Dear Editor,

Enclosed please find the revision of Manuscript ID: NHESS-2017-113 entitled "**Planar Seismic Source Characterization Models Developed for Probabilistic Seismic Hazard Assessment of Istanbul**". We appreciate your time and efforts during the review process. We are also thankful to the reviewers for valuable and constructive comments and for encouraging statements about the manuscript. In the revision, we have taken into account all the comments and made changes accordingly. Details of the actions taken regarding the comments and edits are provided below (all page, line, and figure numbers are given according to revised annotated manuscript).

<u>Reviewer #1 – Main Issues</u>

> *"This article exposes the development of a new hazard model for the city of Istanbul, Turkey. The model proposed mixes active faults and background seismicity. The subject is pertinent and the overall article is well-written and deserves to be published after some modifications are done: adding of a discussion about the slip-rate used in the model, the uncertainties and the output of the models, and improvement the figures."*

We thank the reviewer for the encouraging statements. Details of the changes we made are summarized below.

1. *GPS does not provide slip rates for faults. Geodetic slip rates for major block-bounding structures are deduced from elastic block models.*

As suggested by the reviewer, mentioned sentence is changed as follows: *"Past studies based on GPS measurements (McClusky et al. 2000; Meade et al., 2002; Armijo et al., 2002; Reilinger et al., 2006) suggest a 22 ± 3 mm/yr dextral motion along the major block-bounding structures of the NAFZ, with more than 80% being accommodated along the northern branch."* Page 5- Lines 1-4.

2. *"Slip rate of 19 mm/year is assigned to these segments of the northern strand and 6 mm/year is assigned to Geyve-Iznik Fault based on the values proposed by Stein et al. (1997) with slight modifications due to catalogue seismicity." Why is there a need for modification of the slip-rate?*

Mentioned sentence was not clear enough to explain the applied procedure. In the "moment-balanced" seismic source models, the magnitude recurrence model parameters given in Eq. 4 (Page 10) such as the annual slip rate, b-value, etc. are tested for consistency with the rate of earthquakes associated with the rupture system. These graphs for all rupture systems are given in Figure 4. Eq. 1 shows that the annual slip rate directly increases the accumulated seismic moment; therefore, increasing the annual slip rate moves the red broken lines in Figure 4 upwards. The slip rate participation among the northern strand of NAFZ and Geyve-Iznik fault was given as 16 mm/yr and 9 mm/yr in Stein et al. (1997). However, we achieved a better fit with the associated seismicity of Izmit rupture system by increasing the share of the northern strand of NAFZ to 19 mm/yr. This value is also in good agreement with the annual slip rate given in Murru et al. (2016): they have adopted 20±2 mm/yr based on the proposals of Flerit et al. (2003) and Ergintav et al. (2014). We changed that sentence to clarify this issue (Page 6, Lines 10-14).

3. *"Since the contribution of Düzce Fault to the total slip is around 33% to 50% (Ayhan et al. 2001)". What is the final contribution chosen here and why? Ayhan et al., 2001 states that analysis of GPS data suggest something different, that up to 10 mm/yr are accommodated on the Duzce-Karadere strand of the NAF [Ayhan et al., 1999]. Please keep original reference when possible and explain how catalogue seismicity modifications led you to propose different slip rates for these two fault strands.*

As mentioned by the reviewer, Ayhan et al. (2001) suggested that up to 10 mm/yr of the motion is accommodated on the Düzce-Karadere strand of the NAF. We also utilized the same annual slip rate of 10 mm/yr for Düzce_1, Düzce_2 and Karadere segments without any modifications based on the catalogue. Related text in Page 6 (Lines 18-20) is now updated, citing Ayhan et al (2001).

