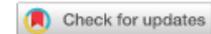


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<https://doi.org/10.1038/s41467-021-25815-w>

OPEN

Probabilistic tsunami forecasting for early warning

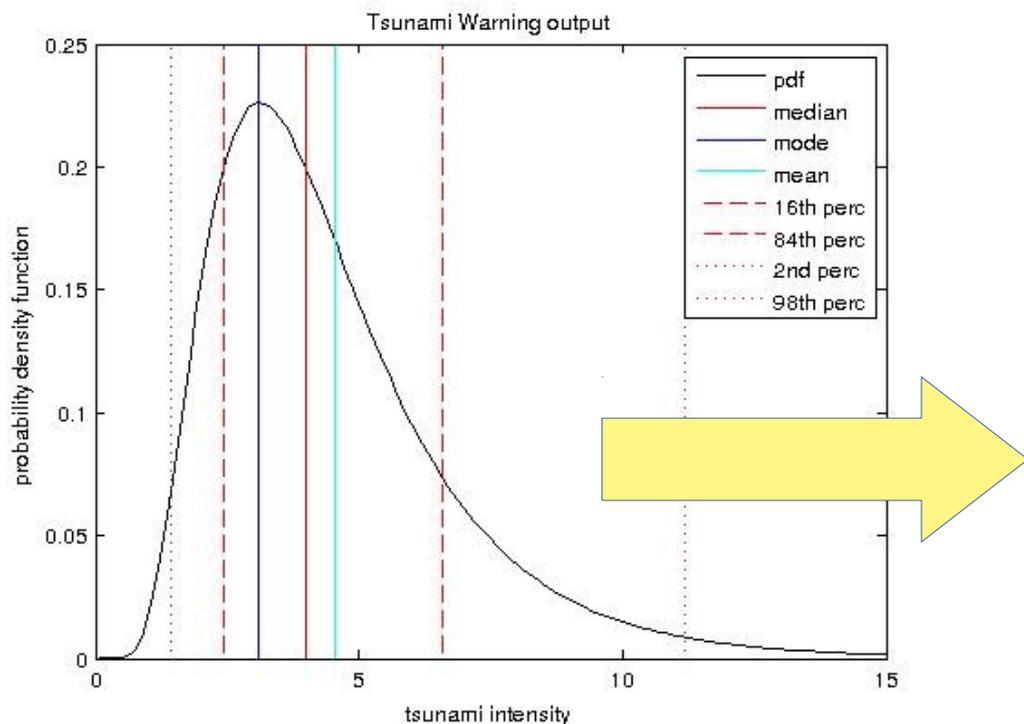
J. Selva ^{1✉}, S. Lorito ², M. Volpe², F. Romano ², R. Tonini ², P. Perfetti¹, F. Bernardi ², M. Taroni², A. Scala³, A. Babeyko⁴, F. Løvholt⁵, S. J. Gibbons ⁵, J. Macías ⁶, M. J. Castro⁶, J. M. González-Vida⁶, C. Sánchez-Linares⁶, H. B. Bayraktar ^{2,3}, R. Basili ², F. E. Maesano ², M. M. Tiberti ², F. Mele², A. Piatanesi² & A. Amato²

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.

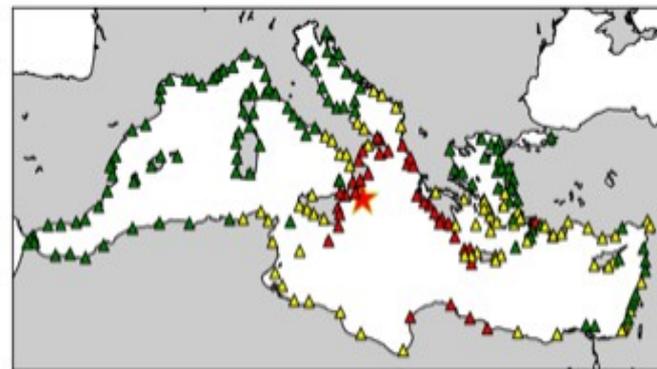
Главное о методе вероятностного прогноза

I: Прозрачное и по возможности полное “трассирование” неопределенностей и погрешности предсказания.

