Dear Reviewer,

Santiago of Chile, April 12, 2019

We have read carefully your review of our article entitled, "Speeding up and boosting tsunami warning in Chile", written by Fuentes M.[(1)], Arriola, S. [(2)], Riquelme S. [(2)], and Delouis B. [(3)], from (1) Department of Geophysics, University of Chile, Faculty of Physical and Mathematical Sciences, Santiago, Chile, (2) National Seismological Center, University of Chile, Santiago, Chile and (3) Géoazur, Université de Nice Sophia Antipolis, Observatoire de la Côte d'Azur, Nice, France.

We are grateful for the time you spent to review our paper, for all your comments and useful suggestions to improve the manuscript. In the following paragraphs we present in detail the answer to all questions, comments and suggestions you made.

Best regards,
Mauricio Fuentes.

General comments

Reviewer: The paper presents a methodology aimed at speeding up the generation of a tsunami forecast as part of tsunami warning operations. The authors modeled tsunamis for twelve of the largest earthquakes that occurred between 1992 and 2015 applying a) their newly proposed linear method assuming an elliptical slip distribution, and b) a fully non-linear method. Comparison of the results indicates that the proposed linear method allows the generation of a much faster tsunami forecast that matches the results of the fully non-linear method with an accuracy of up to 80% but 20 times faster. These results make the paper worthy of publication and of interest to the tsunami warning and disaster management community. As written, however, the paper needs a significant amount of work before we can consider it ready for publication. The text needs major revisions to improve its overall readability and flow. Instead of providing an exhaustive list of all the grammar and composition issues we have found, however, we have taken the liberty of editing most of the text and will attach it as suggested edits with the hope that it will help with the editing process. Please find below some additional comments and specific suggestions

Response: Thank you very much for the tremendous help you provided us with the edited version with valuable suggestions. We have been incorporated all of them because we think they really improve the manuscript. We provided an annotated version of the manuscript with track of changes (red slanted stands for deleted text and blue for new text.)

Specific comments:

(1)

Reviewer: The title of the paper does not reflect the actual contents and results presented in the paper.

The title of the paper suggests that the research results included in it will speed up the issuance of tsunami warnings in Chile. At present, however, most tsunami warning protocols implemented in the world rely on using a quick estimate of an earthquake's magnitude as a proxy to evaluate its tsunamigenic potential. To date, within the context of tsunami warning operations, only the P-wave moment magnitude (Mwp) method implemented at the US Tsunami Warning Centers in the late nineties has significantly speed up tsunami warning in general. More recent earthquake magnitude estimations methods like W-phase, although more robust, accurate, theoretically sound, and faster than other CMT methods, lacked and still lack the speed needed to truly speed up tsunami warning in general. At the time of publication of the seminal paper on the Wphase CMT method paper in 2008, for instance, the PTWC routinely issued tsunami warnings and tsunami messages within 12 minutes of origin time. At present, the PTWC issues its tsunami message products, on average, in less than 6 minutes of origin. In contrast, it still takes between 20-25 minutes to obtain the results of a W-phase CMT inversion, and around 10-15 minutes for a regional implementation. Faster implementations turn possible only in regions with a high density of seismic stations like Chile, Japan, or the West Coast of the United States. Even for these regions the generation an issuance of a tsunami message in less than 5-6 minutes turns close to impossible relying on a W-phase solution. In other words, despite the paper's title, the proposed linear tsunami simulation methodology does not speed up the issuance of tsunami warnings in Chile. The proposed linear method seems to rather speed up considerably the generation of tsunami propagation and inundation forecasts that provide faster and more accurate estimates than those currently in operation. For this reason, the authors should consider changing the title of the paper to something more reflective of both, the scope of the paper and its results such as: "Speeding up Tsunami Forecasting to boost Tsunami Warning in Chile", with the possible substitution of "boost" with "enhance" or "improve" instead.

Answer: We agree with the observation of the reviewer and we have changed the title of the paper.

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(2)

Reviewer: Towards the end of the introduction the authors state that many of the current warning systems have pre-computed tsunami scenarios at their core. This turns inaccurate, as most warning systems currently operational in the world use the preliminary earthquake location and magnitude as a proxy to evaluate tsunamigenic potential and issue their warnings accordingly. Many use pre-computed tsunami scenarios to generate a tsunami forecast following that initial warning, while others use a combination of precomputed tsunami scenarios and real time tsunami simulations based on the linear shallow water equations. Generation of this last type of forecast currently takes between 3 to 7 seconds for an area covering 1000 to 1500 square kilometers around the earthquake's epicenter, and 10 minutes or less for the whole Pacific basin depending on magnitude and resolution settings. See the reviewed text in the pdf file for suggested edits.

Answer: We have taken the reviewer's comments in order to make the Introduction section clearer.

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(3)

Reviewer: All twelve historical earthquakes used in the study generated tsunamis recorded by sea-level instruments, either by tide gauges located along the coast or by DART buoys located in deep water. The paper would benefit by the inclusion of a table listing the tsunami waves heights recorded at these point locations together with the corresponding wave heights predicted by both the linear, and non-linear modeling approaches. Doing so would validate not only a model against another considered theoretically superior but also against the actual field measurements of the phenomenon under study. This turns into the ultimate validation of the accuracy and usefulness of both tsunami modeling, and any forecast based on it.

Answer: For comparison purposes, the best option would be use DART bouys, which are free of non-linear effects in open sea. Unfortunately, none of the buoys were enclosed by our computation domains (for near field), except for a Chilean case. Unfortunately, most of the DART stations were deployed in 2015 or 2016. However, we have included the data that we found and added to the manuscript.

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(4)

Reviewer: The authors should consider renaming some of the sections as suggested in the attached pdf file. In addition, the conclusions should list the most relevant results of the study after a brief summary of the work done in the paper. We attempted to summarize the results in the attached pdf file containing a reviewed version of the text, but the authors should consider adding or modifying whatever they consider relevant.

Answer: Thank you very much for the attached suggestion. We have modified the manuscript including those comments.

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(5)

Reviewer: The labels of figures and tables should describe their contents to make them self-contained. When referencing the figures inside the text we suggest applying the same format to all instances, as for instance "Fig. 1", or "Figs. 2 and 3" instead of using "Figure 1". Please find below a list of suggested edits to the current labels of Figures and Tables in the main text. Consider applying similar edits to the labels included in the supplement:

Figure 1. Schematic showing the discretization of the calculation domain for parallel computation.

Figure 2. Near field simulation of the 2015 Illapel earthquake with an elliptical source (left), and a finite fault model (right). The colors assigned to different areas indicate the expected run-ups in meters: a) red for run-ups larger than 3 m, b) orange for runups between 1 and 3 m, c) yellow for run-ups between 0.3 and 1 m, and d) green for run-ups smaller than 0.3 m.

Figure 3. Regional field simulation of the 2015 Illapel earthquake for an elliptical source (left), and a finite fault model (right). The colors assigned to different areas indicate the expected run-ups in meters: a) red for run-ups larger than 3 m, b) orange for run-ups between 1 and 3 m, c) yellow for run-ups between 0.3 and 1 m, and d) green for run-ups smaller than 0.3 m.

Figure 4. Normalized run-up energy rate during the first two hours of tsunami simulation. The upper left panel shows the run-up rate along latitude and time, the upper right panel the final maximum run-up, and the bottom left panel the normalized energy rate for the whole process as a time series.

Figure 5. Tsunami travel times across the Pacific basin for the 2015 Illapel earthquake.

Answer: We have changed the text following the reviewer suggestions.

Dear Reviewer,

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We are grateful for the time you spent to review our paper, for all your comments and useful suggestions to improve the manuscript. In the following paragraphs we present in detail the answer to all questions, comments and suggestions you made.

Best regards,
Mauricio Fuentes.

General comments

Reviewer: The paper discusses a rapid estimation of potential tsunami energy distribution along the coast (or at certain isobath) from any given earthquake parameters. As a typical forecasting algorithm, the main issue here is the tradeoff between the speed and accuracy. To obtain a timely warning, the proposed algorithm uses a rough source estimate from the W-phase inversion as well as a linear tsunami model. Despite the simplifications, the model produces a sufficient level of accuracy to facilitate the early warning system. Additionally, the proposed method is rigorously tested against historical tsunami events, which is another important factor of this paper that make it worthy of publication. In general, the paper is well-written (except for the discussion and conclusions section) and the main message to convey is easy to follow. However, I would recommend further clarifications in some parts, which can be found in the following specific comments, before the paper can be accepted for publication.

