We thank the referee for the constructive comments and helpful suggestions. We adapted the methodology accordingly and revised the manuscript with regards to the comments, which we feel helped to improve the manuscript. We will upload a revised version of the manuscript and below provide a point-by-point response to the comments. Our response is structured as follows: (1) referee comment, (2) author's response and (3) changes in manuscript.

Many thanks and best regards,

Carolin Kiefer, on behalf of all authors

C1: 'Comment on esurf-2021-23', Anonymous Referee #1, 23 Apr 2021

The manuscript "A 4,000 year debris-flow record based on amphibious investigations of fan delta activity in Plansee (Austria, Eastern Alps)" (esurf-2021-23) presents an exceptional record of debris flow events in Lake Plansee and its catchment in the Eastern Alps. Kiefer et al. combine a detailed geomorphological analysis of fan deltas using LiDAR data and swath bathymetry to a sedimentological analysis of lacustrine deposits to analyze sediment delivery by debris flows to the depo center of the Lake. By analysing the occurrence rate of debris flows as recorded in sediment cores, the authors propose a sharp increase in the occurrence of debris flows in the 20th and 21st century linked to an increase in rainstorm frequency.

(1) The manuscript is generally well written and structured with the exception of a lengthy and at times contradictory discussion at the end of the manuscript (see minor remarks). The only major shortcoming of the manuscript in its present form is the analysis of occurrence rates (see major remark), which cannot account for changes on sub-millenial time scale. Parts of the results and conclusion (including the 7-fold increase at the beginning of the 20st century) might be artefacts of the sampling strategy. Therefore, I recommend reconsidering the manuscript once a viable methodology has been adapted and the manuscript has been updated accordingly. I hope my comments to be helpful during the revision of the manuscript.

Major remark

The temporal analysis of occurrence rates is neither robust nor valid in the present form of the manuscript. Any analysis of the frequency spectrum of events in lake archives is essentially an analysis of the underlaying age-depth function. As I understand it, you are using the mean (or median) scenario from Bacon, which is constrained by seven age estimates for the last 4000 years (see Figure S2). The corresponding sampling rate of one age estimate per 500 years cannot resolve potential rapid sedimentation changes in this record. This sampling rate restricts the analysis to the millennial frequency band (see Nyquist-Shannon sampling theorem). Changes in higher frequency bands (as analyzed in the 21-yr window, see line 255) cannot be resolved. As a result, the inferred changes in occurrence rates during period 1 to 4 might be pure artefacts of the sampling strategy.

Obviously, an analysis of debris flows in the millennial frequency band is not satisfying, especially considering the detailed record at hand. From my point of view, there are two viable options for increasing the resolution of your analysis:

- Increase the sampling rate for the mean age-depth function. An analysis in decadal resolution requires at least two age estimates per decade. Varve counting could be a viable option if the finely laminated sediments in your record represent annual laminae.
- Making use of age uncertainty. Blaauw et al. (2018) showed, that a sample rate of two samples per millennia (as in this case) stabilizes the precision of Bayesian age-depth models. This

suggests that individual simulations of Bacon can mimic higher-frequency changes in sedimentation patterns. Repeating the frequency analysis for different Bacon model simulations in a Monte-Carlo approach could therefore be used to decrease the bandwidth and construct confidence limits on the occurrence rates. Individual model simulations of Bacon are readily accessible in the output of the algorithm (with accumulation rates (years per spacing) usually stored as .out file in the default folder). I am not sure how much this approach would allow to decrease the bandwidth, so I suggest coupling your analysis with a suitable bandwidth selection test (see e.g. Muddelsee, 2014 or Merz et al., 2016 and references therein).

There might be other approaches, but the design of the frequency analysis in its current form requires major revisions to make inferences on debris flow occurrence robust and bring it in line with the excellent set up of this study.

(2) We thank the referee for this important remark along with providing potential options to improve our frequency calculations. We fully agree with the referee, that the presentation of the occurrence rate of df turbidites solely based on their mean ages was imprecise in the previous manuscript, as the age model uncertainties were neglected. In the revised manuscript we have now followed the referee´s recommendation to apply the frequency analysis on a data-based bandwidth coupled with the presentation of the age uncertainty also in the occurrence rate plot as provided by the individual simulations of the age–depth modelling software Bacon (see more details in the specific reply comment below). With this, we think, that the revised version of the manuscript could be greatly improved and now addresses the main critical comment by the referee. However, we do not fully agree with the referee, that in a lacustrine setting the bandwidth selection must follow the Nyquist–Shannon sampling theorem. Lacustrine sedimentation in deep open lakes contain the important characteristic that they are often and in general continuous. In turn, continuous sedimentation adds confidence in reducing the bandwidth for frequency analyses, which has also been done in the past by a similar amount of age constraints and number of event deposits (see e.g. Wirth et al. 2013 and references therein).

