Kartlegging av tsunamifaren gjennom numeriske simuleringer

Steven J Gibbons

(med stor takk til Carl B. Harbitz, Sylfest Glimsdal, Finn Løvholt, Erlend Briseid Storrøsten, Matthias Rauter ++)

- Why Numerical Simulation?
- Long-term Tsunami Hazard Assessment
- Urgent Tsunami Computing
- Landslide Tsunami Modelling

Oslo geofysikeres forening, 2022-11-15

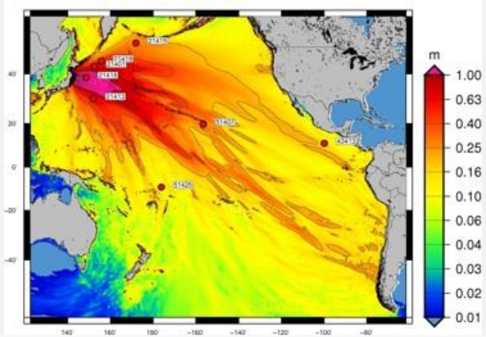
Tsunami sources, propagation, and inundation – from the global to the local scale

Banda Aceh, Sumatra, 2004
~230000 Fatalities

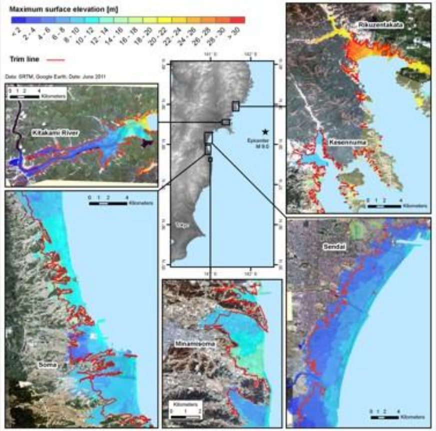
Japan tsunami 2011,
~20 000 dead or missing, huge economic losses

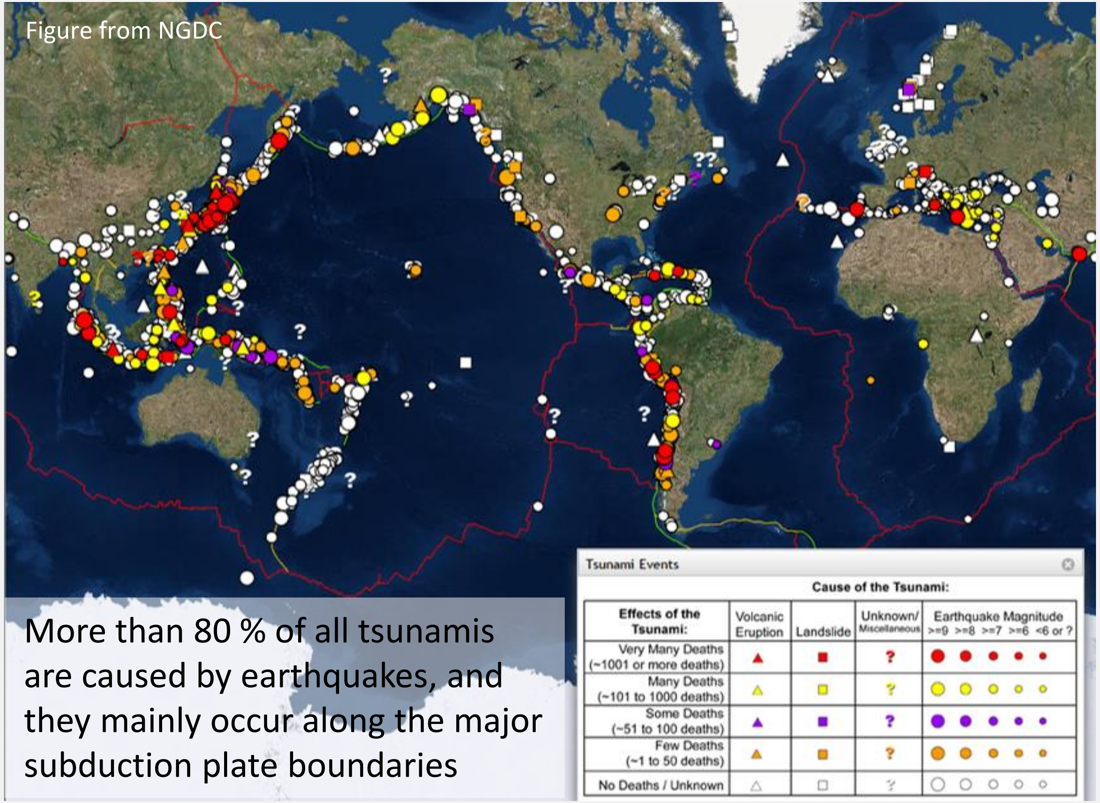
Tsunami sources, propagation, and inundation – from the global to the local scale

They propagate efficiently over the ocean



But the largest risk is associated with inundation from local sources





More than 80 % of all tsunamis are caused by earthquakes, and they mainly occur along the major subduction plate boundaries

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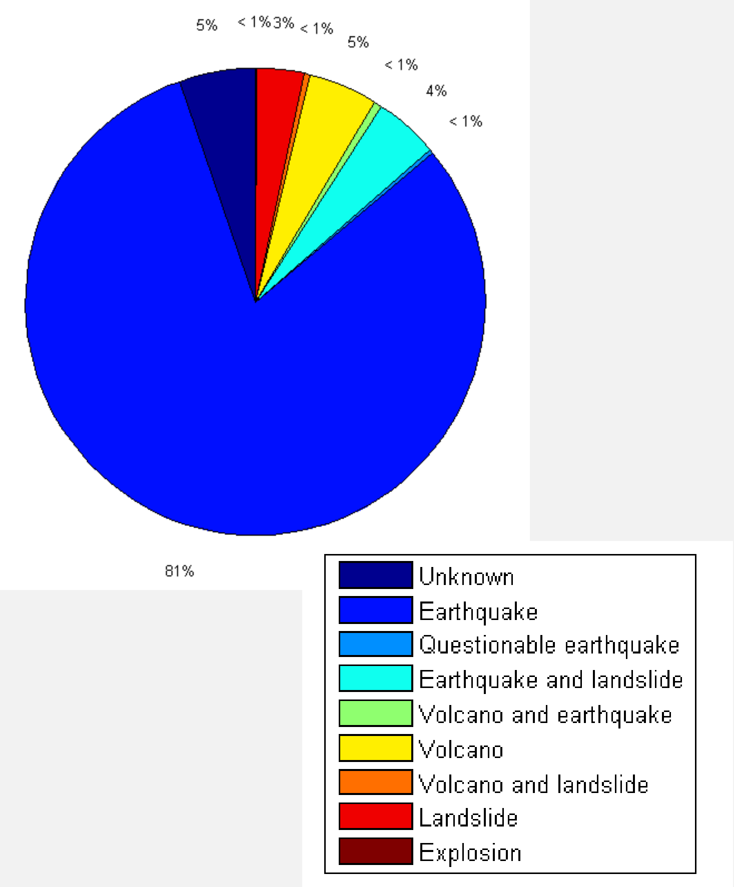
Landslide tsunamis make up a significant portion of the "global tsunami budget"

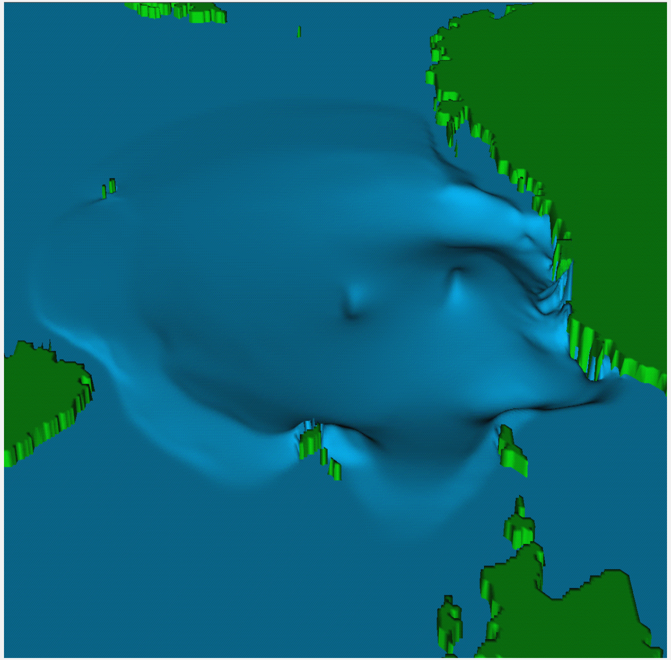
- Earthquakes comprise 80% of the reported sources, the rest by others such as landslides
- Landslides are often the dominating cause when combined with earthquake or volcano
- Likely cause for a majority of the "unknown" events
- Former events may have been underreported / ignored and historical frequencies likely too low



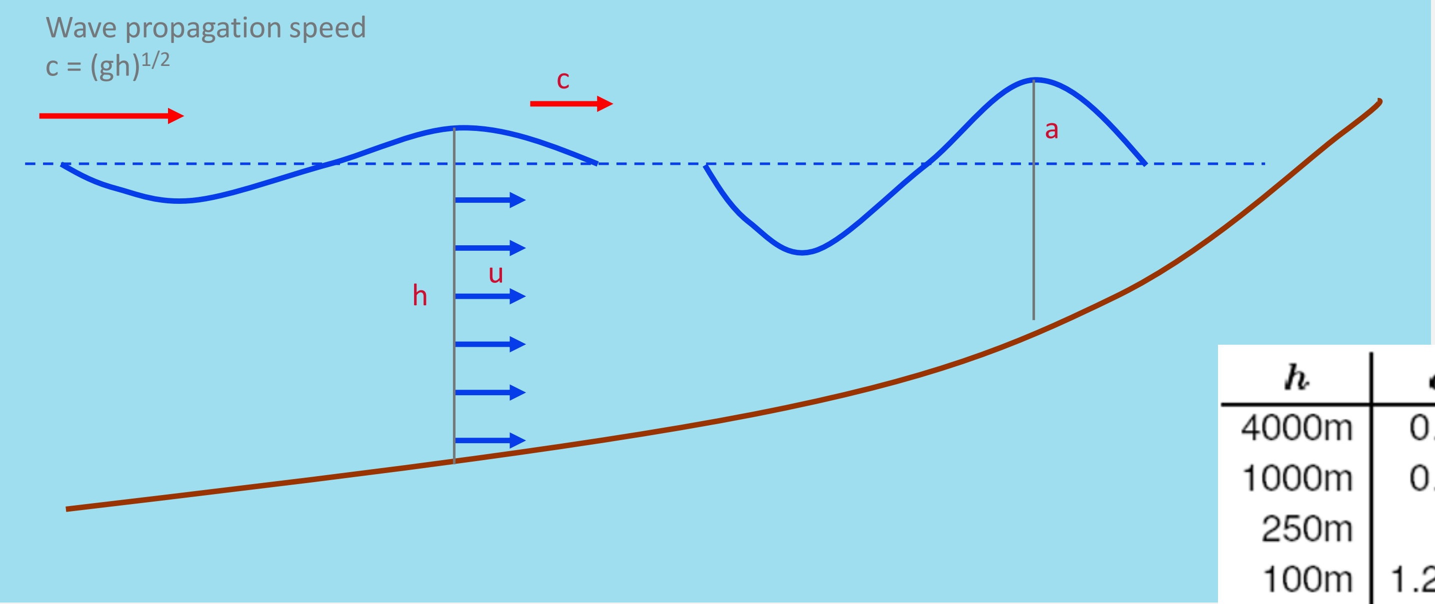
What is a tsunami?

Definition:

- Unusually large wave in a harbour (Japanese)
- Wave generated by huge and sudden displacement of water (e.g. earthquakes, slides, volcanoes, asteroids)
- Run-up heights from cms to hundreds of meters
- Wave period ~1-60 minutes



Tsunamis become shorter and higher when moving from the open sea into shallower waters

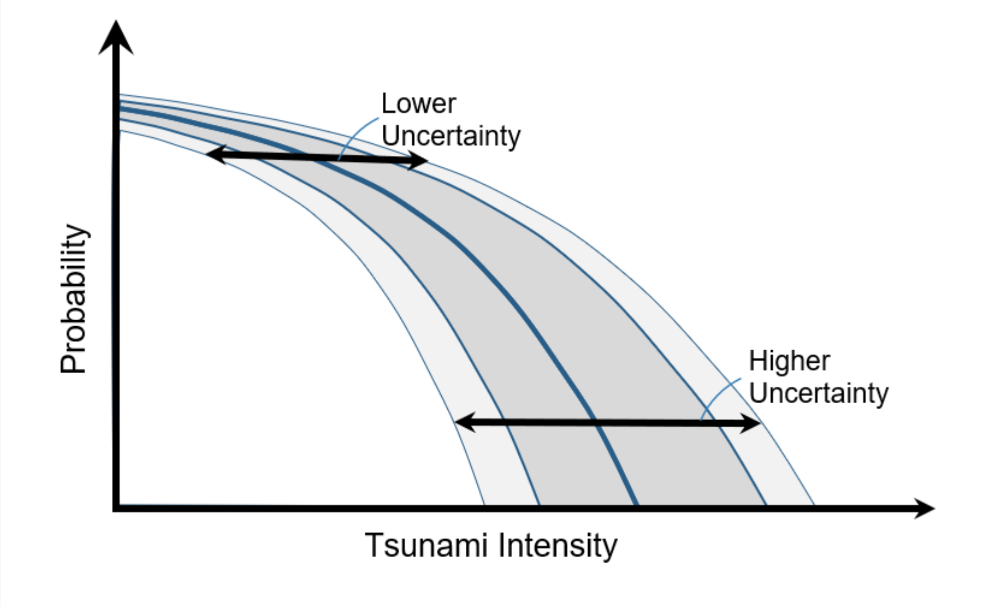


h	a	λ	c
4000m	0.5m	100km	713km/t
1000m	0.7m	50km	356km/t
250m	1m	25km	180km/t
100m	1.25m	16km	113km/t
50m	1.5m	11km	80km/t
20m	1.9m	7km	50km/t
10m	2.2m	5km	36km/t