Response: We provided an annotated version of the manuscript with track of changes (red slanted stands for deleted text and blue for new text.) including all your suggestions.

Specific comments:

(1)

Reviewer: Page 1 Line 8. “Our results show that ... non-linear tsunami code.” The sentence can be misleading. I would suggest to revise it into “Our results show that, at a certain water depth, this linear method : : :”.

Answer: We have included this suggestion.

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(2)

Reviewer: Page 2 Line 1. “: : : are based on precomputed scenarios”. Adding a sentence here with reference to the previous related works would better justify the statement. Here are some papers that can be considered:

Reymond, D., Okal, E. A., Hébert, H., & Bourdet, M. (2012). Rapid forecast of tsunami wave heights from a database of pre-computed simulations, and application during the 2011 Tohoku tsunami in French Polynesia. Geophysical Research Letters, 39(11).

Gusman, A.R., Tanioka, Y., MacInnes, B.T. & Tsushima, H., 2014. A methodology for near-field tsunami inundation forecasting: Application to the 2011 Tohoku tsunami, J. geophys. Res.: Solid Earth, 119(11), 8186–8206.

Mulia, I. E., Gusman, A. R., & Satake, K., 2018. Alternative to non-linear model for simulating tsunami inundation in real-time. Geophysical Journal International, 214(3), 2002-2013.

Answer: We have included the new references and a sentence to mention them in order to improve the previous statement.

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(3)

Reviewer: Page 3 Equation 1. The first line of the equations is a linearized SWE, and the second line refers to the initial condition. What about the third line? Derivative of elevations with respect to time at t = 0?

Answer: The first line is the linearized SWE, second and third line are the initial conditions. The second is the initial wave and the third is the equivalent condition for null initial velocity, which is the standard formulation in the static coseismic displacement approach.

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(4)

Reviewer: Page 3 Line 19. The tsunami propagation is limited at 100 m isobath, while in the supporting information the simulated runups are compared with the actual runup observations. I am aware that the paper aims to estimate the possible runup distribution in general by disregarding the physic of nearshore processes due to the nature of the algorithm. However, such an inconsistent comparison needs to be clearly defined. For example, by including the 100 m water depth contour on the plots and additional sentences in the figures caption explaining about the difference of runup locations between observation and model. Or, better yet, why don't use Green's Law as in the Raymond et al. (2012)?

Answer: As the reviewer correctly pointed-out, the linear estimation uses a "linear run-up" estimation which is the case of a reflective vertical wall boundary condition. Roughly, linear and non-linear approaches should be on the same order (Synolakis, 1987; Synolakis, 1991). Certainly, the approach of Reymond et al. (2012) is valid, however we aimed to keep our approach as straightforward as possible, an also, as it was notice by Synolakis (1987), this kind of boundary condition somehow retrieve the Green's law. There is no way to predict detailed run-up heights without a fully coupled non-linear method nor a high-resolution bathymetry, which is out of scope on this work. We have added some sentences to make this clear as well we have added minor modifications in the figures.

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(5)

Reviewer: Page 5 Table 1. The use of "lon" and "lat" is rather confusing without seeing the corresponding figures. I suggest to add a reference to the supporting information in the Table caption, though it has been mentioned somewhere in the text. Furthermore, mathematical formulation of the correlation coefficient can also be a good addition for the supporting information.

Answer: We have added this reference.

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(6)

Reviewer: Page 6 Table 2. Please explain why the computational time of the elliptic slip distribution is longer than the FFM? From the figures in the supporting information I can see that the elliptic slip models have a smaller subfault size. If that is the case, information on the subfault size should be added in section 2.1 including the reasons for using finer resolution in the elliptic slip model. Also, tT in the caption is written tR on the table.

Answer: The reviewer is right. The size element for the elliptic sources is in general smaller than the FFM. This is to ensure enough resolution on the source model. The typo "tR" was fixed. We have added some sentences making this clear.

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(7)

Reviewer: Page 6 Line 15. It is difficult to grasp the meaning of the last sentence. Please rewrite it.

Answer: The whole paragraph has been rewritten.

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(8)

Reviewer: Page 7. The flow of descriptions in the discussion and conclusions section is not
very smooth. Improvements can be done by either rewriting the whole paragraphs or using bullet-points or numbers to indicate different topic of discussion.

Answer: The whole section has been rewritten.

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(9)

Reviewer: For the Java case (Figure S7), it seems like the fault of the elliptic source is located seaward of the trench (in the outer rise region). If this is true, then the model needs to be revised, because the 2006 West Java event was a shallow interplate earthquake (a typical tsunami earthquake), which is better depicted in the FFM solution (Figure S8). Other than that, the Java Island map in the left panel is inaccurate. I believe this may be caused by a wrong color map scale used for plotting. Please also check the other locations.

Answer: Thank you very much for noticing this mistake. This it was a misunderstood when typing the data with a closer event in the same area. We have verified the whole catalog and we have fixed this problem and remaking this scenario and figure.

Dear Reviewer,

Santiago of Chile, April 12, 2019

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We are grateful for the time you spent to review our paper, for all your comments and useful suggestions to improve the manuscript. In the following paragraphs we present in detail the answer to all questions, comments and suggestions you made.

Best regards,
Mauricio Fuentes.

General comments

Reviewer: This paper presents a method for quick tsunami estimation in Chile early warning system using W-shape inversion for rough source estimation and linear tsunami numerical modeling. They mention this new approach as a fill-in gap method for the warning system. They have also tested their method with historical tsunami events and proved that they have good correlation between the real case and their results. This work is worth to be published. However, it needs major revision in terms of presenting and discussing their results, grammar in the entire text and conclusion. Besides, it is necessary to have further discussion and explanation on figures.

Response: We provided an annotated version of the manuscript with track of changes (red slanted stands for deleted text and blue for new text.) including all your suggestions.

Specific comments:

(1)

Reviewer: Below are the sentences that are not clear to me. They need to be rephrased: 1. Page 1 Line 14 whole sentence 2. Page 2 Line 4 “operating monitoring systems” 3. Page 2 Line 11 “until decreases to 0.5 to 1 m” 4. Page 5 Line 11 : : : whole paragraph 5. Page 5 last paragraph 6. Page 6 Line 4 to 6 7. Page 9 last paragraph.

Below are some of grammar corrections: 1. Page 1 Line 3 “100 km which creates” 2. Page 2 Line 6 “This problem is separated in three parts: the determination of: : :” 3. Page 3 Line 24 “: : :with a fully linear shallow water equation propagation.” 4. Page 4 Line 24 “: : :.have tested as many earthquakes listed below and: : :” 5. Page 6 Line 2 “: : :very first minutes: : :” 6. Page 6 Line 11 “: : :which deploy a specific: : :” 7. Page 7 Line 1 “These kind of maps: : :” 8. Page 7 Line 5 “with a unique and simple: : :” 9. Page 7 Line 9 “: : :and number of people exposed to this hazard: : :” 10. Page 7 Line 13 “: : :details rather than modeling: : :” 11. Page 10 Line 1 “Using the methodology of Sandabata el al. (2018): : :”

Answer: We have rephrased the observed parts and fixed the English grammar.

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(2)

Reviewer: About Figures and Tables: 1. Please refer to Figure 1 in the text. 2. please insert Table 1 after its reference in the text. 3. Figure 2: Does this red color on land represent runup values larger than 3m? Does this mean all of this are experienced more than 3m runup?? 4. Figure 5: please compare and discuss the difference between two maps: in terms of the effect of dispersion etc.. 5. Figure 6: please refer Figure 6 in the text and explain.

Answer:

1.) Figure 1 is now referred in section 3.

2.-) Locating the figures through the manuscript seems to be a post editorial task, since we can not correctly control the insertion of the figures with the provided LaTeX template. However, every reference to a figure or table is mentioned before they are inserted (in the .tex file).

3.-) In figure 2 (and 3), the coastline is divided by geopolitical zones (Chilean regions), the zone adopts the color of the maximum value of the runup distribution in that zone. If only one point overpass 3 m, the whole region becomes red. That is why we pointed-out that this way to divide the country is just referential, because we can easily use another, not being relevant for the algorithm development and more related to the criteria of the final user.

4.) The caption of figure 5 was rewritten in order to make this clear.

5.) Figure 6 is now referred in section 6.

