Interactive comment on "Revised earthquake sources along Manila Trench for tsunami hazard assessment in the South China Sea" by Qiang Qiu et al.

We thank Reviewer 1 for the constructive suggestions which have greatly improved the manuscript. In this revised version, we have addressed the questions and highlighted areas where those changes are made. Our point-by-point responses and changes to each comment are given below.

Overall comments

This paper offers a new set of tsunami scenarios for the Manila trench, devised using updated geometric, coupling and geological results and interpretations. The topic is certainly significant and of interest to readers of NHESS.

I suggest the paper will be suitable for publication following some reasonably straightforward revisions, in particular to better emphasise the inevitable uncertainties in tsunami scenario design. The authors already discuss these issues well in some parts of the paper - but in other parts they gloss over the difficulties. Currently, I think the paper implies that the newly proposed scenarios are "better" than previously published scenarios. I doubt this is justifiable, considering the huge uncertainties in key subduction zone parameters (particularly Mw-max) on the Manila trench. These uncertainties could overwhelm any improvements due to better characterisation of coupling, geometry, etc. Thus, notwithstanding the advances in this paper, it is very difficult to say with confidence that the scenarios in this paper are "necessarily better" than previous scenarios, in terms of how well they represent the tsunami hazard.

Let me stress that this reflects the fundamental difficulty of tsunami scenario design in general, in the face of large uncertainties around frequencies of large-magnitude earthquakes. I don't think it is something that the authors can solve. However, I would like to see the discussion "softened" in various parts of the paper to better reflect these uncertainties. I also suggest they make some passing mention of probabilistic tsunami hazard assessment approaches, which offer a means to integrate uncertainties into the analysis (although this is also not straightforward).

Overall the paper is well written. I have suggested a number of grammatical corrections, but they will be straightforward to address.

Author's response: We are grateful for your positive comments. Your suggestions about putting more emphasis on the large uncertainties in the tsunami scenario are very sensible and are well taken. As you mentioned that designing tsunami scenarios is fundamentally difficult in subduction zones where large uncertainties exist for the frequencies of large-magnitude earthquakes, this is especially true for the Manila

Subduction Zone where no large earthquake occurred historically. Moreover, the spatial and temporal coverage of observational data (GPS, Seismicity, etc) is relatively limited. We have added the uncertainty discussion in various parts of the revised version.

Author's change to manuscript: Please see the detailed changes in our responses to section-specific comments.

Section-specific, high-level comments

Abstract

This reads well. The study sounds interesting and relevant.

Introduction

This generally reads well and provides appropriate background for the study.

Near the end, where you discuss the use of geodetic coupling to constrain the rupture, I would suggest giving some mention of potential problems with using coupling maps to represent future slip. For instance, there is evidence in Alaska that a "currently uncoupled" part of the megathrust may regularly produce tsunamis (Witter et al., 2016). The manuscript discusses some of the challenges with coupling maps later on – so alternatively, you could make this point then.

Author's response: as suggested by Reviewer 1, we have pointed the limits of using geodetic coupling to constrain the rupture in Section 3 before proposing the slip deficit models.

Author's change to manuscript: we added "… and in some cases uncoupled parts of the megathrust may regularly produce tsunamis (Witter et al., 2016)." at lines 316-317.

Somewhere in the paper (perhaps in the introduction), it would be good to mention probabilistic approaches to tsunami hazard assessment (e.g. Grezio et al., 2017; Li et al., 2016), as a contrast to the scenario-based approach in this paper. The main advantage of probabilistic approaches is that they offer a framework within which the uncertainties can be accounted for (e.g. Mw-max). The downside is that they are much more complex to understand and implement than scenario approaches.

Author's response: We have modified the text accordingly in the introduction part and mentioned the difference between the two main tsunami hazard assessment approaches.

Author's change to manuscript: The text is added in lines 137-141: "Scenario-based rupture models are different with the probabilistic-based tsunami hazard assessments within which hundreds and thousands are implemented for rupture uncertainty estimates. Therefore, the probabilistic approaches (Li et al. 2016; Grezio et al. 2017) are often more complex to understand and implement than the scenario-based approaches."

Section 2.

In my opinion this gives an OK justification for the segmentation. However, it is (unavoidably) far from certain that this is the best way to represent things. That's ok, but make sure the manuscript gives appropriate qualification.

Author's response: We have made great effort to collect as much geophysical information as possible to justify the probable segmentation. However, we do acknowledge the segment boundaries given in this study are by no means the only possibility. Such uncertainties have been emphasized in this section.

Section 3

I'm not sure, but it looks like the scenarios are motivated by the assumption that:

- The earthquake of interest has a 1000 year return period; and perhaps also that
- All the strain is released in that earthquake

It's not perfectly clear to me if these are the assumptions, so consider re-writing to make it very explicit.

Assuming I have correctly described your approach – obviously these assumptions are unlikely to be exactly true, because (for example) some strain will be released by smaller earthquakes; furthermore, maybe larger magnitude events occur with even longer return periods. Of course no- one can say for sure at present.

Regardless, I think it is reasonable to define a scenario as "an event which would release 1000 years of strain accummulation". But if this is what you are doing, it should be presented in this way.
Currently the paper attempts to justify the scenario choice from the coupling and paleo data – whereas to me, the choices seem "reasonable, but definitely ad-hoc". See detailed comments.

Author's response: We apologize for the confusion. It is true the scenarios are designed based on the assumptions listed by Reviewer 1. We have modified the main content and made these assumptions clear at lines 354-355.

Author's change to manuscript: Sentence is added in section 3 ".. assuming each event releasing 1000 years of strain accumulation while ignoring possible portion of strain release by smaller events."

Section 4

Generally good, see detailed comments.

Section 5

Here I think the uncertainties in scenario design and our understanding of subduction zonesare not sufficiently integrated into the discussion. See detailed comments.

Conclusions

Generally good, see detailed comments.

Detailed comments

Around Line 36 – I suggest slight edits as follows (bold).

- Since 1900, many megathrust ruptures have triggered numerous devastating near- and far- field tsunamis including the 1952 Mw 8.8-9.0 Kamchatka **event** (e.g., Johnson & Satake 1999; Kanamori 1976), the 1960 Mw 9.5 **event** in the Chile subduction zone (e.g., Cifuentes 1989; Moreno et al. 2009), the 1964 M w 9.2 Alaska **earthquake** (e.g., Plafker 1965), the 2004 M w 9.2 Sumatra-Andaman Earthquake along northern Sunda Trench (e.g., Vigny et al. 2005; Banerjee et al. 2007; Chlieh et al. 2007) , and the more recent 2010 M w 8.8 Maule **event** in Chile (e.g., Vigny et al. 2011; Pollitz et al. 2011) and 2011 Mw 9.0 Tohoku- Oki earthquake along the northwest border of the pacific ocean (e.g., Koketsu et al. 2011; Wei et al. 2012).

Around Line 56-57 – Suggest to replace "are considerably inconsistent" with "differ greatly among studies".

Line 73 – remove "is likely to occur"

Line 76 – add "the" before

"1960s".

Line 99 – Suggest to remove "could only have been" – I think the point is very reasonable, but one could hypothetically imagine various less plausible causes (e.g. asteroid). I'm certainly not promoting that idea – simply noting that logically, "could only have been" might be too strong a statement, and is not required.
Line 123 – Suggest to replace "only ca.1/20" with "only about 1/20". Alternatively, consider "approximately 1/20" or "less than 1/XX".

Line 128 – "we utilize the" – suggest to replace "the" with "a".

Author's response: All the grammatical corrections between line 36 -128 are made according to the suggestions given by Reviewer 1.

Line 132 - "Our rupture models afford standard examples for an improved understanding of the tsunami hazard in the SCS. " – I don't understand this, consider re-wording. Not sure if you mean to imply that your results are necessarily better than previous work? I would be cautious about accepting any notion that "because we use better data, our scenarios are better", given the huge uncertainties about Mw-max, seismogenic depth, etc. I don't think those issues are "perfectly resolved" by your paper (and I would not expect or require that, because they are "deep" problems in general).

Author's response: We have modified the text accordingly.

Author's change to manuscript: At lines 141-142, we added "Here the proposed rupture models afford a physical-based understanding of the tsunami hazard in the SCS."

Line 138-158. I like this discussion, which gives a realistic depiction of the limitations in our understanding of megathrust earthquakes.

Author's response: Thanks for your positive comments.

Line 162: – "Systematic analysis of collections of great earthquakes globally indeed suggests that some of the physical parameters do play key roles in controlling the rupture characteristics (Bilek and Lay, 2018; Bletery et al., 2016; Schellart and Rawlinson, 2013)." – I would suggest adding something like ", although limitations in the historical earthquake record inevitably make it difficult to have high confidence such relationships". For instance, we saw this with the (now discredited) idea that only 'young, fast' subduction zones can host large magnitude earthquakes (Stein and Okal, 2007). It seemed reasonable when proposed, but now we have enough data to say it doesn't work. Given recent "suprises", I think we still suffer from 'lack of data', and cannot be sure about physical controls on ruptures. See also related comments on Section 4 below.

Author's response: We have modified the text according to the suggestions.

Author's change to manuscript: At lines 182-183: ".. although limitations in the historical earthquake records inevitably make it difficult to have high confidence on such relationships."

Fgure 1 – It would help if you explicitly denoted the rupture segments. I appreciate the figure is already crowded, and so some judgement is required here -- but as a reader I did have to spend a bit more time to figure out where the 3 segments are.

Author's change to manuscript: we have denoted the segments using colour-shaded curves.

Line 183: Suggest to replace "While" with "In

contrast,"

Line 190: Suggest to replace "rupture cases" with "ruptures".

Line 260: "they would have be buoyant" – missing a "to" before "be".

Line 288: Missing "a" before "velocity value"

Line 295: Suggest to replace "the coupling map though not the perfect" with "the coupling map, although not perfect,”

Author’s change to manuscript: All the grammatical corrections between line 183- 295 are made according to the suggestions given by Reviewer 1.

Line 302: “To gain a comprehensive understanding of the seismic return time period, large amount of historical seismic data and geological evidence are required.” – I disagree with this – rather, currently it seems implausible to comprehensively understand the seismic return period. In my opinion, a more realistic statement would be something like “Given the short duration of historical records relative to the return-periods of high-magnitude events of interest, and limitations in our capacity to infer earthquake return-periods from first-principles physics, it is unrealistic to expect to develop a comprehensive understanding of seismic return periods.”

Author’s response: This point is well taken.

Author’s change to manuscript: We have modified the text at lines 326-330: “For seismic return time period, given the short duration of historical records relative to the return-periods of large-magnitude events of interest, and limitations in our capacity to infer earthquake return-periods from first-principles physics, it is unrealistic to expect to develop a comprehensive understanding of seismic return periods.”

Line 316: Here the text states that “We, thus, use the only available information that the seismic return period is likely to be ca.1000 year and a giant event had ruptured the Manila trench in the last seismic cycle”. I cannot see that the available information can tell you either of these things. The “1000 year” number appears to be an ad-hoc decision in the earlier paper (it may indeed be a “reasonable ad-hoc decision” – that’s OK – but the key point is that it is not a precise consequence of observations). To be clear what I mean by ‘ad-hoc’, consider the question: Why 1000 year? Why not 2000? Why not 500? Why not 784.37?. Further, I doubt that the paleo work can “strongly” justify the above points, given the limited number of sites and difficulties in interpretation.

In my opinion, it would be much better to say something like “We choose to model scenarios which release 1000 years of accumulated strain, because these represent large, rare and yet plausible events which are of interest for hazard assessment purposes, and the paleo data indicates that large events may well occur”. This would seem to be more consistent with what we actually do know, and reflective of the uncertainties.

Author’s response: This point is well taken.

Author’s change to manuscript: We have updated this part accordingly at lines 347 to 351: “Here we choose to model scenarios, which release 1000 years of accumulated strain, because these represent large, rare and yet plausible events, which are of interest for hazard assessment purposes, and paleo-geological data indicate that large events may occur about 1000 years ago.”

Line 321: Missing "of" before "1000

years".

Line 433: "deficient" – should this be "deficit"?

Line 349: "and beyond behave semi-brittle" consider re-wording, e.g. you could replace

"behave" with "induce".

Line 350: Some suggested edits: "~~By doing so it could~~ **This can** capture ~~the~~ **to** first-order the ~~of~~ potential slip extent (Figure 3c and f), ~~similar as the estimated~~ **with a** depth-range of slip **consistent with observations** from global megathrust great earthquakes (e.g..."