Представление прогноза в виде функции распределения вероятности (PDF)



II: Четкое разделение количественного прогноза (“ученые”) и принятия решения об эвакуации, т.е. фиксации уровня текущей опасности и вытекающих мероприятий (“МЧС”)



Selva et al., 2021, NatComm

Текущая практика: Decision Matrix for the Mediterranean

Depth	Epicenter Location	M	Tsunami Potential	Type of Bulletin		
<100 km	Offshore or close the coast (≤ 40 km inland)	$5.5 \leq M \leq 6.0$	Nil	Information Bulletin	Information Bulletin	Information Bulletin
		$6.0 < M \leq 6.5$	Weak potential of local tsunami	Local Tsunami Advisory	Information Bulletin	Information Bulletin
	Inland (> 40 km and ≤ 100 km)	$5.5 \leq M \leq 6.5$	Nil	Information Bulletin	Information Bulletin	Information Bulletin
	Offshore or close the coast (≤ 100 km inland)	$6.5 < M \leq 7.0$	Potential of destructive local tsunami < 100 km	Local Tsunami Watch	Regional Tsunami Advisory	Information Bulletin
		$7.0 < M \leq 7.5$	Potential of destructive regional tsunami < 400 km	Local Tsunami Watch	Regional Tsunami Watch	Basin-wide Tsunami Advisory
		$M > 7.5$	Potential of destructive tsunami in the whole basin > 400 km	Local Tsunami Watch	Regional Tsunami Watch	Basin-wide Tsunami Watch
≥ 100 km	Offshore or inland (≤ 100 km)	$M \geq 5.5$	Nil	Information Bulletin	Information Bulletin	Information Bulletin

Local ≤ 100 km

$100 \leq$ Regional < 400

Basin-wide ≥ 1000

Information: no tsunami/damage expected

Advisory: run-up < 1 m or height < 0.5 m

Watch: run-up > 1 m or height > 0.5 m

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Оценка погрешности?

Local ≤ 100 km 100 \leq Regional < 400 Basin-wide ≥ 1000

Information: no tsunami/damage expected

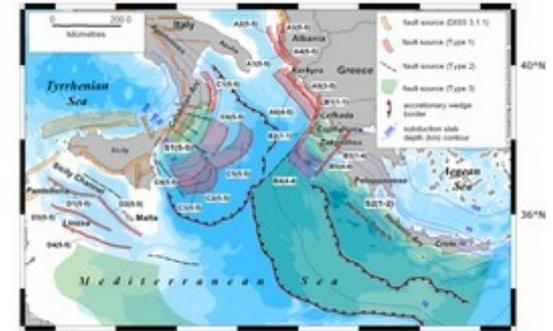
Advisory: run-up < 1 m or height < 0.5 m

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Uncertainty in Tsunami Early Warning

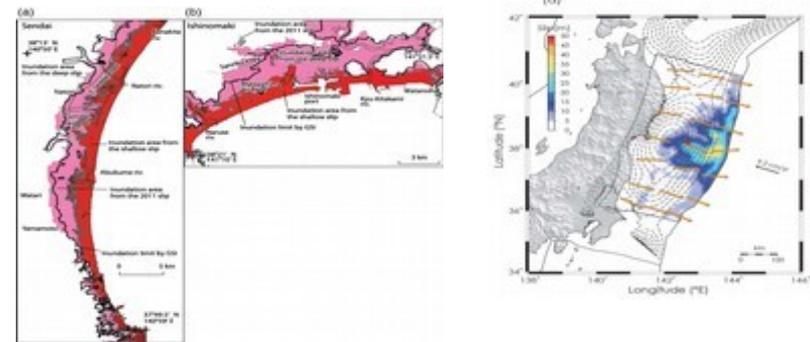
Some Examples of (inherent) Uncertainty Sources

- **Magnitude, location, focal mechanism**
- Fault geometry and slip distribution (**scaling laws variability and slip variations**), up to **local complexity of potential tsunami sources**
- ...



Basili et al., NHESS, 2013

Romano et al., Sci. Rep., 2014

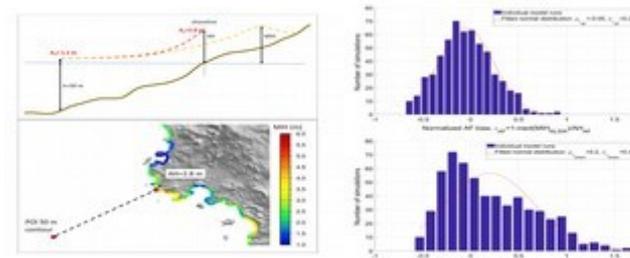


Satake et al., BSSA, 2013

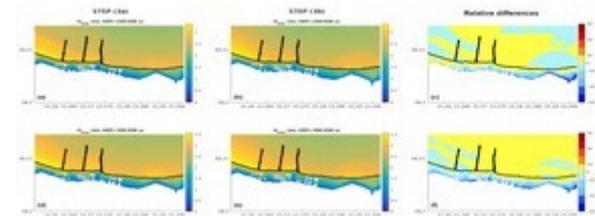
Uncertainty in Tsunami Early Warning

Some Examples of (inherent) Uncertainty Sources

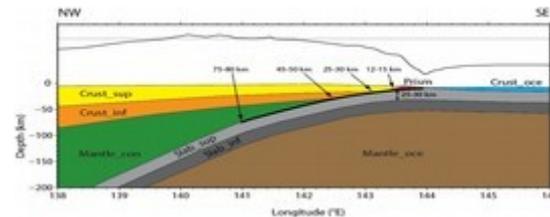
- ...
- Uncertainties in **tsunami modelling and inundation**, especially near coast
- Ignorance/simplification of the **tsunami generation process** (source time-dependence for example **tsunami earthquakes**, non-hydrostaticity,...)
- ...