4. *Could you please compare your slip rate estimates with more recent findings? E.g. Ergintav, 2014 gives 10-15 mm/yr for the Çınarcık Basin fault PIF vs the 19 mm/yr with no uncertainty used in this study; < 2mm/yr for the Central Marmara region: vs the 19 mm/yr with no uncertainty used in this study.*

The slip rate estimate given in Ergintav et al. (2014) for the Prince Island Fault and Çınarcık Basin is 15±2 mm/year (page#5784 of the original reference). Murru et al. (2016) distributed the annual slip rate of 17 mm/year among two parallel branches in this zone; 14±2 mm/year for Çınarcık segment and 3±1 mm/year for the South Çınarcık segment based on the recent works of Ergintav et al. (2014) and Hergert and Heidbach (2010). Therefore, the slip rate value that we have used on the horizontal plane is identical to these recent estimates (Figure 1d). The slip rate given for the Central Marmara Fault by Ergintav et al. (2014) (2 mm/year) is unusually low compared to the previous estimates and may be suffering from the sparsity of the network and GPS coverage on the north shores of Marmara Sea as mentioned by the authors (page#5786). For this rupture system, the annual slip rate we adopted (19±2 mm/year) is in good agreement with the proposal of Murru et al. (2016) (18±2 mm/year) and with the seismicity rates based on instrumental earthquake catalogue (please refer to Figure 4b). The text given here is added to Pages 6-7, Lines (31-10).

5. *Table 1 please add original references used to estimate slip rates, add associated uncertainties and in the text justify your choice of slip rate with respect to the many alternative interpretations.*

Table 1 is modified as suggested by the reviewer. New Table 1 now includes the references for adopted slip rates and uncertainty in the published slip rate values. Additionally, we modified the SSC logic tree to include the epistemic uncertainty in the slip rates and changed the caption of Table 1 accordingly.

6. *The article targets to present "fully-documented and ready to use fault based SSC" (P1L18) which is a good way to share hazard model information. This approach deserves to be promoted in the seismic hazard community. Unfortunately, with this state of the paper, it is most possible to use the results for a reader in order to run a hazard calculation. The geometry of the faults and the background earthquake rates are provided in the supplements but the earthquake rate on faults is absent. Authors should provide these rates for the full logic tree described in this study.*

Thank you for supporting the open access policy for the seismic source models. Typically, the hazard codes do not need the earthquake rates on the fault. The magnitude PDF among the predefined models in the code is selected (in our case this is the Youngs and Coppersmith (1985) composite model), magnitude PDF parameters should be entered (in our case the b-value, M_{min}, and M_{char}) and the earthquake rates are implicitly calculated by the hazard code based on the provided logic tree for each seismic source (in our case for each rupture source). Nevertheless, following sentences are added to the manuscript and the earthquake rates are now provided in the electronic supplement. "*The hazard analyst can incorporate the full rupture model and the complete logic tree provided in this manuscript to most of the available hazard codes without explicitly calculating the earthquake rates. In case that the earthquake rate has to be incorporated to the hazard code; the earthquake rates for each branch of the logic tree given in Electronic Supplement#3 can be used.*" (Page 14, Lines 16-19).

7. *Furthermore, the authors should acknowledge the limitation of their model and the uncertainties that remained unexplored in their logic tree (fault segmentation, fault geometries, slip-rate, scaling law used…) for future user to be able to use their work and run a complete and critical hazard assessment for the city of Istanbul.*
8. *A logic tree is presented, with the exploration of several branches (b values, Mmax) but the results of the logic tree and the influence of each parameters is not exposed. A Discussion part should be added to the article in order to discuss the hazard model, to compare how it perform against the data (modeled seismic rate vs earthquake catalogue), discuss the issue of double counting, and to compare against the other seismic hazard model discussed in the intro. The limits of the models need to be clearly discussed as well. For example, the model allows multi-fault ruptures but the boundary of each system is based on the past*

earthquake rupture (Parson 2004) and the possibility of an earthquake passing from one system to another is not discussed.

Following the suggestions of the reviewer, we added a new Discussion section that deliberates the SSC model parameters and the epistemic uncertainty of the model based on the comparison of the source model fractals of each rupture source with the observed rates of associated earthquakes (Section #6). We added a paragraph to the newly introduced Section#6 that discusses the uncertainties remained unexplored in the provided logic tree. We also shortly discussed the reason why the fault-to-fault rupture concept of UCERF3 is not utilized in the proposed model at the end of this section.

Additionally, we added the following sentence to the main text: "*During the calculations of the smoothed seismicity rates, the earthquakes in buffer zones are not included in smoothing (and not double-counted). The buffer zones are only used to "associate" the earthquakes with the fault zones and collapse the earthquakes to the vertical fault planes.* (Page 12 – Lines 18-21)".

