Reply to the Reviewers' Comments Prof. Willy Tinner (Referee 2)

Main issues

1. Somehow surprisingly an age-depth model is presented but not used to put the data on a time-linear scale, instead depths are preferred throughout the manuscript, which makes it difficult to compare these novel data with existing palaeoclimatic, palaeoecological and palaeoenvironmental records.

   Following the suggestion of the Reviewer we modified accordingly the Figure 10, converting depth in time for the two key intervals of the cored succession using the age-depth model (i.e., the Holocene Thermal Maximum-HTM between ca. 9-7 kyrs BP and the exit of HTM between ca. 6-3 kyrs BP). This is a very useful comment that improve the comparison of our data with those already published (i.e., palaeoclimatic records from the Renella Cave and the Verdarolo Lake). Please see the response to the specific comment N.

2. In some cases, however, the discussion and conclusions need more caution, in particular in regard to mismatches of temporal scales between the different time-series used.

   We modified accordingly, please see the response to the specific comment J.

3. Some factors leading to increased erosion such as human impact and fire are neglected (see detailed remarks) and need attention.

   We agree with the Reviewer and for this purpose we prepared new graphics (revised version of the Figures 7 and 10), including also new analyses (e.g., microcharcoals). Please see the response to the specific comment C2.

4. The Holocene chronology is based on eight 14C dates, the material is most likely of terrestrial origin but may suffer from in-built ages (e.g. wood).

   We see the point of the Reviewer and we will added text in sub-section 4.2 to better discuss the possibility of bias due to the methodology (radiocarbon) and the materials used (listed in the revised version of Table TS2 – Supplementary Material). Please see the response to the specific comment D.

Detailed remarks

A) The abstract is concise and well written, but some mistakes should corrected (“small ice age” is probably Little Ice Age, LIA).

Done.

B) It is not just (Glur et al. 2013) that have observed increasing flood activity in and around the Alps during cold periods. A comprehensive review is provided by Henne et al. (2018) who emphasize the conflict between the available evidence and the hypothesis of the authors: warmer conditions do not always lead to more floods. Flood increases during the Little Ice have been historically recorded and were the consequence of increased precipitation during cold periods (see e.g. Wanner et al. 2000). It might well be that the Alps and the Apennines have different regional flood histories (at least in the northern Alps and the Central European lowlands) and this could be elaborated by the authors.

We agree with the Reviewer. We added text in the Introduction section to better discuss literature data reporting an increasing flood activity during cool periods over the Alpine region.

Lines 75-90: “Many studies suggest a synchronization of a high frequency of flood events with cooling periods. Flood reconstructions from natural archives show very consistently that the floods on the Alpine area have occurred more frequently in times of cold, wet summers (Glur et al. 2013, Henne et al. 2018). This is clearly recognizable, for example, during the LIA. Other studies reported that in the hot and dry periods the floods have been rarer, but stronger in their intensity (Giguet-Covex et al. 2012 and Brönnimann et al. 2018a, Geographica Bernensia, pag.40). At the same time, no specific flood reconstruction is available, as far as we know, for the Apennine area, which has a different precipitation climatology from the inner Alpine region.
The association between cold summers and high flood frequency may hold more for the Alpine region, which has precipitation maxima in summer while in the Apennine area precipitation maxima are occurring in Autumn. In addition, Alpine data are mostly derived from lacustrine archives that are influenced by a combination of factors involving precipitation intensity, duration, seasonality and changes in atmospheric-circulation, land use. These factors might overshadow the physically based positive correlation between temperature increase and precipitation intensity (Utsumi et al., 2011; Brönnimann et al., 2018b).

C1) Still in the introduction pollen is declared as a palaeoclimate proxy (line 82). Fortunately, this is not the use the authors make of their (very coarse) pollen record. Actually, pollen is a palaeovegetation proxy that in some cases and under some conditions can be used to reconstruct climate.

We agree with the Reviewer. We changed text accordingly: “Those caveats call for an even more multidisciplinary approach integrating sedimentary archive information and paleoenvironmental data (e.g., pollen-derived paleovegetation patterns) with climatological observations and physical arguments”.

