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Reply on RC1

Carolin Kiefer et al.

Author comment on "A 4000-year debris flow record based on amphibious investigations of fan delta activity in Plansee (Austria, Eastern Alps)" by Carolin Kiefer et al., Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2021-23-AC1, 2021

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.