Typical data for the 2004 Indian Ocean Tsunami →

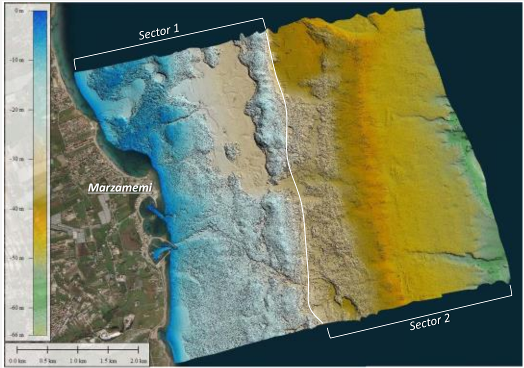
Probabilistic Tsunami Hazard Assessment

- PTHA: **Probability and uncertainty of exceeding a given metric of tsunami inundation at a given coastal location within a given time interval.**

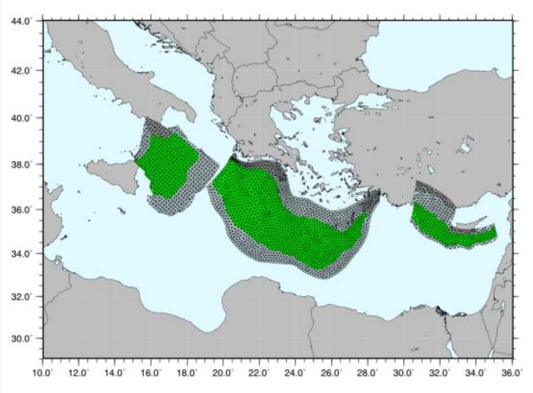


Examples of Stakeholders

- Insurance Premiums
- Emergency planning (evacuation routes)
- Coastal engineering (planning constraints)
- Civil protection (hazard zonation for emergency planning)

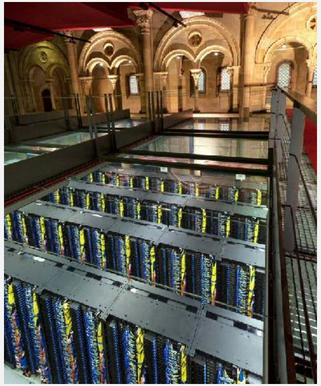


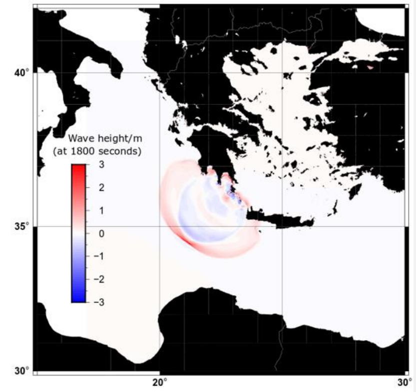
Probabilistic Tsunami Hazard Assessment



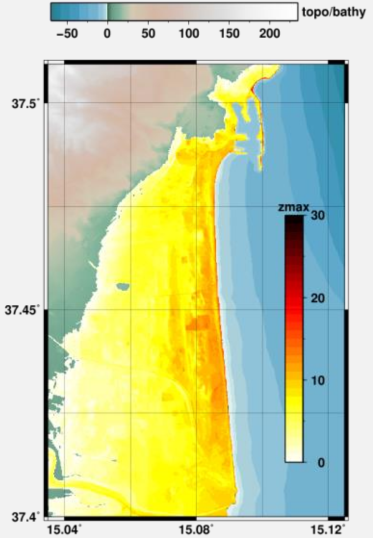
Earthquake tsunami sources (scenarios)

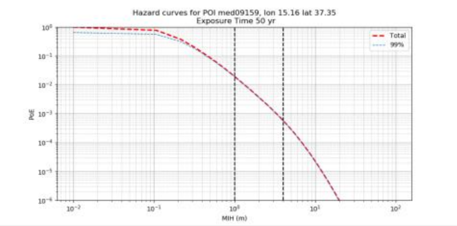
(HUGE discretization of earthquake sources – landslide-generated tsunamis will be considered later)





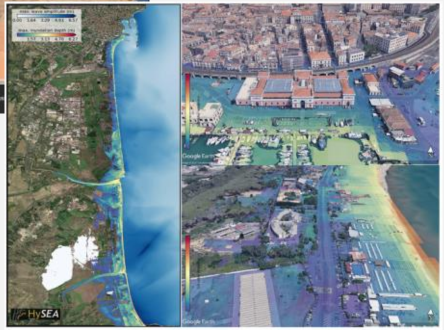
Tsunami simulation (HPC needed)



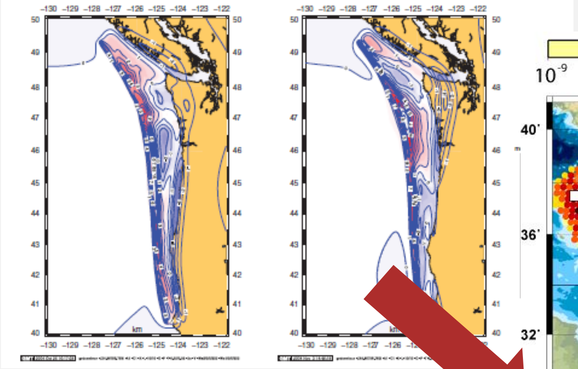


Inundation and Hazard calculation

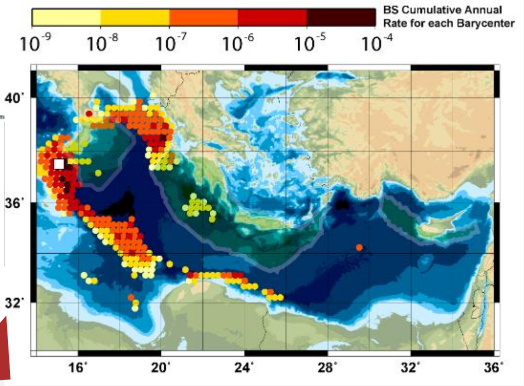
Probabilistic Tsunami Hazard Assessment



Gonzalez et al. 2009, JGR ~25 sources



Gibbons et al. 2020, Frontiers Earth Sci. ~33000 sources



- Increase from a handful of tsunami sources to 10^4-10^5 sources
- HPC can makes much more fine grain source uncertainty treatment possible
- Benchmark PTHA and understand how elaborate source uncertainty treatment needs to be

- ChEESE - high resolution inundation calculations - From regional to local hazard
- Local tsunami hazard based in the NEAM - future community service

ChEESE first project worldwide tackling this problem.

Synergies between HPC and geoscientists key

ChEESE
www.cheese-coe.eu
Center of Excellence for Exascale in Solid Earth

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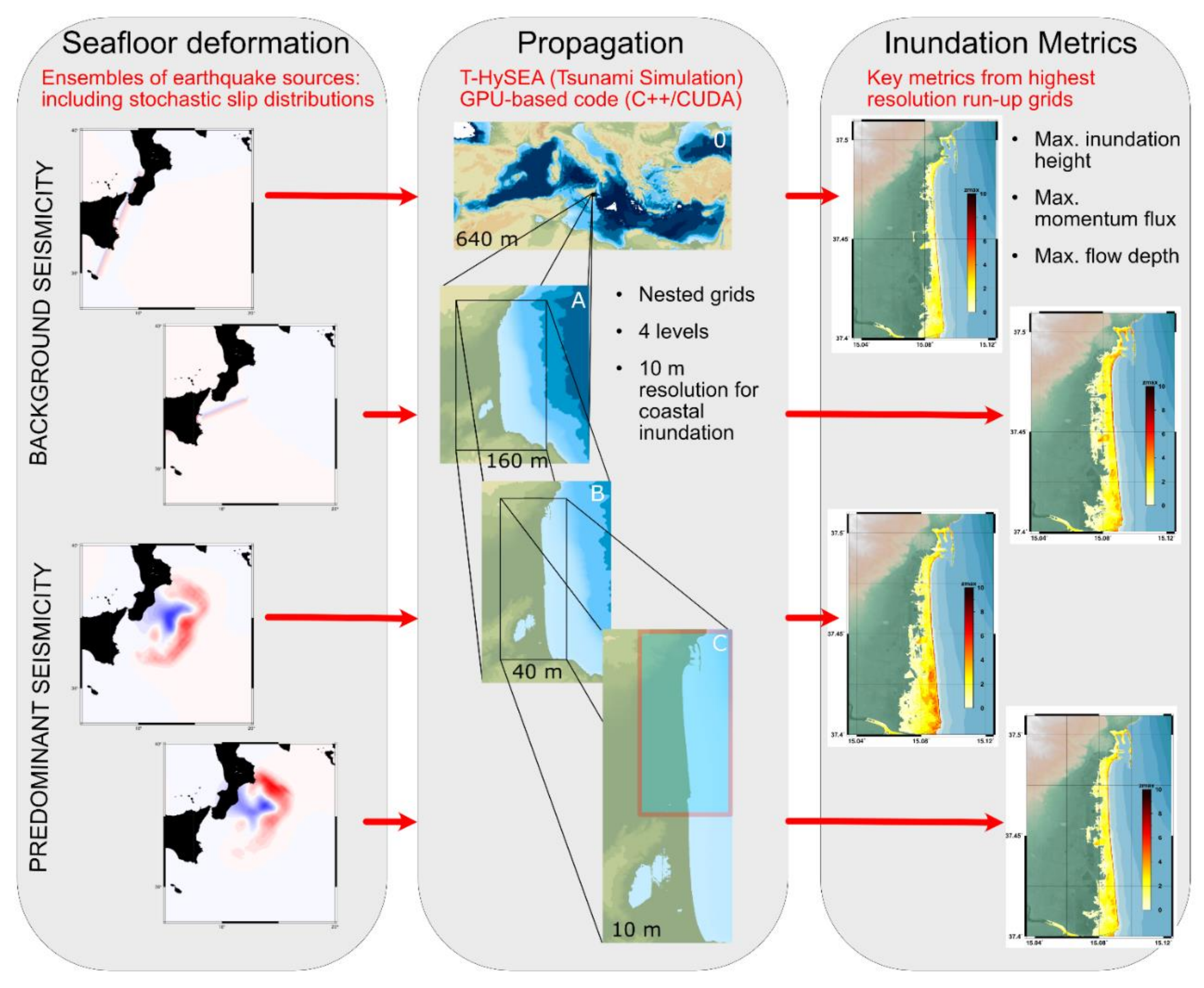

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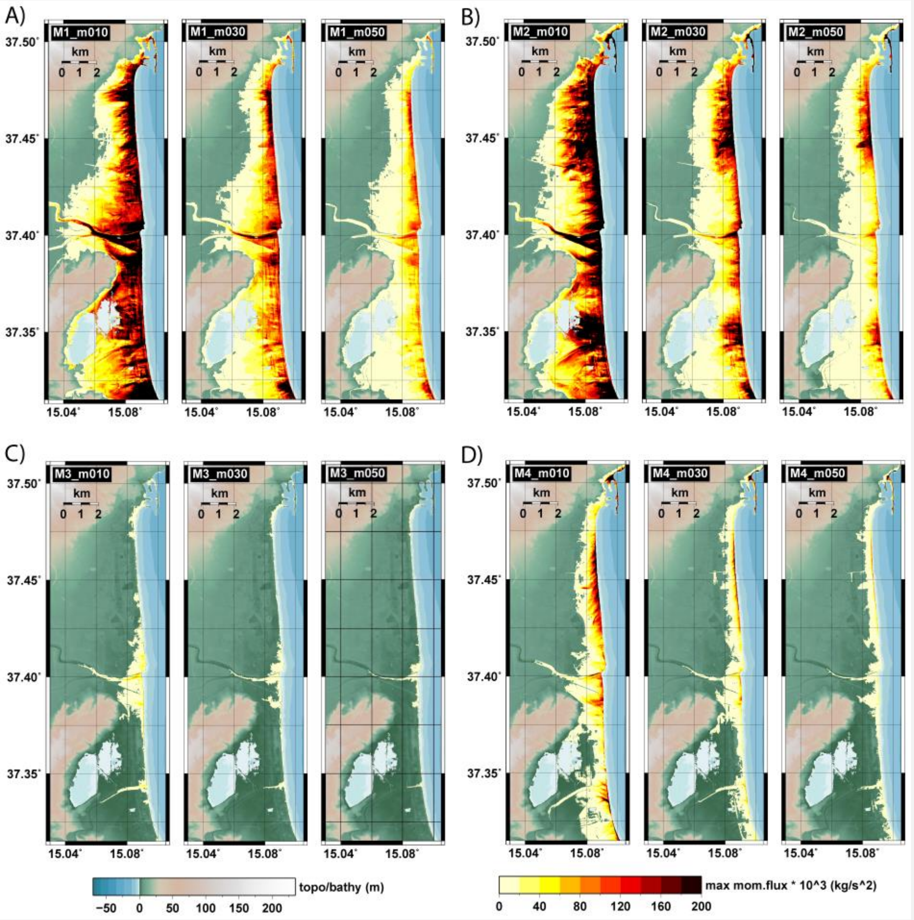
Probabilistic Tsunami Hazard Assessment

- We are not just increasing the resolution at which the simulations go – we are vastly increasing the number of simulations that can be performed.
- We can increase the number of (earthquake sources) – and explore how inundation depends upon model parameters.
- Right: how momentum flux varies for 4 different earthquakes for 3 different values of Manning friction …