C2) Since at latest ca. 5000 cal BP vegetation was strongly altered by humans and land use effects were gradually overruling climate as the main driver of plant community changes. For the Northern Apennine this is discussed in detail in e.g. Vescovi et al. (2010a) and Vescovi et al. (2010b) for Greppo and Pavullo.
At the remote Greppo site in the mountains, pastoral and fire activities increased at ca. 6000 cal BP. At the less remote and warmer site Pavullo, arable farming started around 5000 cal BP. These activities were associated with deforestation (also recorded in the data of the authors, pollen layers P08, P10, P12 with high herb pollen), a process of paramount ecosystem relevance which can also increase erosion and flood activities. This issue needs more attention given that Glur et al. (2013) correctly emphasize that human impact may affect flood reconstructions deriving from single study sites. However, given the signal observed in the Moo Lake data with reconstructed flood activity peaking during the HTM (when human impact was low) and the post-LIA (when human impact was reduced since ca. 1950 AD), the authors can partly rule out such human effects, which I think is very interesting and should be elaborated in the text.

This is a very good suggestion. We better investigated the role of human impact mainly in terms of pastoral activities and fire on the Holocene vegetation changes, especially in terms of trees cover and then on the reconstructed flood activity. Indeed, we performed: *i)* a focus on the pollen percentages of taxa associated with cultivation, pastoralism or generic human disturbance with the addition of two samples in the uppermost portion of Unit 3, and *ii)* a new analysis concerning the microcharcoal record. Our results highlighted:

i) a generally low amount of taxa indicative of human disturbance (i.e., new group “Anthropic indicators” shown in the new version of Figure 7) characterizes all the samples, with an almost total absence of cultivated taxa (only 3 samples – P9, P13 and P14 – contain few grains of cereals: <4%). One relative “peak” (ca. 8%, mainly) is recorded around 8070-7880 cal. years BP (sample P6) due to the categorization difficulties concerning anthropic spontaneous taxa. More consistent “peaks” of ca. 6.5-8% (mainly *Chenopodium*, *Convolvulus arvensis*, *Plantago* cf. *media*, *Urtica*) occur within the stratigraphic interval 2 (samples P8-P10 and P13) and dated between ca. 5780-5630 (P08) cal. years BP and 1270-1110 cal. years BP.

ii) the concentration of microcharcoals is very low (ranging between ca. 0.2-200 mm^2/g), also considering the data obtained by Vescovi et al. (2010a) and Vescovi et al. (2010b). Interestingly, the coarser microcharcoals (>125 micron), which can be interpreted as the product of local fires, are absent throughout the cored

> succession, with the exception of the most recent sample P14 (dated 146-14 yrs BP) that, however, contain only ca. 0.05 mm^2/g.

Thus, according to the Reviewer comments, pollen data reasonably suggest a certain degree of human impact on the decrease of tree cover since about 6000-5500 cal. years BP (up to 30% of herbs within sample P13). This impact is probably due to pastoral activities as documented by the relative abundance of pollen meadow (pasture) taxa and the sporadic presence of coprophilous fungi and other spores like *Sporormiella*, *Dicrocoelium* and *Ascaris* (asterisks in Fig. 7). However, the integration of stratigraphic and pollen data points to a low degree of impact of both pastoral activities and fire as triggering factors for floods, strongly supporting our hypothesis.

All these results are now shown in the new version of Figures 7 and 10 (attached below). Text of section 5 (in particular sub-section 5.1) will be changed accordingly, taking into account the new pollen and microcharcoal data and the Reviewer's suggestions.

D) The chronology is likely sufficient to support the inferences and conclusions of the authors, however, the authors may state that they assume that all radiocarbon samples had no hard-water effects (e.g. in particular for peat, what is the material in the peat layers mainly? Cyperaceae?). Indeed, there are limestones and breccias in the catchment and dating of bulk sediment material under such conditions can lead to wrong reconstructions (see Finsinger et al. 2019). Similarly, do the authors exclude inbuilt ages or reworking effects for wood samples (e.g. were they small twigs, see discussions in Gavin 2001; Oswald et al. 2005)?

For what concerns wood samples, we sampled exclusively small twigs in order to reduce, as much as possible, potential bias due to long-lived plants following the suggestion of Oswald and colleagues. In our opinion, reworking effects can be considered negligible as samples were collected from fine-grained deposits.
About the peaty samples, the high degree of decomposition prevented material identification in terms of taxa. However, pollen analyses highlight the dominance of Cyperaceae that likely represent the main component of peaty layers.
These issues will be briefly presented/discussed in text (in 4.2 sub-section). We have also changed the Supplementary Table TS2 accordingly (upload separately).

E) The July temperature reconstruction of Verdarolo is in agreement with that of Gemini and several other proxies, this may be stated at line 197 to increase the representativeness and validity of the Verdarolo record (see discussion in (Samartin et al. 2017).

Done.

