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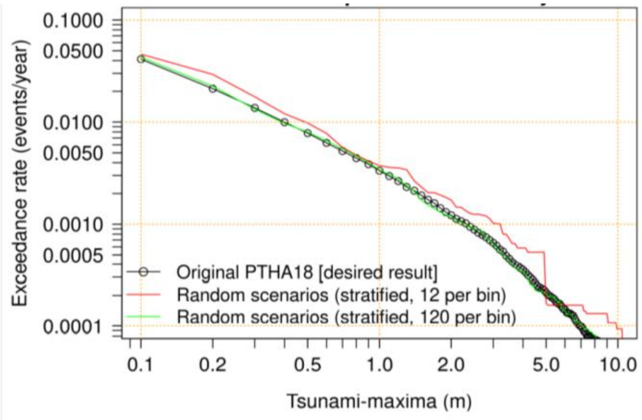
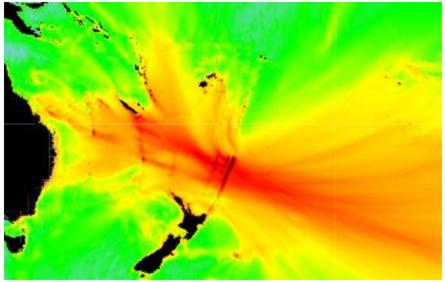
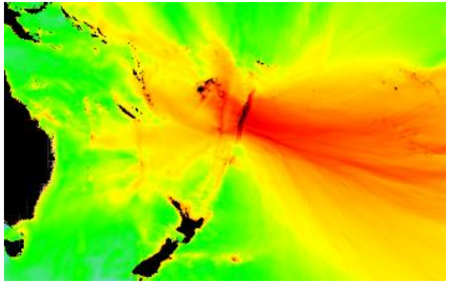
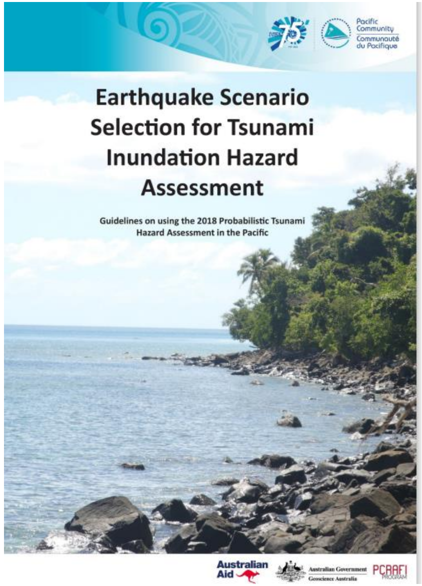
Earthquake scenario selection for tsunami inundation hazard assessment

Monte-Carlo techniques



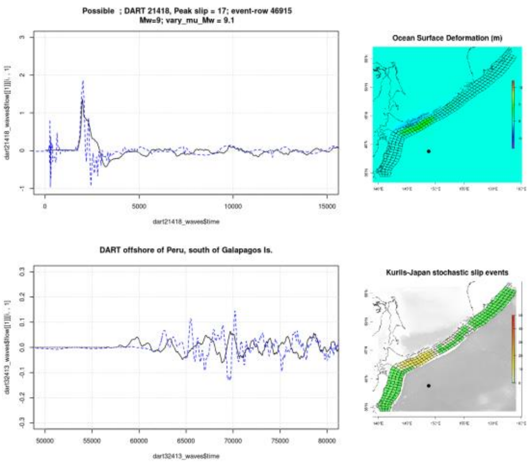


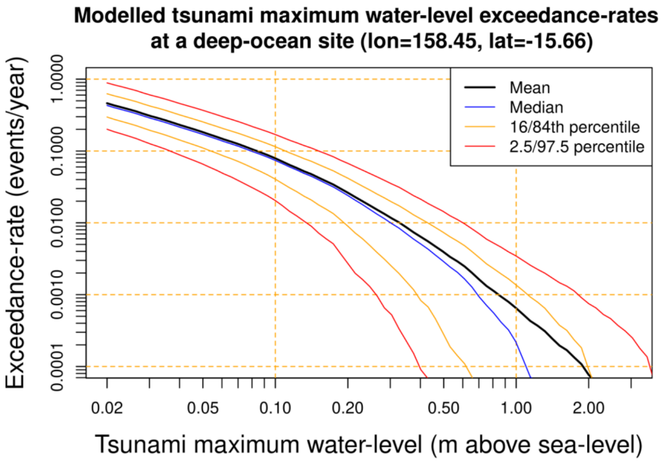


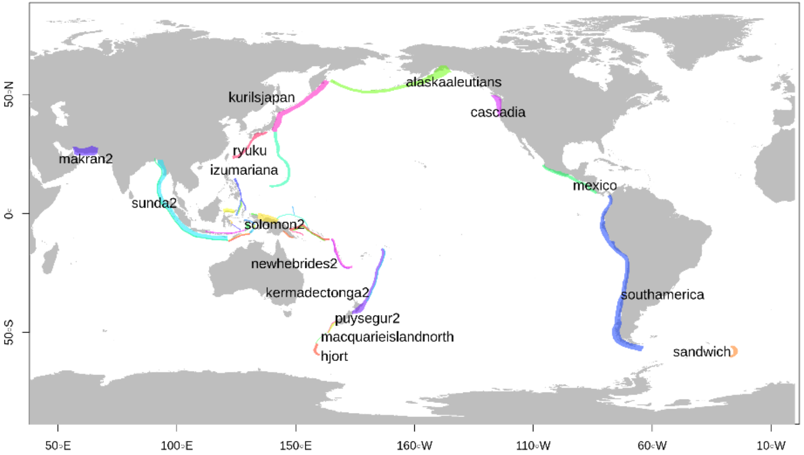


Reminder of the problem

- **Offshore PTHA (earthquake-tsunami only)**
  - Huge # of scenarios modelled in deep water
  - Scenario frequencies
  - Uncertainties in these frequencies

