Effects of Horizontal Resolution and Air–Sea Flux Parameterization on the Intensity and Structure of simulated Typhoon Haiyan (2013)

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Response to referee 1

Dear Referee,

We thank the referee for the comments and suggestions to our manuscript. Please find our responses to your comments and questions below. The comments and questions are given in italics, and our responses are in blue.

GENERAL COMMENTS:
Through numerical simulation experiments and analysis, the authors present a study aimed at evaluating the influence of horizontal resolution and surface flux formulas on the development of Typhoon. The results show the increase of resolution and more reasonable surface flux formulas leads to an improvement of the typhoon intensity simulation. Although the innovation of the paper is not strong, the relevant conclusions of the paper have a positive impact on typhoon forecast.
It is clear a lot of effort has gone into this research. However, I question the design of the sensitivity experiments. As such, the recommendation is for major revisions, and this reviewer feels this manuscript will be improved by addressing the comments below.

We thank the referee's positive comments to our manuscript. We have carried out the numerical experiment of 1 km F2 in response to your specific comment 1. The revised manuscript has been edited by *Wallace Academic Editing* and is considered to be improved in grammar, punctuation, general readability, and native English usage. In addition, we followed the suggestion of *Wallace Academic Editing* and reworded the "impacts" to "effects" in our title, which is now:

> Effects of Horizontal Resolution and Air–Sea Flux Parameterization on
> the Intensity and Structure of simulated Typhoon Haiyan (2013)

Below are our point-by-point replies to your comments.

SPECIFIC COMMENTS

1. *On P8 line 5-9, "Because the simulation result of F2 is somewhat between those of F0 and F1 for other resolutions, we omitted the F2 test at 1-km resolution." However, judging from the time evolution of typhoon intensity, the observed typhoon intensity is located between 1km F0 and 1km F1 experiments. Is there a better coincidence between 1km F2 and observation?*
   On P7 line 20-25, the author also mentioned that "F1 predicts larger CH and CQ at all wind speeds than F2 does, implying that F1 has a potentiality to gain larger enthalpy fluxes", This may also be the reason why the simulated typhoon intensity of 1km F1 is higher than that observed.
   Overall, I think the numerical test of 1 km F2 is very critical and cannot be omitted.

We have carried out the experiment of 1 km F2 as suggested. This added experiment was also suggested in comment 4 by referee 2. Accordingly, we have modified the following figures for adding the experiments with flux option F2: Figs. 4, 6, 8, 9, 10, 11, 12, 13, 14, and 15. We have also modified some related sentences in the revised manuscript. The majority of them can be found in sub-section 2.3 (P8, Experimental designs), section 4 (P12, P14, P15, P16), section 5 (P18). Please find the respective changes in the revised manuscript.

With the new added 1 km F2, the observed typhoon intensity is now located between 1 km F2 and 1 km F1 experiments. The simulated typhoon intensity in 1 km F2 is relatively closer to that in 1 km F0, not 1km F1. We can't say there is a better coincidence between 1 km F2 and observation. Although the experiment 1 km F1 overpredicts the typhoon intensity, overall it still produces the best solution among others.

Regarding the statement quoted here, "*F1 predicts larger CH and CQ at all wind speeds than F2 does, implying that F1 has a potentiality to gain larger enthalpy fluxes*", yes, we consider this to be the reason for the most intense typhoon found in 1 km F1 among others in the 1 km group.

2. *On P4 line 5, the horizontal grid spacing is 1, 3 and 6 km. So why do the authors still use the updated Kain-Fritsch convective scheme? If the convective scheme is not used, do the simulation results change?*

The convection parameterization (K-F cumulus scheme) was used for all resolutions. This is because we intend to keep consistency among all cases. The convective treatment was also mentioned in the comment 1 by referee 2. For typhoon Haiyan, we have carried out several tests with and without cumulus parameterization on the 3 km resolution grid. The 3 km resolution grid is for our control experiment in this study. The tests revealed that, simulations with and without cumulus parameterization produced overall similar simulated storm intensity. We did not perform any convection parameterization test on the 1 km resolution grid, because of our limited computational resource.

