Author responses to Reviewer#1 comments for the manuscript:
"Extremes floods of Venice: characteristics, dynamics, past and future evolution"

The paper touches an interesting and relevant topic because of the recent flooding events in Venice and the start of the operation of the Mose barriers. In general terms I think the paper would convey a stronger message provided that:

We thank the Reviewer#1 for providing comments and suggestions that will help us to improve the manuscript. Reviewer's comments are in bold characters, authors' responses and proposed changes to the manuscript are in slant characters.

a. It emphasizes what is actually new in the paper and the advances with respect to previous publications and the state of the art.

This is a review article and, indeed, the manuscript is classified as a "Review article" in the journal submission system. We thought this was however clear considering the initial sentence of the manuscript "This paper reviews current understanding on the extreme water levels that are responsible for the damaging floods affecting the Venice city center …". Further, the description of this special issue, which is available in the journal web page, clearly writes that "This special issue is composed of three review papers, addressing three different and complementary aspects of the hazards causing the flood of Venice. Review paper 1 describes the tools [...] Review paper 2 describes the factors leading to extreme events, their past evolution, and expected future levels under a climate change perspective. Review paper 3 considers the evolution of the mean relative sea level [...[". We apologize for having missed "Review article:" in the manuscript title and we are sorry for the following confusion. In order to further emphasize that this is a review article and avoid any misunderstanding, we agree that this information should be added to the revised title.

Further, the article complements the discussion of the literature with updates of previous analysis using new datasets (ERA5 in Figs. 2-4) and longer time series that have been made recently available (Figs 5-7), and by extracting information specific for the Venetian floods from recent global datasets (Figs. 8 and 9). We stress that all these figures have never been published before and are based on new data. The assessment of the scientific literature, complemented by the analysis of the most recent events, demonstrated that the superposition of several different factors is fundamental for the occurrence of the extreme sea levels in Venice This was never highlighted in the previous literature and constitutes a major conclusion of our article.

b. It discusses the various contributions to sea level in Venice, distinguishing between internal and external variability.

This review is part of a special issue consisting of three complementary reviews. One of them (nhess-2020-351, Zanchettin et al.) considers trends in the relative sea level and the reader is addressed to it for related issues. Anyway, concerning the Reviewer's comment about a distinction between variability external and internal at the Venice lagoon, different considerations are valid depending on the location within it. The position of the city in the central part of the lagoon makes it very marginally affected by internal fluctuations (which would be very important for Chioggia at the southern end of the lagoon). This will be clarified by expanding section 2.3, complemented by the new version of Fig.1, which allows clarifying several specific issues of the sea level extremes in Venice, which have been mentioned by the Reviewers.