Figure 3: Suggest to increase the size of the panel labels (a), (b), … etc. They are hard to find at present.

Line 381: Add a full-stop "." after

"ruptures".

Line 383: Add "the" after "solves".

Line 386: Suggest to delete "We considered one grid layer for each case to model wave propagations in the SCS because...", and replace it with "A uniform grid was used because ..."

Line 389: Add "the" after "along"

Line 392: Suggest to delete "used to simulate the tsunami wave propagations" and replace with "equal to the initial ocean surface deformation".

Line 432: Suggest to replace "Potential tsunami arrival time" with "The tsunami

travel time"

Line 445: There is a typo here around "as"

Line 446: Remove "further afield".
Line 448: Replace "route" with "routes".
Line 455: Suggest to replace "Whereas" with "Conversely".
Line 466: Suggest to replace "flat gentle dipping" with "flat, gently dipping"

Line 467: Suggest to replace "dipping" with "dip".

Author's change to manuscript: All the grammatical corrections between line 321- 467 are made according to the suggestions given by Reviewer 1.

Line 459 – 467: I think this section gives the impression that we understand how a number of physical factors control the distribution of megathrust earthquakes. To me, the point should be highly qualified, because really we do not have sufficient data to be "highly confident" that such relationships work. An alternative view is that currently, we don't have enough data to say for with confidence how big/how often very large subduction earthquakes occur on any source-zone, or to relate this to physical factors such as mentioned in this section. McCaffrey (2008) is a classic reference in this regard. Also, see Stein and Okal (2007) for an example study which argues against the Ruff and Kanamori (1980) result cited here. You might also note examples of earthquakes which have crossed supposed "rupture barriers", such as the 2007 Solomon earthquake (see discussion in Lorito et al 2015 review paper as a starting point). In this vein, it is also worth noting alternative approaches to modelling Mw-frequency relations which do not make heavy use of such "physical information" – for example Rong et al. (2014), Kagan and Jackson (2013), which only employ basic moment conservation principles and catalogue data.

In sum, I think you should add some discussion of the "unknowns" to this part of the text, perhaps using the references above, so that the reader is not left with the impression that our understanding is better than it actually is.

Author's response: We understand the reviewer's concern about the certainty shown in the previous version. In this revised version, we added some discussion of the "unknowns" according to the reviewer's suggestion.

Author's change to manuscript: We have added this part of discussion in the main text at lines 523 to 533: "While as the boost of geodetic measurements, the relationship between great ruptures and the convergence rate was challenged (McCaffrey 1994; Stein and Okal 2007; and Nishikawa and Idel, 14). The maximum moment magnitude of a potential earthquake is often determined from seismic catalogue data, alternatively determined from basic moment conservation principles and catalog data (Rong et al., 2014; Kagan and Jackson, 2013). Overall, with current short observation time span as compared with multi-century seismic return period, it is improper to make the determination on the relationship between these physical parameters and how big or how often a giant earthquake can occur in any subduction zone (McCaffery, 2008). Clearly, long-term and complete observations within seismic cycles are required for a better understanding of subduction zone rupture behaviors."

Line 475-486: Consider mentioning the 2007 Solomon earthquake here, as a counter-example to your points. This will emphasise the need for caution when making assumptions about rupture barriers.

Author's change to manuscript: We have included the 2007 Solomon example that shows in some cases the rupture went across triple junction at lines 554-555: "…like the 2007 Mw 8.1 ruptured a triple junction (Furlong et al., 2009; Taylor et al., 2008)."

Line 497-514: Here the text appears to be claiming that the scenarios in this paper are "better" than others. I think these conclusions must be softened, because the only way to "scientifically test" this claim would be to observe many tsunami events on the Manila trench, and determine whether your tsunami scenarios better captured the true behaviour. Obviously this is impossible in practice (maybe our ancestors could do it in a few thousand years!). Thus, we are necessarily left with substantial doubt as to whether one set of tsunami scenarios is "better" than another.

In this paper, the scenarios are developed using better data than some previous studies. Does this lead to high confidence that the scenarios are more realistic? I would say "no". Even if we only consider the large uncertainties in Mw-max that have been proposed for the Manila trench (e.g. Berryman et al., 2015), it follows that the scenarios in this paper could be seriously wrong and not necessarily better than others, nothwithstanding the use of better data in the current study.

Let me stress that I do not expect the authors to solve this problem – rather, it reflects the current "deep" uncertainties regarding size constraints for subduction earthquakes. The author's approach to scenario construction is reasonable, but there are too many "deep" uncertainties to conclude it is "better". The text in this section should be softened accordingly. Of course you should still emphasise the good things about the scenarios in this paper (i.e. better data, etc).

Line 504-505: "Heterogeneous slip models, as we observe from finite rupture models of earthquakes, are more realistic and could better explain the observations". Here it's unclear what "observations" you mean. Consider replacing this sentence with "Finite rupture models of historical earthquakes indicate that slip is heterogeneous, and this is represented by our scenarios".

Author's response: We have updated and softened this paragraph accordingly.

Author's change to manuscript: Please see the changes in Section 5 Discussion: "… planar fault with uniform slip assumed rupture cases. We've seen that finite rupture models of historical earthquakes indicate that slip is heterogeneous, and this is represented by our scenarios. Further detailed tsunami hazard assessment in SCS demonstrates that uniform slip models underpredict tsunami hazards as compared to a heterogeneous slip model (Li et al., 2016). Therefore, our refined earthquake rupture scenarios in zones 1 and 2 provide new insights for tsunami hazard assessment in SCS."

Line 520 – 522: Along the lines of my comment above, I would suggest replacing "provide new constraints for" with "enable" – because although I think your scenarios are reasonable, I don't think they really provide strong new constraints as to what is possible on the Manila trench. This is a deep problem that reallistically cannot be solved by the current paper.

Author's change to manuscript: The grammatical corrections between line 504- 522 are made according to the suggestions given by Reviewer 1.

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Interactive comment on "Revised earthquake sources along Manila Trench for tsunami hazard assessment in the South China Sea" by Qiang Qiu et al.

We thank Reviewer 2 for the helpful suggestions. In this revised version, we have addressed the questions and highlighted areas where those changes are made. Our point-by-point responses and changes to each comment are given below.

The authors mentioned "Large variability in the results produced by these models underscores the fact that the seismogenic behaviors of the MSZ are still poorly understood". Based on coupling models A and B of Hsu et al. (2016) in which the spatial distribution of slip rate and coupling rate are available, the authors used a return period 1000 years to calculate the slip deficit of great earthquakes. For zones 1 and zone 2 where the coupling ratios and slip rate are relatively better constrained than zone 3. Because the MSZ is poorly understood, the authors think the current status of the Manila subduction zone could be an analog of the Sumatran subduction zone before the 2004 Mw 9.2 Sumatra-Andaman event between Myanmar and Aceh where a paucity of earthquake > Mw 8 precede the 2004 event (Chlieh et al., 2008; Hsu et al., 2012). Based on those assumptions, the scenarios were created. Due to paucity of observations in zone 3, no coupling ratios were resolved. Geologically this zone is much more complicated than zones 1 and 2 (Lin et al., 2009). It is, therefore, crucial but difficult to precisely quantify individual role of the OOSTs and megathrust in tsunami generation. We propose two end-member scenarios, considering different rupture modes in zone 3 with two steps. We first calculate the slip deficit from the slip deficient rate of models A and B between 19N to 20N. We then consider two end-member scenarios in the region from 20N to 21.7N. The first-member is the seismogenic events with rupture depths determined from a collection of GCMT solutions of the world megathrust earthquakes.

This paper made a great contribution on the literature review of the MSZ system. The authors did provide more geological evident for understanding MSZ, but combined the references regarded geological characteristics of the subduction plate, the geometry, and coupling, and state of the subduction interface to propose a series of fault rupture scenarios. Each scenario reaches the earthquake magnitude from Mw 8.5+ to Mw 9+. Most of the cases not only reached but also beyond the upper limits of previous related studies.

Author's response: We are grateful to you for the positive comments.

Because no new geological evident for understanding the MSZ system, the authors shall carefully state background of creating the scenarios, and also emphasis those probably the upper limit case for the regional tsunami.

Author's response: Thanks for the suggestions. The assumption behind our rupture scenarios is that all the accumulated strain will be released within 1000 years. The 1000-year time interval is informed by the available geological evidences. We have explained this assumption in a clearer way in this revised version. Regarding the upper limit earthquake magnitude, it is challenging to put a specific value due to the fundamental difficulty of determining the actual rupture extent precisely. Nevertheless, we do acknowledge in the paper that the rupture-across-zone earthquake with magnitude ~Mw 9.3 is possible with very low probability. Please see the discussion part in Section 5.

For a scenario with earthquake magnitude greater than 9 and with a return period at 1000 years, geological evident such as tsunami deposit and tsunami boulder shall not so-hard to be found along the coasts of the flooding areas. The authors shall explain this issue.

Author's response: A variety of issues are responsible for the few tsunami deposits in the South China Sea, including intense human activity in the coastal region and the challenge of distinguishing tsunami deposits from storm deposits etc. The intense human activities could explain why all the existing geological evidences are so far only reported in the relatively remote islands inside the SCS. Meanwhile, the coastal area in most part of the SCS is one of the most frequently hit regions by typhoons, therefore, the geological-based interpretation suffers from the challenges of distinguishing tsunami waves from extreme storm surges. With all these difficulties, we still expect that more tsunami deposits are likely to be uncovered at other locations in future studies.

In terms of the numerical model, they look OK to me. Great job.

Author's response: We appreciate your encouraging comments.

Some minor mistakes: Line 822 Figure 1. The "1781/Tainan" shall be "1782/Tainan", or "1781/ Kaohsiung-Pingtung"

Author's change to manuscript: We corrected the event name to "1782/Tainan" in Figure 1.

Line 134: COMCOT solves shallow water equation which is a hydrostatic model.

Author's response: Agreed.

Table S1 is missing. No detail can be found the scenario parameters.

Author's response: Please find Table S1 in the supplementary file and the vertical uplifts grid file are also given in the supplementary data.

Revised earthquake sources along Manila Trench for tsunami hazard assessment in the South China Sea

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Abstract

Seismogenic tsunami hazard assessments are highly dependent on the reliability of earthquake source models. Here in a study of the Manila subduction zone (MSZ) system, we combine the geological characteristics of the subducting plate, the geometry, and coupling state of the subduction interface to propose a series of fault rupture scenarios. We divide the subduction zone into three rupture segments: 14°N-16°N, 16°N-19°N and 19°N-21.7°N inferred from geological structures associated with the down-going Sunda plate. Each of these segments is capable of generating earthquakes of magnitude between Mw 8.5+ and Mw 9+, assuming a-1000-year seismic return period as suggested by previous studies. The most poorly constrained segment of the MSZ lies between 19°N-21.7°N, and here we use both local geological structures and characteristics of other subduction zone earthquakes around the world, to investigate the potential rupture characteristics of this segment. We consider multiple rupture modes for tsunamigenic-earthquake type and megathrust-splay fault earthquakes. These rupture models facilitate an improved understanding of the potential tsunami hazard in the South China Sea (SCS). Hydrodynamic simulations demonstrate that coastlines surrounded the SCS could be devastated by tsunami waves up to 10-m if large megathrust earthquakes occur in these segments. The regions most prone to these hazards include west Luzon of Philippines, southern Taiwan, the southeastern China, central Vietnam and the Palawan Island.

1. Introduction

Large and damaging tsunamis are commonly triggered by megathrust ruptures that occur along convergent plate boundaries (i.e. Subduction zones). Since 1900, many megathrust ruptures have triggered numerous devastating near- and far-field tsunamis including the 1952 M_w 8.8-9.0 Kamchatka event (e.g., Johnson and~~&~~ Satake 1999; Kanamori, 1976), the 1960 M_w 9.5 event in the Chile subduction (e.g., Cifuentes, 1989; Moreno et al., 2009), the 1964 M_w 9.2 Alaska earthquake (e.g., Plafker, 1965), the 2004 M_w 9.2 Sumatra-Andaman Earthquake along northern Sunda Trench (e.g., Vigny et al., 2005; Banerjee et al., 2007; Chlieh et al., 2007) , and the more recent 2010 M_w 8.8 Maule event in Chile (e.g., Vigny et al., 2011; Pollitz et al., 2011) and 2011 M_w 9.0 Tohoku-Oki earthquake along the northwest border of the pacific ocean (e.g., Koketsu et al., 2011; Wei et al., 2012). These earthquakes and their associated subduction zones have been intensively studied from different perspectives, including their tectonic settings and long-term evolution, seismic activities, geodetic and geophysical features. In contrast, the Manila subduction zone (MSZ), which extends from the southern Taiwan to the southern tip of the Luzon Island in Philippines along the eastern margin of the South China Sea (SCS) (Figure 1), receives less attention, even though it shares many similarities with megathrust systems where large tsunamigenic earthquakes have occurred (Hsu et al., 2012, 2016).