9. *The issue of Mmax in the background zone should be discussed in greater detail: please refer to the extensive literature, UCERF3 in particular, for a more up to date discussion on this issue.*

We appreciate the suggestion. Moschetti et al. (2015) mentioned that the development of the maximum magnitude (M_{max}) model for shallow crustal seismicity in the Western United States benefits from the large set of regional earthquake magnitudes from the historical and paleoseismic records; however, the background seismicity model accounts for earthquake ruptures on unknown faults; therefore, the M_{max} distribution must reflect the range of possible magnitudes for these earthquakes. We adopted a similar approach using the fault segments of the southern strand of NAFZ documented in Murru et al. (2016) and calculated the characteristic magnitude for each segment with Wells and Coppersmith (1994) magnitude-rupture area relation. Based on the estimations of characteristic magnitude of earthquakes that may occur on the southern strand of NAFZ, the logic tree for M_{max} of the background zone is modified (Table 6). Related discussion is added to Page 12, Lines 25-32.

10. *Why use the term "planar seismic source" instead of "fault source"?*

Planar seismic source is preferred to emphasize the third dimension of the fault plane.

Reviewer #1 – Specific Comments:

Language edits in all sections are acknowledged. We are indebted for the careful grammar review. Some of the issues pointed out by the reviewer are resolved by adding further explanations throughout the text (please refer to the annotated manuscript). We would like to add a few remarks for addressing some of the specific comments:

1. The references to the fault maps and satellite images used by Gülerce and Ocak (2013) are provided in the original reference; therefore, the details are not elaborated here due to page limitations.
2. 4-32 Here the author that the segment 1 of the Duzce fault is connected with the Izmit system. However, they cannot rupture together. Why so?

In 1999 earthquakes, these two fault systems (Kocaeli and Düzce) were ruptured in two different episodes. A possible explanation of the separate ruptures in different episodes would be the development of the restraining bend along Karadere Segment, which probably locked up the eastern termination of Izmit rupture. Harris et al. (2002) proposed that the rupture of 1999 İzmit earthquake was stopped by a step-over at its eastern end (Mignan et al., 2015). Within the scope of this study, we believe that it is safe to assume the same rupture pattern of 1999 earthquakes based on current information. However, we added the sentences above to the manuscript (Page 4, Lines 24-29).

3. 9-6 Why this choice of adding 0.25 and 0.5 to the M_{max} define using Wells and Coppersmith 1994? Doesn't make the new M_{max} not fitting the scaling law? Why not explore the uncertainty given by Well and Coppersmith or another scaling law in order to grasp the epistemic uncertainty?

We thank the reviewer for pointing that out. We changed the structure of the maximum magnitude logic tree using two different magnitude scaling relations proposed by Wells and Coppersmith (1994) and Hanks and Bakun (2014). The M_{char} values calculated using both equations are quite close to each other and the absolute value of the difference is smaller than 0.13 in magnitude units. To grasp the epistemic uncertainty, average of the M_{char} value from both scaling laws are utilized in the center of the logic tree with 50% weight and both the M_{char} -0.15 and M_{char} +0.15 values are included by assigning 25% weight (Table 6).

4. 9-20 is the moment-balancing the same for all the branches of the logic tree? What is the branch presented in figure 4?

No, it is not the same for all branches of the logic tree. We modified the caption of Figure 4 to indicate the branch of the logic tree presented in each part figure.

5. 9-22 the “best fit” between the rate in the catalogue and the weighted average is defined in which way? It seems that the fit with the smaller magnitude is preferred according to fig 4 because of the large uncertainty on the rate of large magnitude earthquake. Why the authors didn’t choose to use an historical earthquake catalogue in order to improve the estimation of the rate of larger earthquakes?