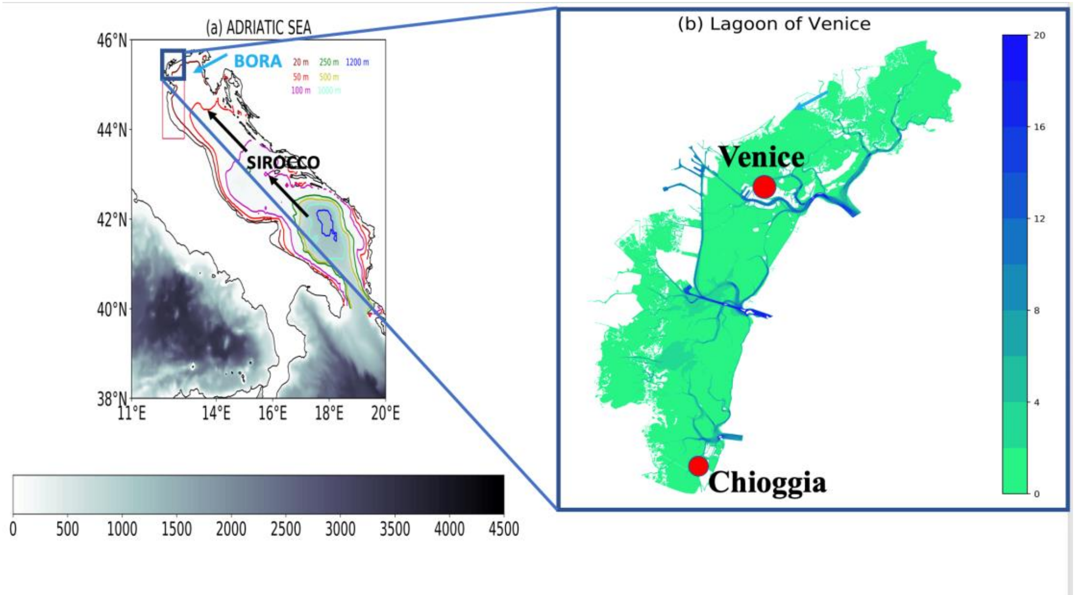


Figure 1: left panel: bathymetry of the Adriatic Sea with the position of Venice and arrows denoting the directions of the two main wind regimes affecting the North Adriatic. Right panel: morphology of the lagoon of Venice with the three inlets connecting it to the Adriatic Sea, and the position of the city and of Chioggia. The red box (which includes the whole lagoon in its northern part) denotes the area represented by the data in Figs. 8 and 9.

c. The same regarding the non-linear and non-stationary effects in the different sea level components.

We admit that scientific literature is never fully explicit on this issue. Practically, in many past predictions with hydrodynamical models only the meteorological forcing was used and the astronomical tide was either added to the model results to get the actual prediction or subtracted to the observations for model validation. The astronomical tide was in turn predicted using a numerical program based on harmonic analysis. Examples of this approach and of its success are Lionello et al. (2006), Bajo et al. (2007), Mel and Lionello (2014) among many others. In general the average depth of the north Adriatic (about 35m) compared with the typical amplitude of the combined astronomical tide and storm surges (about 1m) is the basic explanation that have allowed ignoring nonlinear interaction between these components (see also point 3 below)

refs

Lionello, P., Sanna, A., Elvini, E., & Mufato, R. (2006). A data assimilation procedure for operational prediction of storm surge in the northern Adriatic Sea. Continental shelf research, 26(4), 539-553.

Bajo, M., Zampato, L., Umgiesser, G., Cucco, A., & Canestrelli, P. (2007). A finite element operational model for storm surge prediction in Venice. Estuarine, Coastal and Shelf Science, 75(1-2), 236-249.

Mel, R., & Lionello, P. (2014). Storm surge ensemble prediction for the city of Venice. Weather and forecasting, 29(4), 1044-1057

More specifically, I include some remarks to strengthen the message of the paper:

1. **When talking about the timing of the surges with respect to the astronomical tide and free oscillations, some further discussion on the possibility to lower high sea level by modifying the resonance period could be interesting. As a matter of fact, part of the literature on how to avoid harbour long wave resonance could be applied in here.**

Harbor resonances (2-10 minute periods) have never been associated with sea level extremes in Venice. The extreme sea level propagates through the three inlets and are mostly attenuated by the lagoon hydrodynamics.

Section 2.3 will be expanded to clarify this issue and the absence of internal resonances. The shallow nature of the lagoon (on average 1.5 meters deep) damps out the possible oscillations very fast. We comment more extensively on this issue in point 5 below.

Different coastal defense strategies at the basin scale have an effect on seiches and tides in the perspective of sea level rise (Lionello et al., 2005) and a short note on this is present in section 4.2 of the manuscript. Lionello et al. (2005) have considered two opposite and extreme strategies to contrast sea level rise: a full compensation strategy preserving the present coastline by dams and a no compensation strategy allowing the free inland expansion of the sea. The former strategy shortens the resonant period moving it away from the period of tides, whose amplitude would be reduced as well as surge heights. The latter strategy, on the contrary, would increase the tidal range and the surge heights.

2. **When presenting (section 2.1) the astronomic tides and other components, it would be nice to relate the maximum tidal amplitudes at the Northern shore of the basin to antinodes.**

We assume that the Reviewer means the antinodes of seiches. In fact, the period of seiches and of tides is close to resonance in the Adriatic Sea and it will be affected by climate change (Lionello et al., 2005). A note about this will be added to section 2.1 when describing astronomical tides and seiches and to section 4.2 (see our answer to comment 1)

3. **When presenting (section 2.2) the different contributions to relative extreme sea level the paper would benefit from a more in depth discussion regarding the non-linear feeding between the different components. In particular discussing the cases of constructive versus distractive interference.**