Numerous studies have suggested that 3-4 km resolutions without any cumulus parameterization is sufficient to represent mesoscale convections (e.g.,Weisman et al. 1997; Davis et al. 2008; Gentry and Lackmann, 2010). However, such a grid resolution is still insufficient for representing individual convective cells (e.g., Bryan et al. 2003; Miyamoto et al. 2013). The use of cumulus parameterization with the grid spacing below 3-4 km has been investigated by a number of recent studies. Some studies suggested to activate the cumulus parameterization for simulation of moist convective event with a grid resolution of 4 km (Deng and Stauffer 2006), 3 km (Lee et al 2011) and 2 km (Kotroni and Lagouvardos 2004). Some others, however, revealed that the activation of cumulus parameterization for simulation with grid spacings of 2-3 km produced overall similar simulated storm as in the simulation with explicit convection (e.g., Yu et al. 2011; Li et al. 2018; On et al. 2018). Sun et al. (2013) studied the appropriateness of a variety of cumulus parameterization schemes used in high-resolution simulations. They assumed that the cumulus scheme is closely related to the model convergence in simulating TC intensity. Here, a convergence of model solution in terms of TC intensity is that the simulated TC intensity would remain similar irrespective of any further reduction of the grid spacing. They found a weak convergence in fine resolution (from 3 to 1 km) simulations with most of the schemes, whereas the convergence is relatively strong in the simulations with a scale-aware scheme designed for any resolution. Accordingly, cumulus parameterization may still play a role in the fine resolution (3 to 1 km) simulations. The question then arises as to what is the appropriate design of cumulus parameterization for very high resolution. However, this is far beyond the scope of our present study.

3. *On P8 line 10, the general simulation usually chooses to gradually increase the resolution through nesting, while all resolution simulations in this paper do not use nesting. Why?*

Our large single domain was chosen to cover the majority of simulated Haiyan (2013)'s convection during the period of sensitivity simulation, and to make a cleaner comparison among those experiments running at different resolutions.

Higher-resolution nested model configuration are widely used in numerical weather prediction and regional climate modelling. The main reason for this is because large area of high-resolution model simulation is computationally too expensive. However, consistency between nested grids is also important. With lateral boundaries on multiple grids, model solutions may not be smooth across nested-domain boundaries. In a nested WRF simulation, a discontinuity in precipitation and moisture fields (i.e., a sharp gradient) across the inner domain boundaries has long been recognized by the WRF community. Uncertainty related to the use of multiple nested grids can resulted from mismatched model physics across nested-domain boundaries. For example, Warner and Hsu (2000) revealed that the treatment of convection on the outer grid can affect the explicit convection on the inner grid. Their result indicated that the simulation biases related to the parameterized convection (e.g., errors in precipitation timing, precipitation intensity, and the vertical distribution of latent heating) can greatly modulate the explicit convection on the inner grid through the induced subsidence from the outer grid.

4. *Section 2 should be divided into subsections, such as 2.1 moisture roughness length, 2.2 momentum roughness length, 2.3 bulk transfer coefficients, 2.4 experimental designs.*

We have followed the suggestion of the referee. In the revised manuscript, section 2 has been divided into 3 subsections:
2.1 Flux parameterizations in WRF-ARW (page 4)
2.1.1 Momentum and moisture roughness length for flux option F0 (page 4)
2.1.2 Momentum and moisture roughness length for flux option F1 (page 5)
2.1.3 Momentum and moisture roughness length for flux option F2 (page 6)
2.2 Comparison between modelled and observational bulk transfer coefficients (page 7)
2.3 Experimental designs (page 8)
Please find the respective changes in the revised manuscript.

5. *On P8 line16-17, please show the original resolution of GFS data used.*

The GFS data has a horizontal resolution of 0.5 degree. We have added this information to the revised manuscript (P8, lines 25-26).

6. *From Fig. 4a, it is difficult to distinguish the track difference between different sensitivity tests, and it is suggested to modify this figure.*

We have decided to not modify the plot, because it is still hard to distinguish the track difference between different sensitivity tests even when different symbols were used to denote them. We changed the layout of Fig. 4 instead, so as to make the track plot larger. In addition, we added 2 supplemental figures (Figs. S1 and S2) to show the tracks and central positions of the simulated storms during the mature stage. We prefer to put the detailed information of tracks/positions in a supplement of the manuscript, because we feel that this is not absolutely necessary in the context of our present study. In the revised manuscript, we mentioned the 2 supplemental figures in the figure caption of Fig.4.

The figures are also shown below for your reference:

In Fig. S1, we show the central positions of simulated Haiyan during the time period from 1200UTC 7 November 2013 to 0000UTC 8 November 2013. The simulated tracks and central positions within a 5-hour time slot are shown in Fig. S2. For each experiment, the central time of the 5-hour time slot for picking the hourly positions is taken as the simulated typhoon centered at its nearest location upon the best-track location at 1800UTC 7 November 2013.