The best fit between the rates of the events in the instrumental catalogue and the weighted average of the magnitude recurrence model is achieved by visual interpretation. To achieve a good fit, the seismic source modeler needs to understand the contribution of the magnitude recurrence model parameters to the red broken line in different magnitude ranges. For example, the b-value significantly affects the small magnitude portion of the curve since the Youngs and Coppersmith (1985) magnitude PDF is utilized. Please remind that the b-value is calculated based on the same catalogue but for a larger region when compared to the buffer zone around the fault. Defining a large number of sub-segments for a rupture system also increases the cumulative rate of small magnitude events. The good fit in the small magnitude range of Figure 4 shows that: i) the b-value calculated using the larger zone is compatible with the seismicity associated with the planar source, ii) utilized segmentation model is consistent with the relative rates of small-to-moderate and large events, and iii) annual slip rate is compatible with the seismicity over the fault. As the reviewer mentioned, the large magnitude rates are poorly constrained since the catalogue used herein only covers 110 years and that time span is obviously shorter than the recurrence rate for the large magnitude event. Hecker et al. (2013) explains that by the low rates of the large magnitude events: *“rates of large-magnitude earthquakes on individual faults are so low that the historical record is not long enough to test this part of the distribution”* and suggest using the *“inter-event variability of surface-rupturing displacement at a point as derived from geologic data sets”* to test the upper part of the earthquake-magnitude distribution. Discussion given above is added to the manuscript (Page 11, Lines 15-27).

6. 9-29 higher weight is attributed to single rupture than to multiple fault rupture. What is the basis for this assumption since the distribution used (Youngs and Coppersmith) already predicts more small magnitude earthquakes than large ones? Is this argument stronger than the fit to the data in the weight determination?

Both truncated exponential model and the Youngs and Coppersmith (1985) model assumes more small magnitude events than the large magnitude events. The difference lies in the relative rates of small-to-moderate and large magnitude earthquakes (for further details please refer to Hecker et al., 2013 and Gülerce and Vakilinezhad, 2015). However, the ratio of these rates is the same for the single-segment rupture “source” and for the multiple-segment rupture “source” and this ratio is irrelevant with the weights assigned to the rupture “scenarios”. Higher weights attributed to the single-segment rupture scenarios than the multiple-segment rupture scenarios reflect the preference of the seismic source modeler in addition to the agreement with the associated seismicity. As Figure 4 implies, this preference did not contradict with the cumulative rates of earthquakes associated with each rupture system.

7. 10-4 define “not associated”. What is the size of the buffer zone? And why? Please state whether the background zone and the fault sources should be superposed in the PSHA calculations. (Not clear in figure 5)

Size of the buffer zone is 7 km in each side of the fault line based on the visual interpretation of the spatial distribution of the earthquakes around the fault lines. We assumed that the earthquakes within the buffer zones are "associated" with the fault and the ones that are outside of the buffers are "not associated". Following sentences are added for clarification (Page 12 – Lines 18-21): *"During the calculations of the smoothed seismicity rates, the earthquakes in buffer zones are not included in smoothing (and not double-counted). The buffer zones are only used to "associate" the earthquakes with the fault zones and to collapse the earthquakes to the vertical fault planes. Therefore, the background source and the fault sources can be superposed in the PSHA calculations."*

8. 10-21 "no active fault has been reported". Faults in the vicinity of Istanbul have been described in other studies. See Diao et al 2016 (Secondary Fault Activity of the North Anatolian Fault near Avcilar, Southwest of Istanbul: Evidence from SAR Interferometry Observations).

Greater Istanbul Municipality had conducted a trench study on the KL Fault of Diao (2016) in order to verify its recent activity; however, they found no evidence of Holocene activity. Avcılar region is dominated by active and extensive landslides and surface creep activities as Diao et al. (2016) suspected.

9. 10-30 "previous SSC models": a comparison on the modelled rate will improve the quality of the article.
10. 11-18 this interesting comparison with other model could be done in the discussion part in greater depth.

We appreciate the comments and understand the importance of the comparison of the earthquake rates proposed in here with the previous literature. Unfortunately, previous publications did not provide enough information on earthquake rates for doing this comparison. A similar statement is added to the discussion section to underline the importance of open-access seismic source models in PSHA.

11. Figure 1: A color code for each rupture system could be used. The full name of each rupture system should be indicated on the map to help the reader. What is the number between brackets?

The numbers between brackets were segments lengths. Figure 1 is modified as suggested and the numbers (segment lengths) are deleted for clarity (instead the segment lengths are given in the Table 1) and a color code for each rupture system is introduced.