Over the past decade, attempts to study megathrust earthquakes and tsunamis from the Manila subduction zone are starting to gain momentum. A number of rupture models have been used to assess potential tsunami hazard in the SCS (e.g., Hong Nguyen et al., 2014; Liu et al., 2009; Megawati et al., 2009; Okal et al., 2011; Wu and Huang, 2009) and yet, the simulated tsunami wave heights and the subsequent hazard assessments ~~are considerably inconsistent~~differ greatly among studies (Hong Nguyen et al., 2014; Liu et al., 2009; Megawati et al., 2009; Okal et al., 2011; Wu and Huang, 2009; Xie et al., 2019). The difference often lies in the proposed fault-slip magnitudes of these models, and also the fault geometries used. Large variability in the results produced by these models underscores the fact that the seismogenic behaviors of the MSZ are still poorly understood. Some of the challenges which stand out and need to be resolved include assessing whether the MSZ is capable of hosting M9+ earthquakes; and investigating the amount of tectonic strain it has accumulated, its style of strain accumulation and constraining how that strain is likely to be released in future.

Several lines of evidence suggest that the Manila trench has the potential to host a giant rupture capable of generating a basin wide tsunami. Firstly, both historical earthquake records and modern seismicity databases (Hsu et al., 2012, 2016) indicate an absence of earthquakes larger than M_w 7.6 since Spanish colonization of Luzon in 1560s (Bautista et al., 2012; Megawati et al., 2009; Ramos et al., 2017; Terry et al., 2017). The lack of significant megathrust-related earthquakes in modern records implies that either a predominately aseismic megathrust or a highly coupled interseismic megathrust with the potential for a large (M_w 8.5+) rupture (e.g. Hsu et al., 2012)~~ is likely to occur~~. Several recent studies favor the high interseismic coupling model, since both the analysis of earthquake focal mechanisms and geodetic monitoring results demonstrate that the upper plate is under shortening, which suggests that the megathrust, at least since the 1960s, shows minimal creeping (Bautista et al., 2001; Hsu et al., 2012, 2016). Secondly, the rate of plate convergence across the Manila trench is up to 90-100 mm/year- faster than the convergence rate of the Sumatra, Japan and Nankai subduction zones, all of which have hosted giant earthquakes in the past few decades (McCaffrey, 2008; Megawati et al., 2009; Hsu et al., 2016, 2012;). Since the MSZ did not produce any significant events in the past four centuries, >30m of slip deficit is estimated to have been accumulated on the subducting interface (Megawati et al., 2009; Hsu et al., 2016). Thirdly, historical documents together with a few geological records across the SCS basin have reported nearly 130 tsunami-events with different generation mechanisms (i.e. Earthquakes, submarine landslides, volcanic eruptions). Although the credibility levels of these records varies (Bautista et al., 2012; Lau et al., 2010; Paris et al., 2014) and the geological-based interpretation suffers from the challenges of distinguishing tsunami waves from extreme storm surges, a series of records stand out with similar range of event ages. Notably, four independent geological and geomorphological studies (Ramos et al., 2017; Sun et al., 2013; Yang et al., 2018; Yu et al., 2009) (Figure 1) have purported evidence from coastal deposits which they have inferred to be the result of large tsunami event in SCS around 1000 to 1064 A.D., which is of near coincidence with a historical large wave event recorded in Chaoan, Guangdong in November, 1076 A.D. (Lau et al., 2010). The four independent sites of geological evidence are located at Dongdao island (Sun et al., 2013), Yongshu island (Yu et al., 2009), Badoc island near Luzon (Ramos et al., 2017) and Nanao island in southern Chinese coastline (Yang et al., 2018) (Figure 1). Since these studies identified only one event and if it were indeed generated by one tsunami, then we can conclude that the event was likely to be basin-wide and ~~could only have been~~ triggered by a very large MSZ event. Such an event will be a megathrust earthquake with sufficiently large rupture up to 1,000 km long. Such a long and persistent rupture is comparable to the rupture length of the 2004 Sumatra-Andaman earthquake (e.g. Megawati et al., 2009). With the afore-mentioned pieces of evidence, there is no reason to rule out the possibility that the Manila trench could rupture as an M_w 9 earthquake (i.e. Megawati et al., 2009; Hsu et al., 2016). The current status of the Manila subduction zone could be an analog of the Sumatran subduction zone before the 2004 M_w 9.2 Sumatra-Andaman event between Myanmar and Aceh where a paucity of earthquake > M_w 8 precede the 2004 event (Chlieh et al., 2008; Hsu et al., 2012), despite of the very different geological settings (i.e. age, buoyancy, fault geometry) between these two subduction zones.

The SCS region is vulnerable to potential tsunami hazard. It covers an area ca.3.5 million km^2 (Terry et al., 2017), and is encircled by the coastlines of southeastern China, southern Taiwan, western Philippines, eastern Vietnam, northern Borneo and eastern Malaysia, forming a semi-enclosed basin (Figure 1). The SCS coastline is one of the world's most densely populated with more than 80 million people living in the surrounding coastal cities (Terry et al., 2017). Many of these coastal cities serve as the economic centers and play pivotal roles in their respective countries' economic development. The coastline also hosts a very high density of major infrastructure (i.e. nuclear power plants, ports, airports). Data from the World Nuclear Association shows that more than 10 nuclear power plants are currently in operation or about to start construction in the SCS coastline (http://www.world-nuclear.org/information-library). Thus, if a large megathrust earthquake (e.g. Mw >9) were to occur within the SCS basin (Li et al., 2018), the impact would be amplified and much more devastating as the SCS is only ~~ca.~~about 1/20 the size of the Indian Ocean. It is therefore crucial to provide physical-based earthquake rupture models for a more realistic tsunami hazard assessment in the SCS region.

This study differs from previous studies (e.g., Hong Nguyen et al., 2014; Liu et al., 2009; Megawati et al., 2009; Okal et al., 2011; Wu and Huang, 2009), because we utilize ~~the~~ a geodetic coupling model constrained by 17 years of GPS velocity measurements (Hsu et al., 2016) to propose a suite of better constrained physically based earthquake rupture scenarios. We also consider rupture segmentations constrained by the geological characteristics and the relief of the subducting Sunda plate. ~~Our s~~Scenario-based rupture models ~~don't like~~are different with the probabilistic-based tsunami hazard assessments within which hundreds and thousands are implemented for rupture uncertainty estimates.~~,~~ ~~however t~~Therefore, the probabilistic approaches (e.g., Li et al., 2016; Grezio et al., 2017) are often more complex to understand and implement than the scenario-based approaches. Here the proposed ~~physical-based~~ rupture models ~~afford standard examples for~~afford a~~n~~ physical-based ~~improved~~ understanding of the tsunami hazard in the SCS. As a demonstration, we implement the rupture models to conduct hydrodynamic simulations to assess the tsunami characteristics along the coastlines of the SCS.

2. Refined possible rupture scenarios

Forecasting the extent and the slip distribution of earthquake ruptures is a challenging task. Before the 2004 M_w 9.2 Sumatra-Andaman earthquake (Chlieh et al., 2008), an M_w 9 earthquake had never been anticipated along the Sunda Trench, due to its oblique convergence orientation and seismically inactive feature (Satake and Atwater, 2007). Globally, the eventual ruptures of some unexpected fault locations keep surprising scientists (Bilek and Lay, 2018). We've seen partial ruptures of fully locked megathrusts (Konca et al., 2008; Qiu et al., 2016; Ruiz et al., 2014; Schurr et al., 2014), and piecemeal breaks in the center of perceived seismic gaps (e.g. Salman et al., 2017). Even with improved observations, it remains difficult to constrain the magnitude of potential earthquake in the first order, and even more difficult to define the rupture pattern (e.g., Lay, 2018). A recent example comes from Japan where Loveless & Meade (2010) used a number of inland GPS stations to estimate the coupling state of the Japan megathrust before the 2011 Tohoku-Oki earthquake. They indicated the spatial extent of a possible future rupture. Notably, the rupture models constrained by multiple geodetic data sets after the 2011 earthquake (Koketsu et al., 2011; Loveless and Meade, 2011, Wei et al., 2012) are significantly different to the coupling map of Loveless and Meade (2010). The discrepancy between a coupling map and actual rupture estimates has also been observed at other subduction zones (e.g. Ruiz et al., 2014; Schurr et al., 2014) and for the collision zone between the Indian and Eurasian plates (Avouac et al., 2015; Qiu et al., 2016; Stevens and Avouac, 2015). Clearly, our current knowledge of the seismogenic characteristics of giant earthquakes remains deficient.

Great efforts have been made to investigate the physical parameters that characterize subduction zones with regard to the geometry, geology and dynamics (Schellart and Rawlinson, 2013). Systematic analysis of collections of great earthquakes globally indeed suggests that some of the physical parameters do play key roles in controlling the rupture characteristics (Bilek and Lay, 2018; Bletery et al., 2016; Schellart and Rawlinson, 2013), although limitations in the historical earthquake records inevitably make it difficult to have high confidence on such relationships. Taking into account the geometrical effects, previous studies have divided the entire Manila subduction zone into three segments (i.e. Zhu et al., 2013; Li et al., 2016; Gao et al., 2018). Here we follow the segments proposed by Li et al. (2016), and we provide new constraints on earthquake and tsunami potentials by combining geological information and the geodetic constrained coupling map to adjust these segments accordingly. The modulated three segments are 14°N-16°N, 16°N-19°N, 19°N-22°N, respectively. Their significances are detailed in subsequent sections.

2.1 Rupture segment 1 (zone 1, 14°N-16°N)

The Manila trench primarily starts from ca.13°N west of Mindoro and ends at ca.22°N southwest of Taiwan, and beyond these bounds the Manila trench gradually transform into collision and accretionary belt in the north and south (Figure 1). At the southernmost area of the Manila trench, the strike direction of the trench bends to southeast offshore the Mindoro Island (ca.13°N) before it further collides with Panay (ca.11°N). Within this region (ca.13°N to 11°N) the relocated seismicity suggest the subducting slab dips almost vertically, with an absence of the deep seismicity (Bautista et al., 2001). Based on these features, Bautista et al. (2001) suggest the subducting slab may have been heated up and assimilated into the mantle. We, therefore, interpret that the great megathrust earthquake is less likely south of 13°N. Li et al. (2016) placed the southern boundary of the first segment at ca.12.5°N. ~~While~~ In contrast, Bautista et al. (2001) proposed a slab tear at ca.14°N which is the result of the collision of a micro-continental plate with Mindoro and Panay islands and as evidenced by the narrow seismicity gap north of 14°N that trends northeastward (Figure 2). Based on these geological characteristics and geodetic measurements, together with the fact that the spatial coverage of GPS measurements in this region only allows us to estimate the coupling status starting at 14°N to the north (Hsu et al. 2016), we move the southern boundary of the first segment from ca.12.5°N proposed by Li et al. (2016) to 14°N, but we do not rule out the possibility of ruptures ~~cases~~ that propagate across 14°N to 13°N or even beyond.

Moving to the north, between 16°N to ca.17.5°N, a bathymetric high called Scarborough seamount chain is subducting beneath the Philippine plate. The Scarborough seamount can be traced between ca.12°N to 18°N from the subducting Sunda plate and between ca.16°N to 19°N (Figure 1) after subducting beneath the Philippine plate from the regional tomography model (Wu et al., 2016). This seamount chain has been interpreted as part of an extinct Middle Ocean Ridge (MOR) that is either presently being accreted or subducted under the trench at 16°N (Ludwig, 1970; Pautot and Rangin, 1989). A slab tear was proposed at 16°N based on seismic-related strain energy release of intermediate-depth and shape changes in the dip angle of the slab (Bautista et al., 2001). Although great earthquakes can rupture across the seamounts or morphological bounds occasionally (e.g. Bell et al., 2014; Duan, 2012; Kumagai et al., 2012), global observations suggest that in many cases seamounts or barriers impede (Singh et al., 2011; Wang and Bilek, 2011) or confine rupture propagations (Qiu et al., 2016). Further, we note that slab tears at 14°N and 16°N bound the southern and north tip of the highly coupled west Luzon trough (Hsu et al., 2012, 2016) coincidentally, and these tears may act as morphological barriers to limit the rupture propagation similar to that noted from the 2015 M_w 7.8 Nepal event (Qiu et al., 2016). We, therefore, define the region between 14°N to 16°N as segment 1 (zone 1) (Figure 3a and d).