Glimsdal et al., PAGEOPH, 2019



Volpe et al., NHESS, 2019

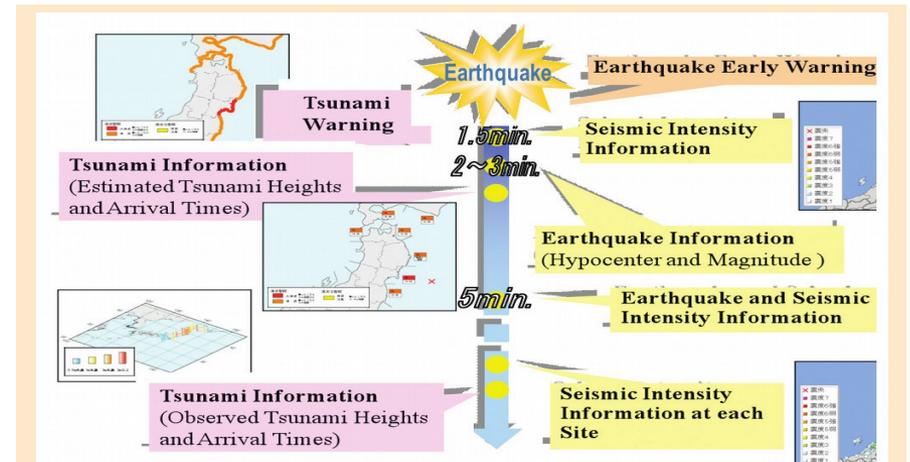


Romano et al., Sci. Rep., 2014

Uncertainty in Tsunami Early Warning

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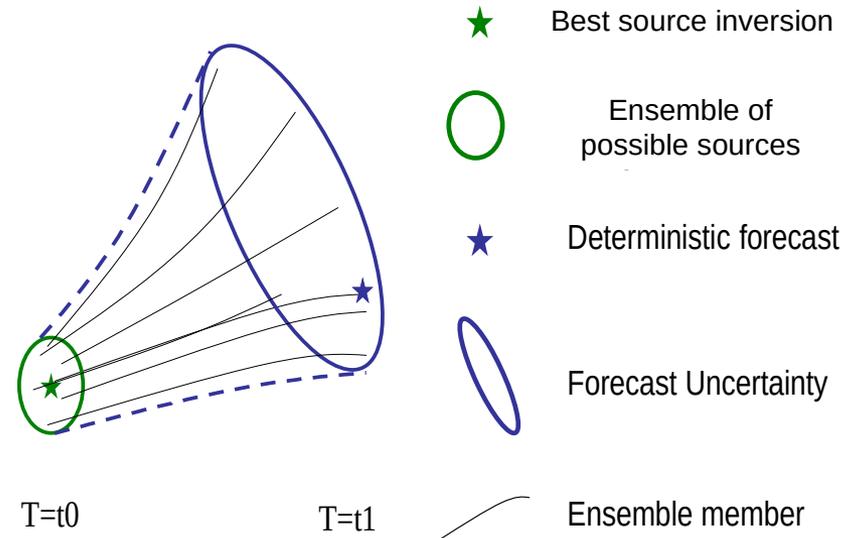
- ...
- ...
- Trade-off between **accuracy** and **earliness**, since soon after the event not all the required information are available!



Courtesy of JMA

Probabilistic Tsunami Forecast

- Рассмотрим **неопределенность источника** на момент начала прогноза; учтем все потенциально возможные источники
- “Трассируем” неопределенность источника через представление ансамбля источников
- Прямое численное моделирование **всех стадий** развития цунами включая шоулинг и оценку затопления



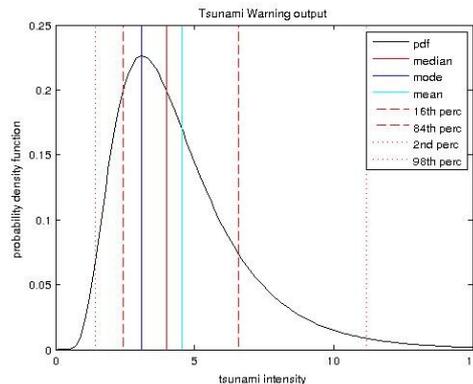
PTF theory

$$P(X > x | E; p, t) = \int_{\Sigma} P(X > x | \sigma; p) g(\sigma | E; t) d\sigma$$
$$\approx \sum_i P(X > x | \sigma_i; p) P(\sigma_i | E; t)$$