In Plansee there are no indications that support drastic changes in sedimentation rate:

- Especially in such finely-laminated, mixed hemipelagic-clastic sediments as present in the sedimentary archive of Plansee, abrupt shifts in sedimentation also cause changes of the **lithotype**. Looking at the core images in Figure 7A, the only striking lithotype change is at the phase 2–phase 3 boundary. As this stratigraphic level is well dated with a radiocarbon date immediately (2 cm) below, we implemented it now as a stratigraphic "boundary" for the age depth modelling in Bacon, facilitating the model to change sedimentation rates if required given the distribution of the radiocarbon dates that inform the model (see revised supplement Figure S2). Therefore, also some of the reported ages slightly changed compared to the previous manuscript especially between 1920–1700 CE.
- Accompanying a change in lithotype, abrupt shifts in sedimentation rate in a clastic lake like Plansee would also cause a thickness increase of laminae, which is not observable in the Plansee sediments.
- Furthermore, abrupt shifts in sedimentation rate caused by phases of enhanced event deposition can be neglected, as all event deposits >5 mm are cut out from the age–depth model resulting in an event-free sediment depth, as also outlined in Line 249 in the revised manuscript.

We highly appreciate the potential options provided by the referee. Varve counting is not an option for this manuscript, because given the high amount of event deposits, varve counting may severely underestimate the ages. Imagine each deposit eroded 1 mm, meaning that with a total of ~138 events and a mean sedimentation rate of 0.45 mm/yr about 307 years of sediment are gone. Such potential minor erosion would artificially enhance peaks in the accumulation curve. Moreover, varve counting would lead to a completely different manuscript and would distract from the main focus of this work, as we aim to trace the major debris flow events from onshore to offshore in a multidisciplinary way. Due to the oxic condition at the bottom water, we would also not expect to have a high preservation potential of varves. However, if the laminae are varves, these are most likely mixed biogenic–clastic varves, where a fundamental part of the varve is built up by the annually clastic input during the spring and summer months (basically the df turbidites). As we aim to study frequency of df turbidites, also using these as an age-constraint would lead to a circular reasoning.

Therefore, as also suggested by the referee, we made use of the age uncertainty provided by the age-modelling software Bacon and coupled this with a suitable bandwidth selection test. First, we applied a bandwidth selection test based on the number of df turbidites after Sheather and Jones (1991), which is also widely used e.g. for kernel statistics and often recommended in data science. This results in a bandwidth of 150.2 years for the whole 4,000 year record and in 16.5 years for the last two centuries, where df frequency is clearly enhanced. Second, we applied the frequency analysis using this 150-yr bandwidth on the event ages of each of the 6,396 individual age-model simulations derived from Bacon. The frequency analysis (with 150-yr bandwidth) on all simulations results in a 95% uncertainty belt providing a general overview of df turbidite frequency over time (Figure 8a), but likely underestimates/smoothens the actual frequency changes where more frequent events occurred, e.g. in the last two centuries. To overcome this issue, we coupled the 150-yr bandwidth occurrence rate diagram with the 21-yr frequency curve of the mean age to also provide a more detailed view on the frequency changes, especially where a higher number of events are present (e.g. the last two centuries). While this 21-yr frequency might be oversampled for the whole 4,000 year record, enough age constraints in the last century (1 coring date, 2 radionuclide ages, 1930 earthquake-induced turbidite) and high event frequency allows for more detailed bandwidth in the frequency analyses. Although we now provide the 21-yr and the 150-yr frequency curves for the whole record, we only discuss the detailed 21-yr frequency changes for the last century in more detail (see Lines 526–530).

The general frequency changes are also represented in the 150-yr frequency plot i.e. increased frequencies after the ~2120 BCE earthquake and for the last century (see Figure 8a), which further supports the interpretation of actual increased df activity at these times. We explain this approach in the methodology section in Lines 271–280 and in the results section in Lines 496–498 in the revised manuscript. Furthermore, we also added the age uncertainty range to the cumulative thickness curve (Figure 8a, Lines 280–281) and to the df turbidite table in the supplement (Table S4). However, we kept the mean ages for the thickness plots, as introducing age uncertainties would make this bar plot unreadable.

Wirth, S. B., Glur, L., Gilli, A., and Anselmetti, F. S.: Holocene flood frequency across the Central Alps - solar forcing and evidence for variations in North Atlantic atmospheric circulation. Quat. Sci. Rev. 80, 112–128. doi:10.1016/j.quascirev.2013.09.002, 2013.

Sheather, S. J., & Jones, M. C.: A reliable data-based bandwidth selection method for kernel density estimation. Journal of the Royal Statistical Society: Series B (Methodological), 53(3), 683–690, 1991.

(3)

>Line 249
"For the age–depth modelling, event deposits >5 mm were removed to obtain an event-free sediment depth."

>Lines 271–281
"Additionally, we calculated the annual occurrence rate of df turbidites using a central running sum with different bandwidths to reconstruct changes in debris-flow frequency over time in different resolutions. First, a suitable bandwidth (150 yrs) was selected based on the average df-turbidite occurrence over the entire core (Sheather and Jones, 1991). We applied this bandwidth on the occurrence rate calculation for each individual simulation of the age–depth model derived from the R-software Bacon v 2.4.3 (Blaauw and Christen, 2011). This results in a data-based frequency analysis that incorporates age–depth model uncertainties. The rather broad bandwidth is suited for showing general changes in frequency over time. To account for a higher resolution in frequency changes especially in periods with higher number of events, we also calculated a bandwidth based on the df occurrence of the last two centuries and applied the resulting 21-yr bandwidth to occurrence rate calculation of the main age. The cumulative thickness over time involves both the thickness and frequency of df turbidites and its slope provides information on df turbidite accumulation rate per year. We calculated the cumulative thickness on the mean values and the 95 % range values of the age–depth model to transfer age uncertainty to the cumulative thickness analysis."