2.2 Rupture segment 2 (zone 2, 16°N-19°N)

As noted in section 2.1, the Scarborough seamount chain is located between ca.16°N to 17.5°N where the subducting Sunda plate meets with the Philippine plate (Figure 1). A regional tomography model also suggests that the subducted seamount chain can be traced between ca.16°N to 19°N (Wu et al., 2016). In this subducted seamount region, the absence of seismicity and seismic-related strain energy release at intermediate depths suggest the possible trajectory of the MOR that is interpreted to be still hot and deforming plastically (Bautista et al., 2001). Globally studies of subducting seamount systems suggest that large fracture zones are formed surrounding the seamount, and the highly fractured region can act as barriers to hinder the rupture propagation (e.g., Wang and& Bilek, 2011). Because the stress concentration in and around the fracture zones is high and may easily reach failure criteria, the seamount can trigger (e.g., Kumagai et al., 2012; Koyama et al., 2013) the failure of highly stressed asperities in the neighborhood, nucleating as a great earthquake (e.g., Kumagai et al., 2012; Koyama et al., 2013). Previous studies also suggest that seamounts cause persistent fault creep (e.g., Singh et al., 2011) or rupture as small earthquakes due to localized areas of high fracture and associated regional stress anomalies (e.g., Wang and& Bilek, 2011). Thus, fault creep and the rupture of single or multiple asperities are all possible in this region.

The Geodetic coupling map constrained by long-term GPS velocity measurements indicates that the seamount chain region (i.e. ca.16°N to 19°N) is less coupled (Figure 3, coupling models A and B), partially due to the fault creep caused by the seamounts or poor constraints by paucity of the offshore observations (Hsu et al., 2012, 2016). The weak coupling extends further north to 19°N, in the area of the southern tip of the North Luzon Trough and west of the northern tip of Luzon Island. This area is likely creeping or weakly coupled (Figure 3, coupling mode A and B). Additionally a trench-parallel gravity anomaly (TPGA) has been interpreted with great subduction earthquakes occurring predominately in areas characterized by strongly negative TPGA, while regions with strongly positive TPGA are relatively aseismic (Song and Simons, 2003). We note that positive TPGA covers from ca.16°N to 19°N (Hsu et al., 2012), coinciding with the geodetically determined weakly coupled and creep regions. Considering all these factors mentioned above, we redefine segment 2 (zone 2) as the region between 16°N to 19°N as (Figure 3b and e) slightly extends further north when compared with the same segment of Li et al. (2016).

2.3 Rupture segment 3 (zone 3, 19°N-22°N)

The area of the megathrust bounded between the southern tip of Taiwan and northern Luzon (between 19°N to 22°N) (Figure 1) is poorly understood, as the current available geodetic measurements are sparse and primarily deployed in the volcanic islands to the east which are far away from the Manila trench (Hsu et al., 2012, 2016). In this region, the Manila trench bends sharply at 20°N (Figure 1). Geologically the bending has been interpreted as the result of the subduction of a high-relief bathymetrical plateau that is sufficient buoyant to impede subduction (Bautista et al., 2001; Suppe, 1988) or may due to thick sediments (Lin et al., 2009). Additionally, here regional block faulting stretches the continental crust, resulting in numerous micro-continental fragments. Further, the 1980s geophysical studies (Taylor and Hayes, 2013) have recovered a magnetic quiet zone characterized to the continental-to-oceanic boundary (Bautista et al., 2001), and this zone was further interpreted with a transition zone between a continental and oceanic lithosphere (Taylor and Hayes, 2013). If these numerous fragments are indeed subducting beneath the Philippine sea plate, then they would have to be buoyant enough to resist the subducting process at 20°N with fast subducting of the neighboring portions of the trench that may extending south to 19°N. Such a situation would result a complex stress field in the upper plates that were mirrored by diverse and complicated focal mechanism solutions (Bautista et al., 2001).

As more marine geophysical data becomes available, there is an increased understanding of the geological structure and potential seismogentic faults (Lin et al., 2009). Detailed analysis of seismic reflection data (i.e. Line 973 in Lin et al., 2009) reveals prominent seismogenic structures in the region, which include frontal décollement beneath the lower-slip domain and out-of-sequence thrusts (OOST) in lower- and upper-slope domains (Lin et al., 2009; Zhu et al., 2013). Evidence from the thermal regime of these structures suggests that the megathrust and part of the frontal décollement are seismogenic (Lin et al., 2009). These seismogenic structures are found to be analogous to that observed in the Nankai prism of the Nankai Trough, Japan, posing potentials for generating great earthquakes and tsunamis as they did in Nankai (Lin et al., 2009; Yokota et al., 2016).

Fan et al. (2016) revealed a low-velocity zone that spans from shallow to deep depths of 20-200km beneath the prism, suggesting that the collision develops northward and the subducting process may stop at 22°N. Coincidently, at the similar latitude (21.5°N), Lin et al. (2009) interpret that south of 21.5°N, the subducting is active while north of this latitude the plate convergence is accommodated by intense compressional deformation of the crust due to the buoyance of the Eurasian plate that resists subduction. Consequently, in light of the geological evidence noted above, we slightly shorten the northern boundary of the segment 3 from Li et al. (2016), and we define the region to be between 19°N to 21.7°N as the segment 3 (zone 3) (Figure 3c and f).

3. Proposed slip deficit models

Using geodetic surface measurements, a velocity value can be derived and used to constrain the elastic strain accumulation rate between the subduction plate interfaces, the so-called interseismic coupling model (Chlieh et al., 2008; Hsu et al., 2012, 2016; Loveless and Meade, 2010; Megawati et al., 2009). This model reveals strain accumulation within seismic cycles that can potentially be released during great earthquakes, although the final rupture extent is commonly not exactly the same as forecasted by the coupling maps (Konca et al., 2008; Ruiz et al., 2014) and in some cases uncoupled parts of the megathrust may regularly produce tsunamis (Witter et al., 2016). However to move towards an associated tsunami hazard assessment from such potential ruptures, the coupling map, although not ~~the~~ perfect, is often the necessary choice (e.g., Power et al., 2012; Megawati et al., 2009).

Using decades-long GPS velocity measurements, Hsu et al. (2016) proposed two coupling models (A and B) that best explain the plate movements and coupling state on the Manila megathrust and other faults on the Luzon island. With this coupling or slip deficit rate estimates and the possible seismic return time period, we can forecast the likely slip distributions that may fail in future earthquakes. For seismic return time period, given the short duration of historical records relative to the return-periods of large-magnitude events of interest, and limitations in our capacity to infer earthquake return-periods from first-principles physics, it is unrealistic to expect to develop a comprehensive understanding of seismic return periods. We thus have to rely on the observations. To gain a comprehensive understanding of the seismic return time period, large amount of historical seismic data and geological evidence are required. The modern seismic records for the Manila trench only trace back to ~1900 and provide constraints on the natural frequency of earthquakes with its corresponding magnitude assuming the Gutenberg-Richter (G-R) earthquake relations, and thus often implemented for tsunami hazard assessment (Li et al., 2016; Power et al., 2012). Historical records since the 1560s suggest that there is no recorded earthquake with *Mw* > 7.6 in the Manila subduction zone, implying that the determined return time period for great earthquake from G-R relation will likely poorly constrained (Hsu et al., 2016). However geological evidence from purported tsunami deposits may provide evidence of tsunamis at four locations in SCS (i.e. Figure 1, Ramos et al., 2017; Sun et al., 2013; Yu et al., 2009; Yang et al., 2018). Some studies suggest that a giant tsunami event might have occurred ca.1000-1064 AD (Ramos et al., 2017; Tang et al., 2018). With an assumption of a-1000-year return period, the magnitude can reach M_w 9+ from geodetic analysis (Hsu et al., 2016). Here we choose to model scenarios, which release 1000 years of accumulated strain, because these represent large, rare and yet plausible events, which are of interest for hazard assessment purposes, and paleo-geological data indicate that large events may occur about 1000 years ago. We, thus, use the only available information that the seismic return period is likely to be ca.1000 year and a giant event had ruptured the Manila trench in the last seismic cycle.

Based on coupling models A and B of Hsu et al. (2016) in which the spatial distribution of slip rate and coupling rate are available, we use a return period of 1000 years to calculate the slip deficit of great earthquakes assuming each event releasing 1000 years of strain accumulation while ignoring possible portion of strain release by smaller events. For the predefined zones 1 to zone 3 (see sections 2.1-2.3), different approaches are used. For zones 1 and zone 2 where the coupling ratios and slip rate are relatively better constrained than zone 3, we calculate the slip deficit by multiplying the slip deficit rate at each triangle node (Figure 3a, b d and e) with 1000 years. The slip deficit models in zone 1 for models A and B (Figure 3a and d) are similar with the maximum slip>50 meters occurred at ca.20-30km seismogenic depth due to the high coupling ratio. For zone 2, the slip model based on A has a compact area and less slip amount as compared with slip model based on B (Figure 3b and e). This is because the extra north Luzon trough fault was introduced in model B, resulting in larger spatial extent and higher coupling while equally explaining the GPS velocity measurements (Hsu et al., 2016).

Due to paucity of observations in zone 3, no coupling ratios were resolved. Geologically this zone is much more complicated than zones 1 and 2 (Lin et al., 2009). Multiple OOSTs are revealed from seismic reflection profiles (Lin et al., 2009; Zhu et al., 2013). Failure of these OOSTs (or called megasplay) faults with high dip angle contributes to generating devastating waves as evidenced from historic tsunami events in other subduction zones (Moore et al., 2007; Park et al., 2002). It is, therefore, crucial but difficult to precisely quantify individual role of the OOSTs and megathrust in tsunami generation.

We propose two end-member scenarios, considering different rupture modes in zone 3 with two steps. We first calculate the slip deficit from the slip ~~deficient~~ deficit rate of models A and B between 19°N to 20°N. We then consider two end-member scenarios in the region from 20°N to 21.7°N. The first-member is the seismogenic events with rupture depths determined from a collection of GCMT solutions of the world megathrust earthquakes (Figure 4). We assume the fault slip pattern follows a Gaussian distribution centered at 25 km of the mean depth from the global great earthquakes. We cutoff slip deeper than 50 km as the rock properties at this depth and beyond ~~behave~~ induce semi-brittle and ductile flow (Hippchen and Hyndman, 2008; Hyndman and Wang, 1993; Wang, 2007). ~~By doing so it could~~This can capture ~~the~~ to first-order ~~of~~ the potential slip extent (Figure 3c and f), ~~similar as the estimated~~with a depth-range of slip consistent with observations ~~observed~~ from global megathrust great earthquakes (e.g., Chlieh et al., 2007; Pollitz et al., 2011; Ruiz et al., 2014; Salman et al., 2017; Wei et al., 2012). For the second mode, we consider tsunamigenic events similar to 2011 M_w 9.0 Japan earthquake in which the earthquake can rupture all the way to the trench. We estimate the plate convergence rate in the fore-arc in zone 3 is 67 mm/year (Hsu et al., 2009) with a 24.5 mm/year shortening under the 91.5 mm/year plate convergence rate with respect to Sunda plate

(Hsu et al., 2016; Sella et al., 2002). We assume 67 mm/year convergence was fully accommodated by the megathrust and implement it as the amplitude of the Gaussian distribution, allowing the maximum slip occurring at the trench (Figure 5a and b). For each rupture mode, we have two slip models corresponding to coupling model A and B, and assume half of plate convergence rate are accommodated by the megathrust (Figures 5a and b, with 80% coupling ratio shown in Figure 6c and d). For the second-member model, we implement rupture on both the megasplay fault and the megathrust assuming each of them accommodating half of the fore-arc plate convergence and a uniform slip on the splay fault as a simple case (Figure 5c and d). We implement this splay fault only with seismogenic rupture events as we think this case is easier due to splay fault's bottom cut to the megathrust at seismogenic depth (Lin et al., 2009). We consider a 50% coupling ratio on both the megathrust and splay fault (Figure 5c and d, with 80% coupling shown in Figure 6a and b). Details about these proposed rupture scenarios are given in the summary Table S1 in the supplementary file.