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We are grateful for the time you spent to review our paper, for all your comments and useful suggestions to improve the manuscript. In the following paragraphs we present in detail the answer to all questions, comments and suggestions you made.

Best regards,
Mauricio Fuentes.

General comments

Reviewer: The paper presents a methodology to speeding up the tsunami forecast in Chile as part of tsunami warning operations. This is a very important topic, in particular because in the last decade many new tsunami warning centers have been established by various countries. This paper presents interesting results for publication. Nevertheless, several issues should be explained, discussed and many data are missing, before accepting the paper. Major revision is necessary.

Response: We provided an annotated version of the manuscript with track of changes (red slanted stands for deleted text and blue for new text.) including all your suggestions.

Specific comments:

(1)

Reviewer: The results of proposed methods depends mainly on the variation of the source parameters between the different methods used, in particular the slip, the dip and the dimension and location of rupture zone, and the focal depth. One first request : the list and values of parameters of the sources of that paper are missing.

Answer: We added a new table in the supplemental material containing the requested information.

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(2)

Reviewer: It can already been checked on the various maps presented, that the location of the epicenter for the elliptic model, and the location of the center of the rupture zone of the fault model are not the same, and there are not the GCMT location. Why ? How do the authors decide the location of the epicenter, and why the locations are different for the different models ?

Answer: Thank you for noticing this mistake. In the elliptical model, the star stands for Centroid location whereas in the FFM model, the star denotes the epicenter location. We have fixed this in the figures and changed the symbol for the centroid in order to avoid confusion.

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(3)

Reviewer: The second question is why did the authors analyzed the results of such method along other coastlines than Chile? It doesn't provide any results about the variability of the warning forecast along the Chilean coastlines. On the other hand, two missing recent events have not been modeled and should be added to the study: Chile 1985 and Antofagasta 1995.

Answer: The main reason is to validate the linear method for the propagation of the tsunami, which needs to be tested in different scenarios. Once we have certain degree of confidence (in statistical terms), we apply it to the particular case of Chile, but not being excluding to be useful in other regions. Also, we decided to pick the last three Chilean tsunamis with associated moment magnitude bigger that 8.0, which also are well recorded and documented.

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(4)

Reviewer: One of the recent papers that describes the effectiveness and rapidity of the W-Phase to get robust centroid moment tensor solutions is by J. Roch at al. (Roch, J., Duperray, P. and Schindelé F. (2016) Very fast characterization of focal mechanism parameters through W-Phase Centroid inversion in the context of tsunami warning, Pure Appl. Geophys. 173 (2016), 3881–3893, DOI 10.1007/s00024-016-1258-3). In that paper, the authors analyzed W-Phase results at global and regional scale with specific Green's functions to provide accurate solution in 15 minutes (10 minutes of signal). Due to the characteristics of the very long period W-Phase, it wouldn't be physically feasible to compute sooner W-Phase waves. But it is well known that the first tsunami wave could impact the Chilean coastlines in less than 15 minutes. The mandate and goal of the National tsunami warning center that is facing near-field tsunami warning is to provide the first warning message in less than 15 minutes after the quake occurrence. As the results of W-Phase would not be available, the authors should explain how they would proceed to provide this first bulletin. The authors should identify a preliminary solution to perform modeling before getting the results of the W-Phase computation and getting results in 15 minutes after the quake.

Answer:

In Zhao et. al. 2017 and Riquelme et.al 2018, the possibility to have a W-phase CMT in 6 minutes is studied with good results. Thus, the fact of computing a W-phase solution in a very short time after earthquake location is well reported. We provide you the doi of both papers.

Zhao et al: https://doi.org/10.1002/2017JB014950
Riquelme et al: https://doi.org/10.1785/0220180146

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(5)

Reviewer: Second point, the authors informed that for their study, they used W-Phase results. How was computed the parameters of all these past events ? In particular, the location of the centroid moment tensor, and on the strike and dip values used for the elliptic method. On this specific method, the authors should present what are the parameters of the seismic sources needed for the elliptic method, and the values of the parameters for all the events processed in this paper.

Answer: The W-phase method provides the full moment tensor. We just retrieved data from the National Seismological Center in Chile. The data can be accessed through IRIS (www.iris.edu) or USGS (<https://earthquake.usgs.gov/>). For instance, the W-phae solution of the Nicaragua Earthquake (the oldest in our list) is here: <https://earthquake.usgs.gov/earthquakes/eventpage/usp0005ddn/moment-tensor>

Therefore, all the parameters you mention are given by this method. Also, we have added a table in the supplemental material with the values used for the elliptic models.

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(6)

Reviewer: The next issue is how they plan to implement the complementary messages using W-Phase source parameters. Would this second message be useful when a tsunami warning would already be sent ? How ? Would the CPA be ready to analyze and use a second message ? What is the national standard operation procedure concerning that issue ? The sensitivity of the parameters (slip and dip variation, rupture zone location and size, and focal depth) should be one of the goal of such method. It is well known that the uncertainty of the magnitude in the first 10 minutes after the quake is about +-0.2. And the focal depth is also not good constrained. The variation of the results with used parameters with the uncertainty should be analyzed. Referee1 suggested to compare with the DART buoy measurement. As currently, Chile has 6 DART installed along its coast, it would be very useful to compare the amplitude computed by the various models on these 6 DART stations.

Answer: Despite there is uncertainty in each of the parameters, we don't try to solve that issue in this paper, but to show how a simple linear method can dramatically decrease the computation times keeping a high degree of accuracy, when compared with standard non-linear methods and the potential for early warning purposes. Nevertheless, the things that the reviewer pointed-out are of high interest and deserve a dedicated study. We have addressed those comments in the discussion section as a future work, including about DART buoys. However, several of the DART stations in Chilean coasts were deployed in 2015-2016 not being possible to use all of them in this study. Also the majority of the buoys belongs to the "far-field domain".

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(7)

Reviewer: The last comment would be on the practical use of such detailed result for a warning purpose. Disaster management authorities need level of warning along the coastlines of their country or county. Typically, 3 levels of warning are in place, decided by

Unesco: 30 cm, 1m, 3 m. Some countries implemented a 4th level (5 or 6 m). The comparison of run-up computation should take into account such operational criteria to assess the accuracy or the discrepancy between two methods. This should be applied to the set of results. Statistics should be done for the 3 or 4 levels of warning, and for a detailed analysis, it should be demonstrated that the proposed method is more conservative or less conservative than the detailed finer source model. The results of the proposed warning method should be discussed in the scope of the consequences of the difference of warning level with the finest warning level obtained with finer source and finer propagation modeling. Is their method more conservative or less conservative than the finest method?

Answer: Once the method is developed, the final user can decide what geopolitical subdivision is more suitable, as well as the number of warning levels. Both are easily adjustable in the methodology being part of the criteria adopted for the government institutions. It is hard to say which one could be more conservative even with such statistical analysis, because there are other factors, namely psychological, communicational, etc. One should have a good compromise between quantitative results and simplicity on the way the information is transmitted (which can be somehow subjective). Nonetheless, this discussion is highly valuable, and we have included in the manuscript.

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(8)

Reviewer: Proposed modifications on figures.

a) Figure 2, the scale of the run-up axis should be the same for both figures left and right

b) Figure 5. The presentation of far field and ocean scale results is useless for the Chilean tsunami warning system and not in the scope of this paper. This figure should be removed.

Answer:

a) Figure 2 is now with same scales.

b) One of the main objectives of this work is to show the power of the linear method, so another simple and fast application, is to compliment any scenario with a global map of travel times, even allowing the inclusion of different effects.

