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Towards the new Thematic Core Service Tsunami within the EPOS Research Infrastructure

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Abstract

Tsunamis constitute a significant hazard for European coastal populations, and the impact of tsunami events worldwide can extend well beyond the coastal regions directly affected. Understanding the complex mechanisms of tsunami generation, propagation, and inundation, as well as managing the tsunami risk, requires multidisciplinary research and infrastructures that cross national boundaries. Recent decades have seen both great advances in tsunami science and consolidation of the European tsunami research community. A recurring theme has been the need for a sustainable platform for coordinated tsunami community activities and a hub for tsunami services. Following about three years of preparation, in July 2021, the European tsunami community attained the status of Candidate Thematic Core Service (cTCS) within the European Plate Observing System (EPOS) Research Infrastructure. Within a transition period of three years, the Tsunami candidate TCS is anticipated to develop into a fully operational EPOS TCS. We here outline the path taken to reach this point, and the envisaged form of the future EPOS TCS Tsunami. Our cTCS is planned to be organised within four thematic pillars: (1) Support to Tsunami Service Providers, (2) Tsunami Data, (3) Numerical Models, and (4) Hazard and Risk Products. We outline how identified needs in tsunami science and tsunami risk mitigation will be addressed within this structure and how participation within EPOS will become an integration point for community development.

Keywords: Tsunami; Natural hazards; Community building; EPOS; Research infrastructure

1. Introduction

Tsunami events in the European and Mediterranean region dating back to pre-historical times have been studied extensively [e.g., Maramai et al., 2014; Valle et al., 2014; Papadopoulos et al., 2014]. Tsunami research in Europe has a long-standing tradition and gained particular momentum in the eighties and nineties through the first EU-funded research projects GITEC [e.g. Tinti et al., 1993; Pedersen et al., 1998; Papadopoulos, 2000]. Since then, the community has grown steadily, with the two episodes of significant acceleration due to the gravest tsunami catastrophes of the XXI century: the 2004 Boxing Day tsunami in the Indian Ocean, and the 2011 East Honshu Tsunami which caused the Fukushima nuclear incident [Synolakis and Kânoğlu, 2015]. That was manifested, on the one hand, by a rapid increase in the number of publications and research projects at various levels, as well as by activities for the establishment of the Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and connected Seas (NEAMTWS) in 2005 together with the development of several national tsunami warning systems, in the framework of the global effort coordinated by UNESCO-IOC (http://www.ioc-tsunami.org/). Moreover, lower impact, but yet significant events caused by non earthquake sources such as the 1929 Grand Banks, 1998 Papua-New Guinea, 2002 Stromboli, 2018 Anak Krakatau (Indonesia) landslide generated tsunamis, or 1954 Great Lakes, 1978 Middle Adriatic, 1979 Nagasaki Bay and 2014 Mediterranean and Black Sea meteotsunamis, have widened the base of the community owing to the multiple tsunami sources and related multidisciplinary research. The tsunami community now includes a wide range of countries and institutions, and covers a very diverse range of disciplines.

As tsunamis often propagate far from their source and thus impact several countries and even other continents, international collaboration is particularly important. In Europe, such international collaboration is manifested in the last decades in the form of several EU projects, and most recently in the community based AGITHAR (Accelerating Global science In Tsunami HAzard and Risk analysis) Cost Action network (https://www.agithar.uni-hamburg.de/) involving 26 countries aiming to consolidate the community and to formalise the structure of collaboration. The AGITHAR networking initiative is tightly connected to the global research arena through the Global Tsunami Model (GTM) network proposed the first time in 2015 and also originated from European partners [e.g. Løvholt et al., 2019; http://www.globaltsunamimodel.org]. A common emphasis among these networking initiatives is to provide a sustainable platform for tsunami research.

As a part of the networking activity, several reviews related to the state-of-affairs in international tsunami research have been carried out in the last few years [e.g. Grezio et al., 2017; Løvholt et al., 2019; Selva et al., 2021a; Behrens et al., 2021; Lorito et al., 2021; Vilibić et al., 2021, Rafliana et al., 2022]. This effort is helping to identify focus areas for more research, but also clear gaps towards the need for standards and advancing operational readiness level related to tsunamis such as Tsunami Early Warning Systems (TEWS) and tsunami risk analysis and assessment. In order to gain further momentum in filling the identified gaps, the above reviews have reiterated the need for a sustainable platform for hosting coordinated activities of the tsunami community. In particular, they point to the need for a hub for tsunami data, scientific products, and services, in order to make tools for researchers more generally available, and interoperable with those produced by other communities. Moreover, new tsunami services based on years of research are continually emerging.