F) In regard to palynology, did the authors really do all identifications at 1000 magnification? The standard is 400 x (to be efficient), only difficult pollen such as Triticum, Avena or Hordeum types is usually observed at 1000 x (line 216). What is in the pollen sum? Please state (e.g. terrestrial pollen, no aquatics, no spores).

We will correct/add information about pollen and microcharcoal analyses in text (sub-section 3.4) as follows:

3.4 Palynological analyses

Palynological analyses were carried out on 14 samples collected from fine-grained layers of core S1 to refine facies characterization and obtain pollen-derived paleovegetation data. Following the radiocarbon dating, we particularly focused on two key stratigraphic intervals. The oldest one (Interval 1 – ca. 11-9 m core depth) encompasses the period between ca. 7300 - 9600 cal yr BP centred on the Holocene Thermal Maximum (HTM). The youngest one (Interval 2 – ca. 5.5-4 m core depth) records the final stages of HTM and the following period between ca. 5500 - 3800 cal yr BP. In these two stratigraphic intervals, the mean sampling resolution is ca. 30 cm.

Palynological analyses were carried out applying a methodology already tested for pollen substrates with some minor modifications (Lowe et al. 1996). The method includes the following phases: about 8-10 g were treated in 10% Na-pyrophosphate to deflocculate the sediment matrix. A Lycopodium spores tablet was added to calculate pollen concentration (expressed as pollen grains per gram = p/g). The sediment residue was subsequently washed through 7 micron sieves and then re-suspended in HC1 10% for remove calcareous material and subjected to Erdtman acetolysis; heavy liquid separation, method was then introduced using Na-metatungstate hydrate of s.g. 2.0 and centrifugation at 2000 rpm for 20 minutes. Following this procedure, the retained fractions were treated with 40% HF for 24 h and then the sediment residue was washed previously in distilled water and after in ethanol with glycerol; the final residue was desiccated and mounted on slides by glycerol jelly and finally sealed with paraffin.

This method preserves the slides for many years after preparation and therefore it is suitable for pollen extractions from geological and paleo-archeological samples. Identification of the samples was performed at 400 magnification and only difficult pollen such as *Triticum*, *Avena* or *Hordeum* types at 1000 magnification.

Determination of the pollen grains was based on the Palinoteca of our Laboratory, atlases and a vast amount of specific morpho-palynological bibliography. Names of the families, genus and species of plants conform to the classifications of Italian Flora proposal by Pignatti (2017-2019) and European Flora (Tutin et al. 1964-1993). The pollen terminology is based on Berglund and Ralska-Jasiewiczowa (1986), Faegri and Iversen (1989) and Moore et al. (1991) with slight modifications that tend to simplify nomenclature of plants. The term “taxa” is used in a broad sense to indicate both the systematic categories and the pollen morphological types (Beug 2004). Identified pollen groups (at least 500 pollen grains) have been expressed as percentages of the total (usually between 500 pollen grains). The component of the pollen sum includes only terrestrial pollen, no fern spores and no aquatic plants.

The following groups were identified: Conifers (*Pinus/Abies alba*), Decidous trees (this group includes quercetum taxa – *Quercus, Carpinus betulus, Corylus avellana,* *Fraxinus*, *Ostrya carpinifolia*, *Tilia* and *Ulmus* + other Deciduous trees), Meadow (this group mainly comprises Fabaceae and Asteroideae, Caryophyllaceae, Cichorioideae and Poaceae), Anthropic indicator (e.g. Cerealia, *Chenopodium*, *Convolvulus arvensis*, *Plantago*, *Urtica*) and Alia that includes all taxa excluded from previous groups. The hygro + aquatic plants, which includes hygrophilous herbs (e.g., Cyperaceae) and helophytes and hydrophytes (i.e., *Lemna*, *Junchus*, *Nymphaea*, *Phragmites*, *Potamogeton* and *Sparganium*), are considered proxy of humid conditions typical of wetlands.

3.5 Microanthracological analysis

The same samples prepared for pollen analysis were also investigated for the identification of microcharcoals. Microanthracological analysis has been used to understand past fire events mostly connected to anthropogenic activities. Point count estimation of microscopic charcoal abundance was carried out, and charcoal fragments encountered during pollen counting were recorded in four size classes, based on long axis length (10–50, 50–125, 125–250, >250 μm) (Whitlock, Millspaugh 1996; Clark 1982, 1997; Patterson et al. 1987; Whitlock, Larsen 2001). The former two classes are thought to be wind-blown transported hence giving information concerning the regional fire events, whereas the latter two are considered the result of local vegetation burning.