~~Speeding up and boosting tsunami warning in Chile~~ Speeding up Tsunami Forecasting to boost Tsunami Warning in Chile

Mauricio Fuentes[1], Sebastian Arriola[2], Sebastian Riquelme[2], and Bertrand Delouis[3]

[1]Department of Geophysics, Faculty of Physical and Mathematical Sciences, University of Chile
[2]National Seismological Center, Faculty of Physical and Mathematical Sciences, University of Chile
[3]Géoazur, Université de Nice Sophia Antipolis, Observatoire de la Côte d'Azur

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Abstract. ~~Chile host a great tsunamigenic potential along its coast, even with the large earthquakes occurred during the last decade, there is still a large amount of seismic energy to release. This permanent feature and the fact that the distance between the trench and the coast is just 100 km creates a difficult environment to do real time tsunami forecast. In Chile tsunami warnings are based on reports of the seismic events (hypocenter and magnitude) and a database of precomputed tsunami scenarios. However, because yet there is no answer to image the finite fault model within first minutes (before the first tsunami wave arrival), the precomputed scenarios consider uniform slip distributions. Here, we propose a scheme of processes to fill the gaps in-between blind zones due to waiting of demanding computational stages. The linear shallow water equations are solved to obtain a rapid estimation of the runup distribution in the near field. Our results show that this linear method captures most of the complexity of the run-up heights in terms of shape and amplitude when compared with a fully non-linear tsunami code. Also, the run-up distribution is obtained in quasi real-time as soon as the seismic finite fault model is produced.~~ Despite the occurrence of several large earthquakes during the last decade, Chile continues to have a great tsunamigenic potential. This arises as a consequence of the large amount of strain accumulated along a subduction zone that runs parallel to its long coast, and a distance from the trench to the coast of no more than 100 km. These conditions make it difficult to implement real-time tsunami forecasting. Chile issues local tsunami warnings based on preliminary estimations of the hypocenter location and magnitude of the seismic sources, combined with a database of pre-computed tsunami scenarios. Finite fault modeling, however, does not provide an estimation of the slip distribution before the first tsunami wave arrival, so all pre-computed tsunami scenarios assume a uniform slip distribution. We implemented a processing scheme that minimizes this time gap by assuming an elliptical slip distribution, thereby not having to wait for the more time consuming finite fault model computations.We then solve the linear shallow water equations to obtain a rapid estimation of the runup distribution in the near field. Our results show that, at a certain water depth, our linear method captures most of the complexity of the runup heights in terms of shape and amplitude when compared with a fully non-linear tsunami model. In addition, we can estimate the runup distribution in quasi-real-time as soon as the results of seismic finite fault modeling become available.

1 Introduction

~~For decades, coastal-exposed countries have been working on tsunami warning systems (Doi, 2003; Wächter et al., 2012). Due to the tsunami source process, most of them are attributed to large subduction earthquake or to landslides, then real-time forecast is out of reach. Regular earthquakes follow a scaling law in terms of its released energy (seismic moment) and its duration (Ide et al, 2007). For instance, a regular M_w 8.5 can last for $\approx$ 2 minutes, whereas tsunami generation is considered quasi-instantaneous after the source time. This implies that a robust tsunami warning system must be related to different monitoring systems of potential triggers (earthquakes, volcanoes, among others). In the case of tsunamis generated by subduction earthquakes, to detect and to characterize the seismic source is crucial. Nowadays, the W-phase method is the preferred for accounting large earthquakes in Chile (Riquelme et al, 2016, 2018). A first moment tensor solution can be obtained in 5 minutes. However, it is well-known that tsunami heights are highly sensitive to the spatial slip distribution of the seismic source (Geist, 2002; Ruiz et al., 2015). Even having a finite fault model, the simulation of the tsunami propagation can take several hours depending on the desired level of resolution. This is the reason why many of the current warning systems are based on precomputed scenarios. Chile and Japan use this methodology for that purpose (https://www.jma.go.jp/jma/en/News/lists/tsunamisystem2006mar.pdf). However, this methodology ignores the complexity of the seismic source resolving for uniform slip models only. In this work we propose a methodology specific for near-field tsunamis triggered by earthquakes that complements information to the operating monitoring systems and helps to make decisions during and after the emergency alert.~~ For decades, countries exposed to coastal inundation have done a lot of work to develop their tsunami warning systems (Doi, 2003; Wächter et al., 2012). Most tsunamis are generated by large subduction earthquakes and landslides, which owing to the characteristics of the tsunami source process, places a real-time tsunami forecast out of reach. Regular earthquakes follow a scaling law that links their energy release (seismic moment) to their duration (Ide et al, 2007). For instance, a regular 8.5 Mw earthquake can last for about 2 minutes, whereas we can consider tsunami generation nearly instantaneous after the source origin time. This implies that a robust tsunami warning system must integrate several systems that monitor different potential triggers such as earthquakes and volcanoes, among others. In the case of tsunamis generated by subduction earthquakes is essential to detect and characterize the seismic source. At present, the W-phase moment tensor is the preferred method for characterizing large earthquakes in Chile (Riquelme et al, 2016, 2018), as it allows to obtain a moment tensor solution within 5 minutes. It is well-known, however, that tsunami heights are very sensitive to the spatial slip distribution of the seismic source (Geist, 2002; Ruiz et al., 2015). Even after having a finite fault model, the simulation of the tsunami propagation can take several hours depending on the desired level of resolution. This is the reason why the tsunami forecasts of many of the current warning systems are based on pre-computed scenarios (Reymond et al., 2012; Gusman et al., 2014; Mulia et al., 2018). Chile and Japan use this methodology for that purpose (https://www.jma.go.jp/jma/en/News/lists/tsunamisystem2006mar.pdf). This methodology, however, ignores the complexity of the seismic source and solves only for uniform slip models. We propose a methodology applicable to near-field tsunamis triggered by earthquakes that complements the monitoring systems in operation, and helps make better decisions during and after an emergency alert.

2 Methodology

~~This problem is separated in three parts. The determination of a seismic source model, the generation of an initial condition and the corresponding tsunami simulation. We define a computation domain around the earthquake source and the coastal areas in the near field. The bathymetric data used is the SRTM15 with 15 arcsec of resolution, based on the STM30 (Becker et al., 2009). The idea here is to trade off accuracy for rapidness. In a near field earthquake tsunami context we care about the maximum inundation place, the extension of the inundation until decreases to 0.5 to 1 m, and the average run-up. This model is not trying to be as accurate as possible and to determine a detailed inundation map but what intends to do is to give an idea of the main area that is going to be affected using the W-phase CMT, which is currently one of the fastest methodology to characterize large earthquake parameters in real time (Kanamori and Rivera, 2008).~~ We can separate this problem into three main parts: 1) the estimation of a seismic source model, 2) the generation of initial conditions, and 3) the corresponding tsunami simulation. We define a computation domain around the earthquake source and the coastal areas in the near field. We use the SRTM15 bathymetric data with 15 arcsec of resolution, based on the STM30 (Becker et al., 2009).

The core idea consists in trading off some accuracy to gain speed. Within the context of tectonic tsunamis generated in the near field we want to know the places with the maximum inundation, the extension of the inundation until it decreases to 0.5 to 1 m, and the average runup. Our model does not aim at computing a detailed inundation map with the best possible accuracy, but rather to provide a fast estimate of the main area prone to inundation relying on the W-phase CMT, currently considered one of the fastest and more accurate methods to characterize the source of large earthquake (Kanamori and Rivera, 2008).

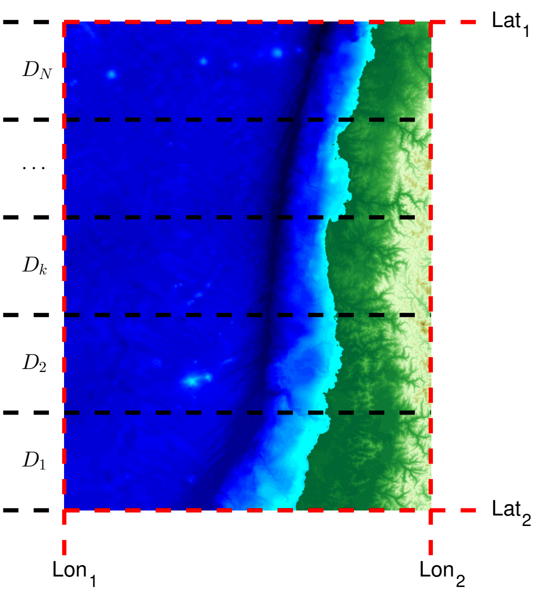

Figure 1. ~~Sketch of the partition of the computation domain for parallel running.~~ Schematic showing the discretization of the calculation domain for parallel computation.

2.1 ~~The~~ ~~s~~ S lip ~~d~~ D istribution ~~m~~ M odel

~~Once an earthquake is firstly described by the W-phase solution, we use an elliptical slip distribution (Dmowska and Rice, 1986) over a region determined with the scaling laws obtained by Blaser et al. (2010). This serves as a first estimation while seismic waves are still traveling, and subsequent finite fault solutions are computed. Thus, we can model the near field tsunami for every finite fault model update.~~ Once a W-phase solution provides a characterization of an earthquake we use an elliptical slip distribution (Dmowska and Rice, 1986) over a region determined with the scaling laws obtained by Blaser et al. (2010). This serves as a preliminary estimation while seismic waves are still traveling, and later finite fault solutions are computed. This in turn allows to model the near field tsunami for every finite fault model update. The elliptic model is discretized with n_y subfaults along-dip and $n_x = \left\lceil \frac{L}{W} n_y \right\rceil$, where L and W are the length and width of the fault plane obtained with the scaling law. With $n_y = 16$, all the studied cases have enough resolution on the source area.