>Lines 496–498
"The frequency analysis of the whole 4,000 year df turbidite record is based on a 150-yr bandwidth, whereas especially the higher number of events in the 20th century requires higher resolution frequency analysis, here on the basis of a 21-yr bandwidth (Fig. 8a)."

>Lines 526–530
"Df phase 4.1 is represented by a strong and fast frequency increase at ~1920 CE, followed by a period of highly frequent debris-flow events ~1980 CE. Since then, the current df phase 4.2 has lower frequencies relative to phase 4.1 but still by far higher frequencies than in the main df phases 1–3. Debris-flow frequency in 4.1 increased by a factor of 8 compared to the reference df phase 3. In df phase 4.2, debris-flow frequency increased by a factor of 7 compared to df phase 3."

Minor comments

(1) Line 255 to 257: Please add a detailed description of the occurrence rate estimation once the approach has been adapted.

(2) We addressed this comment by adding a detailed explanation on our approach in the methodology section in Lines 271–280. Please see the reply to the major remark above for more details to the revised approach, that follows the referee's suggestion.

(1) Line 489–490: I can´t detect any changes in the mean thickness of layers during phase 3. The cumulative function stays linear in my opinion. Can you quantify the change?

(2) We thank the referee for hinting at this flaw. The mean thickness of debris-flow deposits increases in the second half of df phase 3, but we cannot deduce exponential growth. We deleted this sentence and now only describe the frequency change between the phases, where the increase can be quantified

by the change of accumulation rate of df turbidites from 0.1 mm/a (df phase 2) to 0.2 mm/a (df phase 3) as outlined in the revised manuscript in Lines 521–522 and also noted in Figure 8a.

(1) Line 574: Consider replacing “prove” with “suggest”.

(2) We thank the referee for the suggestion. We revised to “suggest” in Line 593.

(3)

>Lines 593–594
„Overprinted lobes of few large debris flows on the active subaquatic fan area suggest that terrestrial deposition dominates recently.”

(1) Line 618–624: Has the vegetation cover stayed constant during the last 4,000 years? Are there pollen records from Lake Plansee or different archives in the Eastern Alps which back up your line of argument?

(2) We agree with the referee that further information from pollen is needed to substantiate our statement. The next pollen record comes from Heiterwanger See a few kilometres west of Plansee. The pollen record reveals first signs of permanent settlement during the Iron Age. Local forest clearance in the centuries around the beginning of the Common Era created arable land and resulted in vegetation changes (Oeggl 2004, Kral 1989). The following Migration Period is characterized by little human activity and reforestation. A period of enhanced forest clearance occurred during medieval times. Agriculture and grazing played a larger role then compared to today. The deposits in the sediment core from lake Plansee show no sudden increase in debris flow frequency during this period of intense forest use. Pollen diagrams from an adjacent Alpine area (Ostallgäu) let us infer that in the Plansee area, forest clearance and settlement decreased during the Little Ice Age (Stojakowits & Friedmann, 2013). No marked increased forest clearance is reported since medieval times and we added this information to the respective paragraph (Lines 635–644).

Kral, F.: Pollenanalytische Untersuchungen im Fernpaßgebiet (Tirol): Zur Frage des Reliktcharakters der Bergsturz-Kiefernwälder. Verhandlungen der Zoologisch-Botanischen Gesellschaft von Österreich 126: 127–138, 1989.

Oeggl, K.: Palynologische Untersuchungen zur vor- und frühgeschichtlichen Erschließung des Lermooser Beckens in Tirol – Berichte der Reinhold-Tüxen-Gesellschaft – 16: 75–86, 2004.

Stojakowits, P. and Friedmann, A.: Pollenanalytische Rekonstruktion der Vegetations- und Landnutzungsgeschichte des südlichen Ostallgäus (Bayern). In: TELMA - Berichte der Deutschen Gesellschaft für Moor- und Torfkunde, Band 43, 55–82, DOI 10.23689/fidgeo-2867, 2013.

(3)

>Lines 635–644
“Human-induced vegetation changes are documented since about 1,000 BCE from a pollen record from peat bog remnants at Heiterwanger See a few kilometres west of Plansee (Kral, 1989). A period of enhanced forest clearance in the area happened during medieval times according to this record. The herein presented sedimentary record of Plansee shows no signs of a drastic increase in debris-flow frequency throughout this period of intense forest use. During late medieval times, the climatic deterioration of the Little Ice Age, war, and epidemics led to a decrease in population and in forest clearance, which can be observed in pollen diagrams from the nearby Ostallgäu (Stojakowits and

Friedmann, 2013). Since then, no further increase of forest clearance or wildfires is reported in the area. Therefore, we infer that there were no significant changes of vegetation before or during the period of increasing debris-flow frequency in the last century (df phase 4)."

(1) Line 647: How can you be sure, that both layers correspond to the heavy rainstorms in 1999 and 2005, especially considering age uncertainty and that not every df turbidite has a corresponding rainstorm event (see lines 652-653)?