Sensitivity to Model Parameters



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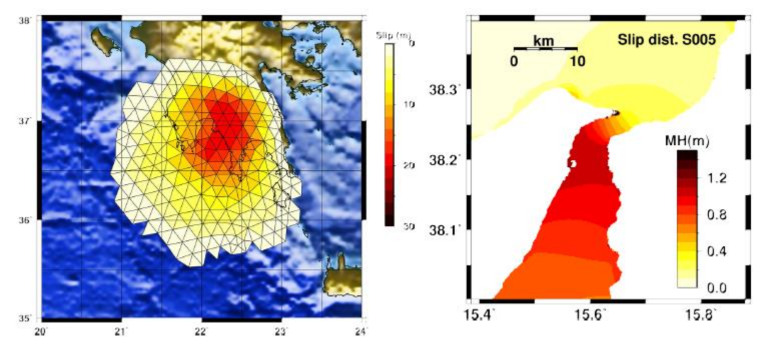
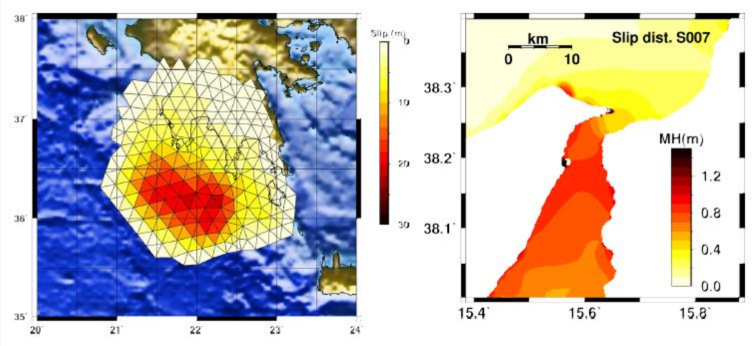
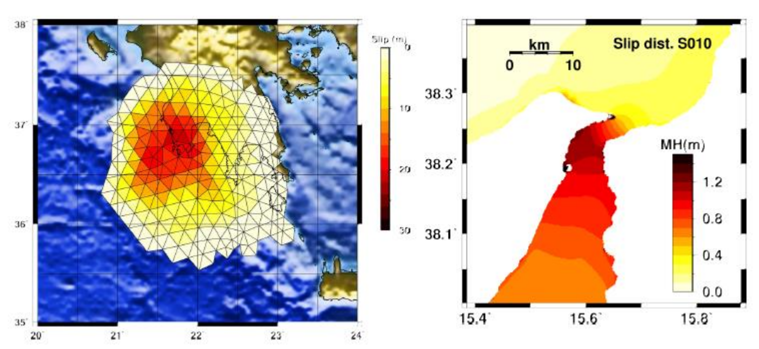
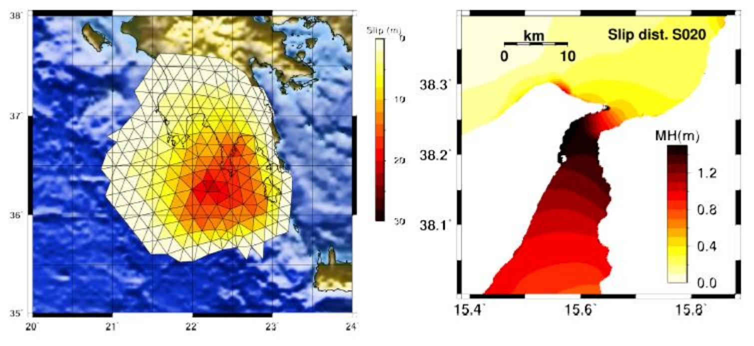
Probabilistic Tsunami Hazard Assessment



Sensitivity to Slip Distribution …

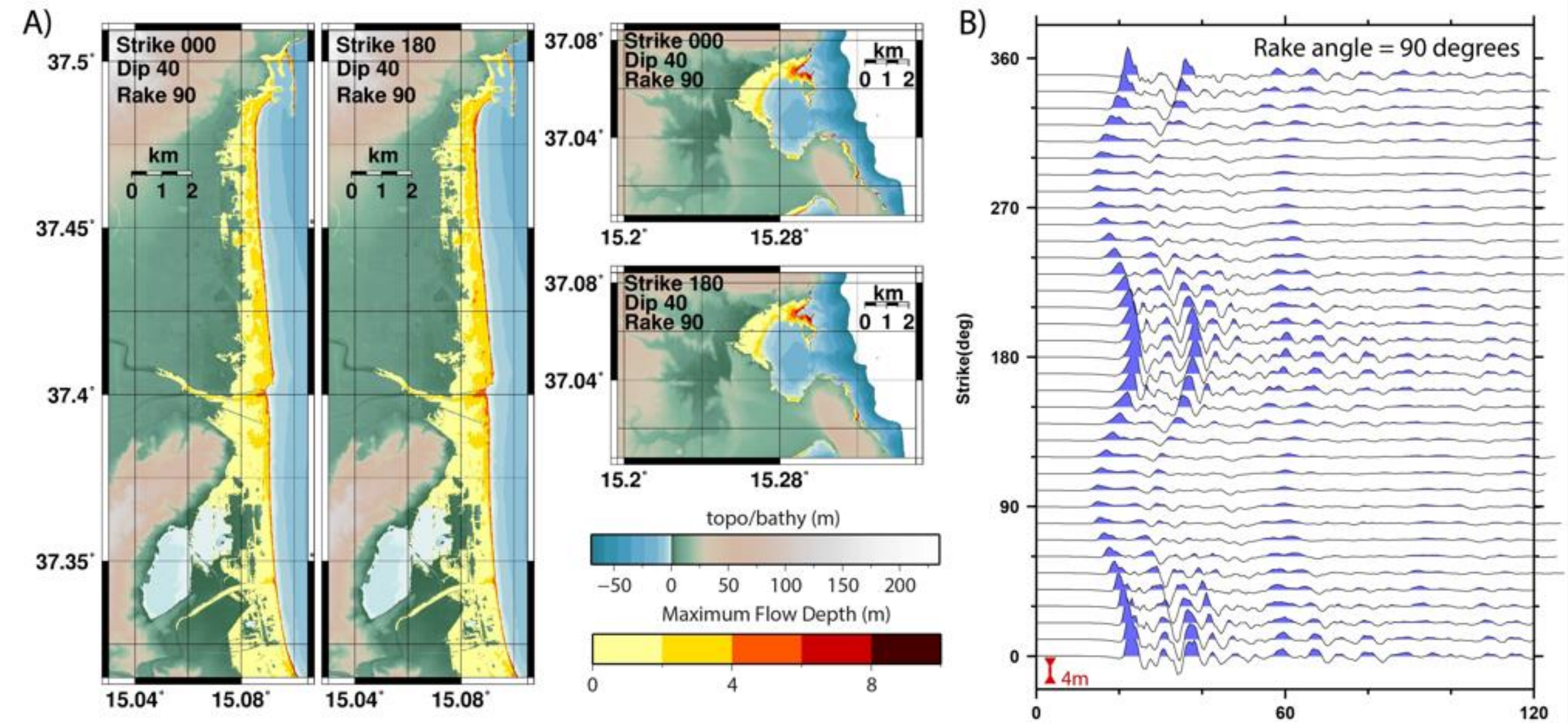






Each image shows a stochastic realization of a magnitude 8.2 subduction earthquake in the Hellenic Arc. The tsunami impact varies greatly!

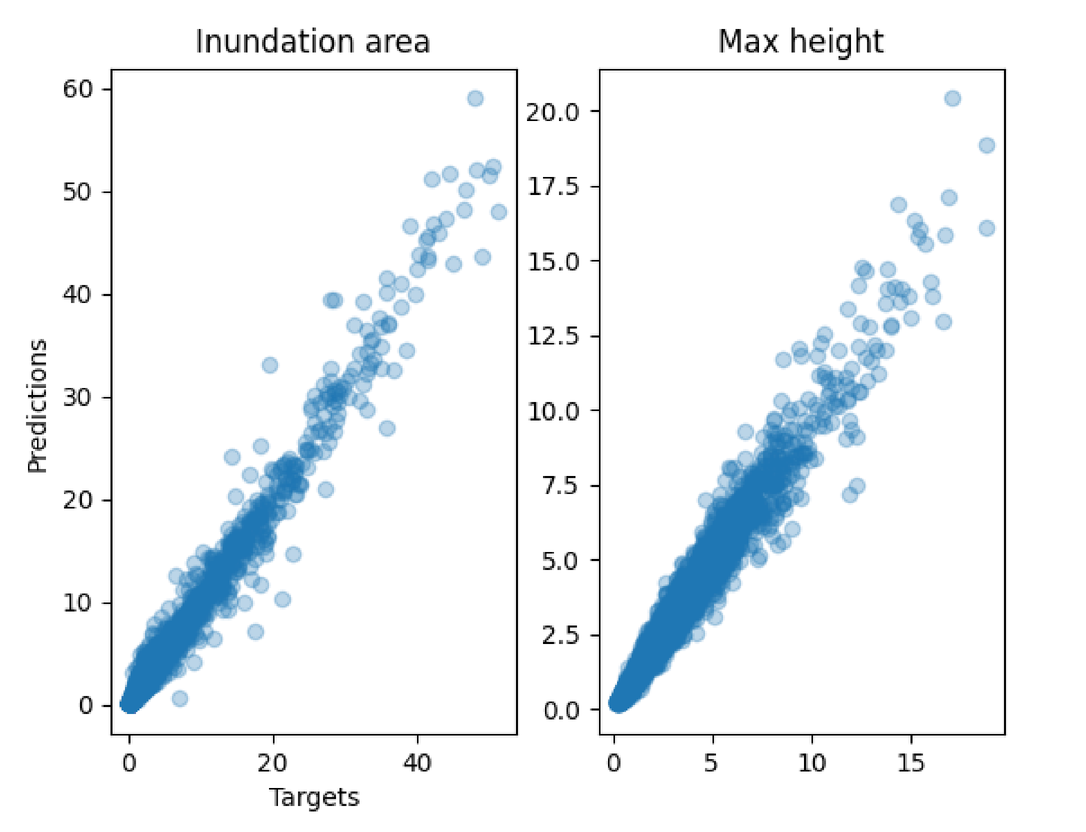
Probabilistic Tsunami Hazard Assessment



Application of Machine Learning to inundation prediction …

Probabilistic Tsunami Hazard Assessment

- Internal project in 2020 to predict inundations of metrics from offshore height measurements.
- Preliminary results are very encouraging but there are many unanswered questions and many more possibilities to explore.



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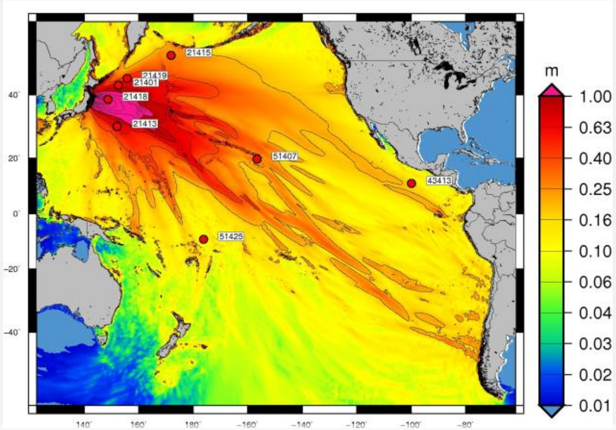
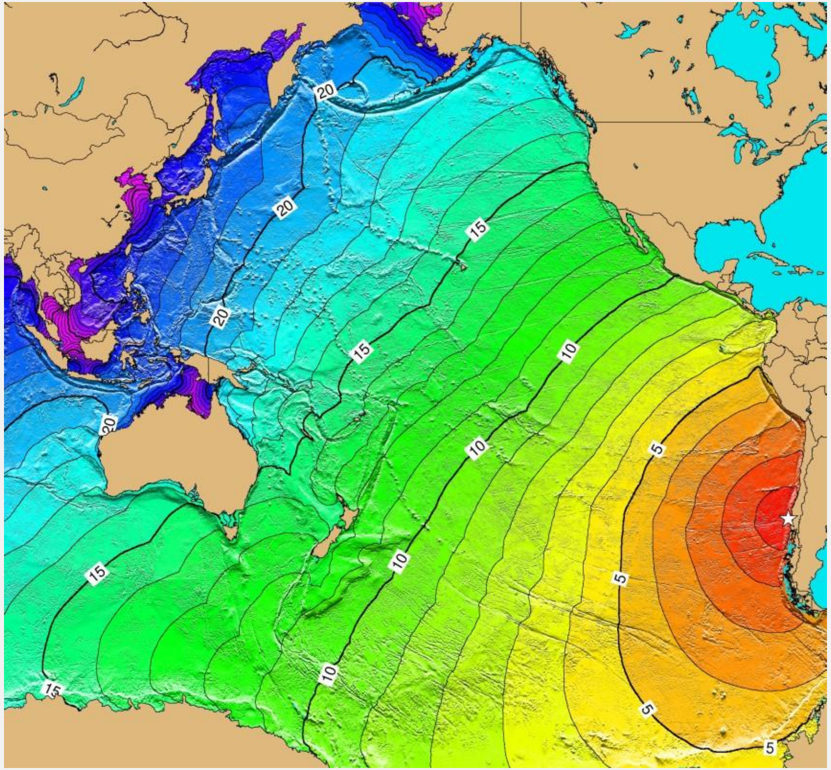
Probabilistic Tsunami Forecast

- Tsunami Warning Centers need to issue alerts following large earthquakes.
- Alerts need to be as accurate as possible: (As few false alarms as possible!)
- Alerts need to happen fast – but at the start there is much uncertainty about the source …



Tohoku 2011 tsunami (Løvholt et al., 2012)



Above: Travel time (hours)

Figure from NGDC/NOAA

Left: Complexity of propagation: focusing

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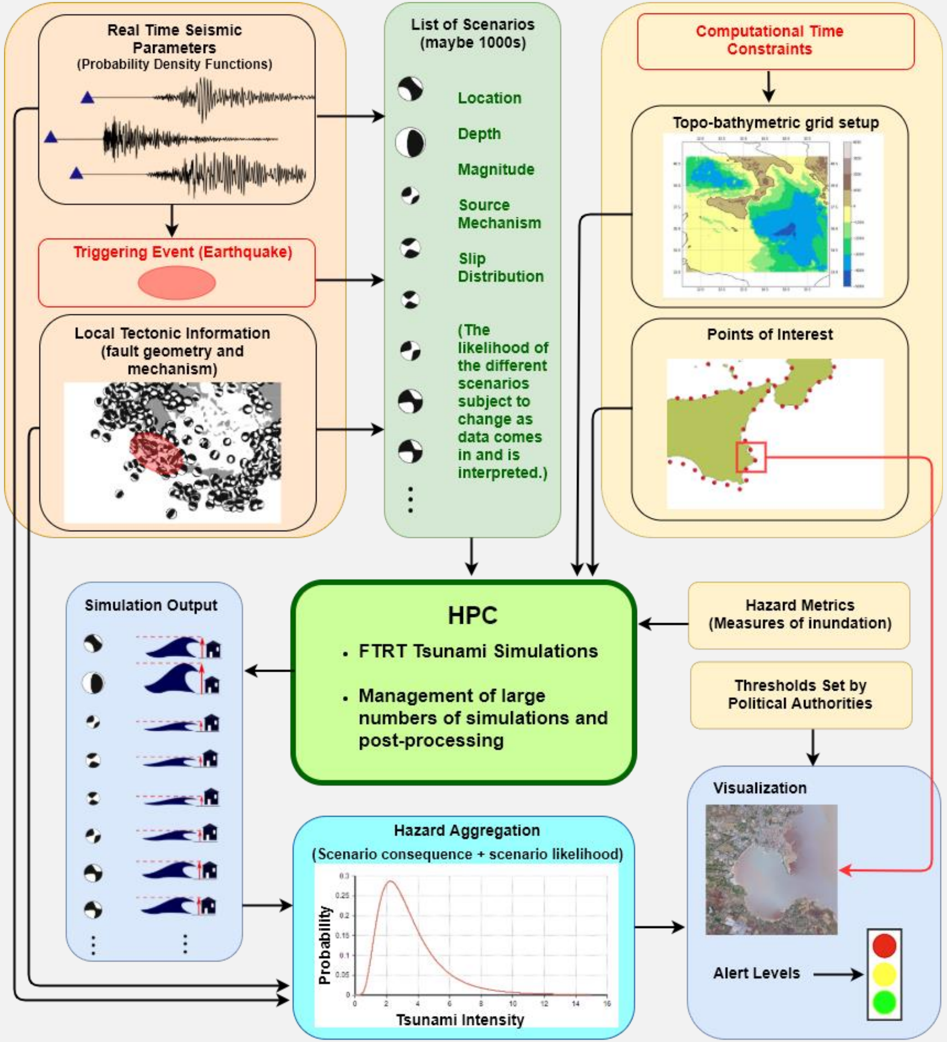
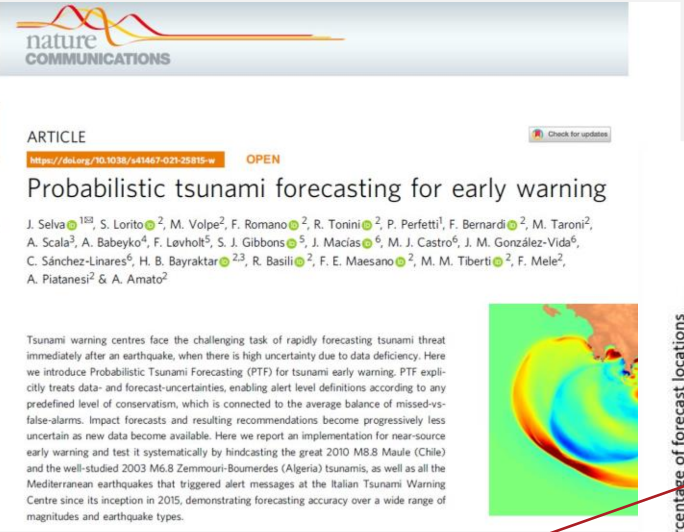
Probabilistic Tsunami Forecast