2.2 ~~The~~ ~~t~~ T sunami ~~i~~ I nitial ~~c~~ C onditions

~~Despite there are evidences of influence in the tsunami generation process with the source time components, for quickness purposes, we model static seafloor deformation induced by a non-uniform slip distribution including the horizontal components, as suggested in Tanioka and Satake (1996). This is obtained with that Okada's equations (Okada, 1985).~~ Despite evidence of influence of the source time components in the tsunami generation process, for speed purposes we model a static seafloor deformation induced by a non-uniform slip distribution that includes the horizontal components, as suggested in Tanioka and Satake (1996). This is obtained by applying the Okada equations (Okada, 1985).

2.3 ~~The~~ ~~t~~ T sunami ~~m~~ M odeling

~~The last part of this methodology is to obtain the tsunami heights along the coast. Usually, tsunami modeling involves complex codes to solve the fully coupled non-linear shallow water equations. Depending on the domain size and resolution, a full tsunami run can take several hours, which make real-time forecast impossible. To overcome this limitation, we solve the linear shallow water equations with a forward finite difference scheme. The propagation inside the domain is governed by the second order PDE with initial conditions:~~ The last part of this methodology is the estimation of the tsunami heights along the coast. Usually, tsunami modeling involves complex codes to solve the fully coupled non-linear shallow water equations. Depending on the domain size and resolution, a full tsunami simulation run can take several hours, which makes real-time forecast nearly impossible. To overcome this limitation, we solve the linear shallow water equations with a forward finite difference scheme. The propagation inside the domain is governed by the second order PDE with initial conditions:

$$\begin{aligned} &\eta_{tt} - g\nabla\left(h\nabla\eta\right) = 0 \\ &\qquad \eta(x,y,0) = \eta_0(x,y) \\ &\qquad \eta_t(x,y,0) = 0 \end{aligned} \tag{1}$$

where $\eta(x,y,t)$ ~~is~~ denotes the water surface, g ~~is~~ the ~~gravity~~ acceleration of gravity, $h(x,y)$ ~~is~~ the bathymetry and $\eta_0(x,y)$ ~~is~~ the initial condition. In the open boundaries, we set a radiation condition (Reid and Bodine, 1968), whereas in the solid boundaries (coasts) we impose full reflection in a vertical wall placed at an isobath of 100 m, before ~~to reach~~ reaching the non-linear zone. Here, a Neumann boundary condition is applied: $\frac{\partial \eta}{\partial \hat{\boldsymbol{n}}}$ where $\hat{\boldsymbol{n}}$ denotes the exterior unit normal vector. The linear method (~~hereafter,~~ LM) allows to obtain a quicker estimation than a full tsunami code since second-order terms are ~~neglected but keeping~~ disregarded while still accounting for the same main features. ~~Also~~ In addition , this approach does not require ~~to compute~~ computing the velocity field, ~~making the~~ an added benefit that makes the computation programs even faster. Each simulation is compared ~~with a fully~~ to its corresponding full non- linear ~~water~~ shallow water equation propagation. We ~~select~~ use the JAGURS code (Baba et al., 2014) ~~which runs~~ written in Fortran90 ~~in a~~ using parallel arrays via ~~with~~ OpenMP and OpenMP + MPI. This code is based ~~in~~ on the classical finite difference method of Satake (2002). For each scenario, ~~the tsunami is propagated during two hours of tsunami-time,~~ we run the simulation for the equivalent of two hours of tsunami travel time to obtain the main features of the runup distributions, despite the fact that later amplification of edge waves and resonances effects can occur. The approximated runup is obtained as the maximum from the vertical wall reflexion boundary condition. This is usually on the same order with the actual runup in a sloping beach model (Synolakis, 1987).

3 ~~Tests and results~~ Implementation and Benchmarking

~~For evaluating the performance of this simple approach, we have modeled nearly all of the great tsunamis in the last two decades. Most of them were already tested with an analytical approach in (Riquelme et al, 2015). The details of the propagation and runup distribution of the 12 events tested are exhibited in the supporting information. For these examples we used the finite fault models obtained from USGS (Hayes, 2017), because they have proven to be operational and robust for real time operations in a global context monitoring. All the computations were performed in a Dell Precision 7920, with two Intel Xeon Gold 6136 processor, 12 physical core each, for a total of 24 physical core, 2 threads each. For each time iteration, the domain is divided in 48 subdomains that are computed in different threads, for a parallel array (Fig. 1). To compute the tsunami initial condition, the Okada's equations were implemented in C-language using threading, as well as the finite difference scheme for the LM. The C-code uses pthread library. With this tool, a data struct containing a pthread_t was defined, and then a routine that send every grid's subdomain to each different core's thread for computation. This method is such reliable as any other linear scheme method, because it solves the same equations. The only significant difference is the threads distribution for time optimization. When a thread finishes, it computes for a certain time step and it joins with the others in order to avoid miscomputations. For instance, with the used machine, in a regular grid of 4 million points with a FFM of 300 subfaults, the vertical and horizontal seafloor displacements can be calculated almost instantly (less than 5 seconds) and two hours of tsunami propagation for 2011 Tohoku, Japan earthquake can be solved in 60 seconds.~~ To evaluate the performance of our approach, we modeled nearly all the great tsunamis of the last two decades. Most of them were already tested with an analytical approach in (Riquelme et al, 2015). The details of the propagation and runup distribution of the 12 events tested are presented in the supporting information. For these examples we used the finite fault models provided by the USGS (Hayes, 2017), as they have proven to be operationally robust for real time operations in the context of global monitoring. All the computations were performed in a Dell Precision 7920, with two Intel Xeon Gold 6136 processors, each with 12 physical cores, for a total of 24 physical cores, and 2 threads each. For each time iteration, the domain is divided into 48 subdomains that are computed in different threads, for a parallel array (Fig.1). To compute the tsunami initial condition, the Okada equations were implemented in the C programming language using threading, together with the finite difference scheme for the LM. The C code uses the pthread library to define a C data structure containing a pthread, and then calls a function that sends each grid subdomain to threads running in different cores for computation. This method is as reliable as any other linear scheme method, as it solves the same equations. The only significant difference is in the threads distribution for time optimization. When a thread finishes, it computes for a certain time step and it joins with the others in order to avoid miscomputations. For instance, on the system used to run our computations for a regular grid of 4 million points with an FFM of 300 subfaults, the vertical and horizontal seafloor displacements can be calculated almost instantly (less than 5 seconds), and two hours of tsunami wave propagation for the 2011 Tohoku, Japan earthquake can be solved in 60 seconds.

4 ~~Examples~~ Discussion of Computational Results

~~All the earthquakes presented here, have produced tsunamis. The range of magnitude varies from 7.7 to 9.1. They occurred in different subduction zones around the world. The largest ones are Tohoku in Japan and Maule in Chile. All of them show a thrust mechanism except for the Samoa event in 2009 which is a normal event. There are a few tsunami earthquakes in this section such as the 1992 Mw 7.7 Nicaragua Earthquake, The 2006 Mw 7.6 Java earthquake. The extension of the earthquakes varies from~~ ~~$L = 150$ km to $L = 500$ km, the range of peak displacement at the source varies from 3 m to 40 m. Therefore, we have tested as many earthquakes and as many source features as possible for this study.~~ All the earthquakes presented here, have produced tsunamis. The range of magnitude varies from 7.7 to 9.1. They occurred in different subduction zones around the world. The largest ones are Tohoku in Japan and Maule in Chile. All of them show a thrust mechanism except for the Samoa event in 2009 which is a normal event. There are a few tsunami earthquakes in this section such as the 1992 Mw 7.7 Nicaragua Earthquake, The 2006 Mw 7.6 Java Earthquake. The extension of the earthquakes varies from $L = 150$ km to $L = 500$ km, the range of peak displacement at the source varies from 3 m to 40 m. Therefore, we have tested as many earthquakes and as many source features as possible for this study.