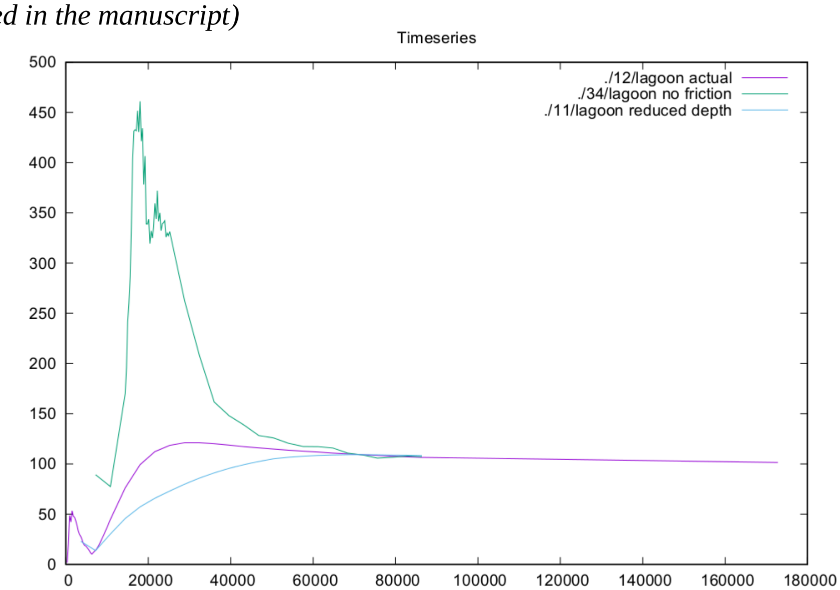
It is well known that tidal and non-tidal components have a certain degree of interaction in shallow water areas with large tidal excursions where shoaling and other non-linear effects are significant (Horsburgh and Wilson, 2007, and references therein). Non-linear interactions of the tide and non-tidal residuals were recently investigated at a global scale by Arns et al. (2020) highlighting a small negative, but small, effect of tide-surge interaction on extreme sea levels in the northern Adriatic Sea. However, in the northern Adriatic Sea, given the relatively small importance of tidal excursions (about 1 m) compared to the local water depth (average depth of about 35 m), it is reasonable to neglect the effect of tides on the surge propagation. Such an assumption has been confirmed by several high-resolution numerical studies demonstrating that tide-surge interactions are negligible, even during the most severe events (Roland et al., 2009; Cavaleri et al., 2019), besides those already mentioned in our answer to point c.

4. **When presenting (section 2.2) the RSL peaks with at least 1.40m that occurred in November 2019 on 12, 13, 15, 17 I think this deserves a further discussion on the possibility of a 2-day resonance period.**

No relevant resonance has occurred in this sequence of high water level events. To clarify this, the following text will be added in the 4th paragraph of section 2.2: "After the exceptionally high water on 12 November, three successive events with water level values higher than 140 cm occurred in just five days. As reported in Ferrarin et al. (2021), these events were driven by three separate Sirocco wind episodes in the Adriatic Sea, which did not trigger any significant seiche oscillations in the Adriatic Sea. Similarly to what happened on 12 November, these flood events were determined by the overlapping of the maximum meteorological contribution, the tide peak and a persistent high monthly mean sea level in the northern Adriatic"

5. **When discussing the propagation of the sea level signal into the interior of the lagoon (section 2.3) it appears that the surge signal propagates nearly without damping while other sea level components appear to experience significant damping. This should be discussed more in depth and explained in "physical" terms.**

Long period oscillations do effectively propagate undisturbed into the lagoon, while the short ones are dumped and sligh amplification occurs in the intermediate range (centered around 5 hours). In the hypothetical case that the inlet depth will be lowered all periods below 12 hours would be heavily damped. Therefore, lowering the depth of the inlets would be a possibility to lower the sea level maxima inside the lagoon. Clearly, there are other implications (e.g., shipping, strong erosion in the inlets) that will make this solution problematic. The figure below shows the amplification factor (in percentage, so that values higher/lower than 100 correspond to amplification/attenuation) of sea level oscillations in the Venice city center with respect to their amplitude at the lagoon inlets, as a function of their period (shown in the x axis, in seconds). In absence of friction a strong resonance would occur in the range from 3 to 11 hours, with a large amplification at about 5 hours (green curve). In reality, friction dampens the resonance and prevents all oscillations below 5 hours to penetrate in the lagoon (violet curve). Drastically reducing the depth of the inlets to 6 m would extend such attenuation up to approximately 12hours (light blue curve). The figure uses output from the model described in Umgiesser et al. (2004) (already cited in the manuscript)



6. **When presenting the evolution of mean sea level pressure fields during intense surge events (section 3.1) further discussion on the cause-effect relationship between the position of the low pressure centre and the pressure gradient could provide an alternative to numerical model predictions and also advance the understanding on these phenomena.**

We agree that the pressure distribution has strong impacts on the intensity of the wind fields, their spatial structure and direction over the Adriatic Sea, which affects substantially which part of the Adriatic coastline is most affected by the storm surge (Međugorac et al., 2018). The first predictions of floods in Venice were indeed based on an autoregressive model based on the values of cross-basin SLP differences (Tomasin and Frassetto, 1979). We will add this information and a comment on the structure of the wind fields in section 3.1. The revised versions of Figs. 2 and 3 including insets with the wind field over the Adriatic Sea are provided below.
ref: Tomasin, A., & Frassetto, R. (1979). Cyclogenesis and forecast of dramatic water elevations in Venice. In Elsevier Oceanography Series (Vol. 25, pp. 427-438). Elsevier.