(2) We have addressed this comment and added more clarity on the uncertainty by adding "potential temporal overlap" to the sentence in Line 676 and by stating the age uncertainty (Lines 684–685).

(3)

> Line 676
"Potential temporal overlap of two df turbidites with the two heaviest rainstorms of the century in 1999 and 2005 CE (Fig. 8b) let us infer that regional (advective) rainstorms lasting over several days are a trigger mechanism of debris flows also in the Plansee region."

>Lines 684–685
"Potential mismatches might also be due to the age error of df turbidites, which has a 95 % probability range from 5 years for the youngest event to 60 years at the begin of df phase 4."

(1) 649-651 You stated in line 540-541, that you would refrain from detailed comparisons to other flood deposits.

(2) We refrain from a detailed (statistical) comparison to other flood deposits for discussing potential climatic drivers on debris-flow activity, because of the greater age uncertainties in our df turbidite record. However, we do not consider the qualitative comparison of several outstanding thick df turbidites in the first and eighth century BCE to enhanced flood activities from other archives as detailed.

(1) Line 661-664 This passage is difficult to relate to passage iv (line 625-634), in which you argue that human influence enhanced coastal erosion and subsequently the volume (not the frequency) of debris flows. If it is only influencing the volume of debris flows, how can human influence affect the frequency of debris flows recorded in the core?

(2) We clarified the possibility that some of the df turbidites in the first of half of the 20th century might reflect human-induced mass wasting events in passage iv (Lines 649–650).

(3)

>Lines 649–650
"Therefore, some of the df turbidites in the first half of the 20th century might actually reflect human-induced mass wasting (see also vi)."

(1) Line 666-667: Does "we" refer to this study or to the results of Diedrich and Krautblatter, 2017?

(2) We increased the clarity by adding "as previously observed" to the sentence in Line 698.

(3)

>Lines 697–699
"Moreover, we herewith provide sedimentological evidence for the increased debris-flow activity in the 20th century, as previously observed on differential LiDAR data from several fans at the northern shore of the lake (Dietrich and Krautblatter, 2017)."

(1) Line 673-676: The absence of other increases in occurrence rates might be an artefact of the applied methodology (see major remark).

(2) We kept the interpretation that debris flow activity is strongly controlled by local high-intensity convective precipitation, as also after applying the frequency calculations on the appropriate bandwidth (150 years) there are no larger frequency changes except the one for the 20th century and after the ~2120 BCE earthquake (Lines 718–720).

(1) Figure 4: The main channel in August is difficult to distinguish from the red background on the map.

(2) We have changed the color of the main channel outline for better visibility.

(1) Figure S2: Age units correspond to BP in this figure, in contrast to BCE/CE notation in the rest of the manuscript.

(2) We have changed the notation to BCE/CE in the new Figure S2.

(1) Table S2: This table only contains five 14C measurements, contrary to six radiocarbon dates shown in Figure S2.

(2) We thank the referee for pointing out this mistake. We have added the other radiocarbon date to Table S2.

We thank the referee for the constructive and insightful comments which we feel helped to improve the manuscript. We will upload a revised version of the manuscript and below provide a point-by-point response to the comments. Our response is structured as follows: (1) referee comment, (2) author's response and (3) changes in manuscript.

Many thanks and best regards,

Carolin Kiefer, on behalf of all authors

RC2: 'Comment on esurf-2021-23', Anonymous Referee #2, 28 May 2021

General comments

The submitted study shows the timing over 4000 years of debris flow events from transport-limited catchments, much of whose deposits extend into an adjacent Lake, creating subaqueous geomorphic field evidence by lacustric deposits. The knowledge of such a long time series is, besides geomorphological interest, also important in connection with positive trends in climate change, or land use, exposure, etc. and gives valuable insight to recent dynamics in the occurrence of debris flow events. The article is basically well written and understandable. The literature cited is up to date and, and here I focus exclusively on the presentation of an extraordinary time series of debris flow events, an important and pioneering contribution to the research community.

(1) Precisely because, at least to me, no comparably long historical review of debris flow events is known, a publication of such a time series requires precise information on uncertainties due to the applied methodology and a discussion of how to deal with it.
Above all I recommend focusing on the creation and trend analysis of the surveyed frequency representation of such a long (and valuable) debris-flow time series, improving reliability of the time series.

(2) We thank the referee for this remark on the reliability of the debris-flow time series. We fully agree that calculating the age model uncertainties is a necessary improvement on the precision of our frequency calculations. In the revised manuscript, we present an improved age model, which now provides ages at 1 mm steps. In addition, we apply a frequency analysis on a data-based bandwidth coupled with the presentation of the age uncertainty also in the occurrence rate plot as provided by the individual simulations of the age-depth modelling software Bacon. For a more detailed answer and the changes in the manuscript, please view our answer to the major comment on uncertainties of age dating below.

(1) All terrestrial and bathymetric observations should be either shifted to a second paper or significantly shortened.

(2) We thank the referee for the suggestion. In the first version of our manuscript, we did not put enough emphasis on describing the necessary and previously underestimated link between on- and offshore morphological studies and the debris flow turbidite record. Finding evidence for the underlying processes was a prerequisite for defining identification criteria and understanding the event stratigraphy in the sediment cores. The geomorphic description of debris-flow fan evolution should therefore not be decoupled from the event deposit interpretation. We shortened the manuscript with regards to recent morphological changes (e.g. section 5.2) and put more emphasis on conclusive

system understanding from a source-to-sink perspective. For a more elaborate explanation, please refer to the answer on the first specific major comment below.