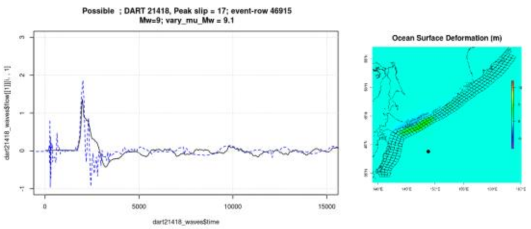


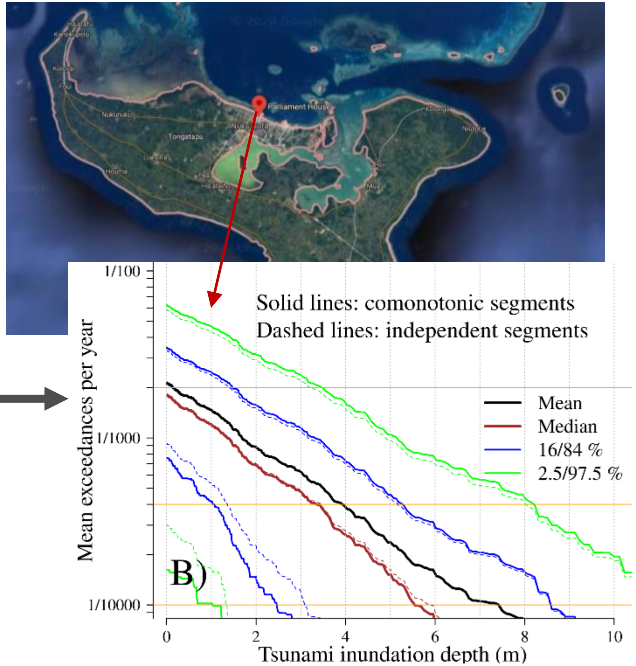




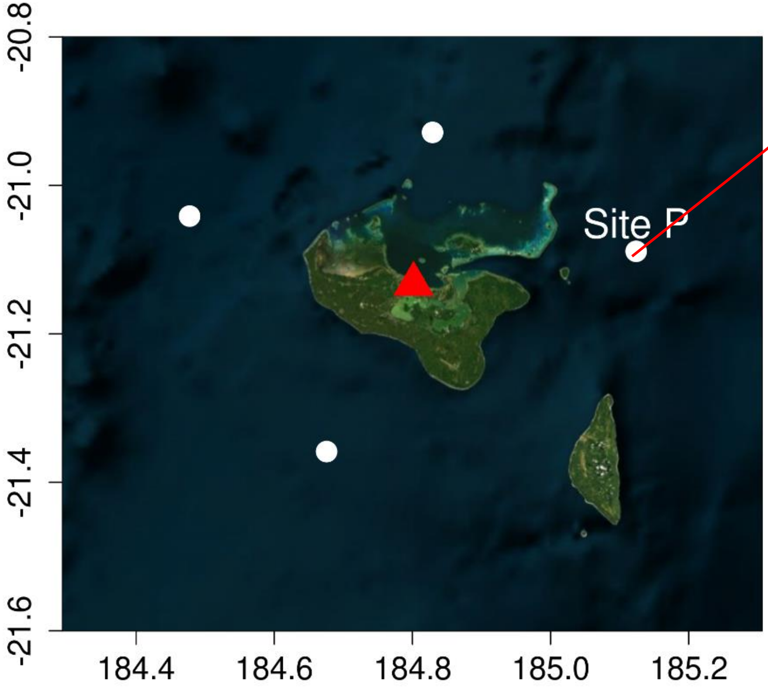
Reminder of the problem

- **Offshore PTHA (earthquake-tsunami only)**
  - Huge # of scenarios modelled in deep water
  - Scenario frequencies
  - Uncertainties in these frequencies
- **Onshore hazard**
  - How big (e.g. depth at site of interest) ?
  - How often (with uncertainty) ?
  - Inundation computation is expensive
    - Cannot model all offshore PTHA scenarios
- **<u>Which scenarios should be used for onshore hazard assessment?</u>**

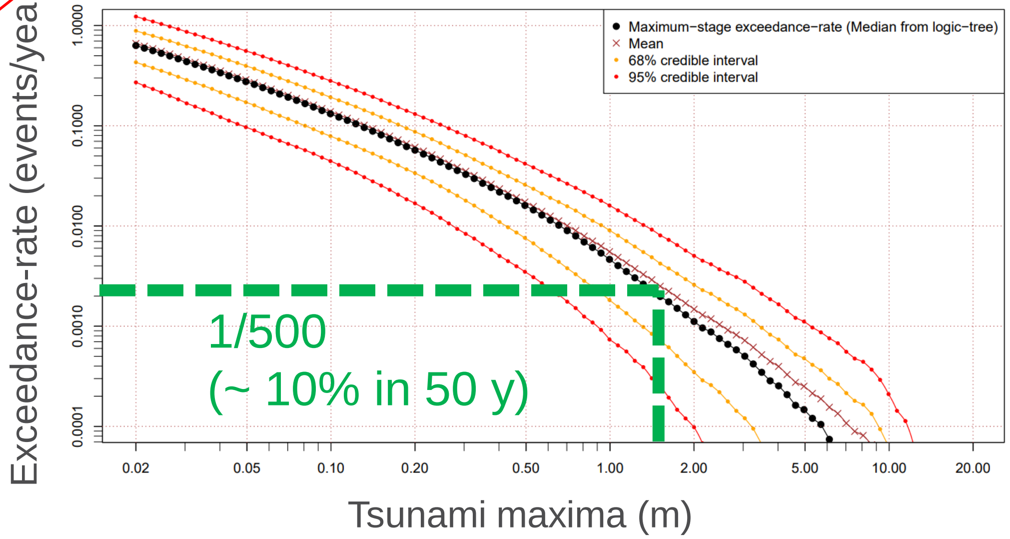




One approach: Find scenarios with offshore waves matching exceedance-rates of interest

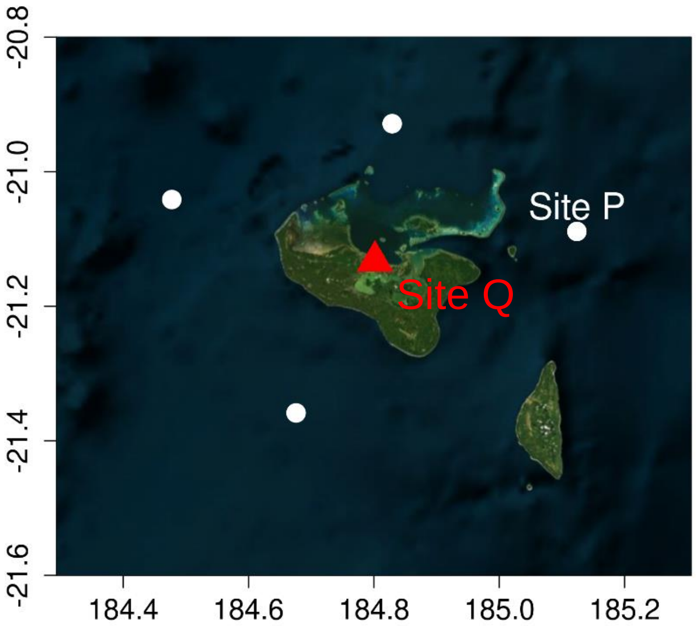


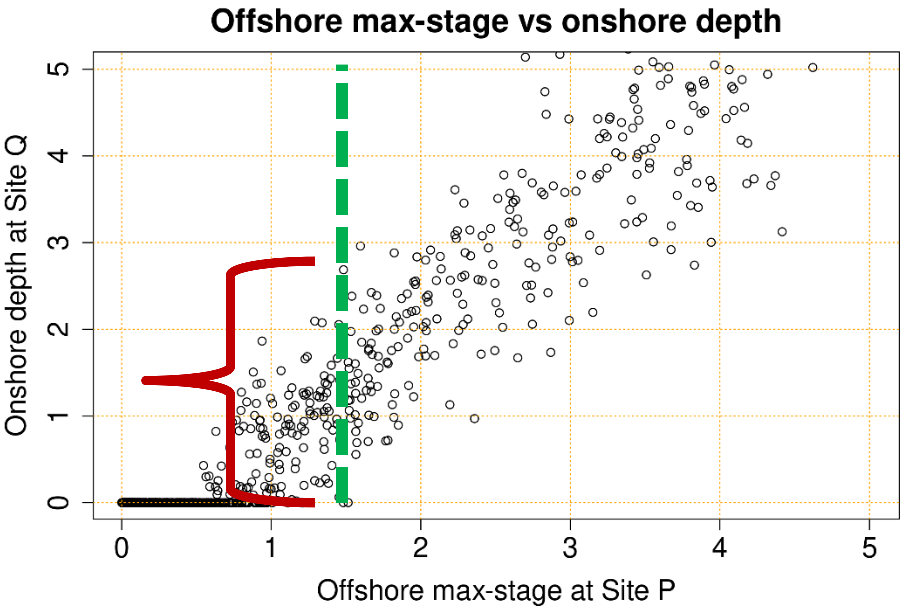
Offshore tsunami maxima vs exceedance-rate



Can offshore waves predict coastal impacts?