The geometry of the OOST is derived from Lin et al. (2009) and covers the area from 20°N to ca.22.2°N, as we ignored the bending portions of the OOST in the north and south although they still can rupture with a low probability. The fault is ca.260 km long, ca.16 km wide, and it strikes 345° to the north and dips 50° to the east (Figures 1, 5 and 6).

4. Tsunami impacts in SCS

4.1 Tsunami simulation set up

We use **Co**rnel **M**ulti-grid **Co**upled **T**sunami model (COMCOT) to simulate the hydrodynamic process of the tsunami waves (e.g., Wang et al., 2008; Philip, 1994; Li et al., 2018; Li et al., 2016) produced by those proposed earthquake ruptures. ~~(~~The initial surface elevations generated by all the proposed rupture models can be found in Supplementary data~~)~~. To account for the nonlinear effect in nearshore region, the simulation solves the non-linear shallow water equations in spherical coordinates for the entire SCS region with a bottom Manning friction coefficient of 0.013 (Li et al., 2018). We used the 1 arc-minute grid of General Bathymetric Chart of the Oceans (GEBCO) data for the modeling. ~~We considered one grid layer for each case to model wave propagations in the SCS~~A uniform grid was used because we don't focus in near- and on-shore processes where highresolution topographical data and good understanding of the bottom friction effect are required. Synthetic gauges along the 20-m isobaths are specified to record the tsunami waveforms. For the initial tsunami waves, we assume the rupture occurs instantaneously and the vertical seafloor deformation produced by the ruptures is ~~used to simulate the tsunami wave propagations~~equal to the initial ocean surface deformation (e.g., Li et al., 2016; Li et al., 2018; Liu et al., 2009).

4.2 Maximum tsunami wave height

For all the simulated scenarios, the resulting wave height in the near-source regions mainly depends on the rupture location and earthquake magnitude. While in the relatively far-field, the tsunami wave directivity effects and bathymetry effects also play important roles (Figures 7 and 8). We describe the tsunami impact of each pair of source models from south (zone 1) to north (zone 3). Slip models in zone 1 generate the largest tsunami waves (>10m) in western Luzon (Figure 7a-b). Central Vietnam experiences a similar tsunami height (4-8 m) with the intermediate far-field area, western Palawan. Southeastern China and southern Taiwan could be attacked with up to 5 m tsunami waves (Figure 7a-b). Moving to zone 2, the slip models show the significant difference in terms of both magnitude and slip distribution between models A and B (Figure 3b and Figure3e). Consequently, the tsunami impact caused by model B is much larger than the one caused by model A in both near-source (e.g., western Luzon and southern Taiwan) and far-field regions (e.g. southeastern China and central Vietnam). Compared with the most affected region by slip models in zone 1, the worst-hit region also moves northward with the rupture location. Similarly, when the earthquakes rupture the megathrust in zone 3, the hardest-hit regions move further to the northern part of the SCS and concentrate in northern Luzon, southern Taiwan and southeastern China (Figure 7e-f). Further, Figure 8 shows the diverse tsunami impacts generated by rupture scenarios in zone 3. Not surprisingly, the results suggest rupture models with higher coupling cases (Figure 8a-b) result larger tsunami wave heights in regions located in northeast SCS despite of the tsunami generation efficacy of shallow slip earthquakes (Figure 8c-d). One interesting phenomenon worthy of mention is the high tsunami hazard of the southeastern China regardless of the rupture locations. This is likely explained by the combined effect of tsunami wave directivity and bathymetry (Figures 7 and Figure 8). Tsunami waves refract significantly in the southern Chinese coast due to the shape and gradient of the continental slope, leaving southeastern China (including coastlines of Guangdong, Hong Kong, and Macau) in the direct tsunami path.

To summarize, the near-source regions including western Luzon, northern Luzon and southern Taiwan face the greatest tsunami hazard. The second most threatened areas are southeastern China, central Vietnam and western Palawan. Archipelagos inside the SCS including Dongsha, Zhongsha and Xisha also suffer severe tsunami attacks (up to 6-8 m tsunami wave height) when large earthquakes occur in zones 2 and 3. Coastal regions of northern Borneo, eastern Malaysia, eastern Thailand, and southern Cambodia are significantly less affected.

4.3 Tsunami travel time

The~~Potential~~ tsunami travel~~arrival~~ time is key information in tsunami evacuation planning. Similar to the other subduction zones, the near-source areas including the coast of Luzon and southern Taiwan suffer the highest tsunami waves with least evacuation time (Figures 7 and 8). We plot the time series of tsunami wave generated by all the source models in selected synthetic gauges near 9 major coastal cities in Figure 9. Depending on the rupture locations, the tsunami arrival time is in minutes or less than half an hour for near-source cities, like Vigan, Kenting and Kaohsiung (Figure 9), posing great challenges to the early warning system and subsequent evacuation process. In other areas tsunami wave travel time is relatively longer for example Vietnam and southeastern China. The arrival time is commonly between 2-3 hours after the earthquake for central Vietnam and 3-4 hours for southern China. For the Archipelagos inside the SCS, the tsunami waves arrive much earlier than they do on the mainland in Vietnam and China, typically ~1 hour earlier. The earlier arrival time in archipelagos make them ideal locations for installing tsunami monitoring instruments (e.g. tide gauges or GPS (see Peng et al., 2019))~~, as~~. Such measurements may provide timely constraints on wave height for the evacuations in far-field areas~~ further afield~~. Detailed inundation maps of the main coastal cities in this region are highly recommended for designing evacuation routes.

5. Discussion

How and where earthquake rupture will occur on a plate boundary is challenging to forecast (Bilek and Lay, 2018; Satake and Atwater, 2007). A comprehensive understanding of a single megathrust behavior may be impractical since the seismic cycle is typically in the order of hundreds and thousands of years, much longer than instrumental records. ~~Whereas~~ Conversely understanding megathrust behaviors over different subduction zones at different time stages of their cycle offers insights into rupture style and characteristics. Previous studies have intensively investigated giant subduction zone earthquakes, gaining useful insights into physical parameters that are related to developing giant ruptures. Such physical parameters include the subducting plate age, rate and buoyance of the slab (Kanamori, 2006; Nishikawa and Ide, 2014; Ruff and Kanamori, 1980, 1983); the forearc structures (Song and Simons, 2003; Wells et al., 2003~~n.d.~~), upper plate characteristics including plate motion (Schellart and Rawlinson, 2013), trench characteristics of the long-term migration (Schellart and Rawlinson, 2013) and sediments thickness (Heuret et al., 2012), and the width of seismogenic zones (Hayes et al., 2012; Schellart and Rawlinson, 2013). While as the boost of geodetic measurements, the relationship between great ruptures and the convergence rate was challenged (McCaffrey, 1994; Stein and Okal, 2007; Nishikawa and Ide, 14). The maximum moment magnitude of a potential earthquake is often determined from seismic catalogue data, alternatively determined from basic moment conservation principles and catalog data (Rong et al., 2014; Kagan and Jackson, 2013). Overall, with current short observation time span as compared with multi-century seismic return period, it is improperly to make the determination on the relationship between these physical parameters and how big or how often a giant earthquake can occur in any subduction zone (McCaffrey, 2008). Clearly, long-term and complete observations within seismic cycles are required for a better understanding of subduction zone rupture behaviors.

Recently a summary study based on global subduction zone observations concludes that mega-seismic events preferentially rupture flat, gentl~~ye~~ dipping interface (Bletery et al., 2016). In the Manila trench, the dip~~ping~~ is gentle and progressively increases from north to south (Bautista et al., 2001). In zone 3, the presence of subducting plateau of the continental fragments results in a gently dipping, near flat interface that potentially favors the development of giant earthquakes (Figures 1 and 2). The dipping degree is in a similar rage with those found in other subduction zones, e.g., Japan-Kuril-Kamchatka, Alaska-Aleutians, Sumatra-Java, South American, and Cascadia, which are known to produce M_w> 9.0 earthquakes (Bletery et al., 2016).

Morphological barriers have been found to have a predominant role in controlling rupture propagation and style. The barriers can confine and arrest rupture propagation (Qiu et al., 2016), and act be a persistent fence to stop rupture (Meltzner et al., 2012; Morgan et al., 2017). Faults bends can also hinder rupture overstep at bending points (Wesnousky, 1988, 2006). In the case of the Manila subduction zone, the presence of Scarborough Seamount chain in zone 2 and slab tear in zone 1 indicates that a giant rupture propagation through zones 3 to 1 is less likely, although we do acknowledge that the rupture-across-zone earthquake is possible with very low probability like the 2007 Mw 8.1 ruptured a triple junction (Furlong et al., 2009; Taylor et al., 2008). Dynamic simulations do show possible scenarios that involve multiple portions of the Manila trench rupturing as a single giant earthquake (Yu et al., 2018). However, the details of the slab tear in zone 1 and the seamount chain in zone 2 were smoothed out in the simulation, due to the challenges of the numerical calculation (Yu et al., 2018).

Regarding the potential source of the geological records, the tsunami simulations suggest the difficulty of creating a scenario which could affect all the four tsunami deposit locations with suffiently high tsunami waves, especially for the record located in Yongshu island (Yu et al., 2009). Assuming all the four records are indeed tsunami deposits, the spatial distribution demands the whole trench to rupture at once and the southern segment needs to extend further to 13° in order to generate tsunami waves propagation southwest direction towards Yongshu. Another alternative explanation could be that the deposits in Yongshu island were generated by large storm event instead of tsunami event.

In summary, our definition of the rupture zones 1, 2 and 3 are derived by taking into account the bathymetry features of the subduction Eurasian plate, earthquake focal mechanisms distributions, structure controlled TPGA and more than 20-year-long GPS measurements. The refined coupling models (Hsu et al., 2016) offer more detailed images that reflect the likely motions on the plate interface. Combination of the coupling models and morphological bounds constrained zone definitions provide more realistic rupture scenarios than planar fault with uniform slip assumed rupture cases. We've seen that previously assumed planar fault rupture cases with spatial uniform slip. Heterogeneous slip models, as we observe from finite rupture models of earthquakes, are more realistic and could better explain the observations.fFinite rupture models of historical earthquakes indicate that slip is heterogeneous, and this is represented by our scenarios. Further detailed tsunami hazard assessment in SCS demonstrates that uniform slip models underpredict tsunami hazards as compared to a heterogeneous slip model (Li et al., 2016). Therefore, our refined earthquake rupture scenarioscases in zones 1 and 2 provide a new insights standard of scenarios for tsunami hazard assessment in SCS. For zone 3, the scarcity of measurements and the presence of complicated geological structures result in a poor understanding of the seismogenic characteristics, although the tsunami-genic potential remains high (Lin et al., 2009). The possible ruptures provided in this study can be a first-order approximation of the earthquake scenarios in the region. Subsequent measurements collected in coming years can help us to refine our understanding in this region.

6. Conclusion

We have proposed updated earthquake rupture scenarios along the Manila trench based on new geological, earthquake focal mechanisms information and geodetic observations. These rupture models provide new constraints forenable tsunami assessment in SCS, and subsequent detailed examination on inundation process for mega-cities along the coastlines of SCS.

Tsunami simulations based on these rupture scenarios indicate that the coastlines of the SCS region are under a risk of devastating tsunami waves, specifically for western Luzon of Philippine, southern Taiwan, the southeastern China, central Vietnam, and Palawan Island. Besides the near-source region, the southeastern China will also be attacked severely due to the bathymetry focusing effect no matter which portion of the Manila thrust breaks.

Southern Taiwan is affected by ruptures in zones 2 and 3, with west Luzon affected by all earthquake scenarios. Central Vietnam and Palawan Island are mostly affected by ruptures in zones 1 and 2. In all cases, the waves sweep these coastlines within ca.3 hours. Our results highlight that it is necessary to conduct further detailed inundation investigations at these severely affected coastal regions, for future preparation on hazard mitigation plans. Our findings also provide useful information that could be used to find possible archived geological recordings of historical tsunami deposits, and call for following paleo-sedimentology studies in the SCS basin.

Author contribution: QQ, LL, YH and YW developed the method of calculating the fault parameters. QQ performed the tsunami simulations. QQ and LL prepared the manuscript with contributions from all co-authors.