Specific major comments

(1) The introduction to the study describes the need for knowledge of long-term time series, with the reader curious about this 4000-year survey. Interestingly, however, it talks about a combination of several geomorphological surveys in different depositional domains. First of all it must be noted that for the creation of the time series it is not comprehensible why on two selected fans a terrestrial and bathymetric evaluation is carried out, which is not related to the time series collected and analyzed due to lacustrine deposits at all. It is argued that the coupled study of debris flow systems on land and underwater will provide new insights into geomorphic expressions from the catchment to the depocenter provide? So what exactly are these new insights and how do they relate to a 4000 year time series? I was under the impression that it was more like two stories in one study. Whereby the terrestrial as well as bathymetric studies are mainly closer in the context of the already published article by Dietrich and Krautblatter (2017). By the way, since the onshore measurement is based on two LiDAR measurements within a year, the question arise how does one use this to elucidate the relationship between terrestrial and subaquatic deposition of recent debris flows? In other words, how and why should the rates differ from chance - based on the scarcity of data? My suggestion would therefore be that the authors refer, in the present article, more or exclusively to the survey of lake sediments and their statements in connection with debris flow frequency. Although the terrestrial and bathymetric investigation contains some interesting and further information, they seem to be dispensable for the creation of the 4000 years time series. It would be more exciting to focus on the time series of debris flows and find out how well you can determine the frequency based on sediment core analyses.

(2) The referee expresses concern on the link between the geomorphic study and the observations in the sediment cores. In this article, we establish a general understanding of how the major debris flows are transported to their final sink and how their deposits are distributed in the basin before interpreting the turbidite layers found in the 4,000 year time series. On- and offshore geomorphic investigations provided the following new insights: (i) we uncover conclusive evidence of subaquatic debris-flow deposits and subaquatic landslide deposits, which enables us to pinpoint the detrital layers to single debris-flow events and subaquatic slope failures in the sediment cores (Fig. 3); (ii) we justify the transect and coring site selection by documenting the recent debris-flow activity and subaquatic expressions on different fan delta types and their catchments (Lines 156-161); (iii) we link wedge-shaped deposits throughout the 4,000 year sediment profile to low-energy debris flow-activity on the juvenile fan delta (Lines 606-614); and (iv) we correlate subaquatic deposits showing high backscatter signals with previously mapped terrestrial debris-flow deposits from 1947 to 2014 (Fig. 2).

The referee doubts the representativeness of our onshore data due to the limited observation period of only three months. We agree on this statement, but by including the bathymetric data and further assessing the evolution of debris flow-deltas, we can understand the geomorphic system and implement the shorter recorded period into a longer framework. The bathymetric data confirmed active progradation on the juvenile fan delta and its significant contribution to the subaquatic sediment deposition, which was indicated by the TLS results. We therefore chose the juvenile fan as a starting point for the core transect. We changed the text (Lines 580-586) accordingly.

(3)

> Lines 18-25

“The amphibious geomorphic investigation of two fan deltas in different developmental stages revealed an evolutionary pattern of backfilling and new channel formation onshore together with active subaqueous progradation on a juvenile fan delta and major onshore sediment deposition and only few but larger subaqueous deposits on a mature fan delta. Geomorphic evidence for stacked and braided debris-flow lobes, subaquatic landslide deposits, together with different types of turbidites in sediment cores facilitated a process-based event identification i.e. debris-flow or earthquake-induced turbidite of the 4,000 year sedimentary record. We directly correlate subaqueous lobe-shaped deposits with high backscatter signals to terrestrial debris-flow activity of the last century. Moreover, turbidite thickness distribution along a transect of four cores allows to pinpoint numerous events to debris-flow activity on a juvenile fan delta.”

> Lines 78-81

“For a conclusive identification of debris-flow turbidites in the sediment core, we map geomorphic landforms in both the subaquatic and terrestrial realms, which document the interplay between the terrestrial source area, the terrestrial and subaqueous sediment transport, potential temporary storage on the fan delta and the final sink in the depocentre.”

> Lines 156-161

“An amphibious geomorphological investigation allowed to assess the influence of catchment conditions, delta dynamics, and deposition patterns and to define additional identification criteria for different processes in the event stratigraphy. The determination of geomorphic landforms i.e. debris-flow deposits quantitatively onshore on a seasonal time scale, and qualitatively on the subaquatic slope gives a general understanding of the system connectivity. Differences in the subaquatic distribution of deposits due to catchment and delta characteristics can be identified and the selection of a transect and coring site can be justified (see Sletten et al., 2003; Irmler et al., 2006).”

> Lines 213-215

“Preceding evaluation of recent fan delta activity in combined LiDAR and bathymetric data defined a suitable fan delta from which the core transect was taken towards the distal depocentre at intervals of 50-75 m (Fig. 1).”

> Lines 451-452

“Besides the event-type distinction based on sedimentological and geochemical parameters, identification and mapping of the respective geomorphic expressions in bathymetric data (Fig. 3a) allows conclusive interpretation on df- and eq turbidites.”