- **Offshore waves are a <u>rough predictor</u> of nearshore & onshore waves**
  - Normally there is lots of extra variability





Can offshore waves predict coastal impacts?

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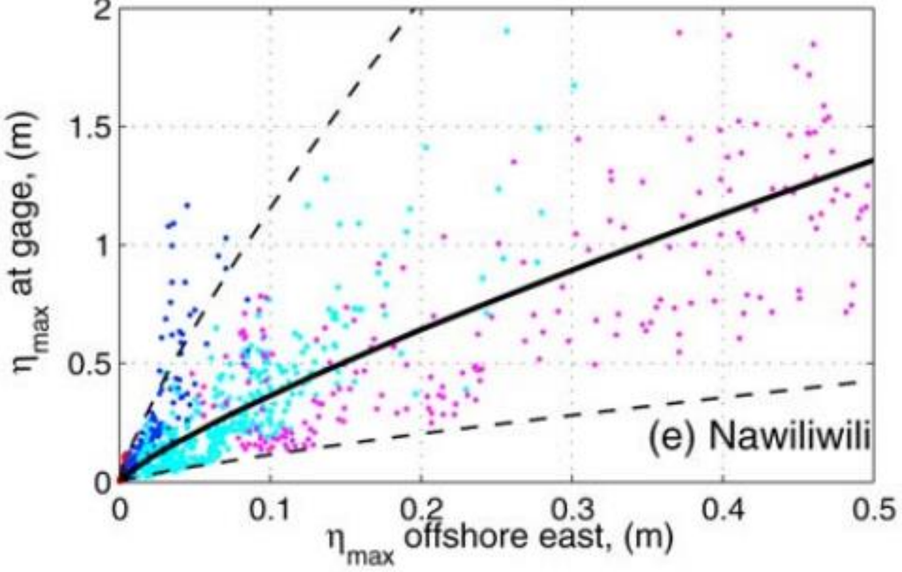
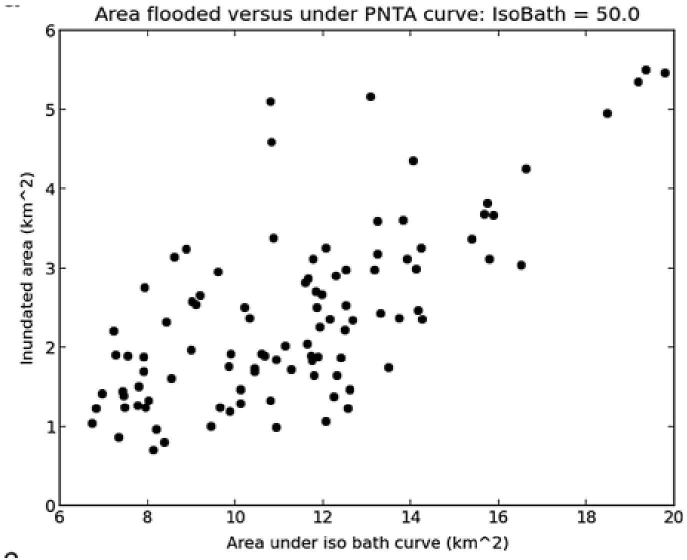
Tang et al., 2009



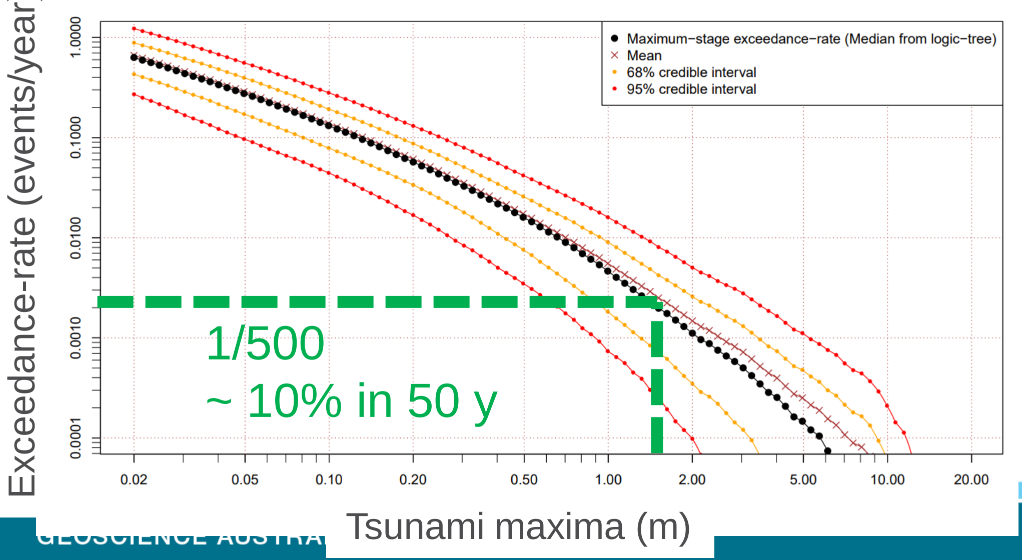
Mueller et al., 2015

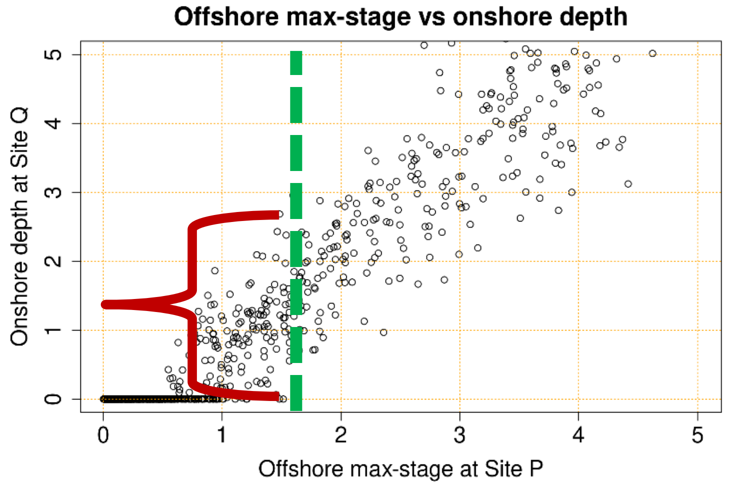


Can offshore waves predict coastal impacts?

- Offshore waves are a <u>rough predictor</u> of nearshore & onshore waves
- Scenario return periods (from offshore sites) might not apply onshore
    - 1/500 offshore wave ≠ 1/500 depth onshore

Offshore tsunami maxima vs exceedance-rate





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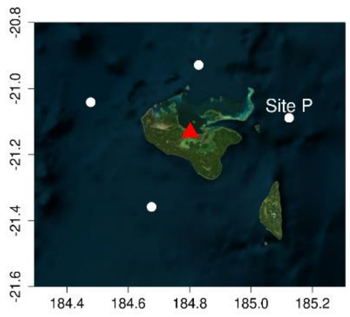


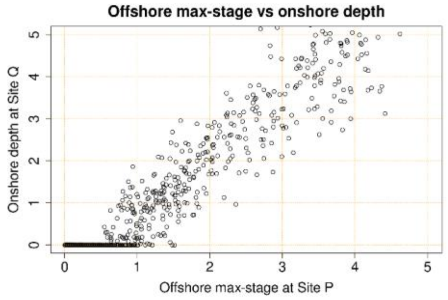
Limitation of scenario-based approaches:

Even if we accept the accuracy of the:

- ❑ *Offshore PTHA*
- ❑ *Inundation model*

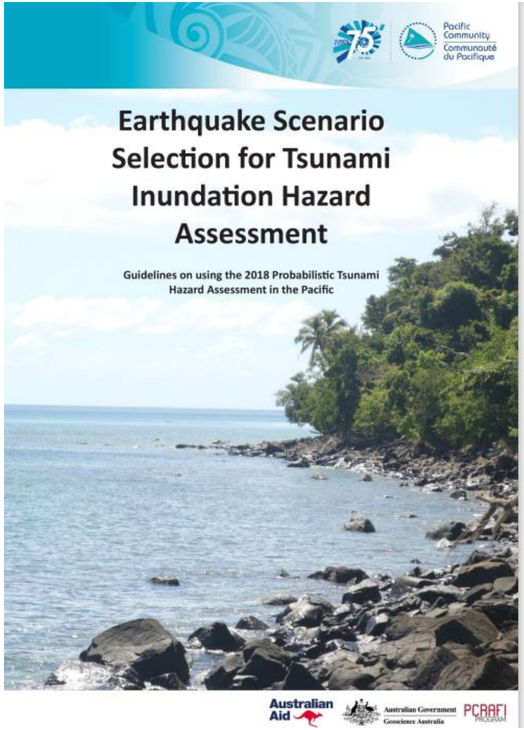
the onshore depths (and exceedance-rates) from scenario-based approach have limited precision

- ❑ *Scenario variability*



How should we use offshore PTHA for earthquake-tsunami inundation hazard assessment?

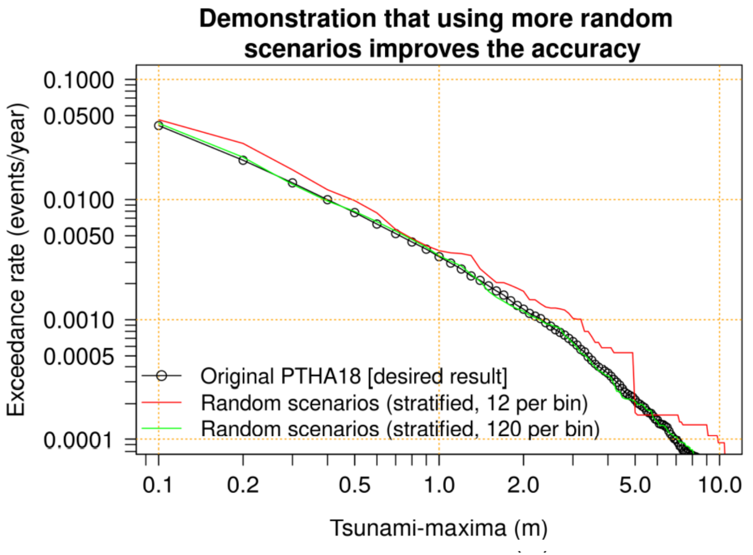
- More than one approach:
  1. **Multiple scenarios (Judith's presentation)**
     - Simple & computationally affordable
     - Not precise – but enough for many applications
  2. **All scenarios ?**
     - "Most accurate"
     - Unrealistic → Too computationally expensive
  3. **<u>Monte-Carlo methods</u>**
     - Approximate the "all scenarios" result
     - Fewer scenarios → more practical



Monte-Carlo methods for using offshore PTHA for inundation hazard assessment

The basic idea of Monte-Carlo methods

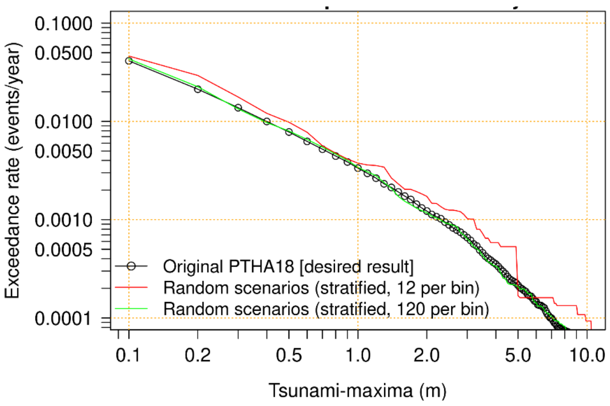
- **“All scenarios” are <u>approximated</u> with a random subset of scenarios:**
    - Hypothetical example
        - 100,000 scenarios (all)
        - Monte-Carlo approximation with 300 random scenarios
            - Inundation modelling feasible!
- **Has some error**
    - Can reduce using more scenarios
        - 3000 vs 300
    - Can reduce using better Monte Carlo methods



One common Monte-Carlo method

- **<u>Stratified-sampling by earthquake magnitude:</u>** **Often used in PTHA**

    1. Group scenarios by magnitude
    2. For each magnitude:
        - Sample ***N*** scenarios (w/ replacement)
            - Sampling weights ~ scenario-rates
    3. Simulate inundation (random scenarios)
    4. Estimate exceedance-rates



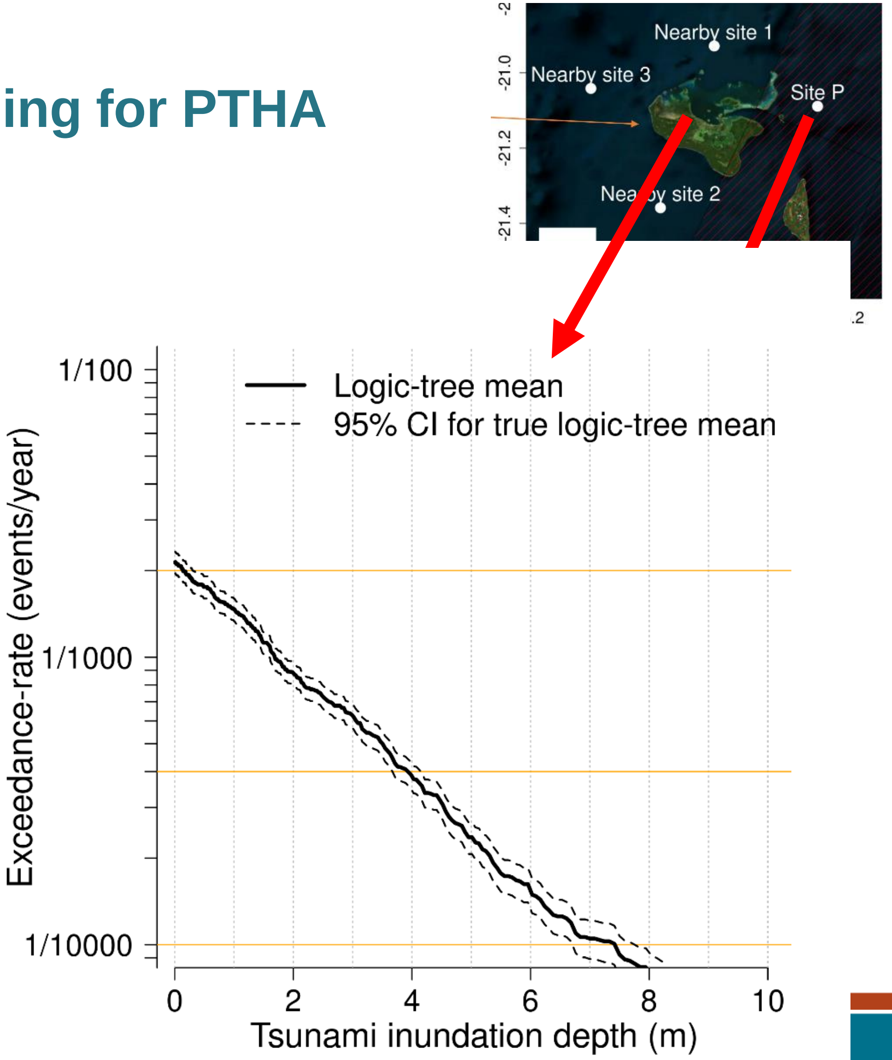
Converges to the "all-scenarios" solution (errors have variance ~ ***1/N***)