- PTF forecasts the outcome of a tsunami accounting for source uncertainties
- Use Faster Than Real Time tsunami simulations and a very large number of alternative models for the source.
- Provide real-time input for rational decision making.
- Future work flows will include real-time observational data (e.g. seismic, tide gauge) to modify probabilities.
- Example of **Urgent HPC**
- Relevance to other Natural Hazards obvious – but applications are less mature



Probabilistic Tsunami Forecast


ARTICLE

https://doi.org/10.1038/s41467-021-25815-w OPEN

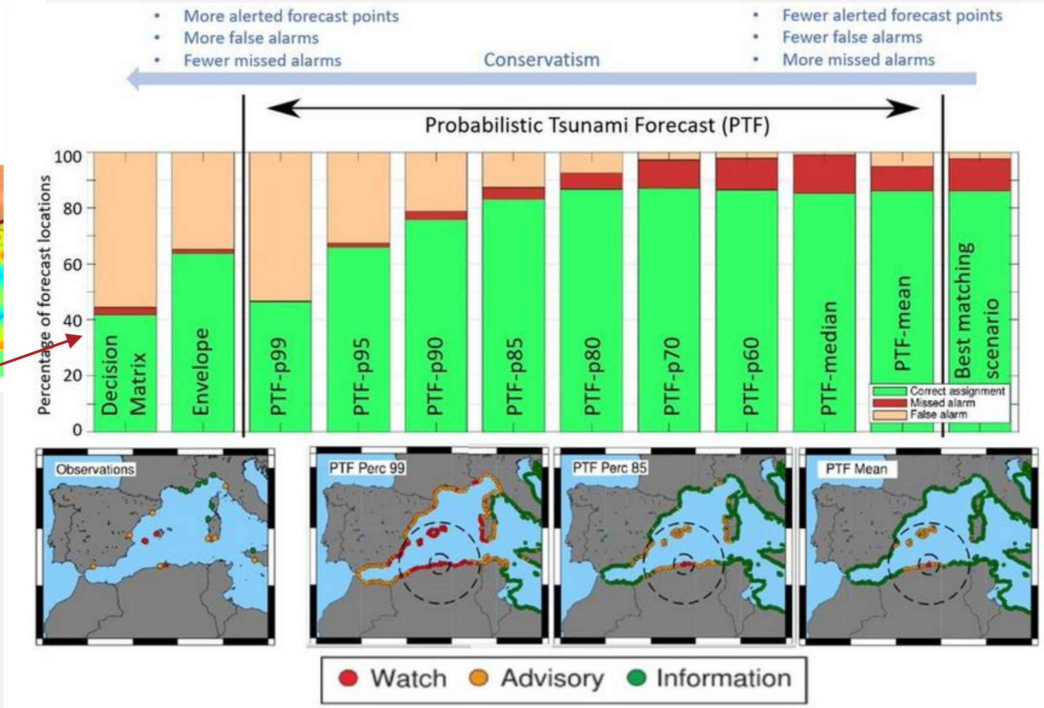
Check for updates

Probabilistic tsunami forecasting for early warning

J. Selva[1], S. Lorito[2], M. Volpe[2], F. Romano[2], R. Tonini[2], P. Perfetti[1], F. Bernardi[2], M. Taroni[2], A. Scala[3], A. Babeyko[4], F. Løvholt[5], S. J. Gibbons[5], J. Macías[6], M. J. Castro[6], J. M. González-Vida[6], C. Sánchez-Linares[6], H. B. Bayraktar[2,3], R. Basili[2], F. E. Maesano[2], M. M. Tiberti[2], F. Mele[2], A. Piatanesi[2] & A. Amato[2]

Tsunami warning centres face the challenging task of rapidly forecasting tsunami threat immediately after an earthquake, when there is high uncertainty due to data deficiency. Here we introduce Probabilistic Tsunami Forecasting (PTF) for tsunami early warning. PTF explicitly treats data- and forecast-uncertainties, enabling alert level definitions according to any predefined level of conservatism, which is connected to the average balance of missed-vs-false-alarms. Impact forecasts and resulting recommendations become progressively less uncertain as new data become available. Here we report an implementation for near-source early warning and test it systematically by hindcasting the great 2010 M8.8 Maule (Chile) and the well-studied 2003 M6.8 Zemmouri-Boumerdes (Algeria) tsunamis, as well as all the Mediterranean earthquakes that triggered alert messages at the Italian Tsunami Warning Centre since its inception in 2015, demonstrating forecasting accuracy over a wide range of magnitudes and earthquake types.

- Current system:
  Decision Matrix
  Conservative thresholds for safety factors mean many false alarms.



Partnere: 1) Istituto Nazionale di Geofisica e Vulcanologia, Le Grazie, 2) Italy, Department of Physics "Ettore Pancini", University of Naples, Naples, Italy, 3) German Research Centre for Geosciences (GFZ), Potsdam, Germany, 4) Norwegian Geotechnical Institute (NGI), Oslo, Norway, 5) Grupo EDANYA, Universidad de Málaga, Málaga, Spain.

Modelling the Storegga slide

Paleobathymetry from Hill et al. (2014) 10.1016/j.ocemod.2014.08.007
We gratefully acknowledge the use of this model.

- We perform numerical simulations of the landslide and resulting tsunami.
- We apply the paleobathymetry from Hill et al. (2014) *(Ocean Modelling v.83, pp11-25)*

ELSEVIER
Ocean Modelling
Volume 83, November 2014, Pages 11-25

How does multiscale modelling and inclusion of realistic palaeobathymetry affect numerical simulation of the Storegga Slide tsunami?

Jon Hill [a, c], Gareth S. Collins [a, 1], Alexandros Avdis [a, 1], Stephan C. Kramer [a, 1], Matthew D. Piggott [a, b, 1]

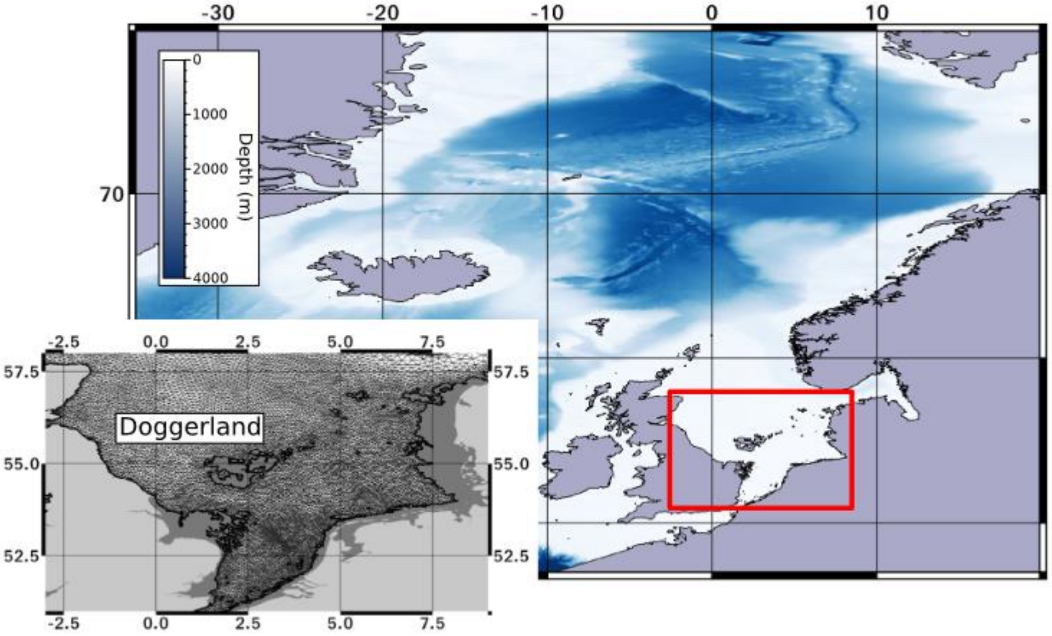


Fig. 1. Bathymetry and coastline used for the simulations using palaeobathymetry (top). A close-up of the east coast of the UK is shown (bottom), including the island known as "Doggerland", where an overlay of the production mesh used in this study is also shown. Shading shows water depth with darker shades indicating deeper water. For the insert the modern coastline is also shown (light grey) over the palaeo-coastline (dark grey).

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Modelling inundation from the Storegga slide is performed in 3 different stages:

Landslide Material Control on Tsunami Genesis—The Storegga Slide and Tsunami (8,100 Years BP)

Jihwan Kim[1,2], Finn Løvholt[1], Dieter Issler[1], and Carl Fredrik Forsberg[1]

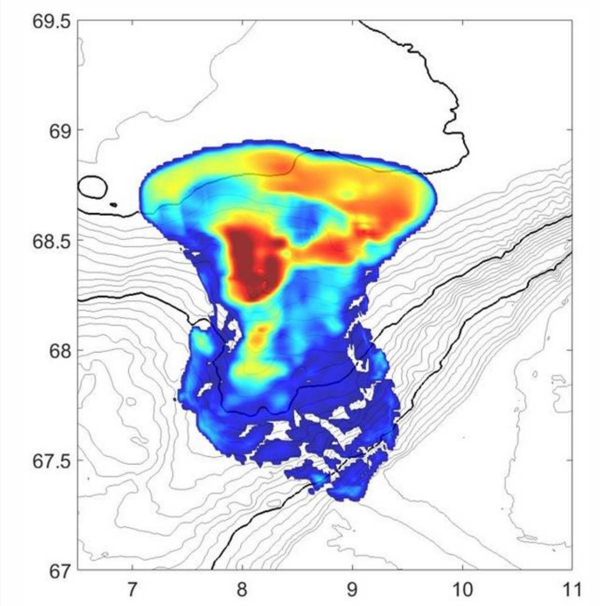
[1]Norwegian Geotechnical Institute, Oslo, Norway, [2]Department of Mathematics, University of Oslo, Oslo, Norway

JGR Oceans

RESEARCH ARTICLE

10.1029/2018JC014893

- 1) Modelling the landslide
  - BingClaw: Simulates the dynamics of cohesive landslides
  - https://www.ngi.no/eng/Services/Technical-expertise/Tsunamis/Model-for-simulating-dynamics-of-cohesive-landslides



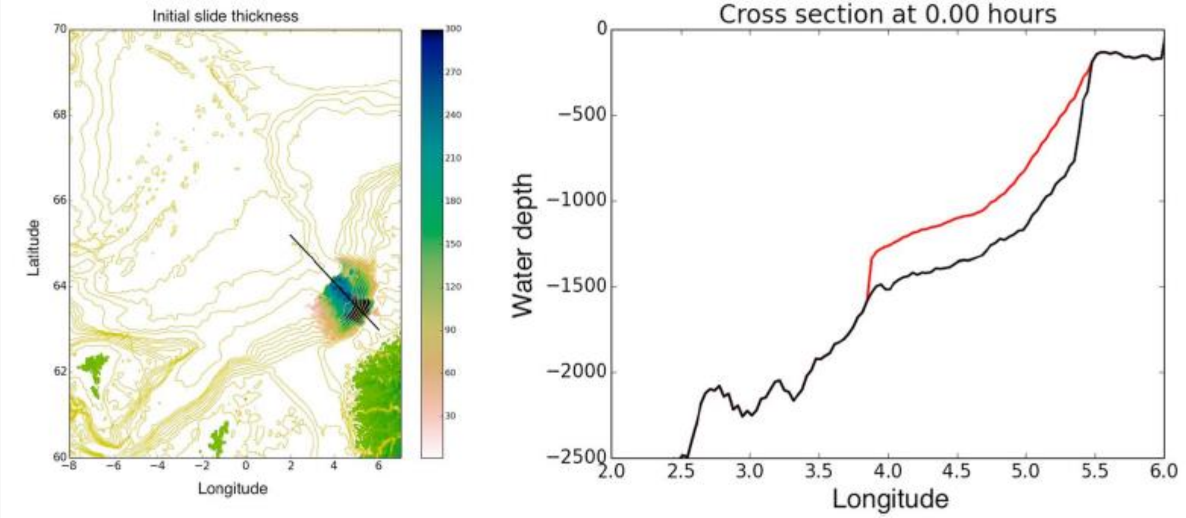


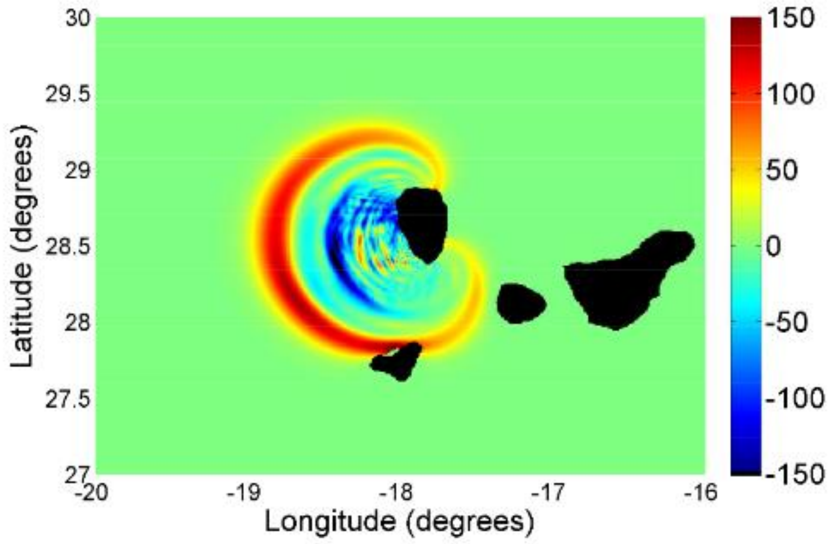
Figure 4. Assumed initial shape of the Storegga Slide simulations with BingClaw: release height distribution (left panel) and longitudinal section (right panel) along the black line in the left panel.