> Lines 580-586

“Due to the limited observation period of three months, the TLS data is not representative when it comes to longer time periods. Nevertheless, we can deduce that deposits currently located in the depositional area of the juvenile fan delta are rapidly subjected to consecutive transport to the lake. Since the juvenile fan contributes more to the subaquatic sediment deposition compared to the mature fan delta, this fan was chosen as a starting point for the core transect.

The discovery of lobe-shaped deposits with high backscatter signals on the subaquatic delta continuation of the juvenile fan provides evidence for recent debris-flow activity and active fan progradation on the juvenile fan. In addition, subaquatic landslide deposits reveal a second process contributing to event deposition in Plansee.”

> Lines 606-614
“In contrast, 14 df turbidites with a major thickness in the fan-proximal cores (black arrows in Fig. 7b) form wedge-shaped sediment bodies near the slope break and can be explained by low-energy debris-flow activity on the juvenile fan, which may be caused by shifts in the delta morphology, (e.g. formation of multiple branching channels) or changes in the connectivity between catchment and depocentre. The linkage of these sediment deposits to the investigated juvenile fan delta reveals that its particular catchment has shown episodic debris-flow activity over at least 4,000 years. Moreover, the sedimentary record holds a short period of exclusively wedge-shaped df turbidite sedimentation (“P” bracket in Fig. 7b), which occurred immediately after the 2120 BCE earthquake expressed as multiple subaqueous mass-wasting deposits overlain by the eq3 turbidite (Fig. 7a; Oswald et al., 2021).”

> Lines 710-715
“Actualistic debris-flow processes and their corresponding deposits are characterized by their geomorphic landforms in both the terrestrial and subaqueous realms. In a transect of four sediment cores from an active juvenile fan towards the distal basin, we distinguish debris flows and earthquakes to be related with different turbidites based on their geomorphological, sedimentological and geochemical characteristics. Debris flows form lobe-shaped deposits with high back-scatter signals on the subaquatic prolongation of a subaerial active channel on the fan delta.”

(1) Concerning the lacustrine event deposits, I find the methodology for event type differentiation very exciting and comprehensible, also in the awareness that it is one of the rare opportunities to observe the process of debris flow in a relatively uninfluenced setting (which, by the way, is also well executed). Nevertheless, the following data processing raises questions.
My mainly concerns regarding this study relate primarily to the uncertainties of age dating. What uncertainties are there in the temporal determination? Which in the event detection? How do these affect the calculated frequency?

(2) We thank the referee for making an important remark on the age-model accuracy. In our new manuscript, we show a revised approach following comments of both referees, which we think greatly improved the age-depth model. We made use of the age uncertainty provided by the age-modelling software Bacon and coupled this with a suitable bandwidth selection test. First, we applied a bandwidth selection test based on the number of df turbidites after Sheather and Jones (1991), which is also widely used e.g. for kernel statistics and often recommended in data science. This results in a bandwidth of 150.2 years for the whole 4,000 year record and in 16.5 years for the last two centuries, where df frequency is clearly enhanced. Second, we applied the frequency analysis using this 150 years bandwidth on the event ages of each of the 6,396 individual age-model simulations derived from Bacon. The frequency analysis on all simulations results in a 95% uncertainty belt providing a general overview of df turbidite frequency over time (Figure 8a), but likely underestimates/smoothens the actual frequency changes where more frequent events occurred, e.g. in the last two centuries. To overcome this issue, we coupled the 150-yr bandwidth occurrence rate diagram with the 21-yr frequency curve of the mean age to also provide a more detailed view on the frequency changes, especially where a higher number of events are present (e.g. the last two centuries). While this 21-yr frequency might be oversampled for the whole 4,000 year record, enough age constraints in the last century (1 coring date, 2 radionuclide ages, 1930 earthquake-induced turbidite) and high event frequency allows for more detailed bandwidth in the frequency analyses. Although we now provide the 21-yr and the 150-yr frequency curves for the whole record, we only discuss the detailed 21-yr frequency changes for the last century in more detail (see Lines 526-530).
The general frequency changes are also represented in the 150-yr frequency plot i.e. increased frequencies after the ~2120 BCE earthquake and for the last century (see Figure 8a), which further supports the interpretation of actual increased df activity at these times. We explain this approach in

the methodology section in Lines 271-280 and in the results section in Lines 496-498 in the revised manuscript. Furthermore, we also added the age uncertainty range to the cumulative thickness curve (Figure 8a, Lines 280-281) and to the df turbidite table in the supplement (Table S4). However, we kept the mean ages for the thickness plots, as introducing age uncertainties would make this bar plot unreadable.

Sheather, S. J., & Jones, M. C.: A reliable data-based bandwidth selection method for kernel density estimation. Journal of the Royal Statistical Society: Series B (Methodological), 53(3), 683-690, 1991.