- Some error, unbiased

Much cheaper than simulating inundation for all scenarios

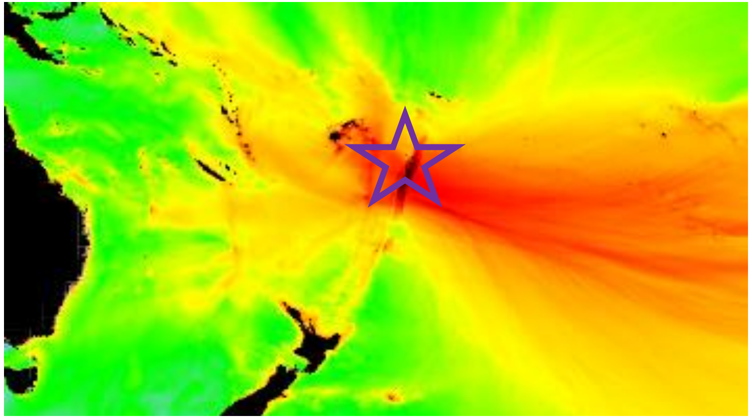
Useful properties of stratified-sampling for PTHA

- **Offshore sites:**
  - Variance of Monte-Carlo errors can be <u>computed analytically</u>
  - No sampling required. Useful:
    - Testing sampling schemes
    - Optimise non-uniform sampling of different magnitude bins
- **Onshore sites:**
  - Variance of Monte-Carlo errors can be <u>estimated from just one Monte-Carlo sample</u>
    - Numerical reliability of onshore hazard

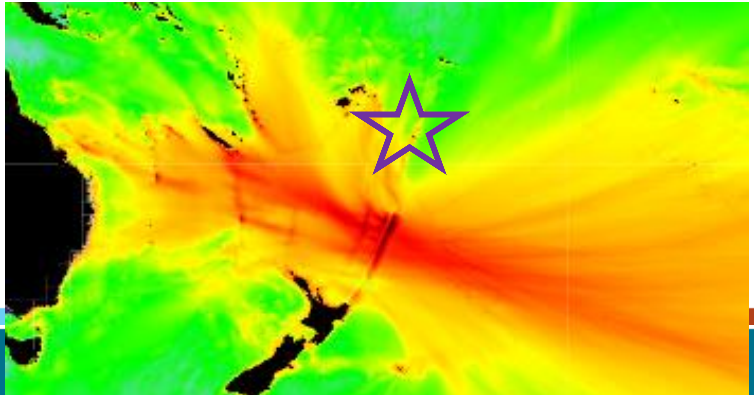


Weakness of stratified-sampling by magnitude

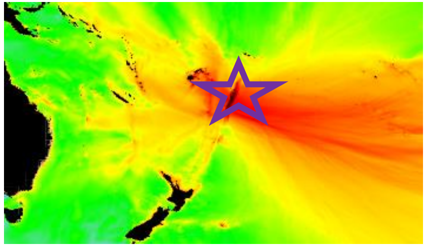
- ***No influence of the tsunami size near site of interest***
  - But this is known in deep water (offshore PTHA)
  - Result: **Many scenarios with little inundation**
- **Example @ Tongatapu, Tonga**
  - Less than 25% of sampled scenarios with waves > 1m offshore nearby
  - Inefficient!



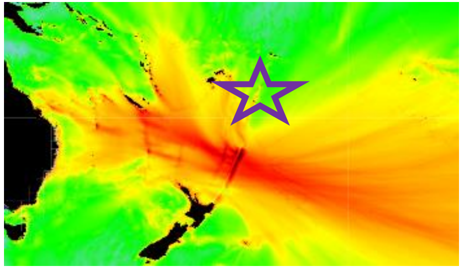
Two scenarios with magnitude 9.4



A solution: Modify the sampling to emphasise larger waves *(stratified/importance-sampling)*



1. Group scenarios by magnitude
2. For each magnitude:
    - ***Biased sampling*** of scenarios (w/ replacement)
        - Sampling weights ~ scenario-rates *** (wave height near our site)**



3. Simulate inundation (random scenarios)

4. Estimate exceedance-rates

    - Theory of importance-sampling → unbiased

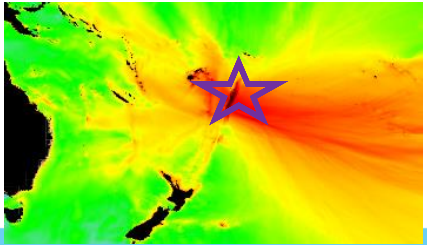
Better represents large tsunamis → less Monte-Carlo error near our site

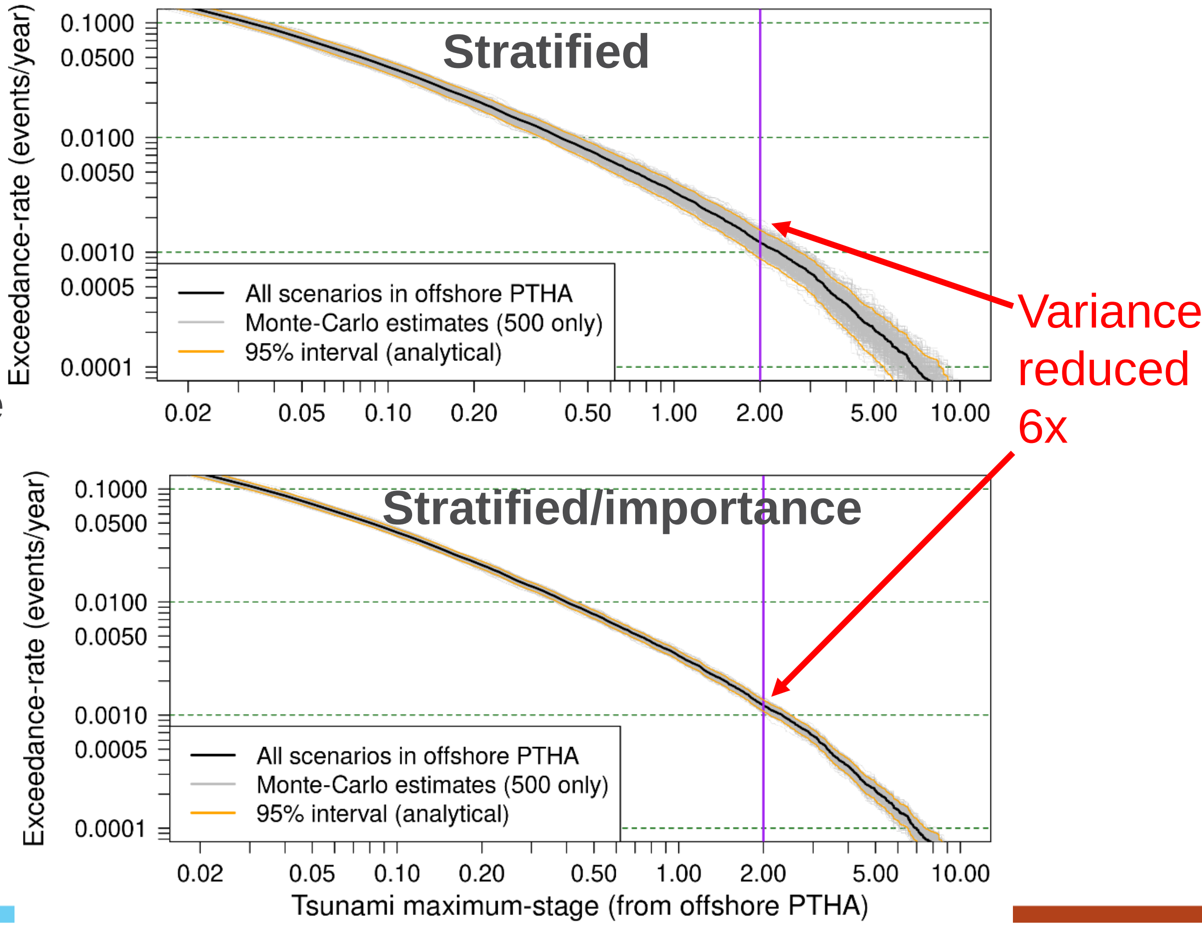
Shares all the other advantages of stratified-sampling

How much benefit?