1. The 1992 Mw 7.7 Nicaragua Tsunami Earthquake

2. The 2001 Mw 8.4 Southern Perú Earthquake

3. The 2003 Mw 8.3 Hokkaido Earthquake

4. The 2006 Mw 7.6 Java Earthquake

5. The 2007 Mw 8.1 Solomon Islands Earthquake

6. The 2007 Mw 8.0 Pisco Earthquake

7. The 2009 Mw 8.1 Samoa Islands Region Earthquake
8. The 2010 Mw 8.8 Maule Earthquake
9. The 2011 Mw 9.0 Tohoku Earthquake
10. The 2012 Mw 7.8 British Columbia Earthquake
11. The 2014 Mw 8.2 Iquique Earthquake
12. The 2015 Mw 8.3 Illapel Earthquake

~~For each event we apply the methodology described before. By using the W-phase centroid moment tensor, a scaling law, and a elliptic slip distribution, the first source is defined. Then, the linear and non-linear tsunami simulations are performed. The resulting runup distributions are decomposed along latitude and longitude, in order to compare both models. The same procedure is repeated but instead considering a FFM solution. Table 1 shows the correlation of the runup distributions between the code JAGURS and the presented here (the linear method). Table 2 summaries the CPU times for each stage of the process for each simulation. There is a high degree of agreement within a short time. Detailed figures of the 24 simulations are provided in the supplementary material, where maximum amplitudes, runup distribution and field measurements are displayed.~~ For each event we apply the methodology previously described, and use the W-phase centroid moment tensor, a scaling law, and an elliptic slip distribution to define the first source. Then, the linear and non-linear tsunami simulations are performed. The resulting runup distributions are decomposed along latitude and longitude in order to compare both models. The same procedure is repeated, this time considering an FFM solution instead. Table 1 shows the correlation between the runup distributions obtained with the JAGURS code (non-linear method) and the method presented in this paper (linear method). Table 2 summarizes the CPU times in seconds for different stages of the process for each simulation. There is a high degree of agreement within a short time. Detailed figures showing the results for the 24 simulations are provided in the supplementary material, where maximum amplitudes, runup distribution, and field measurements are listed. For comparison purposes, the event of 2014 Chile, the DART station 32401 registered 0.25 m of amplitude (An et al., 2014), where the linear method predicts 0.39 m for the elliptic source and 0.12 m for the FFM, whereas JAGURS gives 0.55 m for the elliptic source and 0.15 m for the FFM.

5 Application to compliment tsunami alert. Case study: The 2015 Illapel Earthquake

~~The September 16th a 8.3 Mw earthquake took place in the Coquimbo region in Chile (Melgar et al., 2016; Fuentes et al., 2017). The features of the event were optimals for a tsunami generation. The national agencies deployed the protocols for evacuating the whole chilean coast, even in distant insular territories (SNAM, bulletin #1, Sept. 16th, 23:02 UTC). The decision has to be made the very minutes after the origin time. In general, an accurate prediction of the tsunami runup heights requires a precise image of the seismic source, which nowadays is not available within 5 minutes and worst for real-time by adding the tsunami calculation times. Nevertheless, we can stay close of and quasi real time approach and trigger a first estimation based on the~~

Table 1. ~~Correlation of the runup distribution between the linear solution and the JAGURS code.~~ Correlation of the runup distribution obtained from our linear model solution and the JAGURS code. Correlation is computed with the standard Pearson coefficient. Details can be found in the supplemental material.

Event	FFM lon	FFM lat	Elliptic lon	Elliptic lat
1992 Nicaragua	0.8323	0.8088	0.8841	0.8587
2001 Perú	0.8334	0.8575	0.6697	0.7549
2003 Japan	0.7753	0.7838	0.9139	0.9129
2006 Indonesia	0.7483	0.8531	0.8134	0.9030
2007 Solomon Isl.	0.6422	0.7575	0.8412	0.8626
2007 Perú	0.8380	0.8085	0.8872	0.8896
2009 Samoa	0.6987	0.7353	0.7779	0.8093
2010 Chile	0.7346	0.6039	0.8682	0.7820
2011 Japan	0.8571	0.7074	0.9229	0.8311
2012 Canada	0.6829	0.6034	0.8731	0.8398
2014 Chile	0.7833	0.6473	0.9051	0.8341
2015 Chile	0.9103	0.7663	0.9603	0.8686

Table 2. ~~Results of the CPU time of each event, in seconds. t_{IC} is the time for computing the initial condition, t_{Pr} the time of processing, t_{TP} the time of the tsunami propagation and t_T is the total time.~~ Summary of the CPU time in seconds for the twelve events. t_{IC} indicates the time needed to compute the initial conditions, t_{Pr} the processing time, t_{TP} the time to compute the tsunami propagation, and t_T the total time.

Event	FFM		Elliptic		LM	JAGURS	Total time t_T			
	t_{IC}	t_{Pr}	t_{IC}	t_{Pr}	t_{TP}	t_{TP}	FFM-LM	FFM-JAGURS	Elliptic-LM	Elliptic-JAGURS
1992 Nicaragua	6	4	8	5	31	575	41	585	44	586
2001 Perú	5	3	7	3	18	360	26	368	28	370
2003 Japan	5	3	9	3	22	428	30	436	34	440
2006 Indonesia	4	3	7	2	20	358	27	365	29	367
2007 Solomon Isl.	8	5	10	5	28	658	41	671	43	673
2007 Perú	4	4	9	4	31	546	39	554	44	559
2009 Samoa	4	3	6	2	17	321	24	328	25	329
2010 Chile	7	4	9	5	32	651	43	662	46	665
2011 Japan	6	6	13	6	46	223	58	235	65	242
2012 Canada	2	1	4	1	15	153	18	156	20	158
2014 Chile	5	4	11	5	24	500	33	509	40	516
2015 Chile	4	4	8	4	27	500	35	508	39	512

~~previous elliptical source. Because this can be done in a few seconds, it can be done at the moment instead searching in a precomputed data base of scenarios that are usually restricted. For monitoring purposes, the results can be updated every time a seismic source imaging is received, for both, the near field (at 15 arcsec) and regional field (at 60 arcsec). The whole information is summarized in a coded-color map, following the official coding from the Chilean institutions (Melgar et al., 2016). Color coded maps are self-explicative, which make them easy to interpret (Figures 2 and 3). Each region can be rapidly assigned with a color which deploy an specific protocol for evacuation. All the simulations were performed with two hours of propagation, where the main energy content plays a key role on the inundation process. Figure 4 exhibits the normalized energy rate that generates the runup history along the coast, showing that majority of the global energy is concentrated within the first hour. We can also observe that the first estimation made with the elliptic fault predicts the same levels of inundation as the further finite fault model in the near field, and with minor differences in the regional field. This agrees the common sense where finite fault models act in the monitory stage and time is not as critic as in the very first minutes. For completeness purposes, travel times isochrones are computed along the pacific basin (Figure 5). This is performed by computing a dense set of rays following Sandanbata et al. (2018), which allows to include dispersive effects. Also, we have included the effect of the earth elasticity as shown in An and Liu (2016). This kind of maps can be computed instantly with the very first estimation of the moment tensor and then update.~~ On 16 September, 2017 an 8.3 Mw earthquake occurred in the Coquimbo region, Chile (Melgar et al., 2016; Fuentes et al., 2017). The characteristics of this event made it an ideal case study for tsunami generation. The national agencies implemented the established protocols for evacuating the whole Chilean coast, even the more distant insular territories (SNAM, bulletin 1, Sept. 16th, 23:02 5 UTC). Such decisions have to be made within minutes of origin time. In general, an accurate prediction of the tsunami runup heights requires a precise image of the seismic source, which at present is not available within 5 minutes for real-time after adding the tsunami simulation times. Nevertheless, we can come close to a quasi-real-time approach by triggering a first estimation assuming an elliptical slip distribution. This only takes a few seconds, and can at present be done instead of searching a pre-computed database of scenarios that are usually limited. For monitoring purposes, the results can be updated everytime a seismic source imaging is received, for both, the near field (at 15 arcsec) and regional field (at 60 arcsec). All this information is summarized in a color-coded map following the official coding used by the Chilean institutions (Melgar et al., 2016). Color coded maps are self-explanatory, which makes them easy to interpret (Figs.2 and 3). Each region can then be rapidly assigned a color linked to an specific evacuation protocol. All the simulations were performed for two hours of tsunami propagation where the main energy content plays a key role on the inundation process. Figure 4 illustrates the normalized energy rate that generates the runup history along the coast, showing that the majority of the global energy is concentrated within the first hour. We can also observe that the first estimation obtained for an elliptical fault predicts the same levels of inundation as the full finite fault model in the near field, while we can observe minor differences in the regional field. This makes sense since finite fault model results become available during the tsunami monitoring stage, when time is not as critical as in the very first minutes after origin time. It has to be noticed that is possible to increase the number of warning levels allowing to find the optimal number of states for emitting and communicating the warning bulletin. In this study we choose the UNESCO standard. For completeness, we computed the travel time isochrones across the Pacific Basin (Fig. 5). These computations use a dense set of rays following Sandanbata et al. (2018), which allows to include dispersive effects.