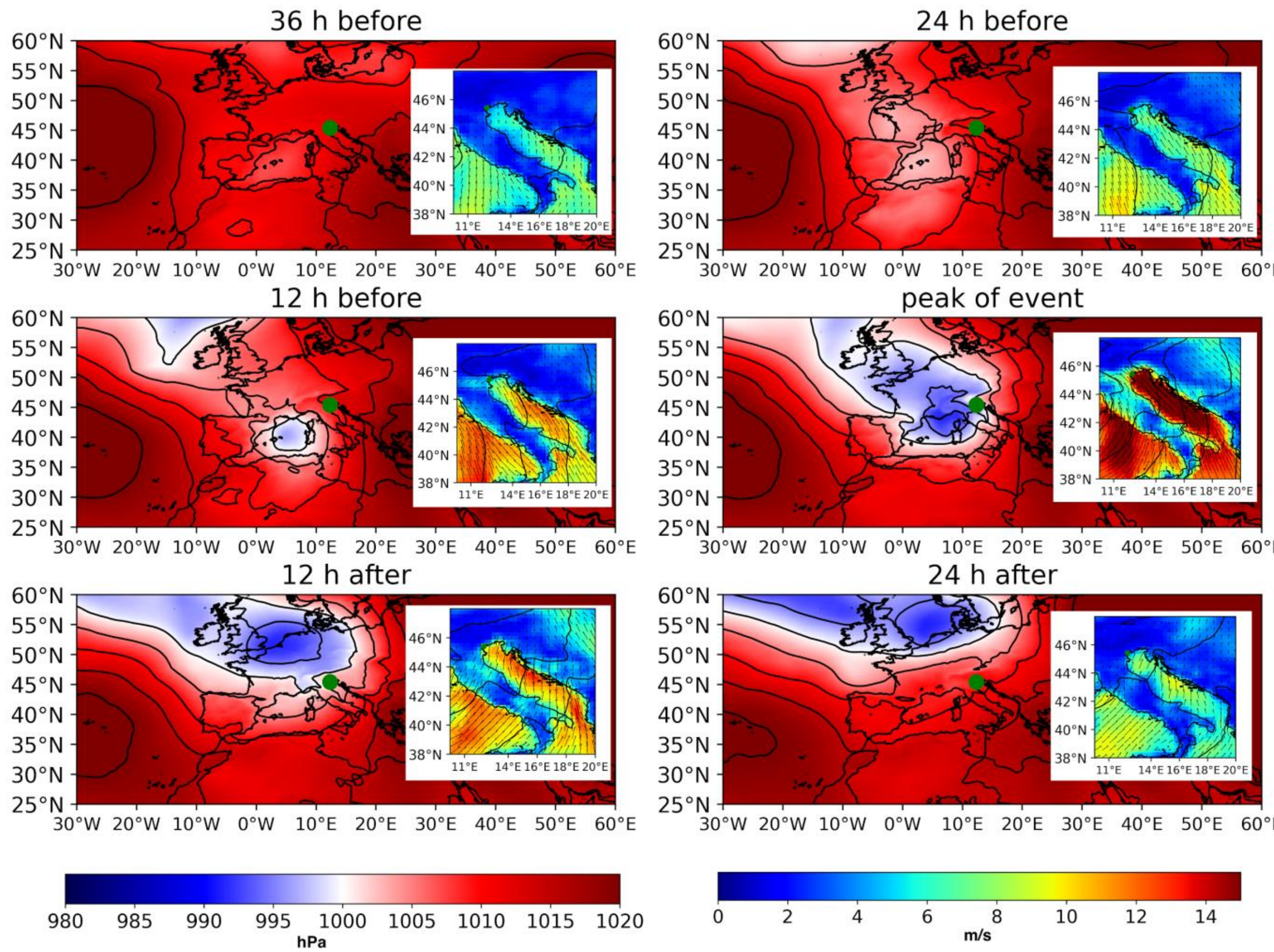


Figure 2: The main panels show the composite of SLP fields (in hPa, left color bar) based on ERA5 data associated with storm surges higher than 50 cm in Venice (see Table 1). The insets show the corresponding wind fields over the Adriatic Sea (m/s, right color bar). The time lags chosen for the composites are 36, 24 , 12 hours before and 12, 24 hours after the peak of the event. The green dot shows the location of the city of Venice.