- **Test at offshore site**
  - Both methods use 1200 scenarios

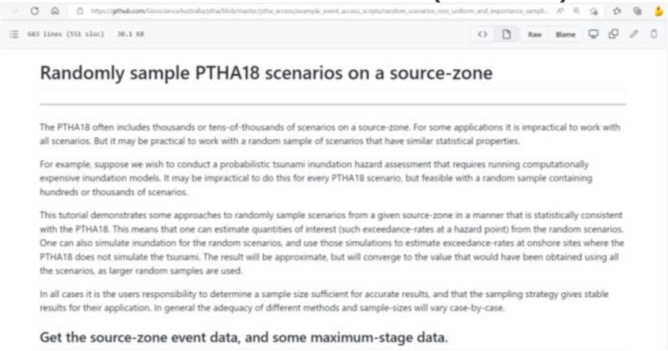
- **Strong reduction in Monte-Carlo error near the site of interest**





Resources to learn to how implement this ….

- Technical report
  - https://purl.org/spc/digilib/doc/dmup7
    - Linked tutorials (online)


Randomly sample PTHA18 scenarios on a source-zone

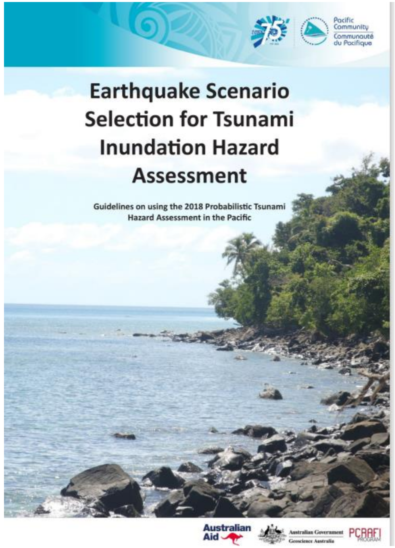
The PTHA18 often includes thousands or tens-of-thousands of scenarios on a source-zone. For some applications it is impractical to work with all scenarios. But it may be practical to work with a random sample of scenarios that have similar statistical properties.

For example, suppose we wish to conduct a probabilistic tsunami inundation hazard assessment that requires running computationally expensive inundation models. It may be impractical to do this for every PTHA18 scenario, but feasible with a random sample containing hundreds or thousands of scenarios.

This tutorial demonstrates some approaches to randomly sample scenarios from a given source-zone in a manner that is statistically consistent with the PTHA18. This means that one can estimate quantities of interest (such exceedance-rates at a hazard point) from the random scenarios. One can also simulate inundation for the random scenarios, and use those simulations to estimate exceedance-rates at onshore sites where the PTHA18 does not simulate the tsunami. The result will be approximate, but will converge to the value that would have been obtained using all the scenarios, as larger random samples are used.

In all cases it is the users responsibility to determine a sample size sufficient for accurate results, and that the sampling strategy gives stable results for their application. In general the adequacy of different methods and sample-sizes will vary case-by-case.

Get the source-zone event data, and some maximum-stage data.



- Journal Paper:
  - https://academic.oup.com/gji/article/230/3/1630/6566343
    - Associated code online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From offshore to onshore probabilistic tsunami hazard assessment via efficient Monte-Carlo sampling

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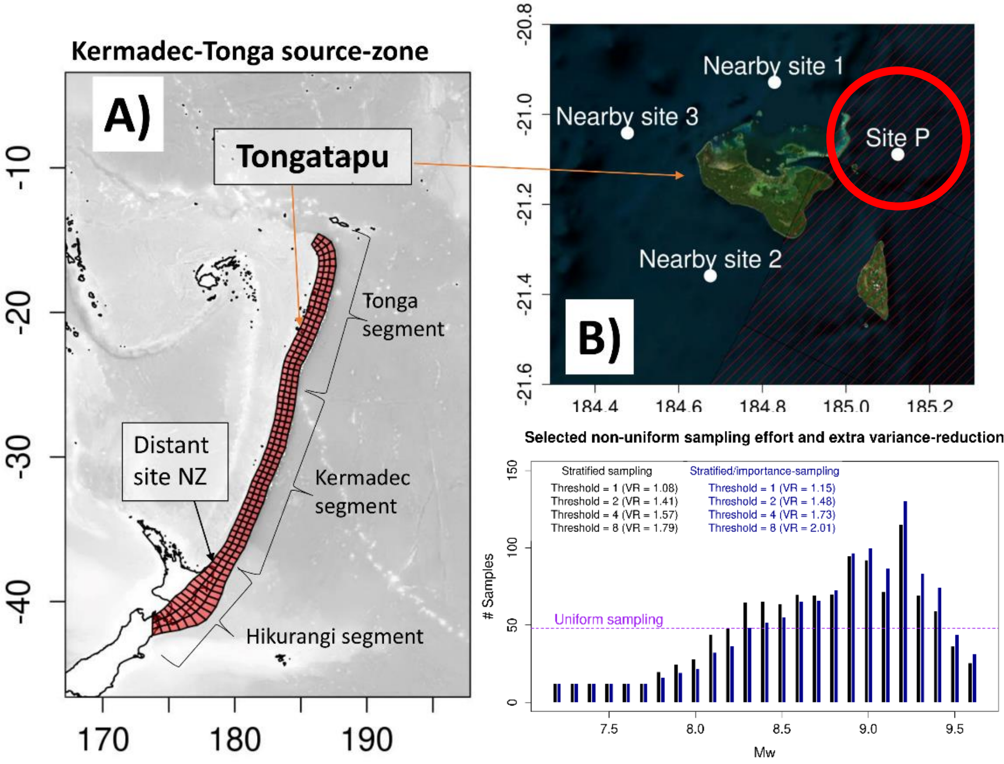
Summary

Offshore Probabilistic Tsunami Hazard Assessments (offshore PTHAs) provide large-scale analyses of earthquake-tsunami frequencies and uncertainties in the deep ocean, but do not provide high-resolution onshore tsunami hazard information as required for many risk-management applications. To