PTF: Probability distribution (PDF) of different tsunami intensities at all forecast point, given our knowledge

Propagation factor: Probability of different *tsunami intensities* in all *forecast points* given a scenario

Source factor: Probability that a scenario well represents the ongoing event E at the present state of knowledge



- The **list of scenarios (ensemble)** should be sufficiently large to virtually represent all possible sources;
- The source factor should account for **real-time information** (about source and propagation), dealing also with **missing information**;
- The quantification of the **propagation factor** is the computational challenge, when we consider all potential sources

PTF methodology

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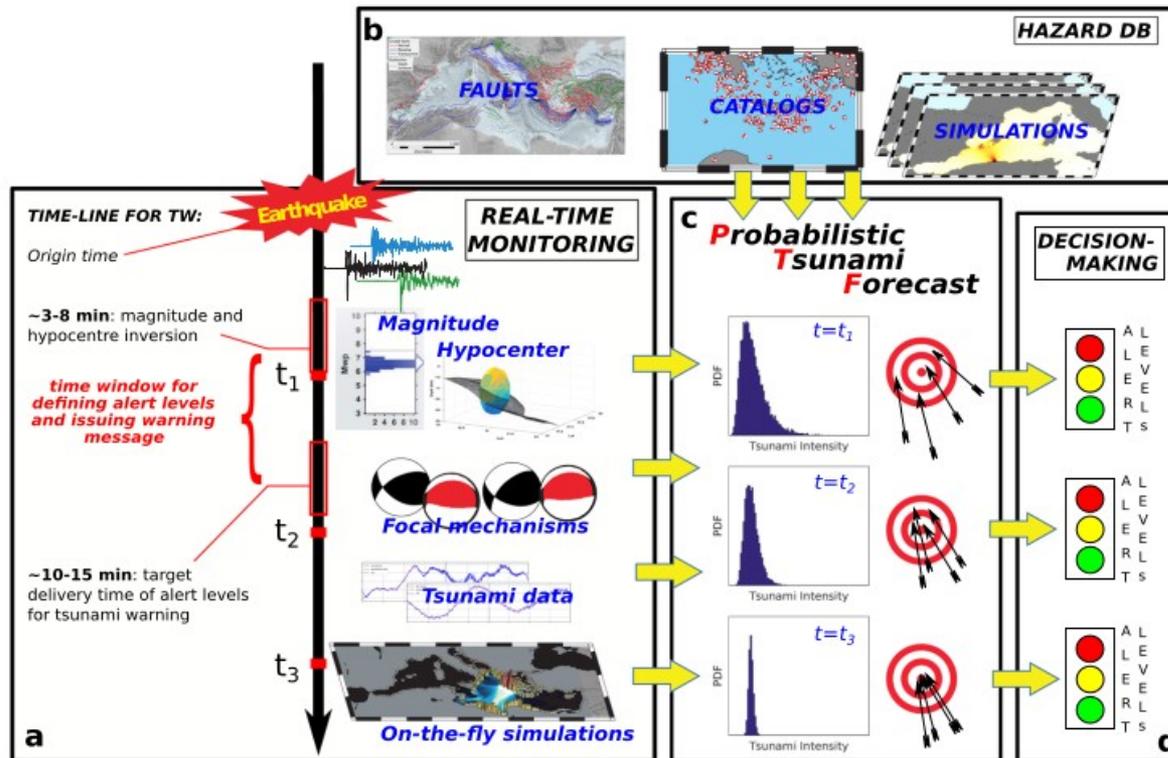
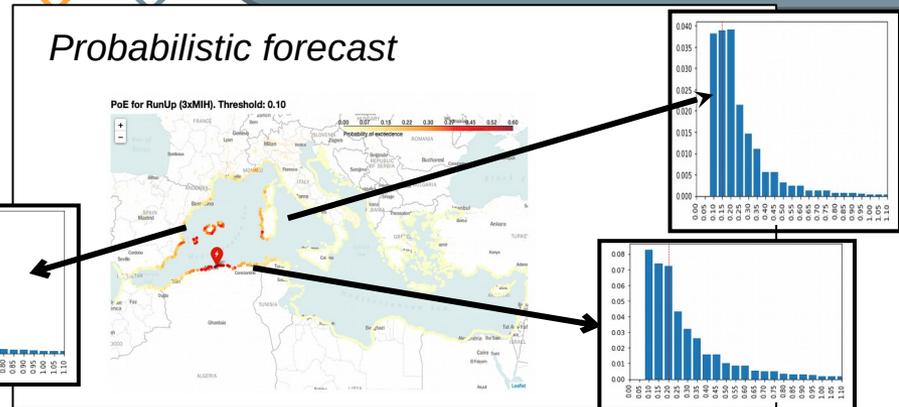
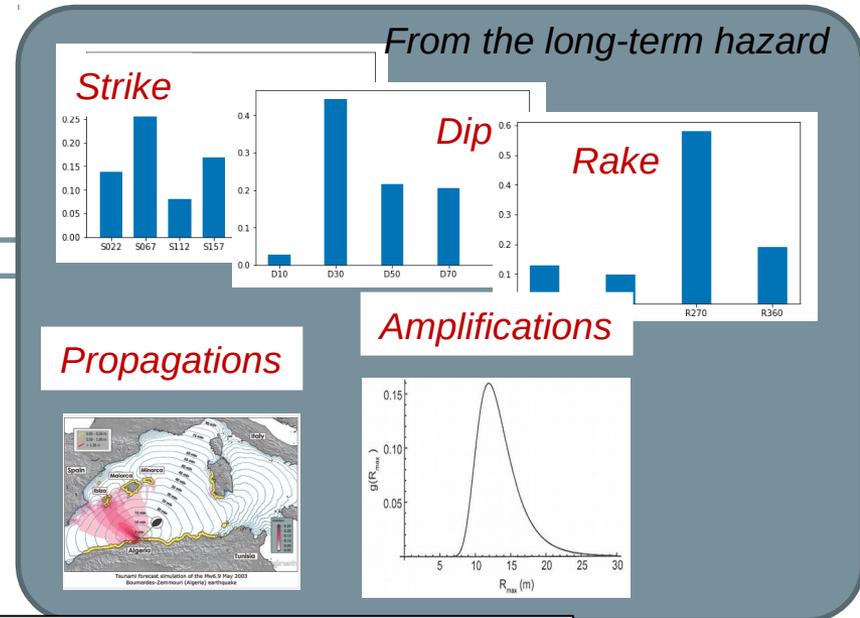
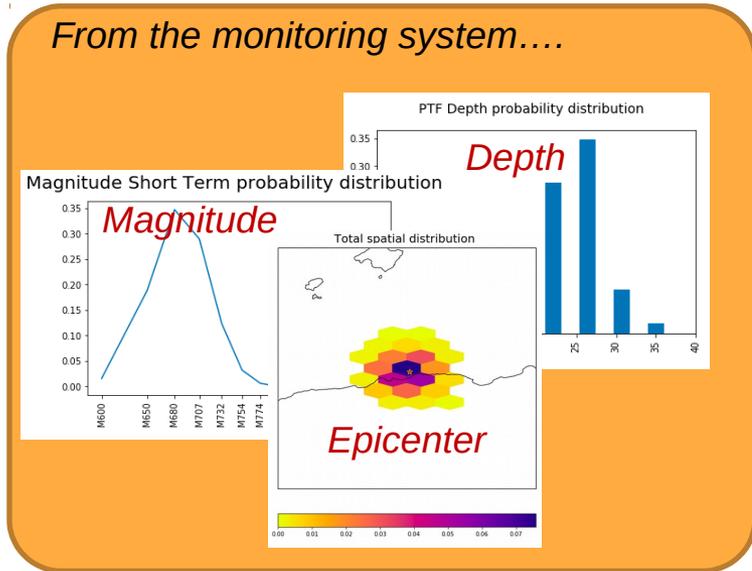