(3)

>Lines 271-281
"Additionally, we calculated the annual occurrence rate of df turbidites using a central running sum with different bandwidths to reconstruct changes in debris-flow frequency over time in different resolutions. First, a suitable bandwidth (150 yrs) was selected based on the average df-turbidite occurrence over the entire core (Sheather and Jones, 1991). We applied this bandwidth on the occurrence rate calculation for each individual simulation of the age-depth model derived from the R-software Bacon v 2.4.3 (Blaauw and Christen, 2011). This results in a data-based frequency analysis that incorporates age-depth model uncertainties. The rather broad bandwidth is suited for showing general changes in frequency over time. To account for a higher resolution in frequency changes especially in periods with higher number of events, we also calculated a bandwidth based on the df occurrence of the last two centuries and applied the resulting 21-yr bandwidth to occurrence rate calculation of the main age. The cumulative thickness over time involves both the thickness and frequency of df turbidites and its slope provides information on df turbidite accumulation rate per year. We calculated the cumulative thickness on the mean values and the 95 % range values of the age-depth model to transfer age uncertainty to the cumulative thickness analysis."

>Lines 496-498
"The frequency analysis of the whole 4,000 year df turbidite record is based on a 150-yr bandwidth, whereas especially the higher number of events in the 20th century requires higher resolution frequency analysis, here on the basis of a 21-yr bandwidth (Fig. 8a)."

>Lines 526-530
"Df phase 4.1 is represented by a strong and fast frequency increase at ~1920 CE, followed by a period of highly frequent debris-flow events ~1980 CE. Since then, the current df phase 4.2 has lower frequencies relative to phase 4.1 but still by far higher frequencies than in the main df phases 1–3. Debris-flow frequency in 4.1 increased by a factor of 8 compared to the reference df phase 3. In df phase 4.2, debris-flow frequency increased by a factor of 7 compared to df phase 3."

(1) The used age-depth model by Oswald et. Al (2021) is primarily showing ages cal year BP.

(2) We changed the ages to CE/BCE in the revised supplement.

(1) Table S2 does not provide information on the uncertainties of the top layers or recent past.

(2) We added 95% range values of the age model for every debris-flow turbidite to the supplementary table S4 and stated the mean uncertainties in the text (Lines 510-511).

(3)

>Lines 510-511
"Mean age uncertainties are ± 6 years (2018-1960) and ±19 years (1959-1920; see also Supplementary Table S4)."

(1) On the one hand, I would expect the deviations from the mean age dating to be given for each identified event in table S4 and, on the other hand, I would find it methodologically very exciting how to deal with these uncertainties when the stratification of different drill cores of the events is known and overlapping by the dating-uncertainties? How to assign the identified df deposits to a specific year? At least in the recent past a validation with e.g. dendrochronological dating would have been useful?

(2) We appreciate the question on how to deal with absolute and relative age uncertainty. We address this problem by applying the frequency analysis on each of the 6,396 iterations of age-model simulation derived from Bacon instead of the mean event ages. The referee suggests to further calibrate the last decades by on-fan dendrochronological dating of the debris flows. We plan to include this technique in our future research to obtain terrestrial evidence and reduce age uncertainties for the lacustrine deposits. The inclusion of dendrochronological methods is, however, beyond the scope of the present study.

(1) This raises further the question whether all identified events can be used for a frequency analysis or for the classification of the four different phases based on different event rates?

(2) We address this comment in the revised discussion of human impact (Lines 636-656) and give more detailed information on human-induced vegetation changes based on pollen records. A period of enhanced forest clearance during medieval times (Kral 1989) is not reflected in a sudden increase in debris-flow frequency in the sediment core archive. Since then, no further increase of forest clearance or wildfires is reported in the area, so we infer that changes in vegetation can be neglected before or during the period of increasing debris-flow frequency in the last century (phase 4). We clarify in the new manuscript (Lines 649-650), that human induced mass wasting in the first half of the 20th century possibly created subaquatic detrital layers which cannot be distinguished from debris-flow deposits. This influence was considered in the frequency calculation (Lines 695-697).

Kral, F.: Pollenanalytische Untersuchungen im Fernpaßgebiet (Tirol): Zur Frage des Reliktcharakters der Bergsturz-Kiefernwälder, Verhandlungen der Zoologisch-Botanischen Gesellschaft in Wien. Since 2014 "Acta ZooBot Austria", 1989, 127–138, 1989.

(3)

>Lines 636-644
"Human-induced vegetation changes are documented since about 1,000 BCE from a pollen record from peat bog remnants at Heiterwanger See a few kilometres west of Plansee (Kral, 1989). A period of enhanced forest clearance in the area happened during medieval times according to this record. The herein presented sedimentary record of Plansee shows no signs of a drastic increase in debris-flow frequency throughout this period of intense forest use. During late medieval times, the climatic deterioration of the Little Ice Age, war, and epidemics led to a decrease in population and in forest clearance, which can be observed in pollen diagrams from the nearby Ostallgäu (Stojakowits and Friedmann, 2013). Since then, no further increase of forest clearance or wildfires is reported in the

area. Therefore, we infer that there were no significant changes of vegetation before or during the period of increasing debris-flow frequency in the last century (df phase 4)."

>Lines 649-650
"Therefore, some of the df turbidites in the first half of the 20th century might actually reflect human-induced mass wasting (see also vi)."

(1) Is it possible to quantify the classification of the 4 phases by statistical test? However, once the uncertainties of the event frequency is known a trend analyses should be conducted, showing if changes in the occurrence rate or deposition rate/a are distinct or covered within the uncertainty estimates?