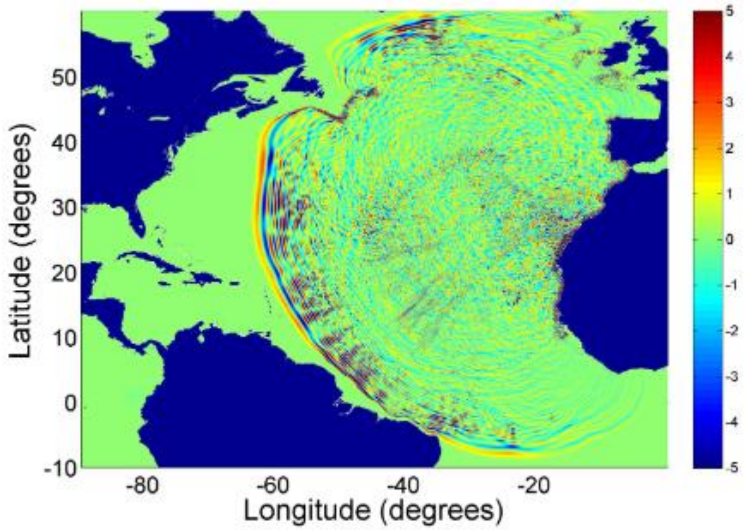
Modelling inundation from the Storegga slide is performed in 3 different stages:

- 2) Modelling the tsunami

GloBouss: Simulates oceanic tsunami propagation given a dynamically changing seafloor

https://github.com/geirkp/geirkp.github.io/tree/master/bouss



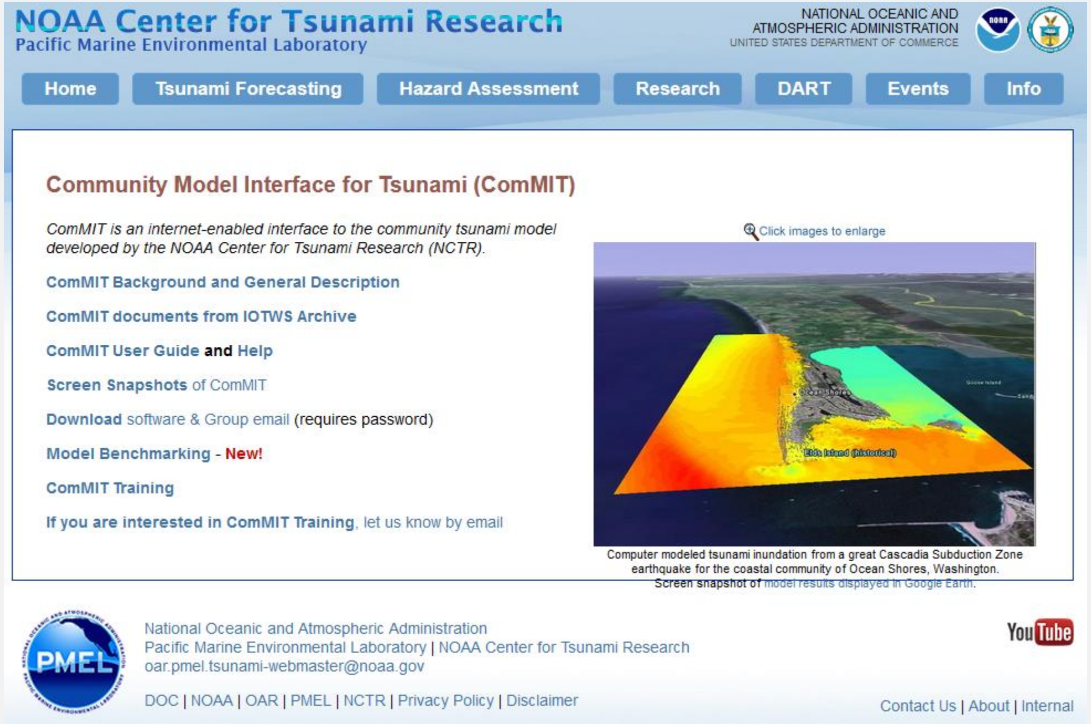


Modelling inundation from the Storegga slide is performed in 3 different stages:

- 3) Modelling the inundation

  MOST/ComMIT(NOAA): Simulates inundation at high resolution

  https://nctr.pmel.noaa.gov/ComMIT/



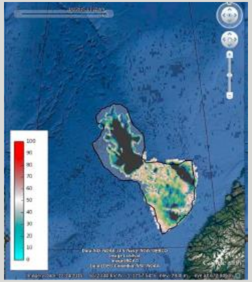
- Uses nested or «telescopic» grid to model the behaviour of the tsunami on and close to the shoreline.

Modelling inundation from the Storegga slide is performed in 3 different stages:

Stage 1: Landslide

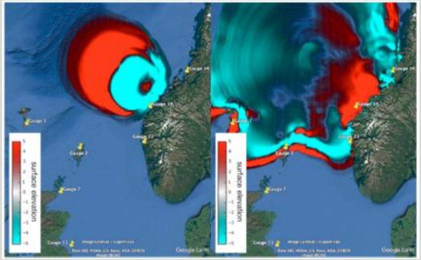
Large number of parameters controlling run-out

- Densities
- Hydrodynamic drag
- Yield strength
- Remolding



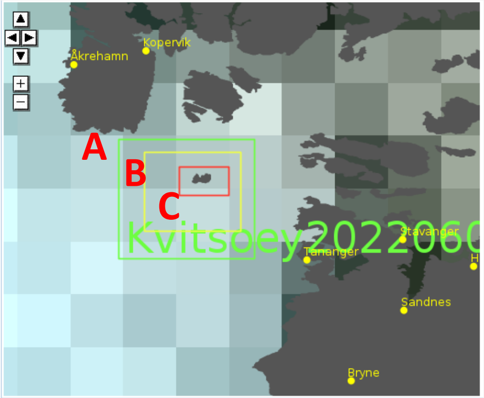
Output:
Sea floor heights as a function of time

Stage 2: Tsunami («global»)

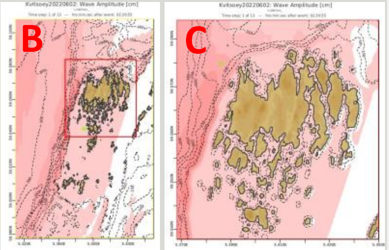


Output:
Sea surface heights and wave velocities as a function of time

Select coastline of interest:



Stage 3: Tsunami («local»)



Modelling inundation from the Storegga slide is performed in 3 different stages:

- 1) Modelling the landslide

  BingClaw: Simulates the dynamics of cohesive landslides

- There are many variables controlling the volume, duration, runout, and dynamics of the slide.
- We need to perform a sensitivity study on the controlling parameters and find what best agrees with observations.

We need validation!

- Validation by comparison with bathymetric runout observations
- Validation (when combined with tsunami simulation) of run-up heights.

Modelling inundation from the Storegga slide is performed in 3 different stages:

- 1) Modelling the landslide: validation by runout

  BingClaw: Simulates the dynamics of cohesive landslides

(from Kim et al: https://doi.org/10.1029/2018JC014893

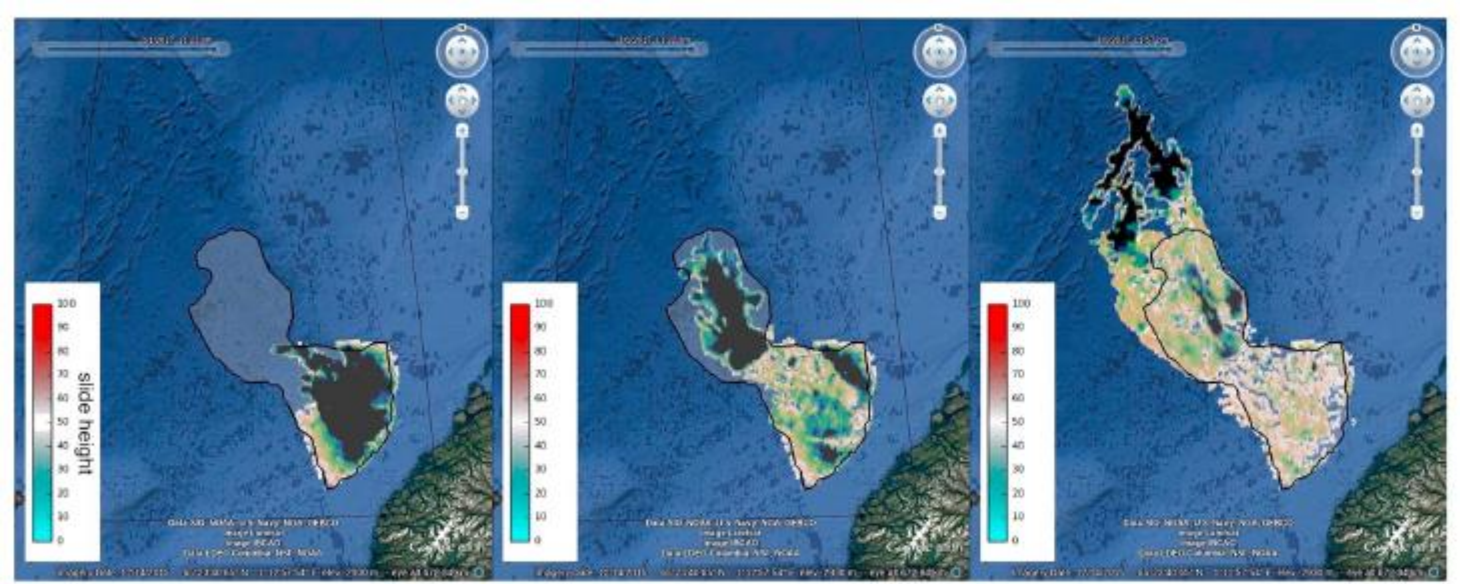


Figure 6. Final runout of the Storegga slide for three cases, simulated with BingClaw: $(\tau_{y,0}, \tau_{y,\infty}, \Gamma) = (15\,\text{kPa}, 3.5\,\text{kPa}, 5 \times 10^{-5})$, $(12\,\text{kPa}, 3\,\text{kPa}, 5 \times 10^{-4})$, and $(7\,\text{kPa}, 1\,\text{kPa}, 5 \times 10^{-2})$ (from left to right). The deposit inferred from the bathymetric analysis is indicated by the black line.

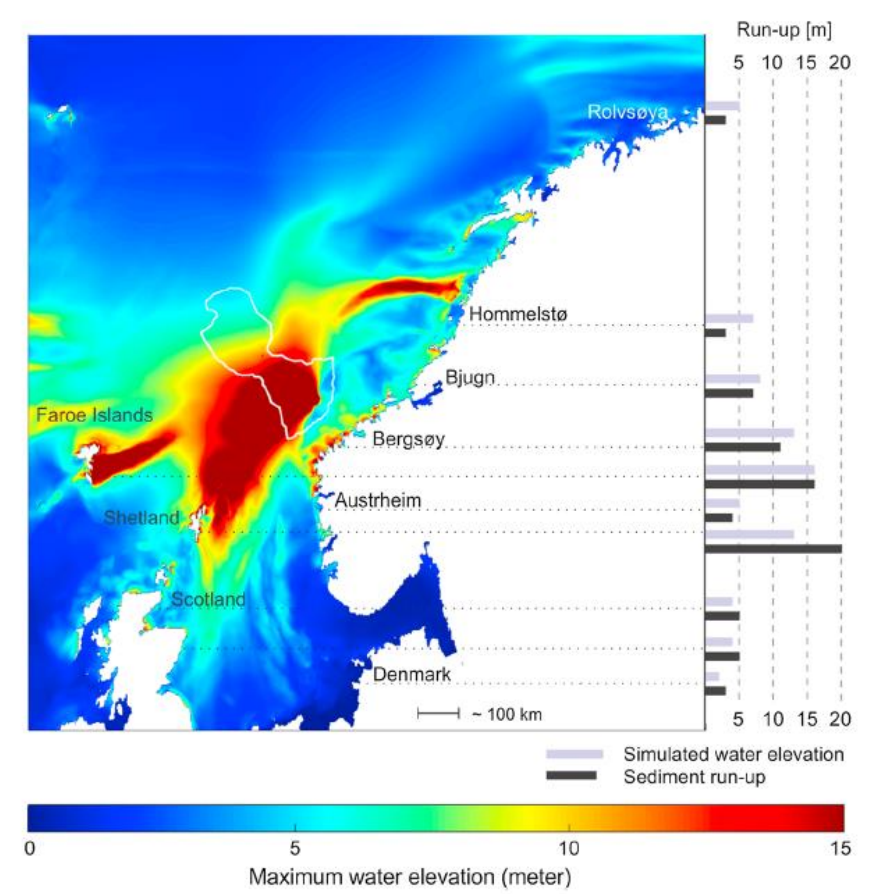
Modelling inundation from the Storegga slide is performed in 3 different stages:

- 1) Modelling the landslide:
  validation by tsunami run-up comparison

  - There are run-up observations and numerous coastal locations along the affected coastlines.
  - A coupled landslide-tsunami model provides time-series of wave-heights for specified locations and we can evaluate which models best fit the observations.

(from Løvholt et al: https://doi.org/10.1002/2017GL074062)

Figure 3. Maximum water elevation for the Storegga Slide tsunami, simulated using the debris flow landslide source. Blue-purple bars show the simulated elevations close to the field sites, black bars show the mean observation heights of sediment run-up [*Smith et al.*, 2004; *Bondevik et al.*, 2005; *Romundset and Bondevik*, 2011; *Fruergaard et al.*, 2015].