Fig. 1 PTF concept. **a** Timeline for tsunami warning: real-time information from an earthquake that just occurred and from the ongoing tsunami gradually integrates **b** local long-term hazard information, **c** progressively increasing the precision of the probabilistic forecasts (hazard curves) produced by the Probabilistic Tsunami Forecasting (PTF). **d** At any time, PTF can be transformed into alert levels (here represented as traffic lights) useful for decision making. In the current study, implementation refers to the time t_1 , when only earthquake magnitude and hypocentre estimates are available from real-time observations.

Probabilistic Tsunami Forecast



Testing PTF: Maule 2010 M8.8 earthquake

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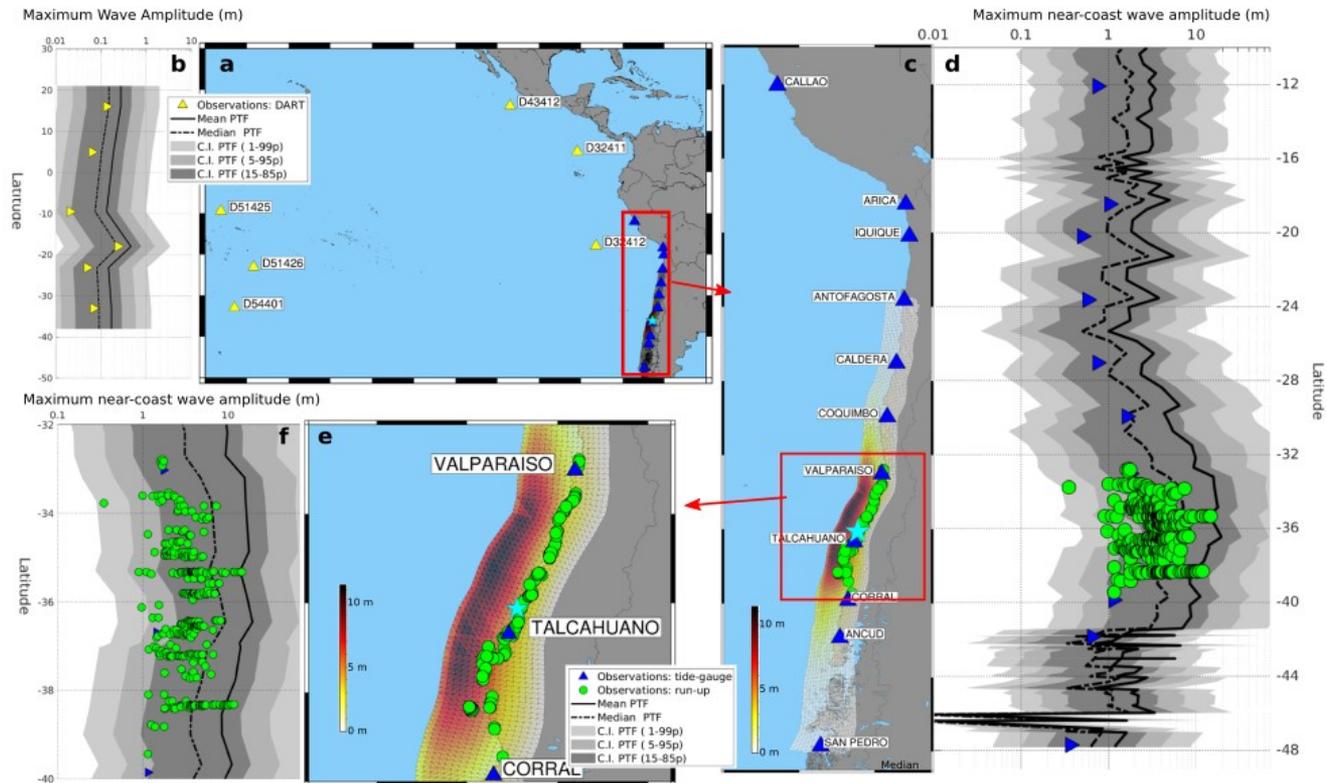
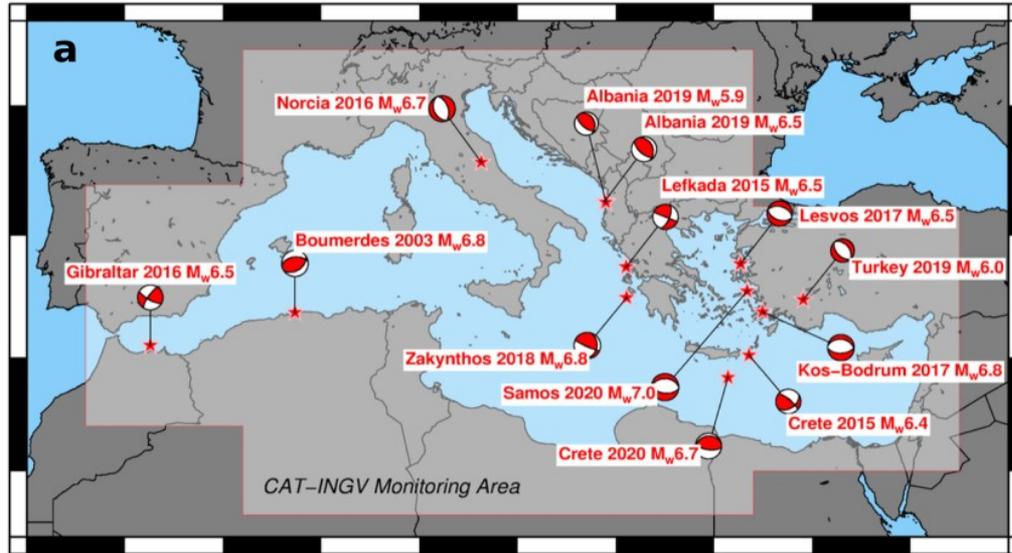