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Figures

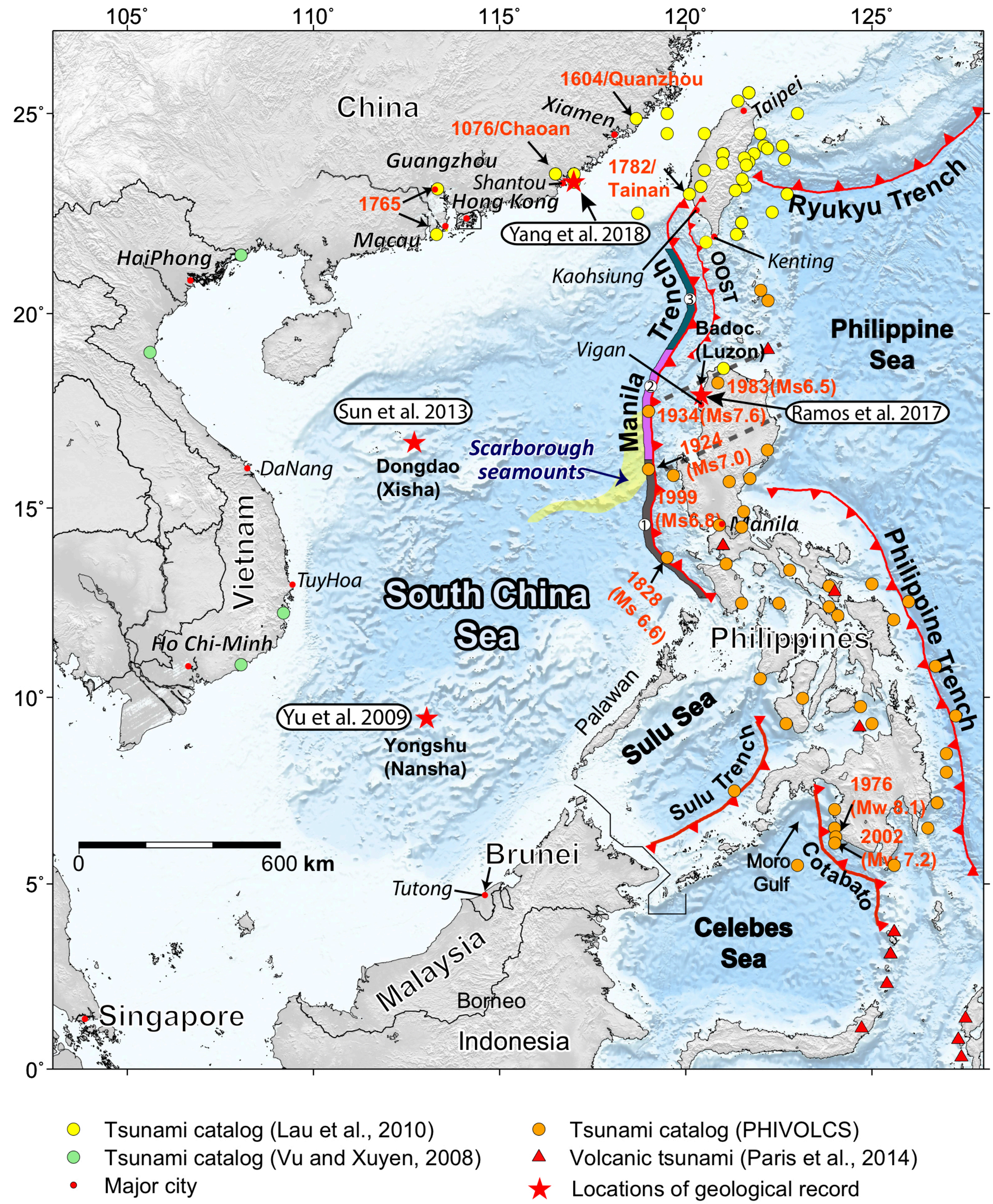


Figure 1. Tectonic setting and historical tsunami catalogs in the South China Sea region. Colored circles indicate published tsunami catalogs and are labeled in the legend. Red triangles represent historical tsunamis related to volcanic activities. Red barbed curves show the megathrusts in this region. Geological tsunami records are marked with red stars (Ramos et al., 2017; Sun et al., 2013; Yang et al., 2018; Yu et al., 2009). The megacities are labeled in the legend and the seafloor subducting features are highlighted in the map. The historical earthquakes with M_w > 6.5 in Philippines are labeled. The likely tsunami events reported in the mega-cities are also labeled in the map. The two dashed lines represent the possible trace of the subducted Scarborough seamounts underneath the overriding plate as imaged from tomography study (Wu et al., 2016). The rupture zones are denoted by the color-shaded curves.

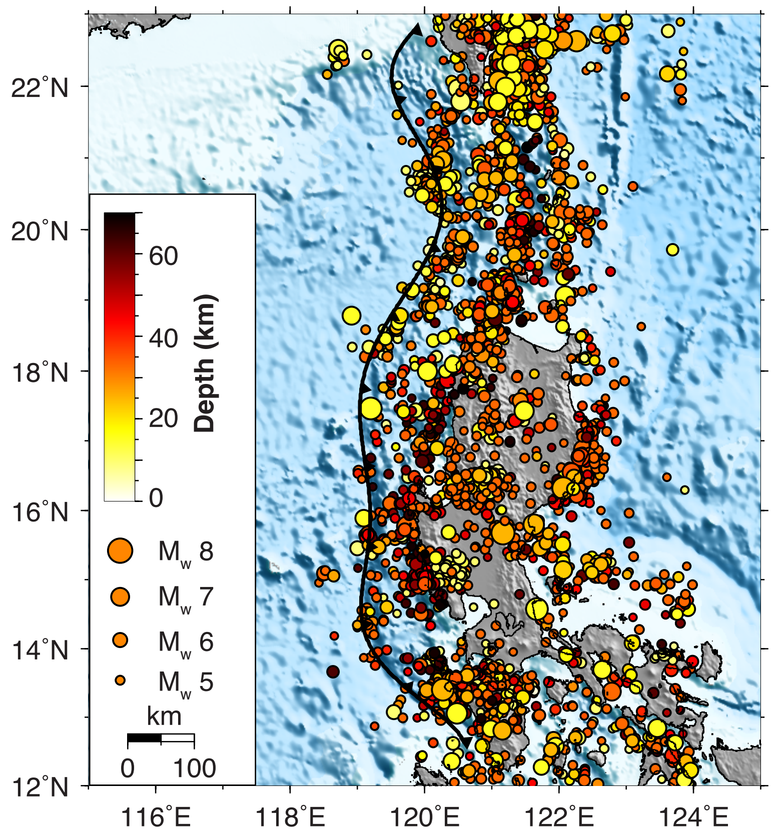


Figure 2. Seismicity (M_w > 4.5) in the Manila subduction zone between 1900 and 2018. This data set is downloaded from USGS catalog. Color represents the depth and size scales the seismic moment magnitude indicated in the legend.

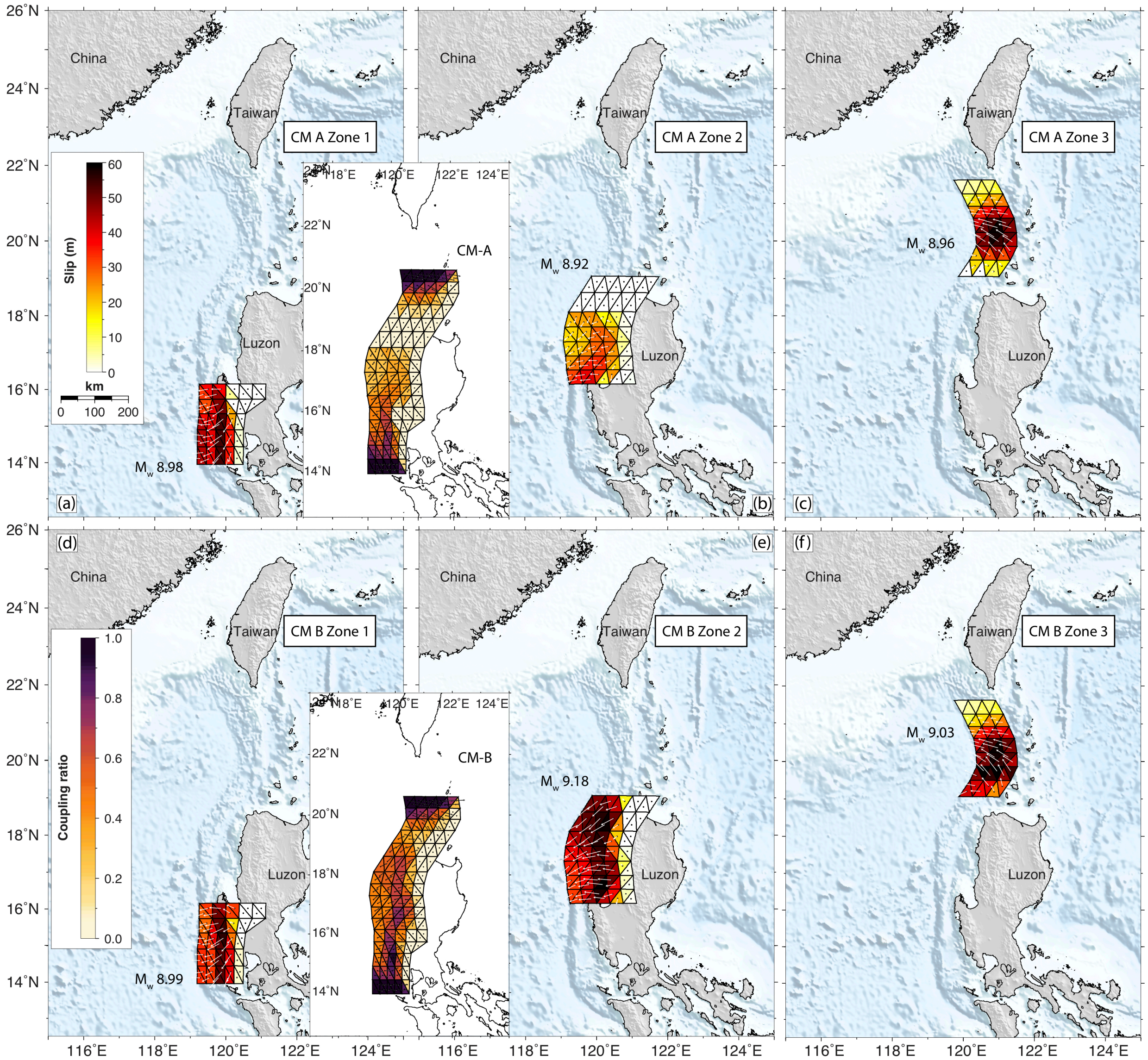


Figure 3. Proposed rupture slip models based on coupling models from Hsu et al. (2016) assuming a 1000-year seismic return time period. (a) and (b) show the slip models from coupling model A (Hsu et al., 2016) in zone 1 and 2, respectively. (c) shows a proposed hybrid model based on coupling model A (19 °N to 20 °N) and a Gaussian shape of slip distribution (20 °N to 21.7 °N) with 50% coupling ratio in zone 3. (d), (e) and (f) represent the same slip models with (a), (b) and (c) but based on coupling model B (Hsu et al., 2016). CM refers to coupling model. Coupling models A and B are from Hsu et al. (2016) that are shown in the inset map. White arrows show the possible slip directions during earthquake. Vectors in the coupling maps show the slip deficit direction that is accumulated for future release in earthquakes. The estimated seismic moment of each model are labeled in each subplot with rigidity 30 GPa. The slip magnitude and coupling ratio are shown by its corresponding color scales.