G) The discussion starts with a figure description over 6 lines (332-337), this is not really exciting, is actually very descriptive (and may stay confined to the figure caption). Why not starting more dynamically with lines 345 (and following text), stating that high flood activity occurred during the HTM? This would make the text more appealing.

We agree with the Reviewer and we shifted part of the text in figure 10 caption:

Figure 10: Sedimentological and palynological features of two key stratigraphic intervals (intervals 1 and 2) from core S1 compared with the most relevant paleoclimate data available from literature for the area of interest (for references please see Figure 7). The Anthropic Index (AI) has been calculated as: (Anthropic indicators/tree percentage)*100 following Accorsi et al. (1998).

H) Model simulations confirm that the HTM was more humid during the summer. This outcome is mainly driven by (orbitally forced) summer insolation and the resulting mid latitude (i.e. Mediterranean and European) evaporation. It seems unlikely that enhanced tropical monsoon activity may have led to wetter climate as far north as the Northern Apennines by vapor transport or related phenomena deriving from the monsoons (see e.g. discussion in Tinner et al. 2009). On the contrary, the strong highpressure field resulting from monsoonal activity north of the ITCZ at ca. 30 N was particularly active during the Early Holocene (causing very dry conditions over the Mediterranean), to become weaker during the Mid Holocene including the HTM, which likely allowed westerlies to reach the Mediterranean, thus creating more humid conditions.

Please discuss and refine, Skinner and Poulsen 2016 is about tropical air masses and related humidity changes, not mid-latitudes.

Studies have documented how mid-latitude extreme precipitation events are very often linked to the transport of remote tropical air masses, in the form of strong confluent airflows, ahead of polar cold fronts, which concentrates water vapour into narrow and very elongated (>2000km) plumes (Atmospheric rivers). Atmospheric rivers have been found to be responsible for more than 90 % of the total poleward atmospheric water vapor transport through the middle latitudes (Ralph and Dettinger 2011). Krichak et al. 2015, documented how this mechanism is also relevant also for Mediterranean extreme precipitation events, especially the ones occurring in autumn, in addition to local evaporation from the Med sea. In that context the study of Skinner and Paulsen 2016 shows that "the atmospheric environment associated with mid-Holocene fall rainfall resembles that of the tropical-extratropical interactions, or tropical plumes, observed in present-day northwest Africa [*Geb*, **2000**; *Nicholson*, **2000**; *Knippertz et al.*, **2003**]. Specifically, tropical convection carries moisture into the midlevels of the troposphere where it is transported northward into the Sahara within strong southerly flow between an upper level trough and anticyclone [e.g., *Knippertz*, **2003**]." In that context an increase in frequency or intensification of tropical plume export could also have had an effect of increasing water vapour availability over the Mediterranean for heavy precipitation events.

I) Lines 361-364: which Alpine lakes do the authors mean? The new one by the authors? Are the authors referring to summer temperatures and more intense summer precipitation (the proxies are about that, see Samartin et al. (2017), please refine.

Done. We refined the paragraph to be more specific. "In Fig.7 we observe a positive correlation (at the millennial scale) between reconstructed (July) temperatures at Verdarolo site, precipitation intensity from nearby speleothem records from Apuane caves (Regattieri et al., 2014; Zanchetta et al., 2011) and high HTM flood activity recorded in S1 core. Our findings support the evidence from other authors (for example Marcott et al. 2013, Giguet-Covex et al., 2012), which are associating greater warmth with more extreme precipitation events, probably rarer and more concentrated at the end of Summer/Autumn, when conditions are more favourable."

J) It is true that July temperature during the period 1961-2018 increased by about +4.3 C in the data of the authors (lines 366-378, 11 yr running average). However, this is at an intermediate level between weather and climate. At climatic temporal scales > 30 years for July means, the increase might be more similar to +2 C (14 vs 16 C). Why is this important? The proxies involved have in the best case multidecadal resolutions, in the case of Samartin et al. (2017) ca. 80 years for the past 1000 years and ca. 250 years for the YD/Holocene transition. Caution is therefore needed. No way to reconstruct rates of climate change at decadal scales with such data, they were instead designed to study multi-centennial trends such as the HTM. Where resolution of multiproxy studies was high enough (reaching decadal scales) the early Holocene warming in proximity of the Northern Apennines was estimated to ca. 3-4 C within 48

years (Schwander et al. 2000; von Grafenstein et al. 2000). Please refine to avoid mismatches of temporal scales.
M) Lines 462-465 see remark J and please refine to consider mismatches of temporal scales of time-series involved.