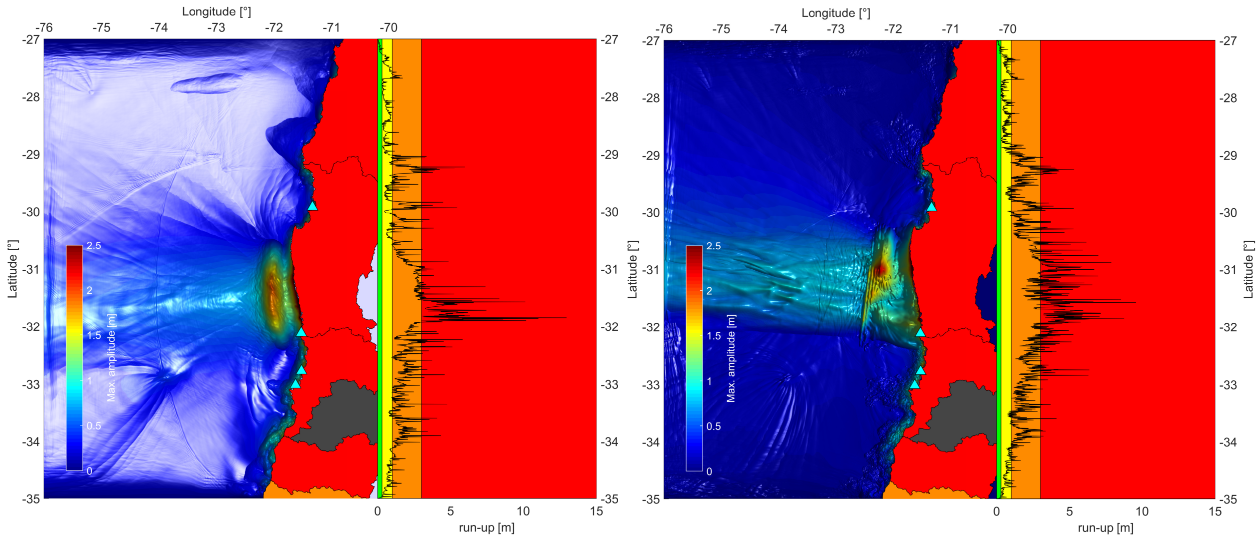

Figure 2. ~~Near Field Simulation of the 2015 Illapel Earthquake for elliptic source (left) and finite fault model (right). Red color represents the run-ups larger than 3 meters. Orange color is between 1 m and 3 m. Yellow color ranges between 0.3 m and 1 m. Green color codes run-ups smaller than 0.3 m.~~ Near field simulation of the 2015 Illapel earthquake with an elliptical source (left), and a finite fault model (right). The colors assigned to different areas indicate the expected runups in meters: a) red for runups larger than 3 m, b) orange for runups between 1 and 3 m, c) yellow for runups between 0.3 and 1 m, and d) green for runups smaller than 0.3 m.

We have also included the effect of the earth elasticity as shown in An and Liu (2016). These kind of maps can be computed instantly together with the very first estimation of the moment tensor and then updated.

6 ~~Discussion and~~ Conclusions

~~Despite linear theory has been used in other tsunami warning systems, for instance, in the PTWC (http://unesdoc.unesco.org/images/0022/002203/220368e.pdf), now it is used in combination with more complex sources and faster algorithms with an unique and simple product easy to interpret. The non-complexity of the source, does not seem to be a problem when it comes to do a fast run-up estimation regarding emergency response. Establishing levels of hazard in real time, tries to generate a more accurate extension of the area affected by the tsunami, the maximum inundation that can reach, and how many people will be exposed to this hazard along the chilean coast. This method intends to rapidly predict the run-up distribution. Using some simplifications in the tsunami equations it is possible to model rapidly the observed run-up. Obviously, this is not a high performance computing code, but even with many details outside the modeling such as complexity of the source, fine bathymetry and simplified equations, it can predict an important percentage of the run-up. The idea of extension even without the mathematical rigorosity we would like, is not inexact when we think of the idea of an emergency response system that needs to trigger actions that can save lives and reduce economic losses after the occurrence of a large earthquake.~~

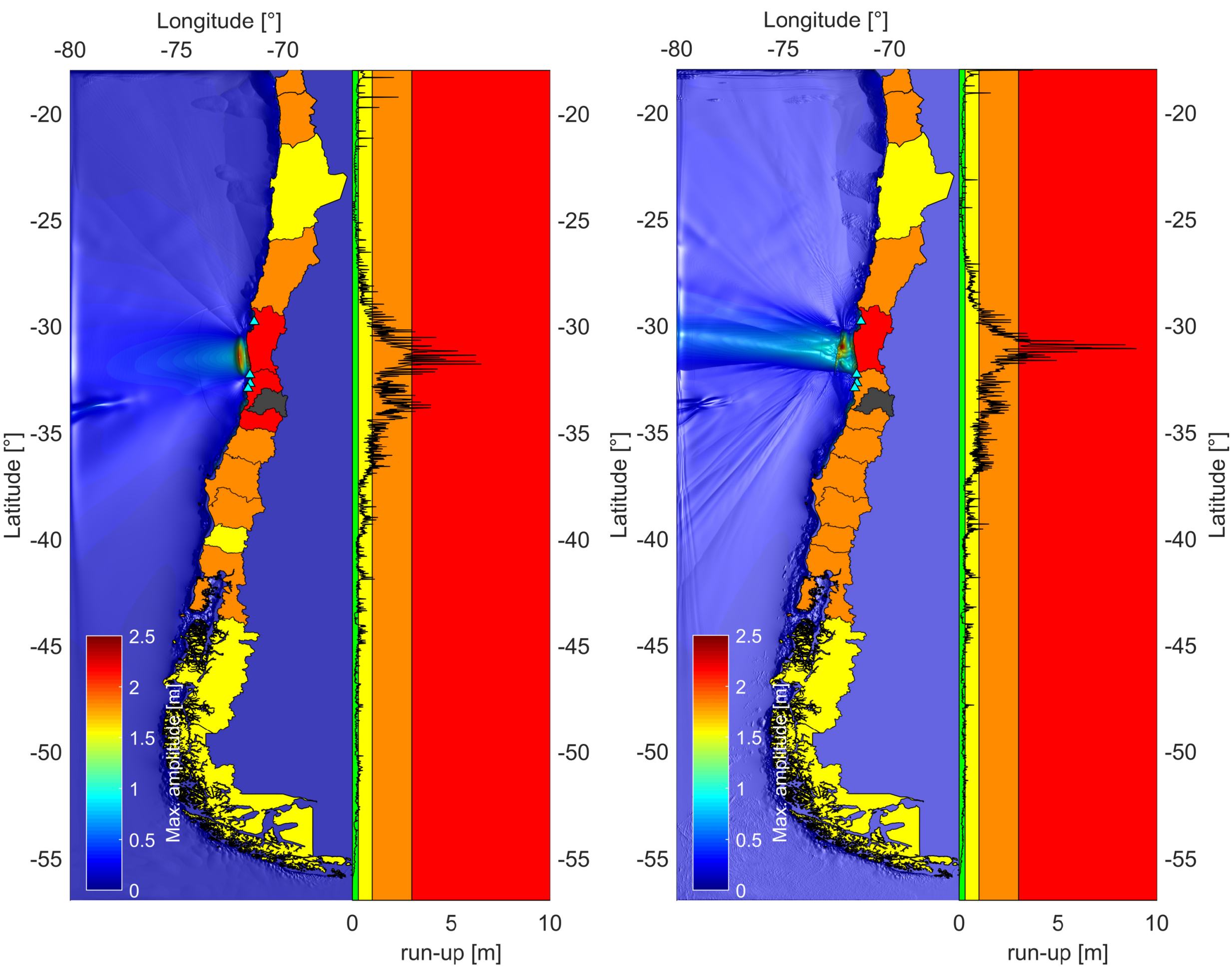

Figure 3. ~~Regional Field Simulation of the 2015 Illapel Earthquake for elliptic source (left) and finite fault model (right). Red color represents the run-ups larger than 3 m. Orange color is between 1 m and 3 m. Yellow color ranges between 0.3 m and 1 m. Green color codes run-ups smaller than 0.3 m.~~ Regional field simulation of the 2015 Illapel earthquake for an elliptical source (left), and a finite fault model (right). The colors assigned to different areas indicate the expected runups in meters: a) red for runups larger than 3 m, b) orange for runups between 1 and 3 m, c) yellow for runups between 0.3 and 1 m, and d) green for runups smaller than 0.3 m.