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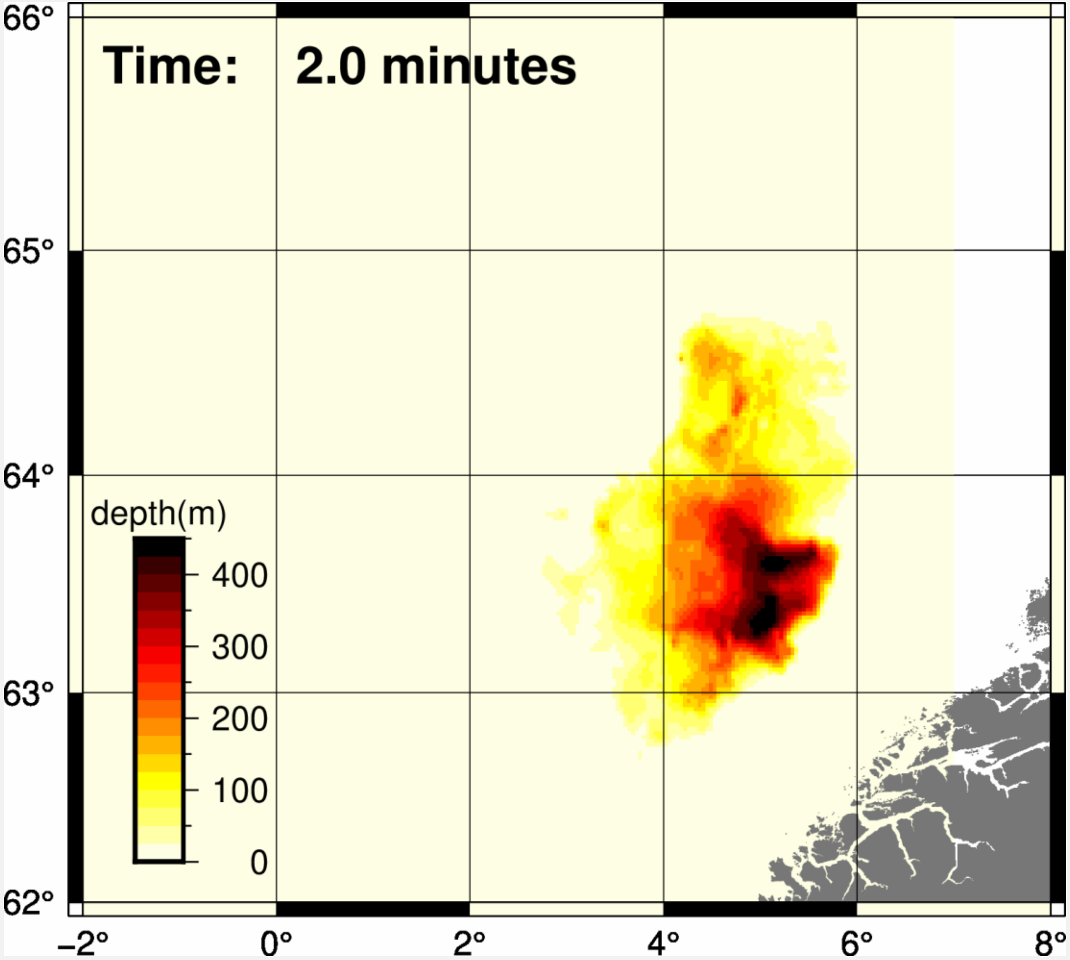
Modelling inundation from the Storegga slide is performed in 3 different stages:

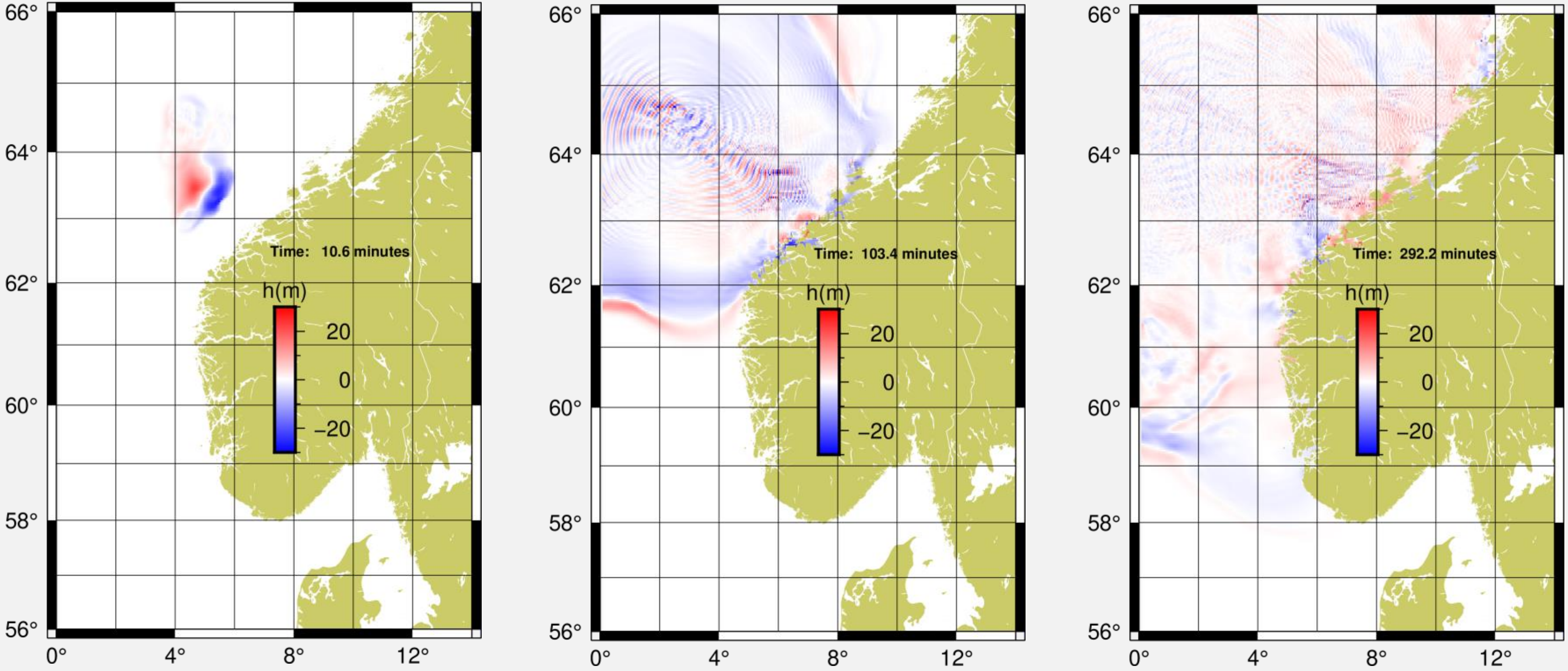
- 1) Modelling the landslide:
  - Visco-plastic landslide model.
  - Writes out height of deposit at regular intervals.
  - This changing sea-floor forces the wave-motion in the tsunami simulation.



Modelling inundation from the Storegga slide is performed in 3 different stages:

- 2) Modelling the tsunami

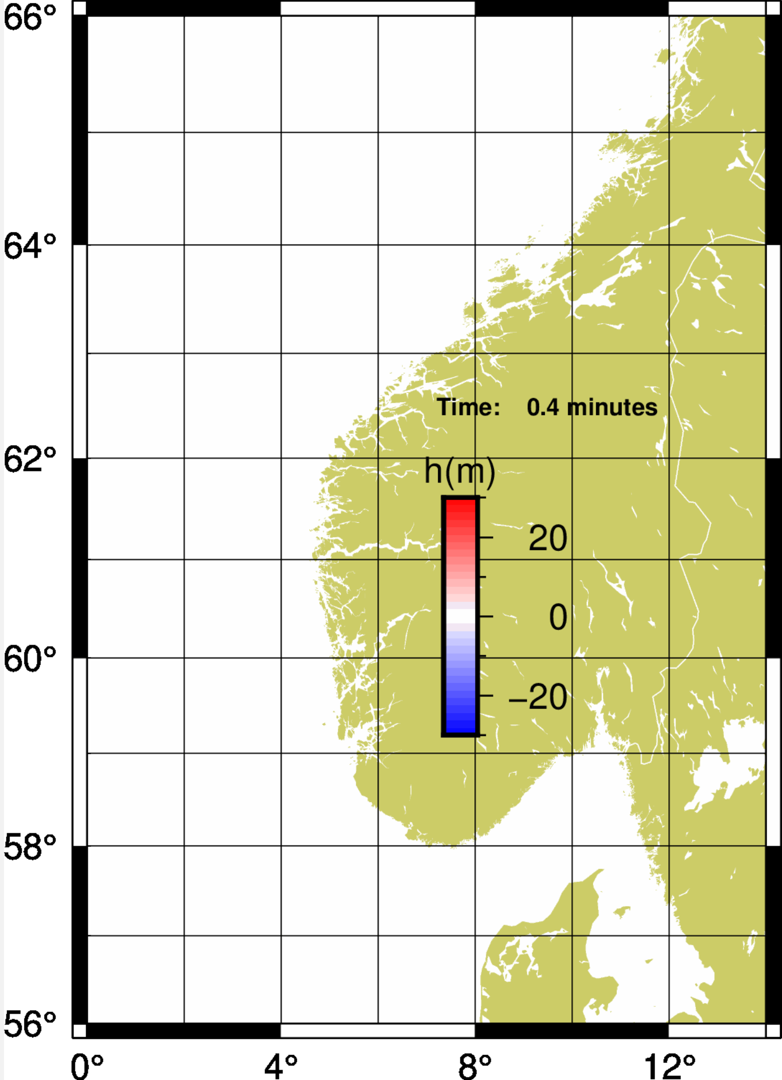
GloBouss: Simulates oceanic tsunami propagation given a dynamically changing seafloor



2) Modelling the tsunami

GloBouss: Simulates oceanic tsunami propagation given a dynamically changing seafloor

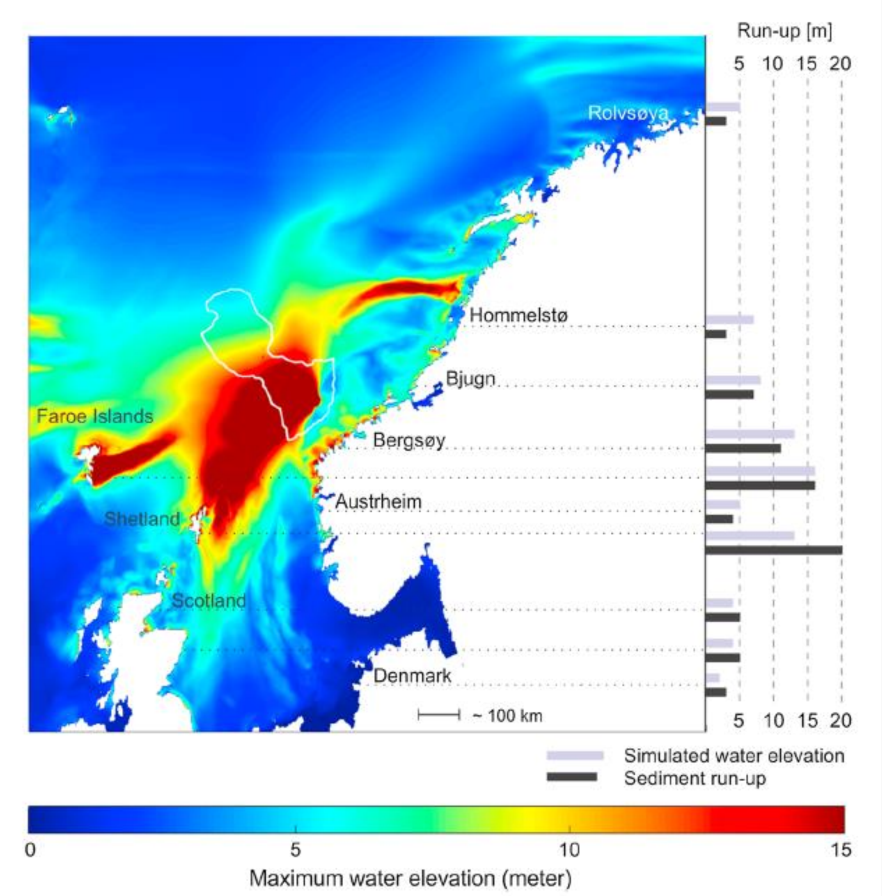
- Approximately 3 hours from the slide initiation are displayed in this animation.
- Notice that the first motion is dominated by very long waves.
- The speed and height of the wavefront varies significantly with direction.



2) Modelling the tsunami

GloBouss: Simulates oceanic tsunami propagation given a dynamically changing seafloor

- We can also calculate the maximum water elevation for all locations and the maximum flow velocities.
- The velocities – and/or the momentum flux – can often be a more pertinent metric of the tsunami impact than the height alone.



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Under Pressure:

Modelling inundation from the Storegga slide is performed in 3 different stages:

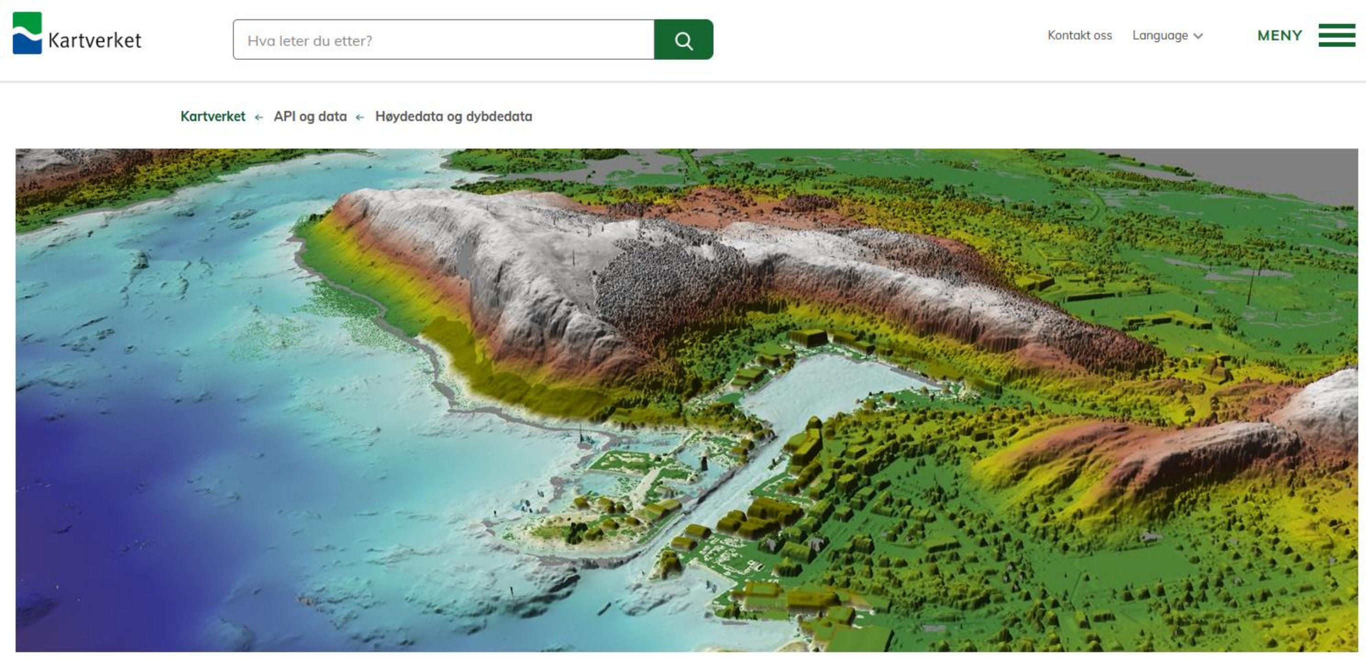
- 3) Modelling the inundation

  MOST/ComMIT(NOAA): Simulates inundation at high resolution

  https://nctr.pmel.noaa.gov/ComMIT/

https://kartverket.no/api-og-data/terrengdata

- Need high resolution bathymetry/topography!