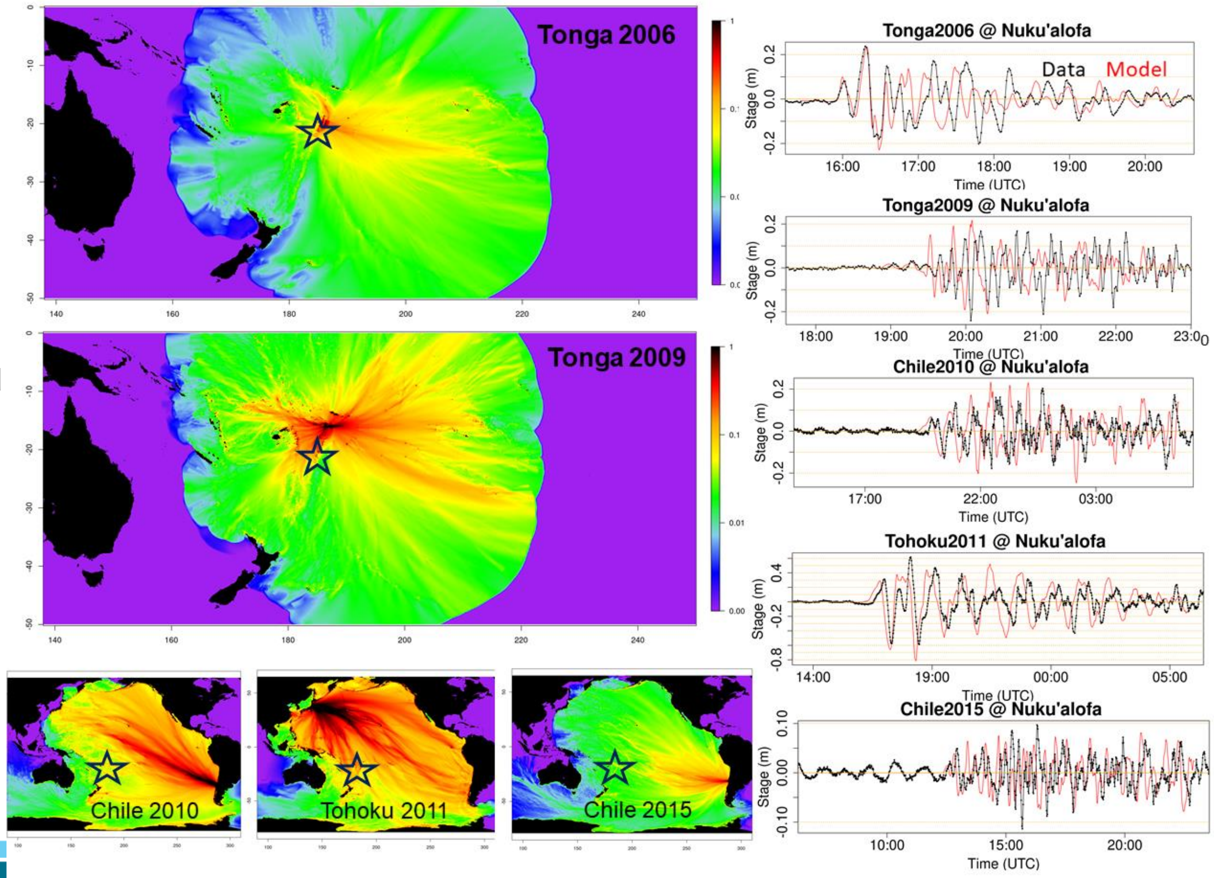
Application: Inundation Hazards @Tongatapu, Tonga

- **1200 random scenarios from Offshore PTHA**
    - Stratified/importance sampling
    - Non-uniform sampling of magnitude-bins
- **Initial testing of the Monte-Carlo performance offshore**
    - <u>Variance reduction by factor of 4 to 18</u> near Tongatapu
        - Compared to uniform stratified-sampling

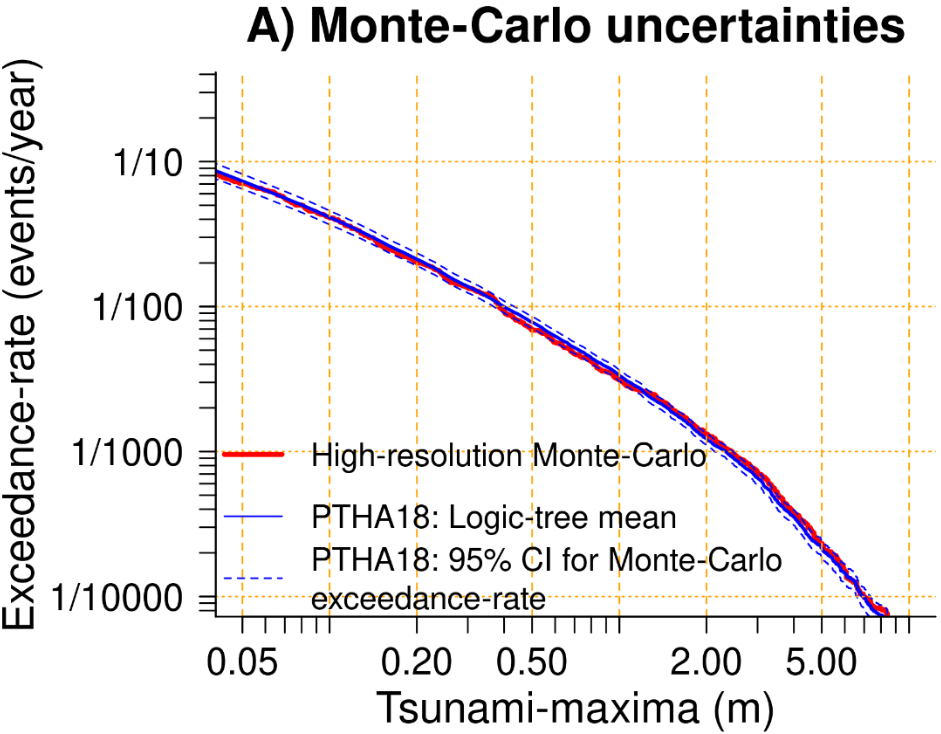


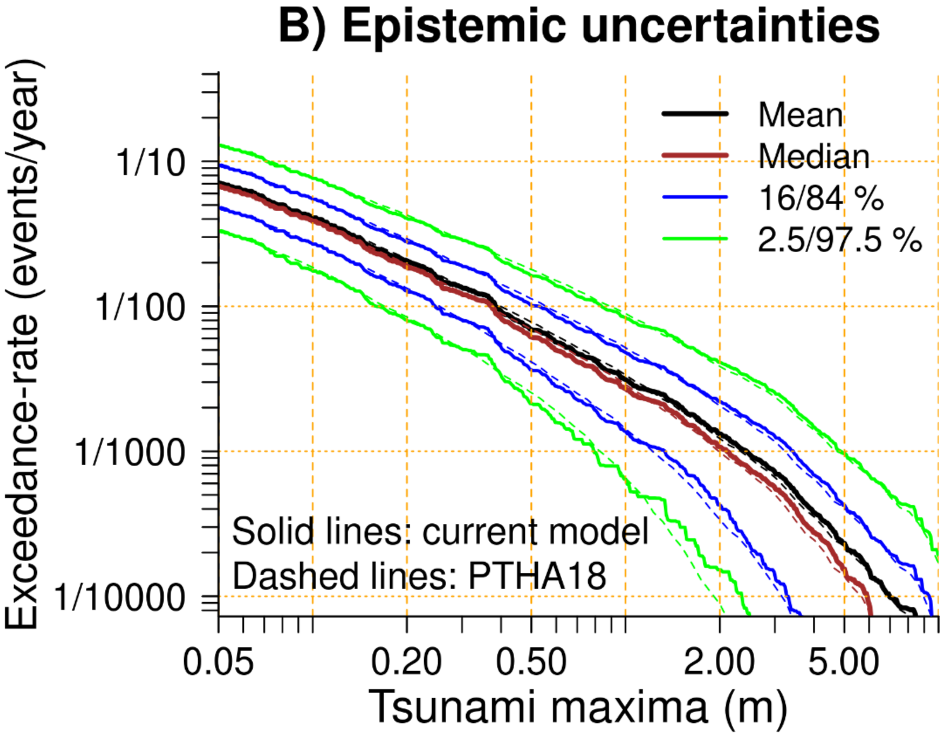
Application: Inundation Hazards @Tongatapu, Tonga