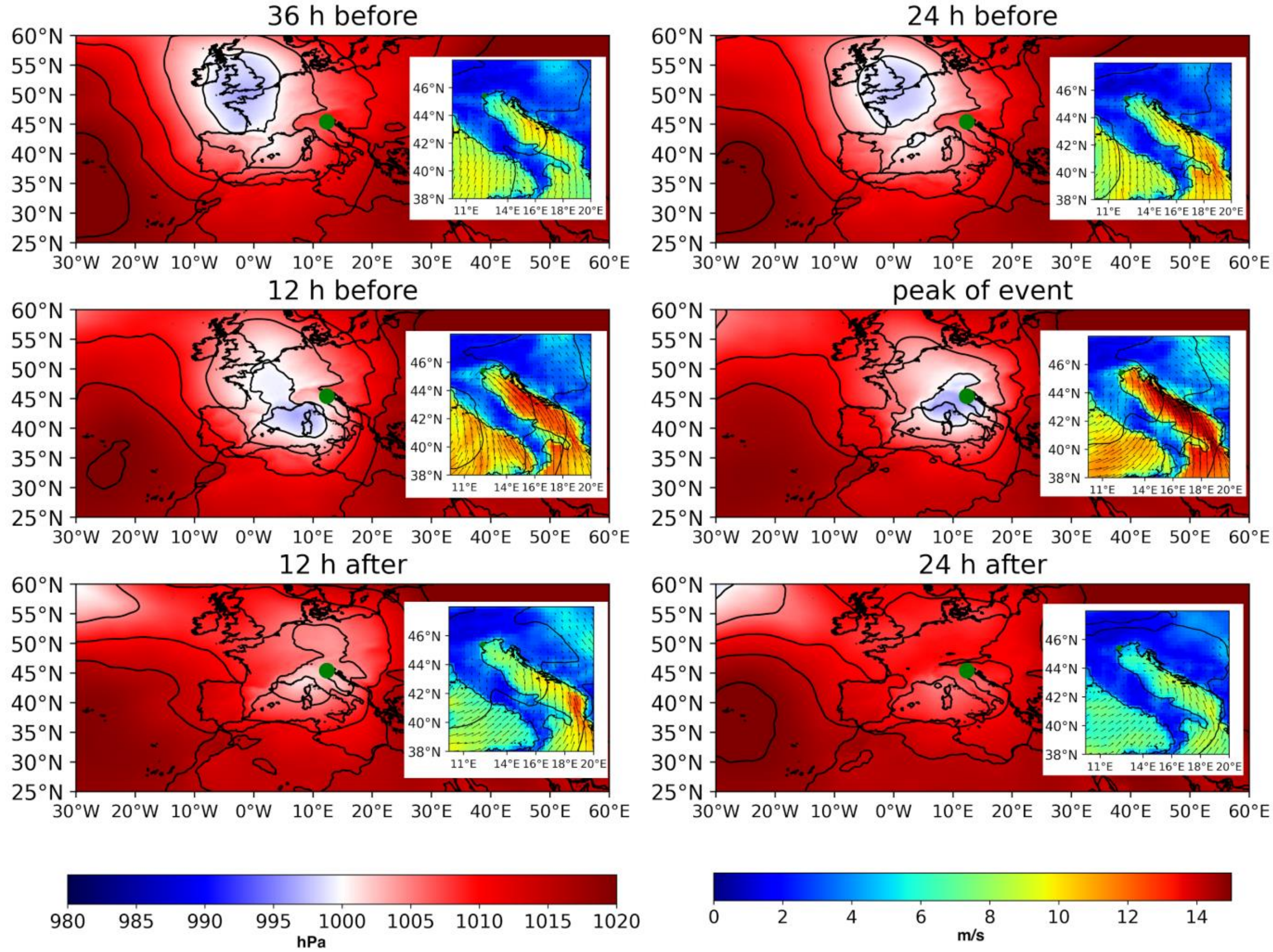


Figure 3: Same as figure 2, except it is based on the events in Table 1 with storm surge height lower than 50 cm