TERRENGDATA. Høgdedata og djupnedata kan brukast til å lage terrengmodellar. Illustrasjon: Kartverket

Modelling inundation from the Storegga slide is performed in 3 different stages:

3) Modelling the inundation

MOST/ComMIT(NOAA):

https://nctr.pmel.noaa.gov/ComMIT/

- Need high resolution bathymetry/topography!
- And it needs to be corrected for changes over the last 8000 years(!)

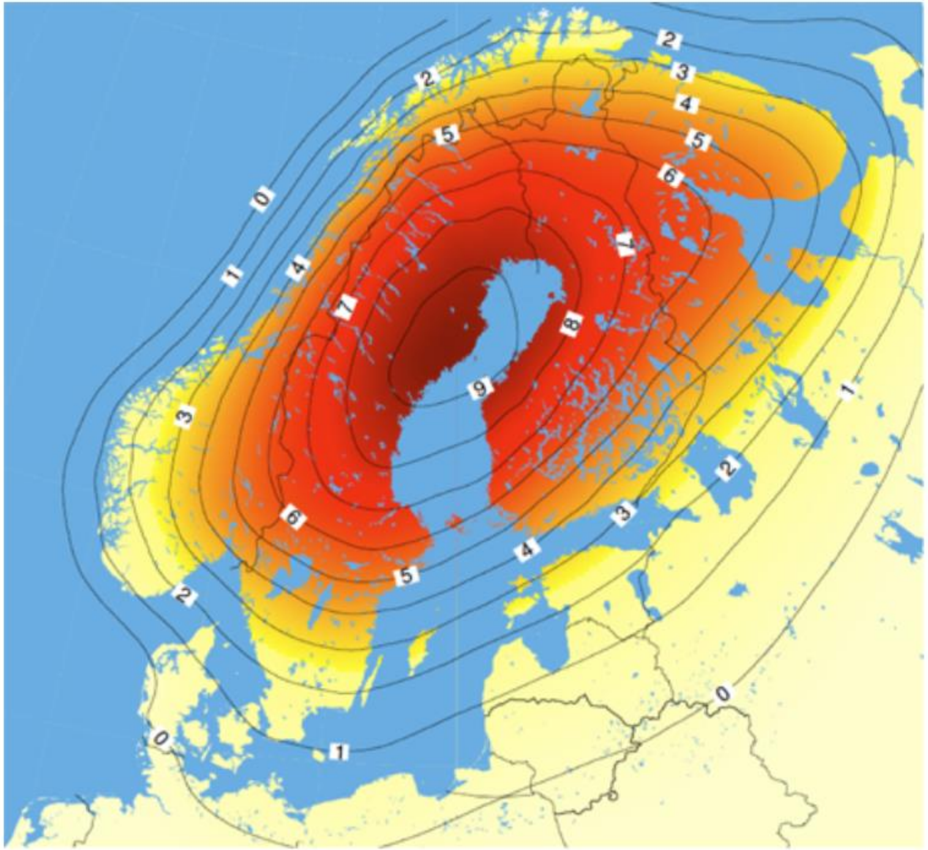


Figure 1. Fennoscandian land uplift (mm/yr) relative to the centre of the Earth.

Figure: https://www.maanmittauslaitos.fi/en/research/interesting-topics/land-uplift

Modelling inundation from the Storegga slide is performed in 3 different stages:

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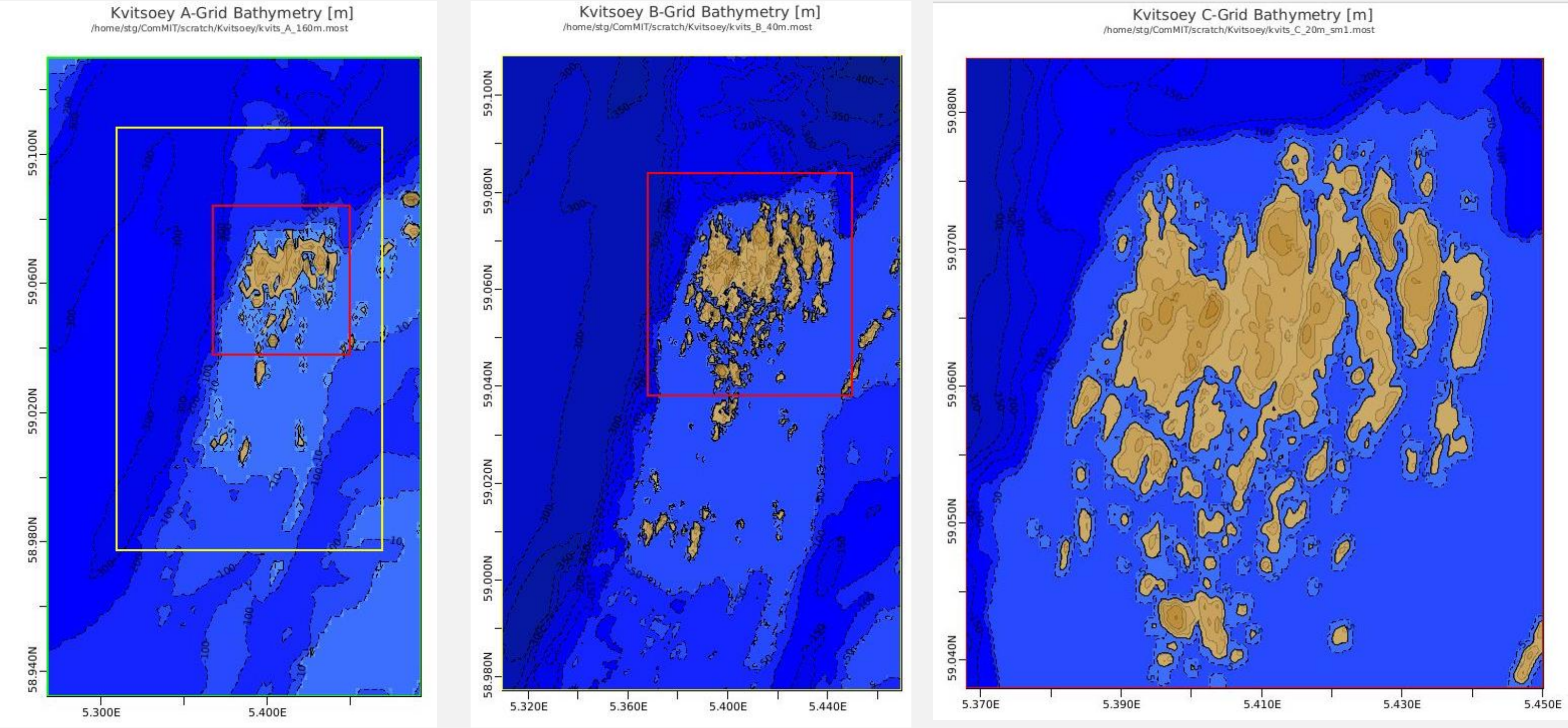

Modelling inundation from the Storegga slide is performed in 3 different stages:

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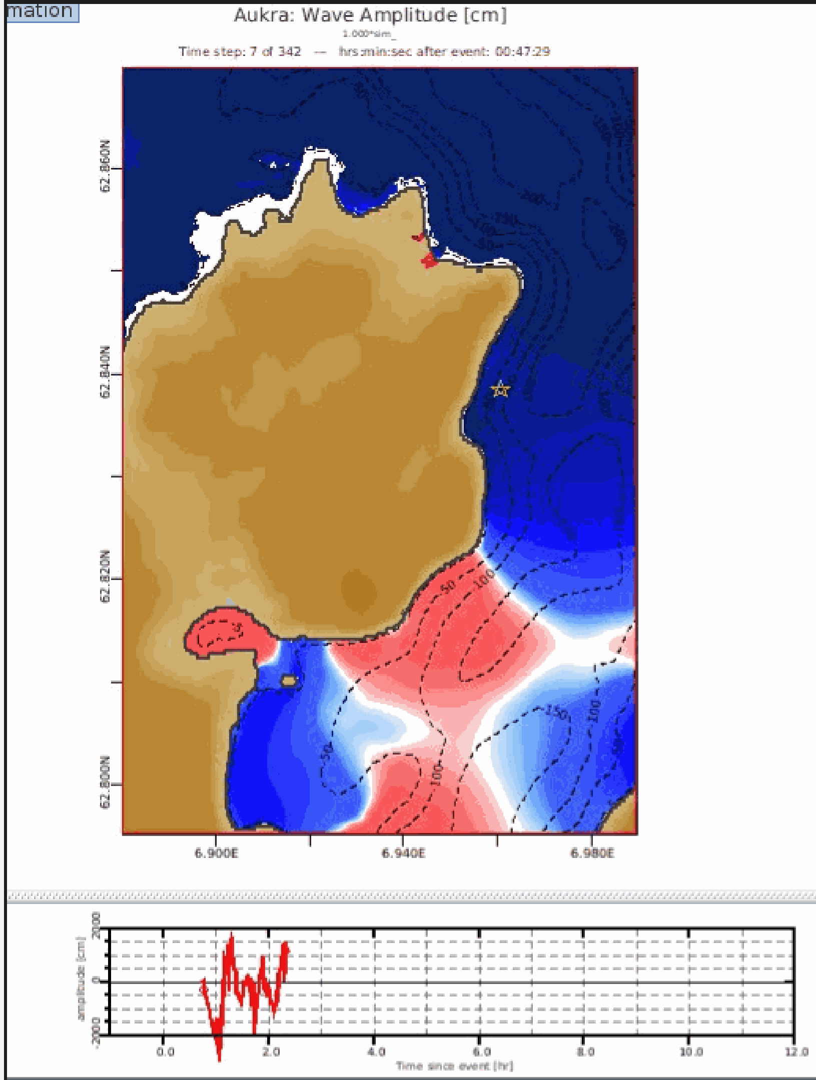

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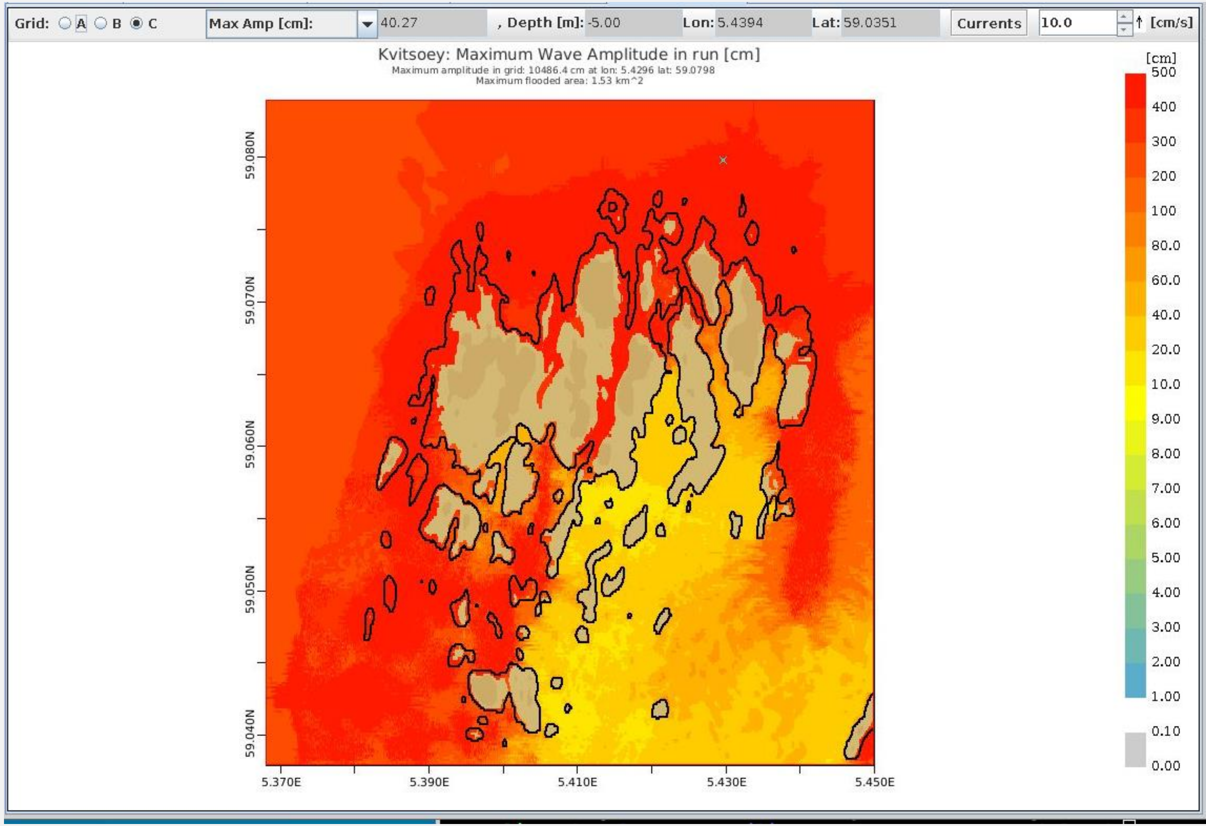