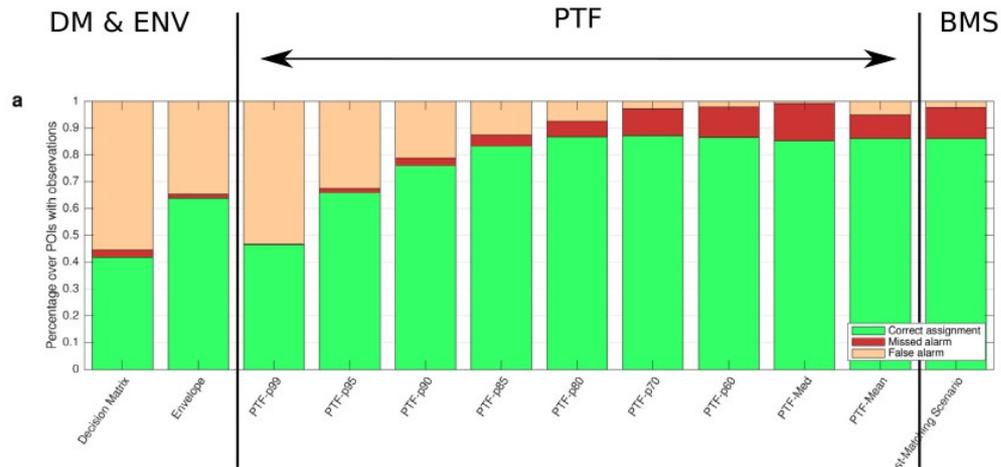
Fig. 4 PTF for the 2010 M8.8 Maule tsunami. **a** Epicentre and location of deep-sea (DART) observations (yellow triangles) and **b** corresponding comparison between deep-sea observations and PTF forecasts (black lines and grey areas). **c** Epicentre (star), average of the slip distributions used in the ensemble, and location of coastal observations (tide-gauges and run-up as blue triangles and green circles, respectively; run-up is halved to compare with wave amplitude, see Supplementary Note 6). **d** Graphical comparison between coastal observations and PTF forecasts (black lines and grey areas). **e, f** Same as **b, c** zoomed over the area with run-up measures.

Selva et al., 2021, NatComm

Testing PTF: Alert levels for the Mediterranean set



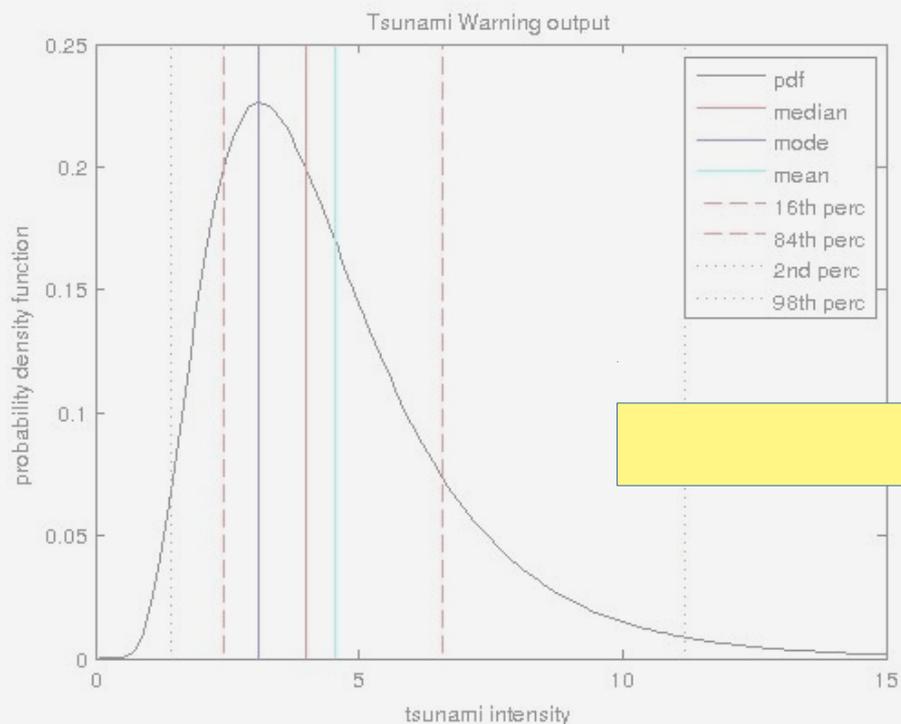
DM: Decision matrix
 ENV: Scenarios envelope
 BMS: Best matching scenario