In Europe, the more relevant "host" for this is the EPOS platform (https://www.epos-eu.org).

EPOS is the natural environment for integrating the European tsunami research network. Building research and development activities in the framework of the EPOS platform will foster community progress in such important aspects as:

- preservation, standardisation, and dissemination of scientific data and products;
- converting research and engineering assets (data, software) into offline and online services with standardised access policy;
- ensuring sustainability of service provision according to FAIR principles;
- need to better integrate tsunami products with products and services of other research communities (other EPOS Thematic Core Services, or TCSs).

In July 2021, the tsunami community got the official status as a candidate Thematic Core Service (cTCS). An integral reason for the acceptance was the consolidation of the tsunami research community, to which had contributed the networking activities in AGITHAR and GTM on the one hand, and the transnational efforts for the establishment of the NEAMTWS on the other hand. The "candidate TCS" status was granted to the tsunami community by the EPOS General Assembly for a period of 3 years. It is expected that during this candidate phase, the cTCS Tsunami will be developed into a fully-operational EPOS TCS. It is worth noting that, following the conception, preparatory, and implementation phases from 2008-2019, EPOS has now entered the pre-operational phase which is expected to turn into the operational phase in 2023.

The case of the tsunami community entering EPOS infrastructure is of interest not only for the tsunami community itself. As the first new community entering EPOS, the process leading to the acceptance of a new TCS is of general interest for all communities that want to enter EPOS, and for EPOS itself towards learning how to integrate new thematic communities. Prior to 2021, the EPOS-family consisted of communities that were a part of EPOS from its preparation phase. Procedures and regulations regarding acceptance of new communities were not developed, implemented, or tested. Thus, the case of the tsunami community has also become a practical use case for EPOS extension, building a road for future community growth.

2. Tsunami community in Europe and relevance of building TCS Tsunami within EPOS RI

2.1 General characteristics of the community: from science to risk reduction

The tsunami community involved in the effort of the TCS construction currently includes 30 partner institutions across Europe from 14 countries (Figure 1).