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Background

- H2020 EU project SLATE PhD student Matthias Rauter developed a novel landslide tsunami model → Computiational Fluid Dynamics (CFD) model in OpenFOAM
- Available by the end of the SLATE project
- Need to for NGI to take advantage of the unique model
- Basis for filling gap in basic physical understanding

Lake Askja landslide 2014

Tsunami simulation of 2014 Lake Askja tsunami

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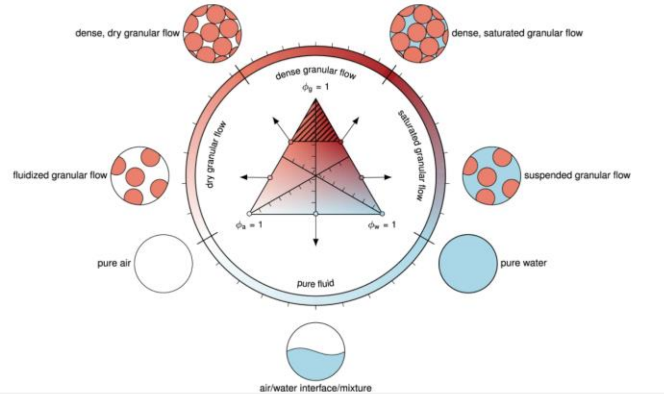
Main novel aspects of the model

Multi-phase coupling,
porous landslide



Advanced landslide rheology from
solid to granular behaviour

$$\nu_g = \mu(I) \frac{p_s}{2\,\bar{\phi}\,\rho_g} \frac{1}{\|S_g\|},$$

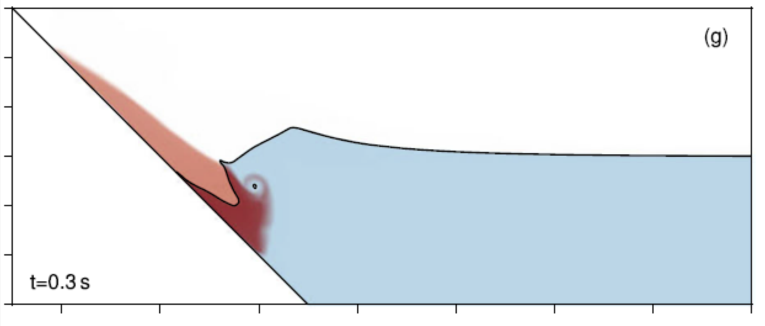
$$\mu(I) = \mu_s + \frac{\mu_d - \mu_s}{I_0/I + 1},$$

$$I = \frac{2\,d\,\|S_g\|}{\sqrt{p_s/\rho_g}}.$$

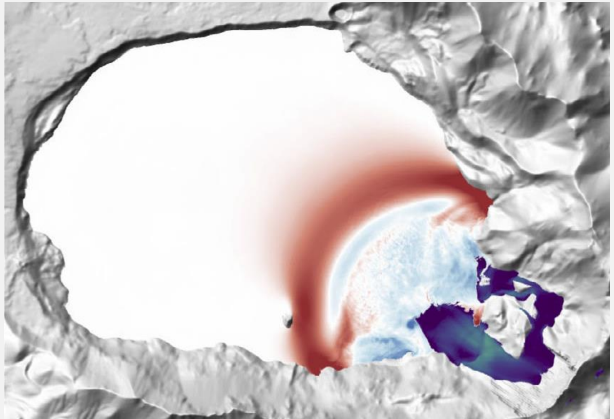
$$S_g = \frac{1}{2}(\nabla \mathbf{u}_g + (\nabla \mathbf{u}_g)^T) - \frac{1}{3}\nabla \cdot \mathbf{u}_g \mathbf{I},$$

…

Simulating lab scale experiments

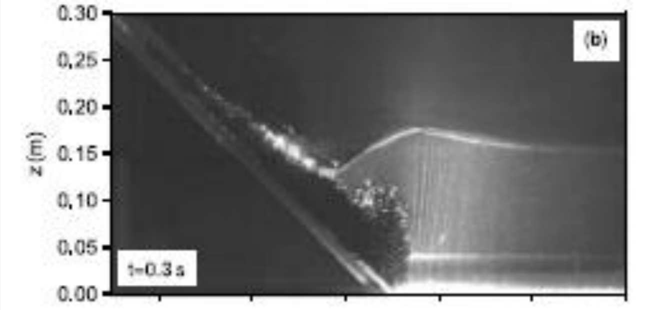


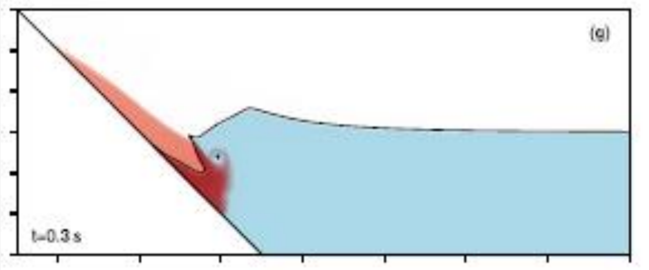
To full 3D simulations

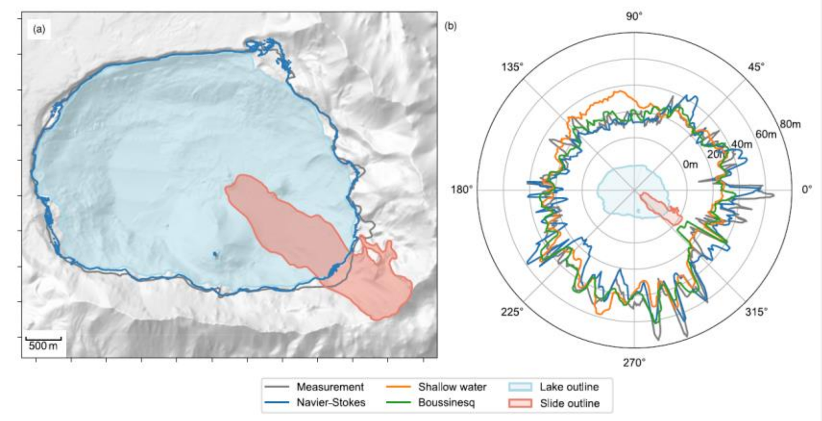


Main scientific findings

- First model matching consistently **both landslide AND tsunami observations** from the laboratory to the field scale
- Close agreement with both landslide run-out and wave observations
- Advanced landslide material behaviour, direct simulation with **no attempt to calibrate** the landslide parameters
- Fundamental leap forward of the complexity can model of landslide-tsunamis







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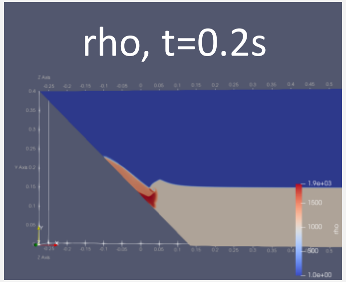
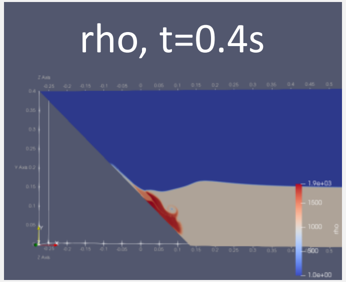
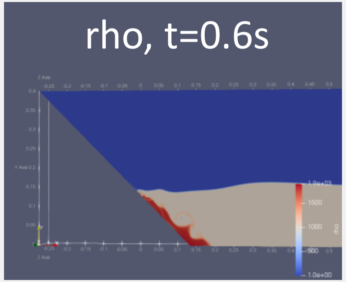
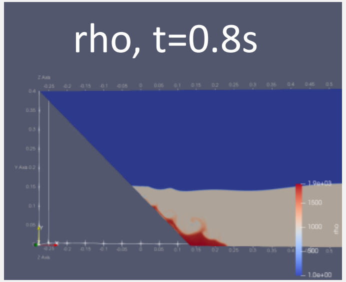
From lab experiments to large scale landslides?

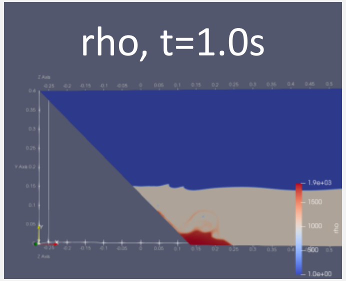
- Full CFD models can contain far more accurate physics
- They are (orders of magnitude!) more expensive to run than depth averaged models
- We cannot model the uncertainty to the same extent that we can with the simpler models











Plots: paraview

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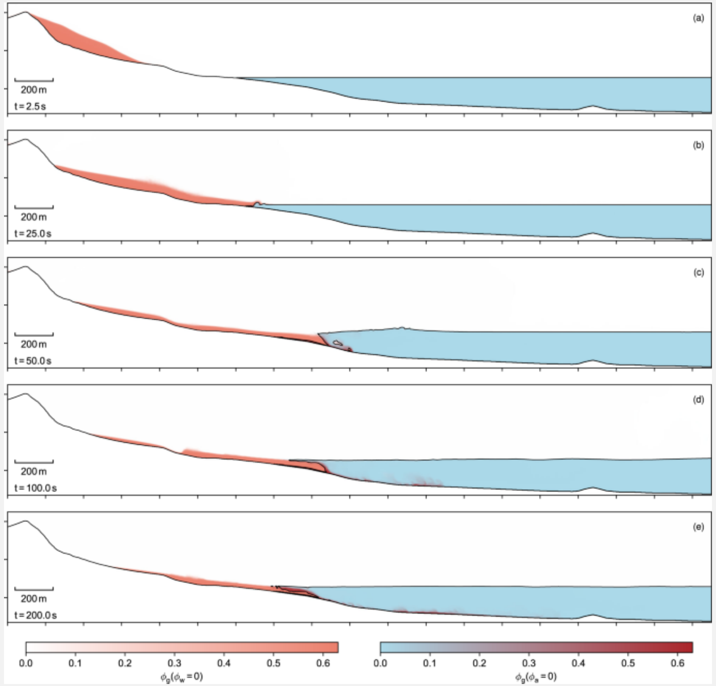

Above: snapshots of Lake Askja simulation calculated by Matti Rauter.

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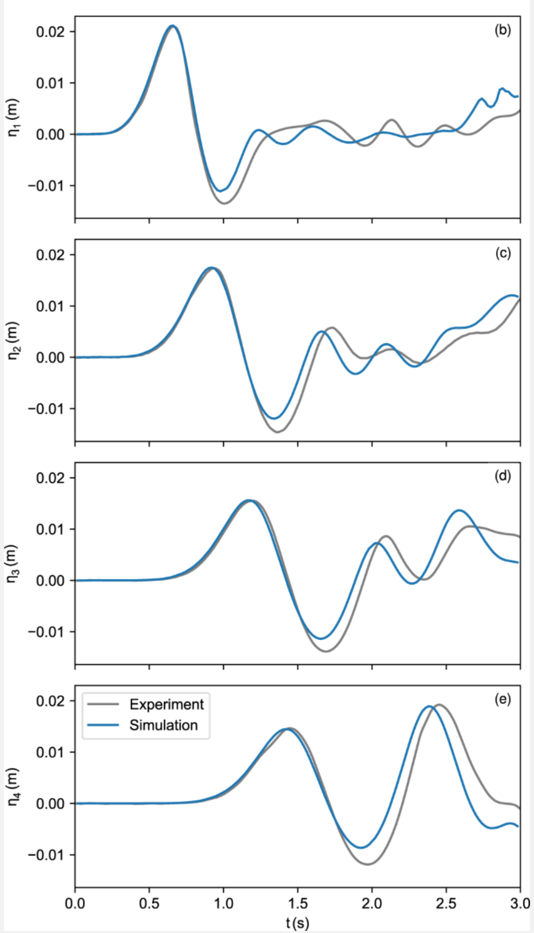
Next steps

- Run and compare model results in 2D towards models use by NGI today
- NGI operational models used in practical projects
  - Depth averaged landslide, tsunami
  - Do not take into account all physics of impact
- CFD model
  - Full 3D, but too resource intensive for use in projects
  - Closely benchmarked with experiments
- Possible outcome – tuned depth averaged models in practical consulting project and R&D based on advanced physics
  - More confidence and less uncertainty in hazard maps?



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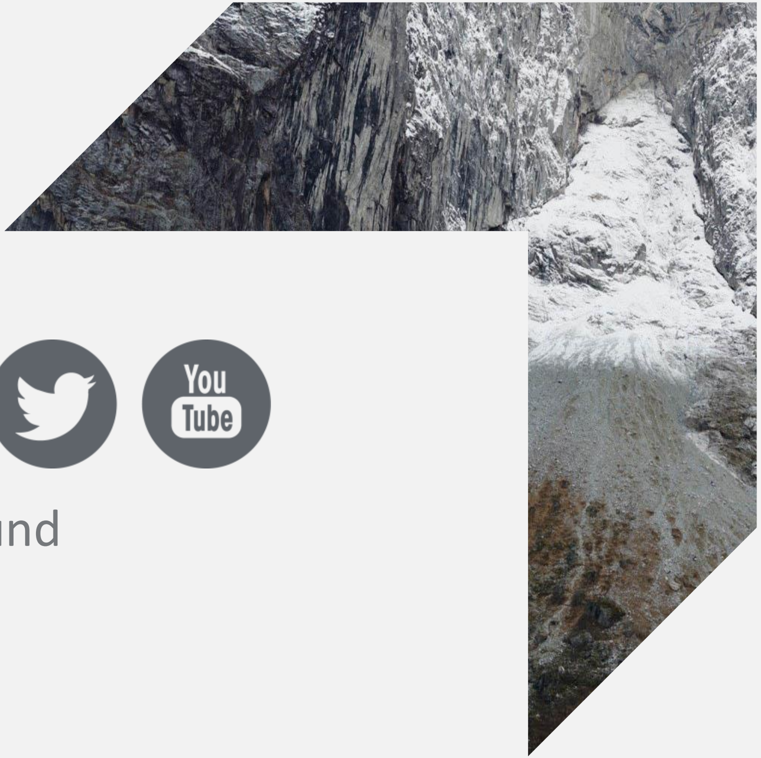
Conclusions

- Numerical simulations are necessary to estimate tsunami hazard!

- HPC (High Performance Computing) is needed for
  - Capability Computing (how fast/how large/how complex)
  - Capacity Computing (vast numbers of calculations e.g. for uncertainty)
  - Urgent Computing (great time constraints)

- Simulation allows us to estimate the impact of ancient landslide tsunamis

- Likely advances in source physics in future tsunami modelling



#onsafeground

Thank you!

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