The value +4.3°C (in 100 years) refers to the temperature trend estimated with a linear regression (Mann_Kendal_Test method used for significance) from the Eraclito ER dataset, covering the period 1961-2018. It has not to be confused with the actual increase in the same period which is lower, near +2°C. The trend is computed from the row July monthly averages while the 11yr running average is used only in Fig.8 to smooth the curve in the graph. The idea of calculating the trend over 100yr is an attempt to make comparison feasible with proxies with a multidecadal temporal resolution. As you pointed out, this comparisons paraphs hold in the first 1000 year of proxy reconstruction while, for the YD/Holocene transition, the comparison is less meaningful. Although we agree, we could not draw firm conclusions, the observed recent trend it is very high and similar or superior to estimated trends from other studies, including Henne et al. 2018, which report as a maximum trend +3–4 °C in 50–100 years at the onset of the Holocene. We realize that in the earlier version of the manuscript, we were only briefly mentioning the problem of contrast instrumental data with reconstructed temperature data (line 377-378). We will argument better this comparison and be less firm in our conclusion.

K) Discussion of pollen, what kind of conifers were involved? I assume Abies alba mainly during the HTM. This implies that Abies alba reached its peak during the warmest period of the Holocene, in sample P7 (which chronologically coincides with the HTM peak of Samartin et al. 2017). Thus the sentence at lines 423-424 should be "In the P7 sample we observe a further increase in conifers (75%, mainly Abies alba) and a consequent reduction in deciduous trees (10%) during warmest HTM conditions."
This finding might be explained by the fact that Abies alba is a warm-temperate tree (not a boreal conifer) that prefers rather moist conditions (see discussion in Tinner et al. 2013), which is in full agreement with the interpretation of the authors.

We better explained in Figure 7 the encountered conifer taxa and their trends within the two intervals of interest (i.e., Interval 1 and Interval 2 in Figs. 7, 10). We agree with the Reviewer's comments about *A. alba*, as the highest relative abundances characterise the HTM (derived from the temperature curve of Lake Verdarolo; Samartin et al., 2017) and the most humid Holocene period (from the δ18O curve of Renella Cave; Zhornyak et al. 2011; Zanchetta et al., 2011; Combourieu et al., 2013; Regattieri et al., 2014). Interestingly, a peak of ca. 60% occurs at sample P7 dated around 7300 cal. years BP in correspondence of the maximum temperature values (please see also Figs. 7, 10). We will accordingly add text about these data in section 5.

L) Lines 436-439. The creation of openland and grassland was a consequence of land use, not climate. To reduce the forest cover to 30 %, semi-desert conditions would be needed, even in hot coastal Sicily arboreal pollen was at ca. 80% during the Late Holocene, when land use was low. The authors should cite relevant literature from the Northern Apennines (e.g. Vescovi et al. 2010a and Vescovi et al. 2010b) that permits attributing such changes to human impact through high taxonomic resolution (e.g. increase of Rumex acetosa and R. acetosella at Greppo as proxies of pastoral farming, of Plantago lanceolata and Cerealia at Pavullo as proxies of arable farming).

We see the point of the Reviewer as explained in response to comment C2. Specifically, pastoral activities are quite well documented by pollen data and spores in samples P9-P13, however no evidences of significant local fire are detected by means of the microcharcoal analysis (as explained in the response to comment C2).

N) Figure 7: A pity the new Moo record is not on a time scale. How will future research be able to compare this with new results on a depth scale? Figure 10: x-axis label for pollen is missing. Is this 100%?

We modified figures 7 and 10 in order to plot our data firstly against core depth (i.e., Figure 7, where we added the label for the horizontal scale) and then selected index/data against a time scale (i.e., Figure 10).

Figure 7. Stratigraphy of core S1, main palynological features and microcharcoal content. Relative abundances of pollen groups, explained in text (sub-section 3.4), are reported along with the frequencies of hygrophilous herbs and aquatics. Asterisks point to samples containing coprophilous fungi and other spores like *Sporormiella*, *Dicrocoelium* and *Ascaris*. These data are compared with the most relevant paleoclimate reconstructions available from literature for the area of interest. Panel (a) Reconstructed mean July air temperature from Lago Verdarolo (from Samartin et al., 2017); Panel (b) δ18O speleothem records and reconstructed precipitation trends (mean anomaly time series) from Renella cave (slightly modified from Combourieu et al., 2013; Regattieri et al., 2014; Zanchetta et al., 2011; Zhornyak et al., 2011) and Panel (c) June (red) - December (blue) insolation values records reported for 45° Nord (from Samartin et al., 2017). Main Holocene climate phases and events are also shown. Available radiocarbon ages are reported as calibrated years BP.