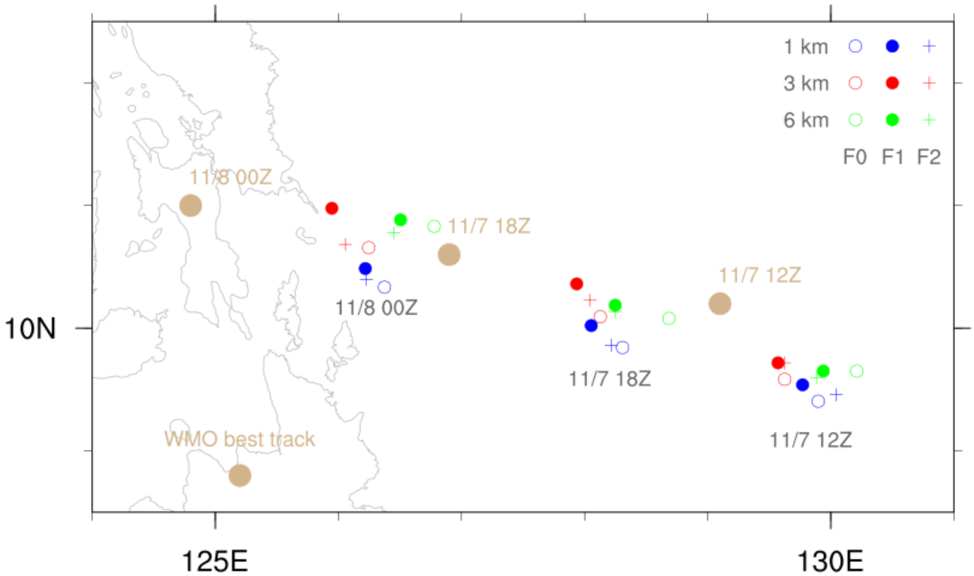

Fig. S1

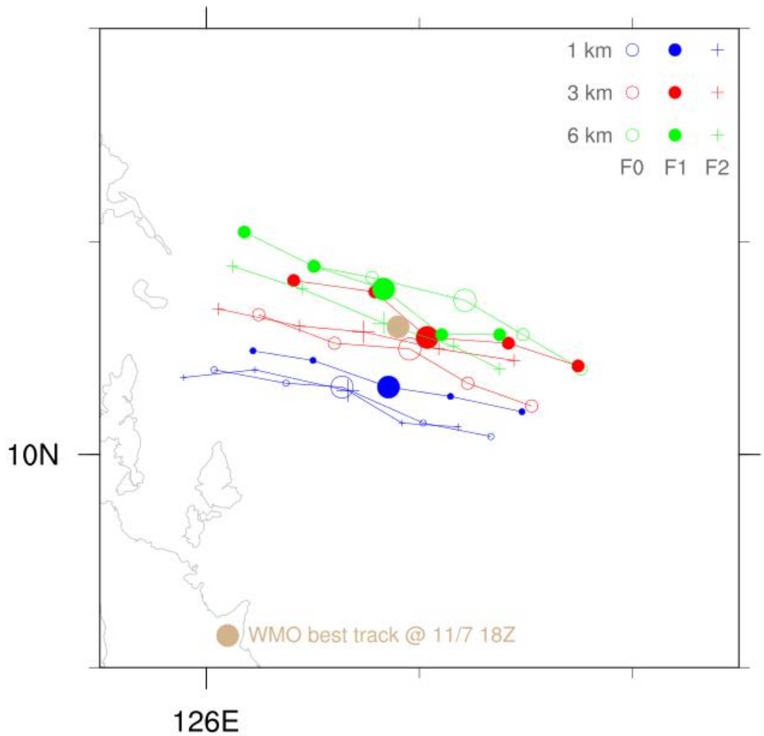

Fig. S2

7. *On P9 Line 6, "The intensity is not very sensitive to the resolutions of 3 and 6 km…", while I think it is sensitive enough.*

We agree. In the revised manuscript, this sentence has been modified (P9, lines 11-13):
'The intensity is sensitive to model resolution. Overall, the intensity increases as the resolution is changed from 6 to 3 km, but it significantly increases as grid spacing is reduced to 1 km.'

8. *There is no observed typhoon structure in this article as a comparison, and it is suggested to add corresponding figures.*

We do not have observations for the structure of typhoon Haiyan. In the former manuscript, we have provided a reference (Shimada et al. 2018) which revealed the observational information for the structure of Haiyan (2013). Please find the information on page 11 (lines 30-34) and page 12 (lines 1-5).