7. **When discussing the future evolution of extreme sea levels (section 4.2) some further discussion on the projection of surges should be included. In fact, in a former section, mention is made on the possibility that surges will get smaller while here the possibility of non-significant changes or significant reduction are presented on an equal basis. This evolution of surges should also be related to the projections of storm trajectories and peak intensities in this part of the Mediterranean, since both are expectedly related.**

The summary final sentences of section 4.1 will be slightly rephrased as: "the amount of current evidence shows that the frequency of floods has clearly progressively increased through time after the mid-twenty century. However, there is no clear indication of a sustained trend at multi-decadal time scales in either the frequency or the severity of extreme meteorological events. The frequency of extreme meteorological events is characterized by a substantial interannual and interdecadal variability, which explains differences among studies that have considered different periods and different thresholds. The long term increase of flood frequency is largely caused by the relative mean sea-level rise (connected to both climatic change and land subsidence, see Zanchettin et al., 2020, in this special issue)". This review considers the frequency of floods using an extremely long time series of nearly 150 years duration of daily sea level - from 1872 to 2018. Theanalysis confirms previous studies that after subtracting the long-term sea level mean, the frequency of extremes has no sustained trends (at multidecadal time scales) in spite of the presence of large fluctuations at multiple time scales.

The studies presented in section 4.2 are not fully comparable with each other in that some of them (e.g., Lionello et al., 2017) considered separated contributions from SLR and changes of storminess, while others (e.g., Vousdoukas et al., 2017; Vousdoukas et al., 2018) considered directly the overall change of extreme water levels. Further, Vousdoukas et al. considered the 100-year return values, while Lionello et al. considered annual maxima and 5 and 50-year return values. When considering only the effect of marine storminess results suggest non-significant changes or even a significant reduction of the intensity of future surges, which might amount to up to about 5% for the RCP8.5 emission scenario at the end of the 21st century. All these studies agree on the future increase of relative mean sea level being the dominant factor for changes in extreme sea level events.
We are confident that a revised manuscript with this partial rephrasing of sections 4.1 and 4.2 clarifies the point raised by the Reviewer.

8. **When discussing (section 5) the limited consideration of wave set up so far I think it would be worthwhile to add the role of infra gravity waves both cross shore and edge waves since they can also contribute small variations to mean sea level which may be critical for the resulting flooding damages.**

Both Reviewers have raised the issue of the importance the wave induced components and we fully agree that a more extended explanation on its lack of relevance for the floods of Venice will be beneficial.
The city of Venice is located in the center of a large and shallow lagoon, with an approximate extension of 500 km^2 and an average depth of about 1 meter. The lagoon is connected to the Adriatic Sea by three inlets (500-1000 m. wide and from 8 to 17m. deep), through which high water levels propagate from the open sea, along a complex pattern of very shallow areas and canals (from 2 to 20 meters deep) to the city center. The lagoon is separated from the sea by two long (about 25 km in total) narrow (less than 200 m average width) and sandy islands, reinforced with artificial barriers in the most vulnerable parts. The elevation of these islands is such that they separate the lagoon from the open sea also during the most extreme events, with the exception of the 4th November 1966 flood, when they were breached in several points.
The floods of Venice do not occur because water overtops coastal barriers or defenses. Therefore, wave run-up and infra-gravity waves and nearshore processes (though certainly relevant along the sea-side front of Lido under some conditions) have never been considered when computing sea level extremes inside the lagoon. Wave set-up at the Adriatic shore has been estimated only during some extreme events (e.g., De Zolt et al., 2006), but not inside the lagoon inlets.
The elevation of the natural barriers separating the lagoon from the Adriatic Sea has so far prevented overtopping caused by wave run-up and infragravity-waves, except in the 1966 flood when waves may have contributed to total water levels. In the future this is unlikely to change as barrier islands will continue being protected by coastal defences and maintained by beach nourishment. Hence, waves do not need to be considered. It cannot be excluded that these factors will become relevant in case of extreme sea level rise in the future, but present evidence is that waves do not need to be considered.

9. **When presenting (lines 430 and following) the projected attenuation of storm surges again it should be discussed whether the projection represents a decreasing trend and relating that to the projected wave conditions.**

Lionello et al. (2017) show substantial consistency of the projected attenuation of waves and surges. This information will be added in the revised first paragraph of section 4.2

10. **Finally there are some “typos” that should be corrected (e.g. line 36 or line 265).**

We agree that the manuscript requires checking for typos and also some marginal rephrasing