- **Inundation model**
  - Nonlinear shallow water equations (spherical)
    - 2-way nesting
    - 7.5 m grid-size onshore @ Tongatapu
- **Tested against obs. of five historical tsunamis**
  - Source models from offshore PTHA
- **Simulated inundation for all random scenarios**

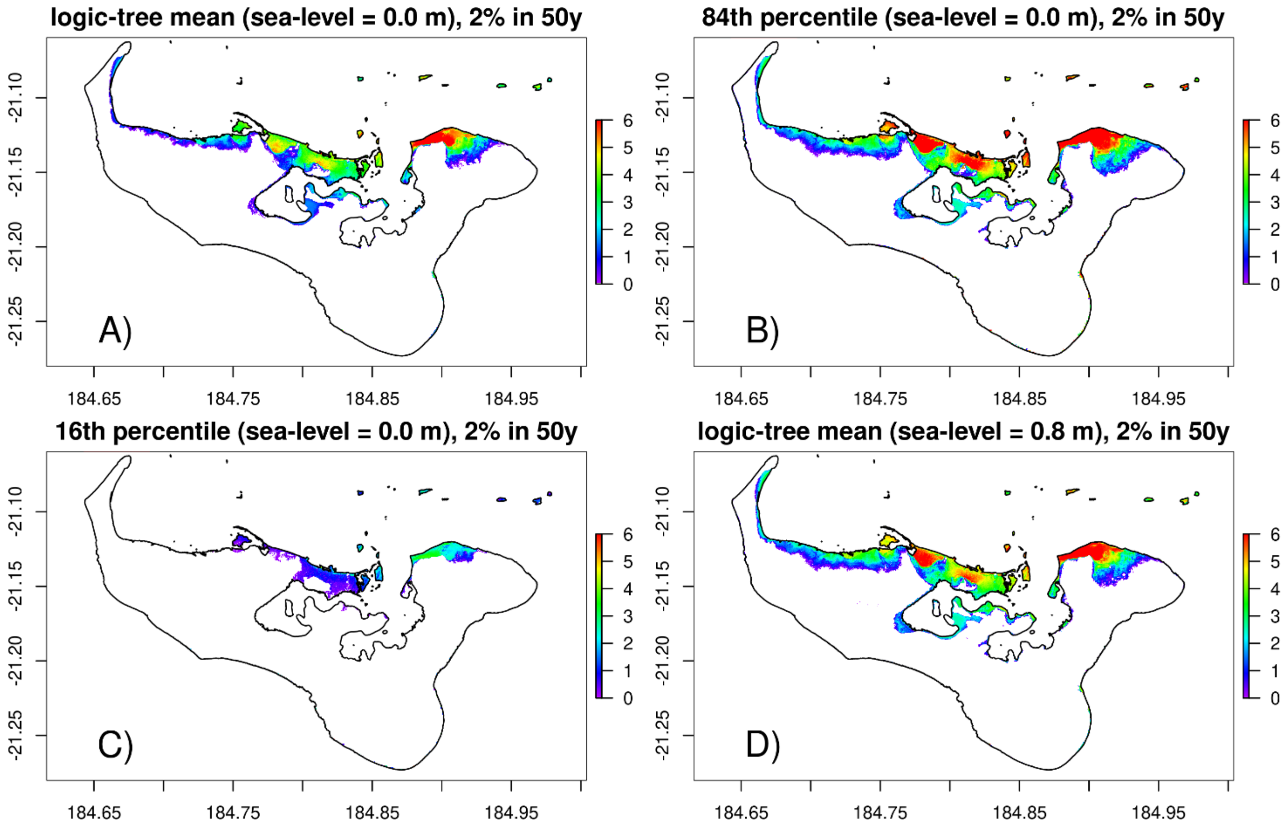


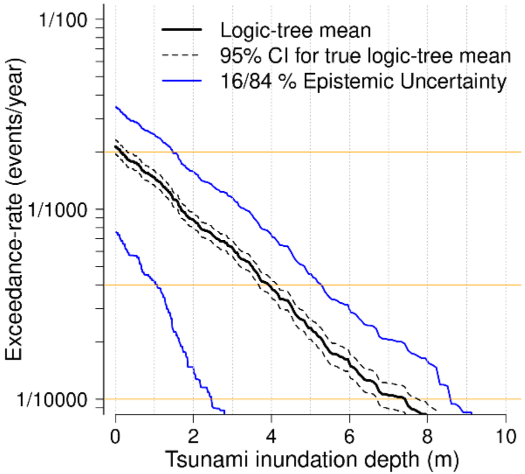
Sanity check: Do our results match PTHA18 offshore?





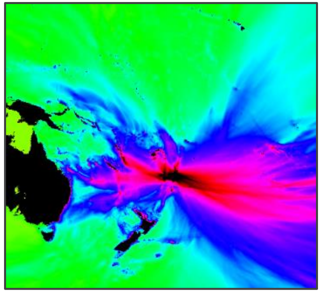
Results: Onshore hazards with quantified uncertainties

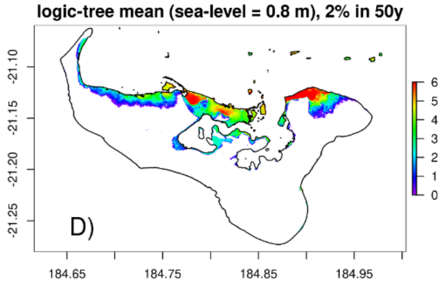


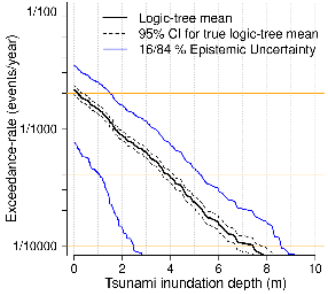


Summary

- **How to transform offshore PTHA into onshore hazard?**
  - **Monte-Carlo methods provide one approach**
    - Rigorous
    - Quantify uncertainties in the onshore hazard
      - Reflecting the offshore PTHA uncertainties
    - Tailor to particular site of interest for efficiency
- **Downsides of Monte-Carlo approach:**
  - More computationally expensive (vs scenario-based)
  - Is it worth it? Case-by-case decision.
    - Will the extra information by useful for your application?

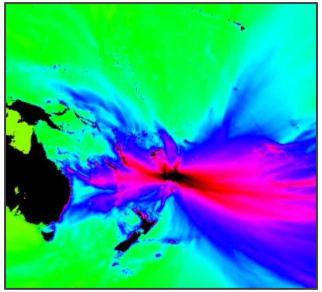


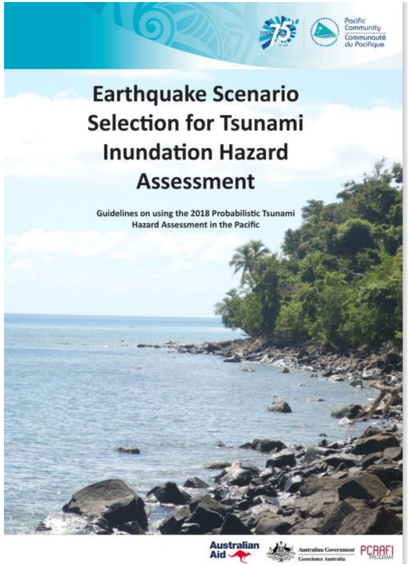




Don’t forget the other limitations!

- Tsunamis are also generated by non-earthquake sources!
- Inundation models are not perfect!
- PTHA18 (and other offshore PTHAs) are not perfect!
    - Significant testing at global scales
    - Limited testing at your specific site.
        - Compare to other information
            - Paleotsunami, historical record
    - <u>Expect the science to evolve over time.</u>
- Yet our guidelines should (largely) be applicable to future offshore PTHAs





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