9. *The authors can introduce the use of contoured frequency by altitude diagrams. Maybe some readers are not familiar to those figures.*

We have added a paragraph to briefly introduce the use of CFADs. In the revised manuscript, these sentences have been added (from P16 lines 27-32 to P17 lines 1-7):

The CFADs is a statistical method for summarizing the vertical distributions of meteorological fields. A CFAD is constructed by collecting frequency distributions of a particular variable at evenly spaced altitudes within an area, compiling them into a two-dimensional (data bin and altitude) data set, and portraying the data on a single contour plot. The ordinate in the plot represents the altitude variation, and the abscissa the frequency bin. For each altitude on a CFAD, the frequencies should add up to 100 %. For a given CFAD, each point depicts the frequency of occurrence of the data in that bin at a specific altitude. Accordingly, the CFADs ignore horizontal variability and provide a bulk statistical measure for comparing the vertical structure of evolving fields of cumulonimbus clouds or any convective systems. Here, we take Fig. 13a as an example. On this CFAD, there are higher percentages (e.g., bounded by 20 %) found in the higher reflectivity bins at lower altitudes and found in the lower reflectivity bins at higher altitudes. The former can indicate convective cells or precipitations, whereas the latter can indicate snow or stratiform precipitation. Therefore, consider a set of CFADs for an evolving cumulonimbus clouds, say from the initiation to the mature stage, the maximum percentage at each altitude would change from vertically oriented to negatively tilted toward lower reflectivity values. More detailed interpretations of the use of CFADs can be found in the work by Yuter and Houze (1995).

10. In general, this quality of this paper is a little difficult to be understood by readers. I hope the authors can carefully revise some long sentences to make it easy to understand.

The revised manuscript has been edited by *Wallace Academic Editing* and is considered to be improved in grammar, punctuation, general readability, and native English usage.

11. Why doesn't the positive effect of reasonable surface flux formulas be enhanced efficiently if the grid spacing is relatively large? It should explain more clearly in the paper.

The surface fields and vertical structures between different resolution groups are more significant than that between flux options (cf. Figs. 6,8,9,10, and 11). The analyses indicate that the typhoon intensity is mainly controlled by the model resolution. Therefore, there are higher frequency of occurrences for extremely high wind speeds found in the experiments with higher resolution. From the description of the flux options given in section 2, we understand that near-surface wind speed is an influential factor for the calculation of bulk transfer coefficients. Accordingly, it is because of the low frequency of occurrences for extremely high wind speeds, the positive effect of the more reasonable surface option (F1) cannot be enhanced efficiently with a relatively large grid spacing of 6 km.

We have added several sentences to explain the above concept in the revised manuscript. The referee can find them on pages 13 (lines 29-32), 16 (lines 10-17), and 20 (lines 3-6).

TECHNICAL CORRECTIONS

We are very grateful for your careful corrections. In the revised manuscript, we have amended these sentences as suggested.

1. Page 3, Line 27, change "reaches" to "reached" Done. Now on page 3, line 24.
2. Page 7, Line 29, change "were" to "was"
Now on page 8, line 4. This should be a plural verb.
3. Page 7, Line 31, change "level-off" to "level-offs" Done. Now on page 8, line 5.
4. Page 8, Line 3, change "between" to "among" Done. Now on page 8, line 10.
5. Page 8, Line 4, this sentence is incomplete.
We have amended this sentence: "Accordingly, F1 is expected to have the highest potential to achieve the most intense storm among the three options because *it has* the highest values of C_K/C_D almost at all wind speeds." Now on page 8, line 9-10.
6. Page 9, Line 30, change "agree" to "agrees" Done. Now on page 10, line 5.

7. Page 11, Line 18, change "enhanced" to "enhancement" Done. Now on page 11, line 24.
8. Page 12, Line 29, change "increases" to "increase" Done. Now on page 13, line 1.
9. Page 13, Line 22, change "detail" to "detailed" Done. Now on page 13, line 33.
10. Page 13, Line 23, change "increase" to "increases" Done. Now on page 13, line 34.
11. Page 15, Line 5, change "between" to "among" Done. Now on page 15, line 16.
12. Page 15, Line 13, change "consider" to "considering" Done. Now on page 15, line 25.
13. Page 15, Line 24, change "that" to "than" Done. Now on page 16, line 1.
14. Page 17, Line 26, change "represent" to "represents" Done. Now on page 18, line 21.
15. Page 18, Line 21, change "fluxes" to "flux" Done. Now on page 19, line 16.
16. Page 18, Line 32, change "later" to "layer" Done. Now on page 19, line 27.
17. Page 19, Line 19, change "as" to "for" Done. Now on page 20, line 16.

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