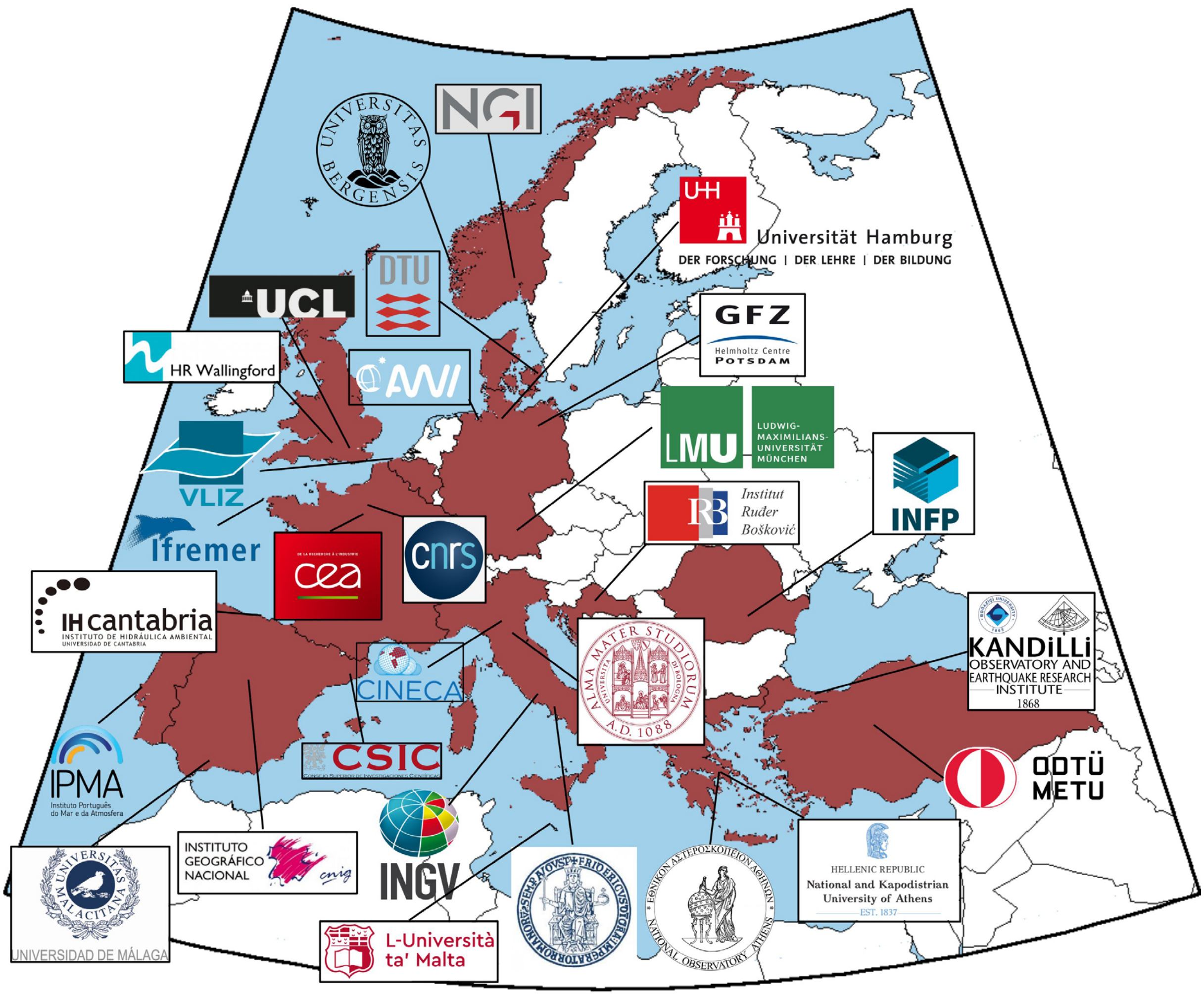

Figure 1. European institutions currently contributing to the construction of the new EPOS Candidate TCS Tsunami, with the countries to which they belong coloured in brown.

The European tsunami research community is composed of universities and public and private research centres. There is a well-established tradition of collaborative research, as testified by a long record of EU-funded projects. In addition to the seminal ones, already mentioned in the introduction, among collaborative projects with a specific focus on tsunamis we note the NEAREST, SEAHELLARC, and TRANSFER FP6 projects, the TRIDEC and ASTARTE FP7 projects, and the NEARTOWARN and TSUMAPS-NEAM prevention and preparedness projects funded by the DG-ECHO [see e.g. Hammitzsch et al., 2013; Papadopoulos and Fokaefs, 2013; Basili et al., 2021]. These efforts have covered an ideal chain binding together data-collection and fundamental science, numerical simulations, hazard and risk assessment, and disaster risk reduction, through input to both emergency and long-term coastal planning, awareness raising, and early warning. They have demanded excellence across a broad range of disciplines, including geology, seismology, oceanography, engineering, computer science, and social science, to mention a few. The progress from all of these efforts has consolidated a leading role of the scientific community in the construction of tsunami warning systems in the region: in the framework of the NEAMTWS coordinated by UNESCO Intergovernmental Oceanographic Commission (IOC). As of today, five institutions in the tsunami community act as accredited Tsunami Service Providers (TSP) in the NEAMTWS, namely CENALT (France), NOA (Greece), INGV (Italy), IPMA (Portugal), and KOERI (Turkey). Moreover, additional institutions participate in national tsunami warning systems (e.g. in Spain and Romania). The TSPs are also involved in national contingency planning for tsunamis, first and foremost with hazard and risk mapping. This necessitates a strong link and continuous interaction with civil protection agencies and local authorities responsible for the implementation of the last mile of the warning chain. Such interactions have included hazard mapping and evacuation planning [e.g. Tonini et al., 2021], NaTech Risk assessment (Risks from Natural Hazards at Hazardous Installations), and comprehensive efforts such as the UNESCO Tsunami Ready Programme.

There are also institutions that contributed significantly to the development of tsunami warning systems outside of Europe. One example is that of several German Institutions, led by the GFZ (Potsdam), which have organised – in the frame of the GITEWS project – a consortium for building the Indonesian Tsunami Early Warning System (InaTEWS) together with Indonesian institutions and authorities following the 2004 Indian Ocean tsunami [Rudloff et al., 2009, Hanka et al., 2010].

Most of the tsunami warning centres worldwide, including those in the NEAMTWS, exploit for their day-to-day operations the sea-level data monitoring facility maintained by VLIZ, Belgium, on behalf of the UNESCO-IOC. The data are also being archived and constitute an invaluable source of information for researchers worldwide.

It is also important to note that some members of the European tsunami community play a leading role in the global hazard and risk assessment (e.g. for UNDRR/GAR or UNESCAP), or act as consultants for decision and policy makers (e.g. within EU DRMKC/JRC or UNDRR/GRAF).

