock cliff sections are shown. C) M3C2 differences between Oct. 2017 and April 2018 point clouds. A lack of common tie points detected in the left side of the region results in relative distortion of the models and high errors in the change detection.



315 **Figure 6: Changes calculated from batch co-alignment of four surveys simultaneously. A-C) M3C2 changes between successive surveys following simultaneous co-alignment. In panel B) bands of change in the lower half of the cliff show more diffuse erosion due to mechanical weathering. D-F) the same comparisons following the separate processing workflow.**

Survey	UAV	Number of photographs	Sparse cloud points	Common tie points	% Common tie points
~~Kielerbach~~Daan River (figure 3)					
May 17, 2017	Phantom 3 Adv.	197	136479	-	-
Jan. 30, 2018	Phantom 3 Adv.	298	168953		-
Combined alignment		-	304532	900	0.30
-					-
Rügen Kieler Bach (figure 4)					-
April 03, 2018	Mavic Pro	442	125634		
May 29, 2018	Mavic Pro	331	200863		
Combined alignment			313513	12984	4.14
~~Batch processing (figure 6)~~					-
~~Oct. 18, 2017~~	~~Mavic Pro~~	~~839~~	~~363485~~	-	-
~~Jan 24, 2018~~	~~Mavic Pro~~	~~338~~	~~125121~~		-
~~April 03, 2018~~	~~Mavic Pro~~	~~442~~	~~128640~~		-
~~May 29, 2018~~	~~Mavic Pro~~	~~575~~	~~324391~~		-
~~combined alignment~~		-	~~918741~~	~~22896~~	~~2.49~~
-					-
-					-
Rügen Konigsstuhl (figure ~~4~~5)					
April 03, 2018	Mavic Pro	250	111464		
May 29, 2018	Mavic Pro	249	157677		
Combined alignment			264597	4544	1.72
Oct. 18, 2017	Mavic Pro	414	195901		
April 03, 2018	Mavic Pro	246	117227		
Combined alignment			311773	1355	0.43
Rügen batch processing (figure 6)					
~~Daan River~~					-
~~May 17~~Oct. 18, 2017	~~Phantom 3 Adv.~~Mavic Pro	~~197~~839	~~136479~~363485		
Jan. ~~30~~ 24, 2018	~~Phantom 3 Adv.~~Mavic Pro	~~298~~338	~~168953~~125121		
April 03, 2018	Mavic Pro	442	128640		-
May 29, 2018	Mavic Pro	575	324391		-

Combined alignment	~~304532~~918741	~~900~~22896	~~0.30~~2.49

Table 1: survey characteristics