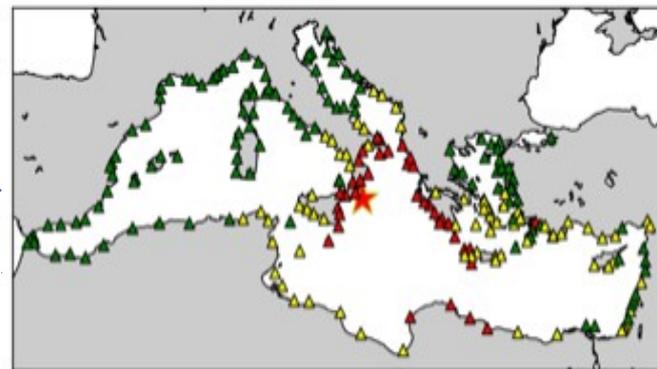
Selva et al., 2021, NatComm

Главное

I: Прозрачное и по возможности полное “трассирование” неопределенностей и погрешности предсказания.
Представление прогноза в виде функции распределения вероятности (PDF)

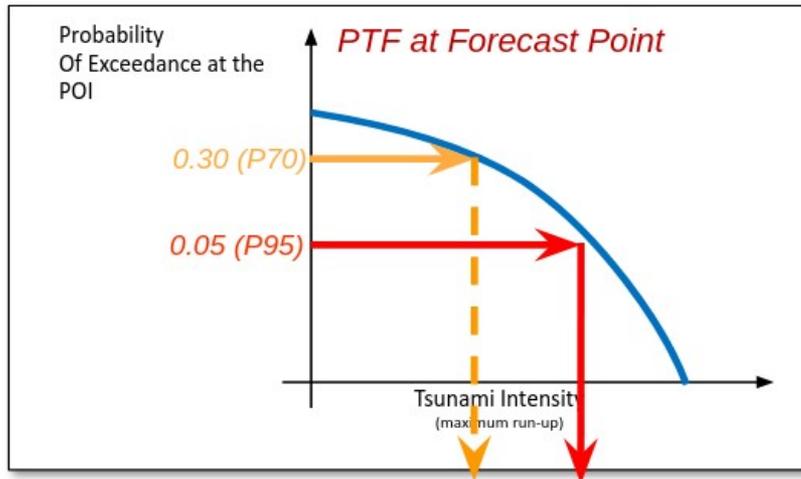


II: Четкое разделение количественного прогноза (“ученые”) и принятия решения об эвакуации, т.е. фиксации уровня текущей опасности и вытекающих мероприятий (“МЧС”)



Selva et al., 2021, NatComm

From PTF to Alert Levels



Information: < 0.10 m wave amplitude
Advisory: 0.10 < wave amplitude < 0.5 m
Watch: wave amplitude > 0.5m

Set an “acceptable risk” threshold:

h corresponding to 5% exceedance probability (95th percentile)

Example 1: 1.22 m → **Watch**

Example 2: 0.40 m → **Advisory**

In the same target, two possible alert levels:

Ex1: $P(> 1.22 \text{ m}) = 0.05$

Ex2: $P(> 0.40 \text{ m}) = 0.30$

⇒ different levels of conservatism
⇒ political choice

5 ноября, World Tsunami Awareness Day

INGV проводит Первый онлайн эксперимент применения методики РТФ в режиме *Urgent Computing* с использованием GPU-кластера CINECA

- РТФ в реализации Urgent Computing для симуляции ситуации раннего прогноза для землетрясения 30 окт 2020 в районе о. Samos (M7.0)
- Задействовано 800 нод, состоящих из 4 Nvidia V100 GPUs каждая на кластере Marconi100 @CINECA в Болонье
- ~ 38 000 вариаций источника (для охвата 2-sigma неопределенности в параметрах источника)
- Код: Tsunami-HySea (конечные объемы), нелинейные уравнения мелкой воды с затоплением. Сетка 30 arcsec, область расчета ~5x5°. Опорные точки расчета: каждый 2 км вдоль изобат 50 и 10 м. Закон Грина для оценки заплесков.
- ~10 минут вычислительного времени

ВЫВОДЫ

- PTF позволяет явным и прозрачным образом оценить и представить неопределенность и погрешность прогноза. Тем самым дает механизм разделения объективного научного прогноза и задачи принятия решения (decision making).
- При минимальной входной оперативной информации – оценки магнитуды и положения землетрясения – PTF исходит из долгосрочной региональной модели вероятностной оценки опасности цунами (РТНА), обеспечивая быстрый предварительный оперативный прогноз. Этот прогноз может впоследствии уточняться исходя из поступления новых наблюдений.
- PTF в режиме Urgent Computing позволяет углубить дискретизацию источников и плотность точек наблюдения улучшая результирующую точность прогноза.