In particular, the Joint Research Centre of the European Commission (JRC) has been long involved in the work of the UNESCO-IOC. For example, JRC deployed Inexpensive Sea-Level Devices (IDSL) in the NEAM region and Indonesia; assisted the capacity development in establishing National Tsunami Warning Centres in the NEAM region; and have been fostering the Tsunami Ready program with the 'Last Mile' projects in Greece, Turkey, and Malta, and with the DG-ECHO funded project CoastWAVE. They also integrated rapid tsunami impact assessment into the Global Disaster Alert and Coordination System (GDACS).

Several factors necessitate a strong interaction between the tsunami community and other geoscience communities or those dealing with multi-hazard and multi-risk problems. The diverse range of potential tsunami sources, together with the range of hazardous phenomena that coastal sites are often subject to, require strong interaction with seismology, volcanology, meteorology, and engineering geology communities among others. That tsunamis are often part of hazard cascades demands strong links to the multi-hazard community, for example through the European ARISTOTLE partnership [Michelini et al., 2020] (http://aristotle.ingv.it/tiki-index.php); ARISTOTLE provides expert advice to the European Emergency Response and Coordination Center (ERCC) to establish whether impacts by geophysical and natural phenomena may turn into a disaster or even a catastrophe.

Finally, another community-shaping aspect is the low-probability/high-impact nature of tsunamis. The relative scarcity of observations makes it harder to understand the physics of the phenomenon and its recurrence as a function of the intensity from natural occurrences. As a result, tsunami research strongly relies on numerical simulations. In particular, there is a growing need to perform realistic impact assessment across a wide range of scales on large computational domains and to explore large ensembles of tsunami scenarios to quantify uncertainty [Gibbons et al., 2020]. For early warning purposes this must be achieved in a very short time [Selva et al., 2021b]. To increase the resolutions and the number of scenarios that can be simulated, to incorporate more detailed physics into numerical simulations, and to speed up the computations, tsunami science makes large use of numerical simulations to complement observations.

Regarding the topical areas of hazard and risk, the two seminal networking initiatives already mentioned in the Introduction, namely, the Global Tsunami Model (GTM) and AGITHAR COST Action network, have contributed significantly to integrating efforts. To this end, the EPOS platform is being considered as the perfect environment for the community to coordinate the development of community services and to harmonise research outcomes for the broad spectrum of stakeholders.

2.2 Technology

The tsunami community benefits from, and provides input for important technological developments in HPC and in sensors.

As mentioned in the previous section, tsunami numerical modelling is pervasive in the research, risk assessment, and warning activities. The large uncertainties involved, together with the wide range of spatial and temporal scales relevant for capturing numerically the tsunami evolution, create a growing necessity for massive High Performance Computing (HPC) resources. As a result, the tsunami community is partnering with other communities such as seismology and volcanology in cutting-edge efforts in cooperation with HPC centres and the private sector for developing efficient software and workflows to deal with large-scale problems, for example in the ChEESE (https://cheese-coe.eu/) and eFlows4HPC (https://eflows4hpc.eu/) projects. To ease these tasks, there is an effort to employ a wide range of emerging techniques including urgent computing, data analytics, and artificial intelligence. The tsunami community is therefore taking advantage of the significant investments being made in the framework of the European High Performance Computing Joint Undertaking (EuroHPC-JU, https://eurohpc-ju.europa.eu/), and it also provides important use-cases to it. The large use of numerical simulations also creates the necessity to preserve and further distribute as a basis for future research the simulation results, which can be considered as a new type of data, making a case for infrastructure and standard development within, for example, EUDAT (https://www.eudat.eu/).

The tsunami monitoring operations benefit greatly from the development and integration of novel observational techniques and sensors. These include high-precision coastal real-time GNSS (Global Navigation Satellite Systems) for a better characterization of the tsunami source, and deep-sea sensors including ocean bottom seismometers, tsunameters, smart cables, and possibly DAS (Distributed Acoustic Sensing) technology [Angove et al., 2019; Howe et al., 2019; Mulia and Satake, 2020; Matias et al., 2021]. These instruments are crucial to reduce the uncertainty related to the tsunami source and to the tsunami itself, which is complementary to the uncertainty exploration allowed by tsunami simulations with supercomputers.