<u>Reviewer #2 – General comments.</u>

> *"This is a technically-solid, well-documented paper describing the implementation of a seismic source model for the North Anatolian Fault Zone. The paper is not a research paper, and therefore does not really attempt to advance new ideas or change the way the earthquake process is understood in the region. Instead, it simply describes a segmented seismic source model and the calibration of parameters of interest (e.g. Gutenberg-Richter A+B values) to the faults. Whether this is appropriate for this journal or not, I cannot say definitively. It would have been nice to see a little more scientific research. However, the work that is done is of good quality, quite well documented and no doubt of use and interest to the community."*

We thank the reviewer for the encouraging statements. The state-of-the-art in seismic hazard assessment and seismic source characterization models are generally published in consultancy reports and typically not easily accessible for the earthquake engineering practitioners. Abrahamson (2000) proposed that one of the sources of the problems leading to the large variability in the seismic hazard practice is the lack of well-written, easy to understand papers on the topic of seismic hazard assessment. With the help of the review comments, the manuscript is significantly improved; therefore, we hope that the reviewer would see the scientific and/or practical contribution of the updated manuscript.

> *My only technical concerns are that the B values estimated for the faults are quite low (≈0.7). This is may be due to catalog completeness issues, or overly aggressive declustering that removes too many events. Though the methods used to decluster the catalog are mentioned, there are no statistics on the number or percentage of events removed or other information that would help with this sort of diagnostics. Alternately, it is possible that the NAFZ does have a very low B value. This would be quite notable, and worthy of more scientific*

> *investigation. I am not a regional expert so I cannot comment on this directly, but it is necessary to discuss in the manuscript.*

The b-value estimated for Zones 1-3 varies between 0.68-0.76. We understand that the estimated values are relatively small when compared to the b-values estimated for large zones (b≈1); however, our findings are consistent with the current literature. Şeşetyan et al. (2016) provided a thorough analysis of the b-value for the whole Turkish territory and proposed that b=0.77 for Central Marmara region and b=0.67 for North Anatolian Fault Zone (please refer to Figure 15 of Şeşetyan et al., 2016). The catalogue completeness intervals used in Şeşetyan et al. (2016) and in this study for 4.7<M<5.7 earthquakes are exactly the same; therefore, we do not expect that the b-values estimated here depends on the catalogue completeness intervals utilized in this study. The small differences in the b-values proposed by Şeşetyan et al. (2016) and the b-values estimated in this study due to the geometry of the selected zones and the differences in the compiled catalogues. In addition, the b-value used by Moschetti et al. (2015) for Western United States (b=0.8) is not very different than our estimates. Discussion given above is added to the manuscript (Pages 8-9, Lines 29-2).

The reviewer suggested that the estimated b-value might be affected from the aggressive declustering that removes too many events. This issue is thoroughly discussed in Güner et al. (2015) and Azak et al. (2017), showing that the declustering methodology utilized in this study (Reasenberg, 1985) results in higher estimates of the b-value when compared to the other declustering methods. We provided additional details on the declustering at Page 7 (line 31).

Finally, we would like to underline that the b-value only controls 6% of the released seismic moment by the exponential tail of the implemented composite magnitude PDF (Youngs and Coppersmith, 1985), therefore it has no substantial effect on the hazard (Gülerce and Vakilinezhad, 2015).

References given here (but not included in the manuscript):

1) Abrahamson, N. A.: State-of-the-practice in seismic hazard evaluation, ISRM International Symposium, 2000.
2) Eroğlu Azak, T., Kalafat, D., Şeşetyan, K., Demircioğlu, M. B.: Effects of seismic declustering on seismic hazard assessment: a sensitivity study using the Turkish earthquake catalogue Bulletin of Earthquake Engineering (online first), DOI 10.1007/s10518-017-0174-y, 2017.
3) Diao, F., Walter, T. R., Minati, F., Wang, R., Costantini, M., Ergintav, S., et al.: Secondary Fault Activity of the North Anatolian Fault near Avcilar, Southwest of Istanbul: Evidence from SAR Interferometry Observations, Remote Sensing, 8(10), 846, doi:10.3390/rs8100846, 2016.
4) Güner, B., Menekşe, A., Özacar, A. A., and Gülerce, Z: Kuzey Anadolu ve Doğu Anadolu Fay Zonu için Deprem Tekrarlanma Parametrelerinin Belirlenmesi, 3. Türkiye Deprem Mühendisliği ve Sismoloji Konferansı Bildiri Kitabı, 14-16 Ekim 2015, İzmir (in Turkish).