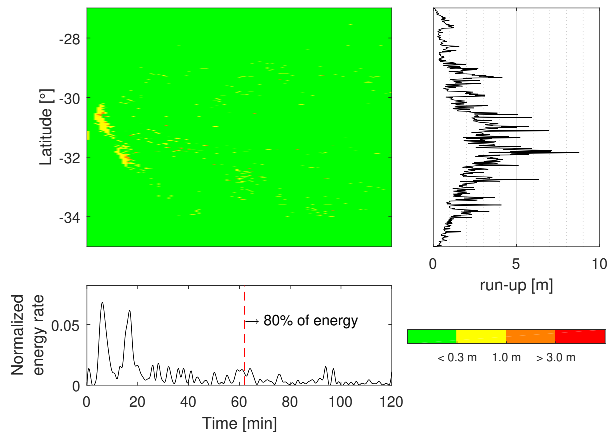

Figure 4. ~~Normalized run-up energy rate during the first two hours of tsunami simulation. Upper left panel display the run-up rate along latitude and time. Upper right panel shows the final maximum run-up and bottom left panel exhibits the normalized energy rate of the whole process as a time series.~~ Normalized runup energy rate during the first two hours of tsunami simulation. The upper left panel shows the runup rate along latitude and time, the upper right panel shows the final maximum runup, and the bottom left panel shows the normalized energy rate for the whole process as a time series.

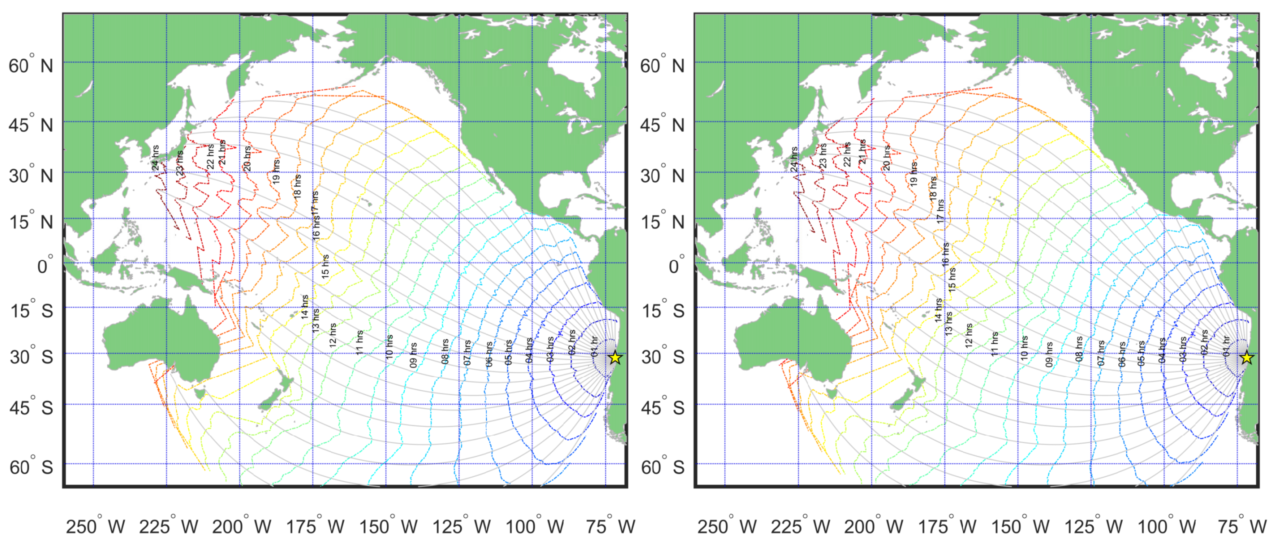

Figure 5. ~~Travel times along the pacific basin due to the 2015 Illapel Earthquake. Left panel is purely Shallow Water and right panel includes dispersion and earth elasticity for a wave frequency of 2 mHz.~~ Tsunami travel times across the Pacific basin for the 2015 Illapel earthquake.The left panel shows the travel times after the shallow water equations, while the travel times in the right panel include the effects of dispersion and the earth elasticity for a wave frequency of 2 mHz.

~~Using the methodology of Sandanbata et al. (2018) it is possible to instantaneously calculate the tsunami arrival times from sources generated in the far field. This can also be done using tsunami modeling, however this takes a longer time of calculation then this numerical methodology is accurate enough to calculate tsunami travel times from far field events. When we compare it with tsunami modeling codes, such as JAGURS, this method includes more than 80% of the predicted run-up in a 15 arcsec bathymetry at least 20 times faster. The main purpose of this study is to produce fast run-up estimations with reasonable accuracy. The idea here is to compliment the tsunami warning information while full and long calculations are being done (Figure 6). This simple method provide simple and reliable information about the tsunami threat, which allows to entities to take decisions properly.~~ In this study we propose a method that disregards the fine complexity of the seismic source while using fine bathymetric data and a set of simplified equations to model more than 80% of the runups with enough accuracy for tsunami warning purposes up to 20 times faster. Our method also aims at rapidly predicting the spatial distribution of the runups using some simplifications in the tsunami equations. Despite lacking the mathematical rigorosity that we would otherwise prefer, the method we propose is not inexact within the context of an emergency response system that needs to trigger actions that can potentially save lives and reduce economic losses after the occurrence of a large earthquake. We summarized our approach in a flow chart (Fig. 6). Taking into account the results of our study we can list the following as the most noteworthy results:

1. Although other tsunami warning centers use linear theory as part of their operations, for instance at the PTWC (http://unesdoc.unesco.org/images/0022/002203/220368e.pdf), in this study we have combined it with the use of more complex sources and faster algorithms to generate a unique and simple product easy to interpret.

2. The non-complexity of the adopted source does not seem to significantly affect the results of a fast runup estimation for emergency response purposes. By computing different levels of tsunami hazard in near-real time we estimate more accurately the extent of the area potentially affected by the tsunami, the maximum level of inundation, and how many people will be exposed to this hazard along the Chilean coast.

3. Using the methodology of Sandanbata et al. (2018) it is possible to instantaneously calculate the tsunami arrival times from sources generated in the far field with enough accuracy. This can also be done via tsunami modeling, but at the expense of longer computation times.

4. When compared to other tsunami modeling codes such as JAGURS, results obtained from our method match more than 80% of the predicted runup for 15 arcsec bathymetry while obtaining the results at least 20 times faster.

5. The simple method proposed in this study provides a fast, reliable, and intuitive characterization of the tsunami threat, which in turn allows disaster mitigation agencies to take appropriate action.

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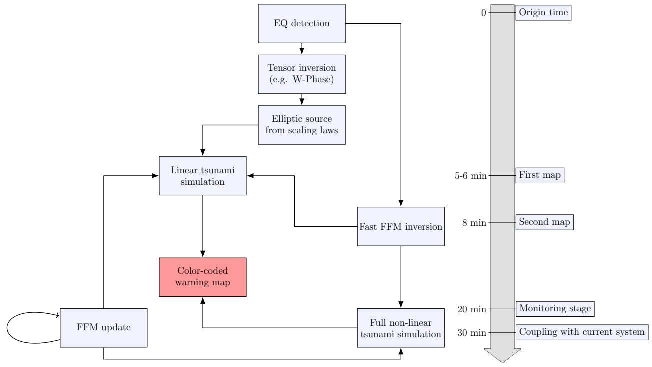

Figure 6. ~~Flow chart of the proposed methodology.~~ Flow chart of the methodology proposed in this study.

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