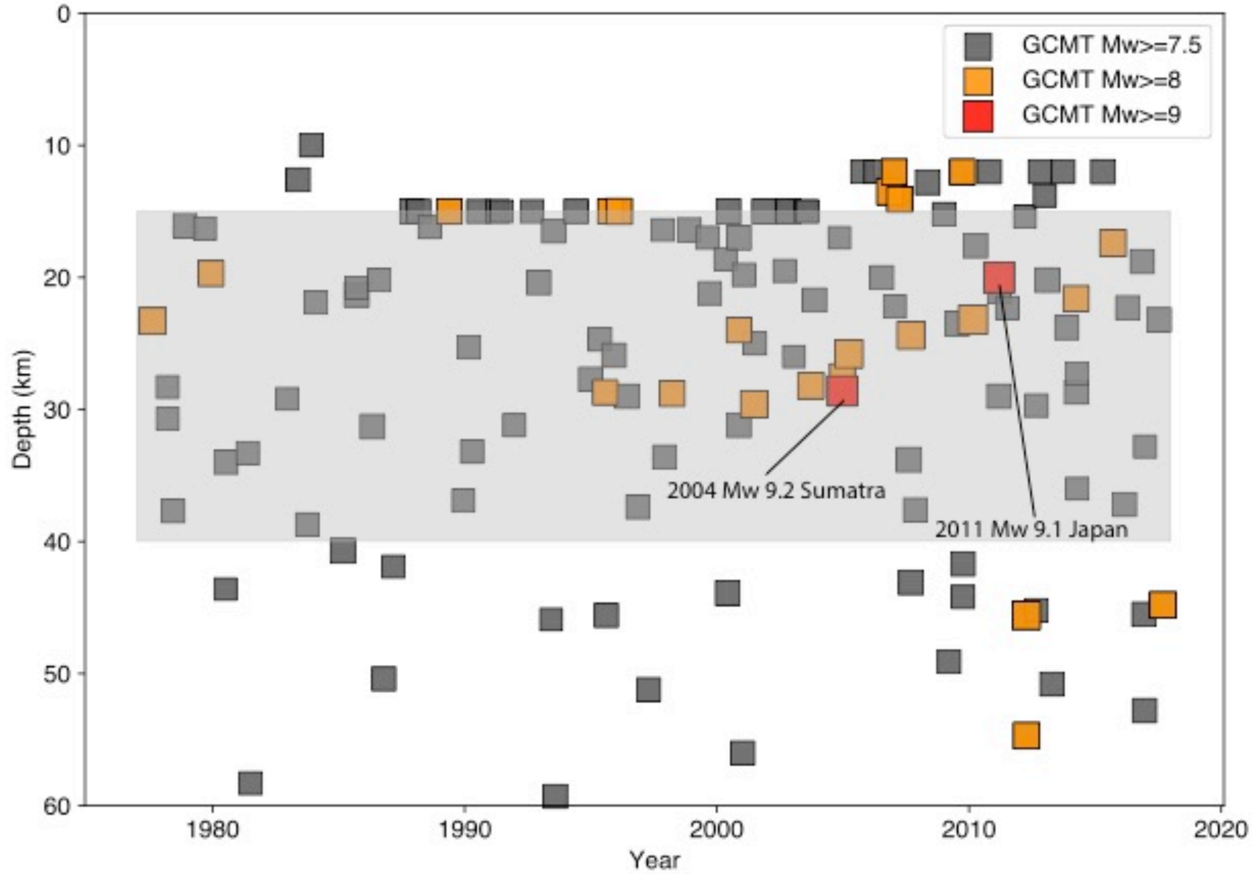


Figure 4. Depth distribution of the seismicity in the Manila subduction zone between 1970 and 2018. This data set is downloaded from GCMT catalog. Colors represent the seismic moment magnitude. The giant 2004 Sumatra and 2011 Japan earthquakes are highlighted in the map.

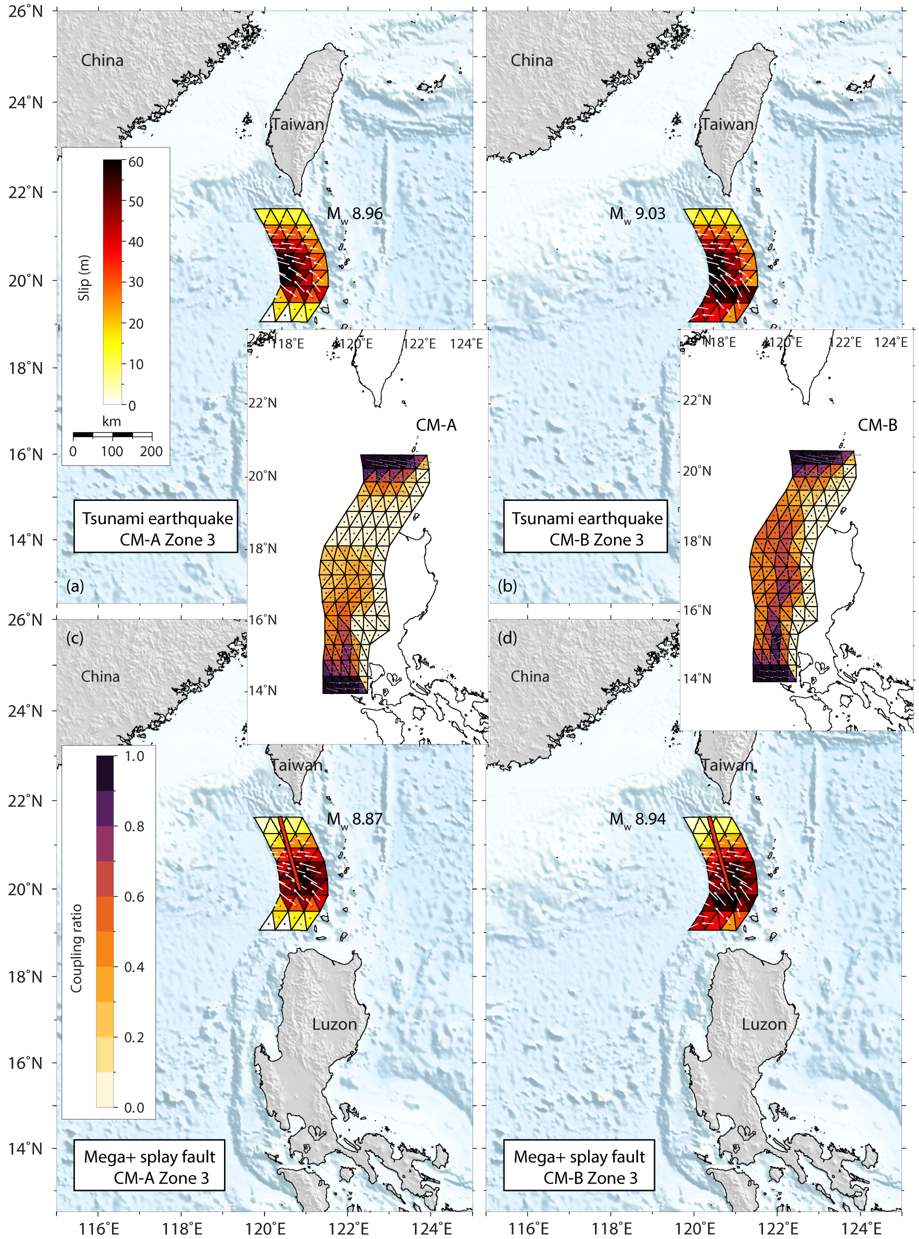


Figure 5. Proposed slip models in zone 3. (a) and (b) show shallow rupture type of slip models (e.g., Tokoku-Oki) based on coupling models A and B (Hsu et al., 2016), respectively. (c) and (d) represent megathrust (Figure 3. c and f) rupture together with the out-of-sequence megasplay type of slip models, respectively. We assume 50% coupling for the megathrust and the megasplay faults. CM refers to coupling model shown in the inset map. White arrows show the possible slip directions during earthquakes. Vectors in the coupling maps show the slip deficit direction that is accumulated for future release in earthquakes.

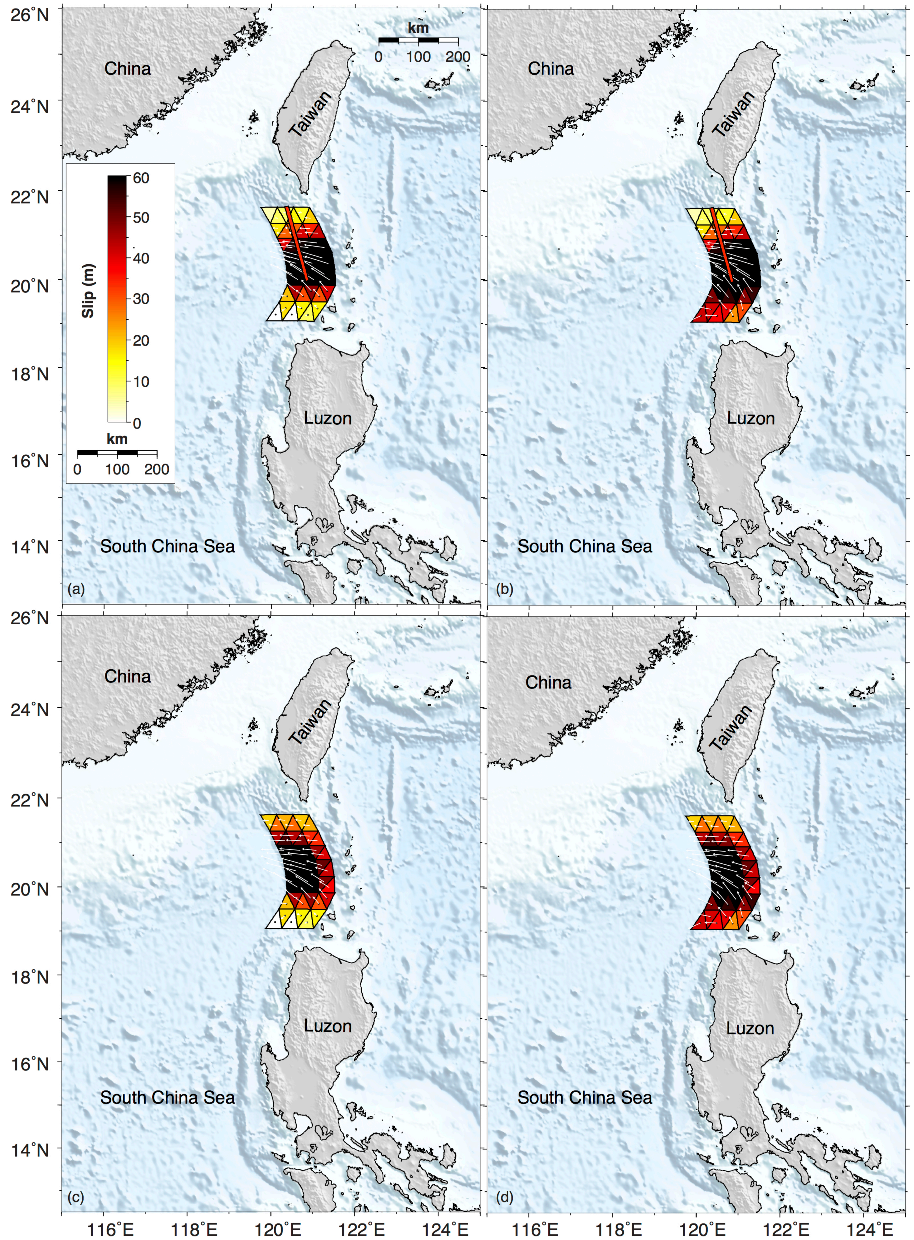
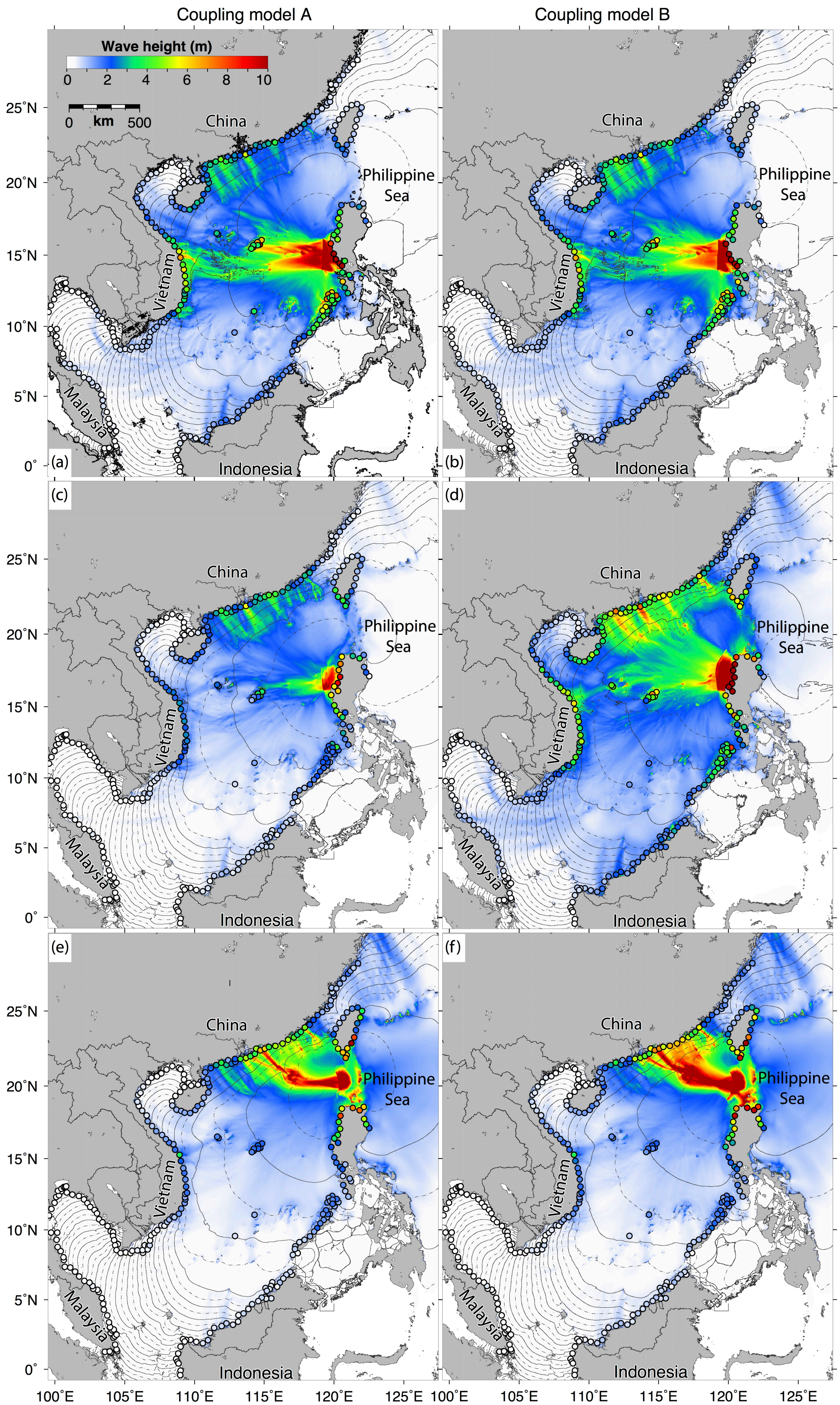