(2) We thank the referee for the important question on determining statistically robust changes. We opted for a change-point analysis of the inter-event periods using the R function *cpt.meanvar* with a clustering algorithm *BinSeg* following Albrecher et al. (2019) and references therein. The debris-flow phases derived from the change-point analysis (Table 1) coincide with previously described lithotypes within the sediment cores (Lines 463-468). We added information on this in the methodology section (Lines 268-270) and in the results section (Lines 492-495).

Albrecher, H., Bladt, M., Kortschak, D., Prettenthaler, F., and Swierczynski, T.: Flood occurrence change-point analysis in the paleoflood record from Lake Mondsee (NE Alps), Global and Planetary Change, 178, 65–76, https://doi.org/10.1016/j.gloplacha.2019.04.009, 2019.

(3)

>Lines 268-270
"Phases with similar frequency of df turbidites (df phases) were statistically distinguished by a change-point analysis of the inter-event periods using the R function *cpt.meanvar* with a clustering algorithm *BinSeg* following Albrecher et al. (2019) and references therein."

>Lines 492-495
"Four main phases with similar frequency of df turbidites (df phases) are differentiated by a change-point analysis of inter-event periods of the 4,000 years debris-flow record (Fig. 8a, Tables 1, S2). Strikingly, the autonomously differentiated df phases temporally coincide with the above-described lithotypes indicating the major influence of debris flows to subaquatic event deposition in Plansee."

Specific minor comments:

(1) The shown correlation between precipitation and lake deposition is rather poor with respect to debris flow events, which can hardly be plausibly explained with precipitation data from a measuring station 7km away. Are there possibly better precipitation data (INAC?). However, the quality of the frequency series should be secured first.

(2) Potential mismatches between precipitation and debris-flow deposition might occur due to the age error of df turbidites, which we added in the new manuscript (Lines 683-685). Moreover, the data shown is daily precipitation, and debris flows can respond to hourly extremes. Of course precipitation occurs often locally concentrated in Alpine terrain. However, rainstorm activity is temporally concentrated coincident to certain meteorological conditions like Vb circulation systems, so there is a high correlation of nearby meteorological stations. Here we are even lucky enough to have a 100 year

recording in 7 km distance, much better than in most similar studies that observe rainstorm frequencies over longer times scales in the Alps and local effects in rainstorm frequencies will also smooth out as an effect of the long observed period and the decadal view of rainstorm activities (see Lines 688-692).

(3)

>Lines 683-685
"Moreover, the precipitation sums are recorded on a daily base, where short but extreme convective precipitation are not distinguishable. Potential mismatches might also be due to the age error of df turbidites, which has a 95 % probability range from 5 years for the youngest event to 60 years at the begin of df phase 4."

(1) When considering earthquake activity in relation to the event rate presented, correlations become apparent and are also discussed. Although it is argued that only the strongest shaking events, well above the local intensity of VI, produce a distinct postseismic landscape response in a lacustrine record, Figure 6 (Supplementary) in Oswald et al. (2021) shows intensities above VI for the 1930 Namlos earthquake. Can an increase (if the time series is valid) after 1930 really be ruled out due to higher sediment availability caused by the earthquake?

(2) From our debris-flow record we deduce that debris-flow activity increases already at ~1920 CE. The possible minor catchment response for the 1930 CE earthquake with a local intensity of VI½ to VII at Plansee (Oswald et al., 2021) is in accordance to other lacustrine studies worldwide, where significantly enhanced fluvial sediment transport to lakes has only been observed for seismic intensities of ~VIII-IX (e.g Howarth et al., 2016; Moernaut et al., 2014). For the intensity VI-VII, the Environmental Seismic Intensity Scale (Michetti et al., 2007) also shows rather small landslide volumes. We therefore infer that the postseismic landscape response is not the dominant factor influencing debris-flow activity after 1930 at Plansee. We clarified this in our new manuscript (Lines 665-671).

Howarth, J. D., Fitzsimons, S. J., Norris, R. J., Langridge, R., and Vandergoes, M. J.: A 2000 yr rupture history for the Alpine fault derived from Lake Ellery, South Island, New Zealand, GSA Bulletin, 128, 627–643, https://doi.org/10.1130/B31300.1, 2016.

Moernaut, J., van Daele, M., Heirman, K., Fontijn, K., Strasser, M., Pino, M., Urrutia, R., and Batist, M. de: Lacustrine turbidites as a tool for quantitative earthquake reconstruction: New evidence for a variable rupture mode in south central Chile, Journal of Geophysical Research: Solid Earth, 119, 1607–1633, https://doi.org/10.1002/2013JB010738, 2014.

Michetti, A. M., Esposito, E., Roghozin, E., Guerrieri, L., and Porfido, S.: Environmental Seismic Intensity Scale - ESI 2007-, 2007.

(3)

>Lines 665-671
"The M 5.3 Namlos 1930 CE earthquake with local intensity of VI½ to VII at Plansee (Oswald et al., 2021) possibly had a minor influence on the sediment availability in the catchment. Given that debris-flow activity increases already at ~1920 CE, we infer that the postseismic landscape response after the 1930 CE earthquake is not the dominant factor influencing the debris-flow activity in the following decades. This is in accordance to other lacustrine studies worldwide, where significantly enhanced

fluvial sediment transport to lakes has only been observed for seismic intensities of ~VIII-IX (e.g. Howarth et al., 2016; Moernaut et al., 2014).”