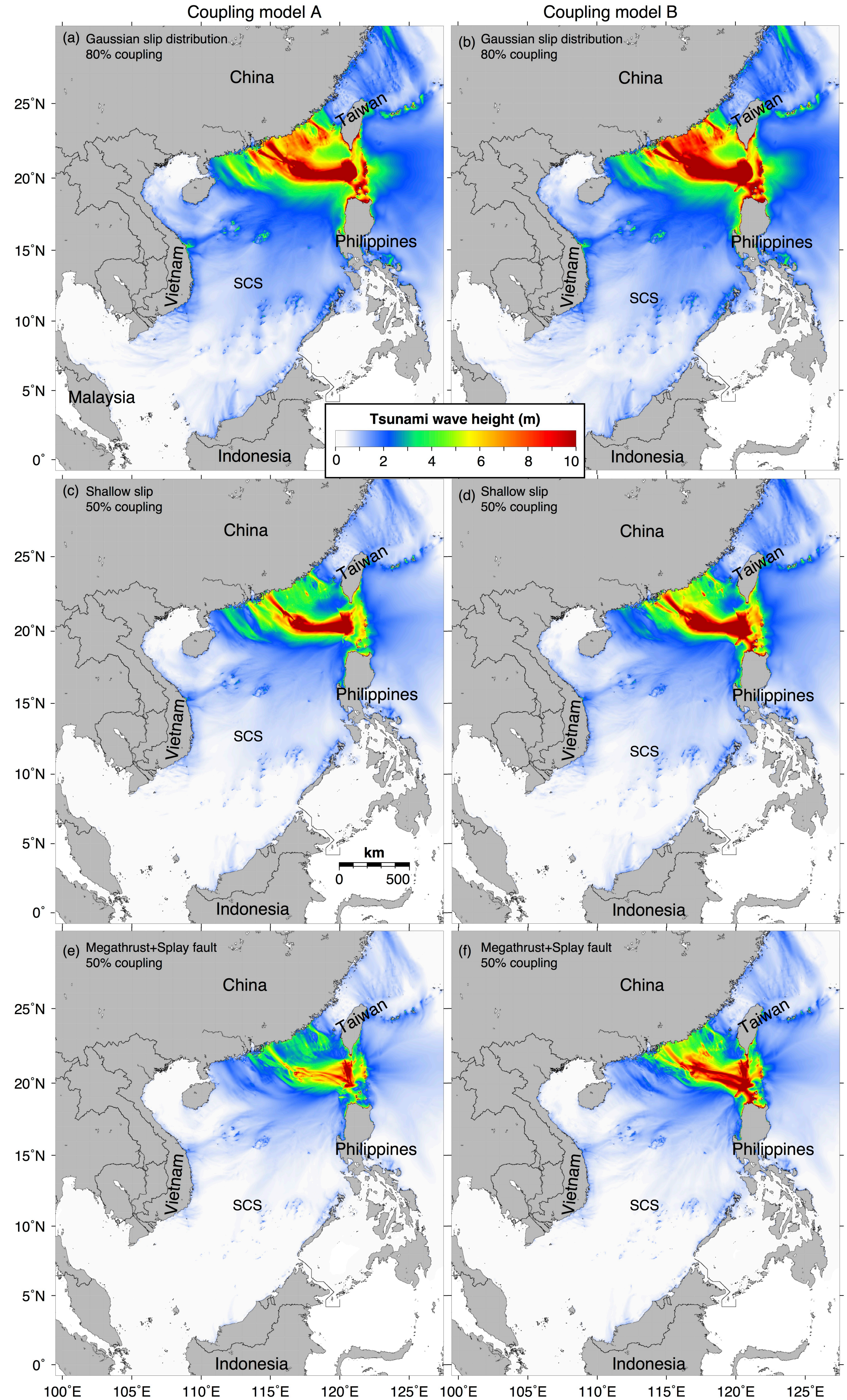
Figure 6. (a) Seismogenic megathrust rupture together with mega-splay rupture scenario with 80% coupling ratio on each of them from model A of Hsu et al. (2016). (b) same with (a) but from model B of Hsu et al. (2016). (c) Shallow rupture (e.g., Tohoku-Oki rupture) the same as Figure 3.a but with 80% coupling ratio on the megathrust. (d) Shallow rupture (e.g., Tohoku-Oki rupture) same as Figure 3.b but with 80% coupling ratio on the megathrust. A 1000-year seismic return period was assumed in the slip calculation.



Coupling model A
Coupling model B
Wave height (m)
0
2
4
6
8
10
0
km
500
China
Philippine Sea
Vietnam
Malaysia
Indonesia
(a)
(b)
(c)
(d)
(e)
(f)
25˚N
20˚N
15˚N
10˚N
5˚N
0˚
100˚E
105˚E
110˚E
115˚E
120˚E
125˚E

948

Figure 7. Modeled maximum tsunami wave heights and arrival time contours in SCS. (a), (c) and (e) show the maximum tsunami wave heights generated from rupture zones 1, 2 and 3 based on slip models calculated from coupling model A (Hsu et al., 2016), respectively. (b), (d) and (f) show the same maximum tsunami wave heights but with slip models calculated from coupling model B (Hsu et al., 2016). In zone 3, we show Gaussian slip distribution with 50% coupling ratio scenario with other example scenarios shown in Figure 8. The solid black contours show hourly tsunami arrival time with half an hour increment (dashed contours). The colored dots show the subsampled location at 20-m water depth, with color showing the maximum wave heights.



Coupling model A
Coupling model B
(a) Gaussian slip distribution
80% coupling
(b) Gaussian slip distribution
80% coupling
(c) Shallow slip
50% coupling
(d) Shallow slip
50% coupling
(e) Megathrust+Splay fault
50% coupling
(f) Megathrust+Splay fault
50% coupling
China
Taiwan
Philippines
Vietnam
SCS
Malaysia
Indonesia
Tsunami wave height (m)
0 2 4 6 8 10
km
0 500
25˚N
20˚N
15˚N
10˚N
5˚N
0˚
100˚E 105˚E 110˚E 115˚E 120˚E 125˚E

959

Figure 8. Maximum tsunami wave heights from different rupture characteristics in zone 3 with hybrid coupling models. (a), (c) and (e) show the maximum tsunami wave heights based on coupling model A (Hsu et al., 2016). (b), (d) and (f) show the same maximum tsunami wave heights but with slip models based on coupling model B (Hsu et al., 2016).

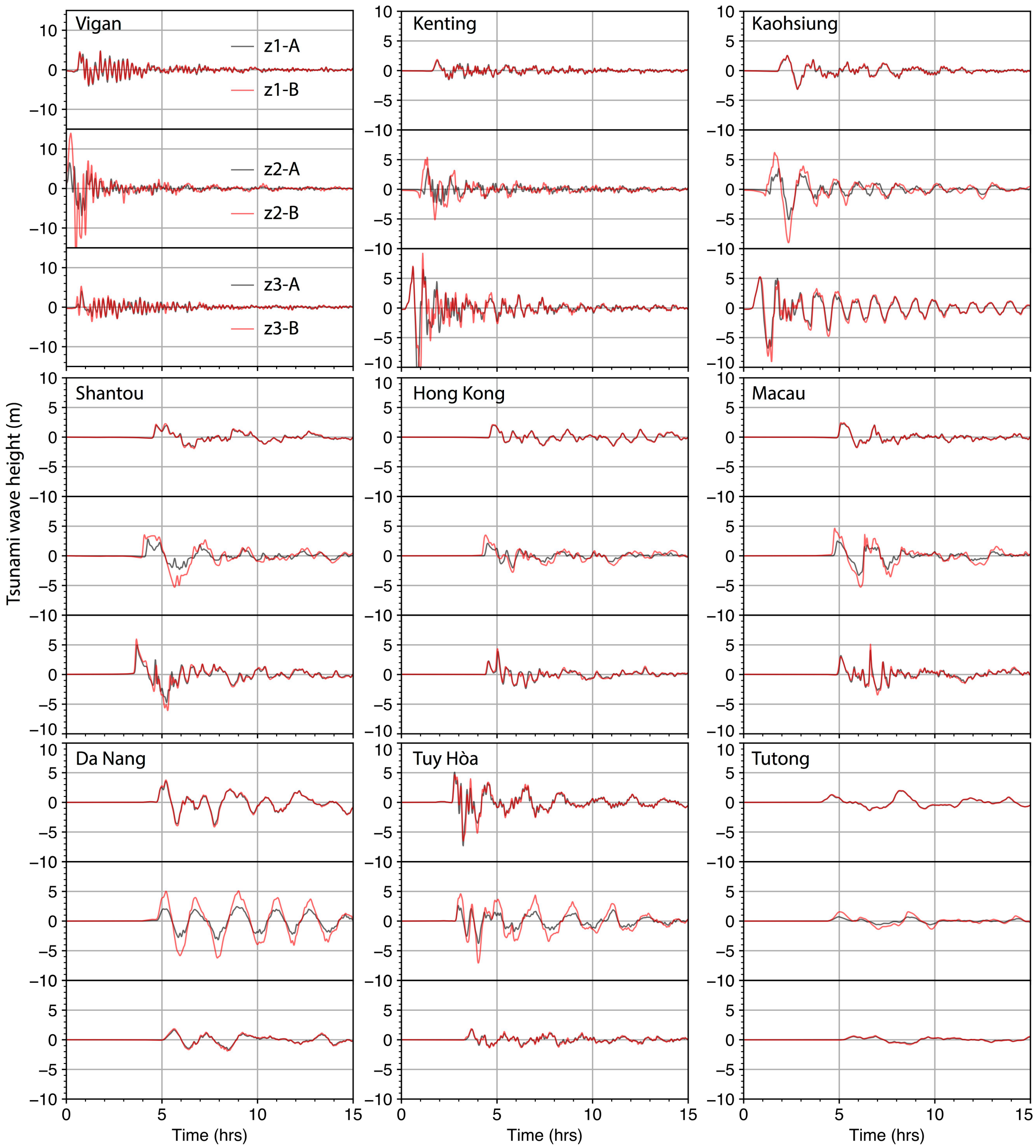


Figure 9. Simulated tsunami wave time histories at example coastal cities in the SCS region. Top panel, middle and bottom of each subpanel show simulated waves from ruptures in zones 1, 2 and 3, respectively. A and B represent coupling models A and B from Hsu et al. (2016). For rupture zone 3, we show the Gaussian slip distribution with 50% coupling ratio cases (Figure 3. c and f) as examples.