2.3 Relevance to EPOS RI

As a result of this brief excursus, it should be clear that the European tsunami community can greatly benefit from joining EPOS. On the other hand, the following aspects can enrich the EPOS RI portfolio, since they are relevant to the EPOS vision, mission, and practice:

- The strong interdisciplinarity of the tsunami community. This would foster a natural interaction with other EPOS TCSs, e.g. TCS Seismology, TCS Near-Fault Observatories, TCS Volcano Observations, TCS GNSS Data and Products, and in turn would contribute to reinforcing the multi-hazard/multi-risk characteristics of EPOS itself.
- The well-developed international (beyond Europe) links of the tsunami community. This would help to build and sustain the global character of EPOS.
- The rich portfolio of stakeholders: research, private sector, civil protection agencies, tsunami early warning centres, policy makers. This would strengthen the societal impact of EPOS.
- The need for state-of-the-art numerical modelling, computational resources and observation systems, which would contribute to trigger a new generation of distributed services in EPOS and shape the demand for the management of new types and volumes of data. This makes the community naturally linked to the Destination Earth (Destin-E) initiative, a part of European Commission's Green Deal and the Digital Strategy (https://digital-strategy.ec.europa.eu/en/policies/destination-earth), which may strengthen the link between EPOS RI and this long-term European initiative aimed to create by 2030 a digital replica of the Earth through the convergence of different "digital twins". Digital twins rely on the integration of continuous observation, modelling and high-performance simulation, resulting in highly accurate predictions of future developments, i.e. climate adaptation, extreme weather events, natural disaster evolution and more.
- The integration of real-time and near-real time data flows and related products, such as tsunami early warning, which will open new perspectives in data management and distribution

2.4 Relevance to ICG/NEAMTWS

Plans to build a TCS Tsunami within EPOS-ERIC have been reported on a regular basis since 2018 to the ICG/NEAMTWS (the Intergovernmental Coordination Group of the NEAMTWS; whose primary goal is operational tsunami early warning in North-Eastern Atlantic, the Mediterranean and connected Seas) operating under the Intergovernmental Oceanographic Commission (IOC) of UNESCO. The feedback from ICG/NEAMTWS has always been positive and supportive (see also Chapter 3).

The structure of the ICG/NEAMTWS is primarily oriented towards coordinating actions taken by Member States of the IOC bordering the North-Eastern Atlantic, the Mediterranean and connected seas. On the other hand, the orientation of the Tsunami TCS, analogous to all other TCSs in EPOS, is more towards institutional expertise. This constellation allows the integration of institutions that are not (yet) actively involved in the ICG/NEAMTWS early warning capacity building activities. The opportunity for synergy lies in merging of data repositories, access to jointly developed tools and methodologies, as well as access to previously restricted data sources (see Section 4.1 below).

It should be mentioned that TCS Tsunami will certainly not establish its own Tsunami Early Warning Centre, neither perform any operational early warning. Tsunami Early Warning is a prerogative of the five currently accredited Tsunami Service Providers (TSPs). Nonetheless, in the case of a tsunamigenic event in the NEAM region, after the tsunami alerts have been sent by the official TSPs to the risk managers in charge, the opportunity to have shared data documenting the event will be highly appreciated, for example by tsunami researchers and the public.

3. History of becoming a new EPOS Candidate TCS

First ideas about forming the new EPOS TCS Tsunami trace back to 2017 with presentations of a future potential TCS Tsunami in the EPOS Project Development Board and its Service Coordination Board. In April 2018, the basic concept of a Tsunami TCS was presented at the Annual General Assembly of the European Geosciences Union (EGU) in Vienna, Austria. In September 2018, an initiative group of researchers supported by EPOS leadership met for a one-day kick-off meeting at the venue of Munich airport, Germany. This meeting can be considered as a starting point of a community-building activity towards joining the EPOS RI. Two months later, in November 2018, the initiative was presented at the ICG/NEAMTWS-XV meeting in Paris, as noted in the minutes: "*The Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas (ICG/NEAMTWS), having met for its 15th Session in Paris, France, 26-28 November 2018, … acknowledges and supports with interest the bottom-up initiative from the tsunami scientific community in the NEAM Region towards the establishment of a Tsunami Thematic Core Service (TCS) within EPOS —The European Plate Observing System, a European Research Infrastructure Consortium (ERIC)*". It is, however, important to underline that EPOS-TCS initiative has no aims to substitute the agreed NEAMTWS operational framework under the IOC but will have the potential to strongly support its further development and improvement in an integrated and synchronised manner.

After the Paris meeting, a series of networking activities and dedicated meetings followed in preparation of the construction of the potential Tsunami TCS. In April 2019, the plan of a Tsunami TCS was presented and discussed at the splinter meeting SMI51: "Global Tsunami Model and EPOS" during the General Assembly of the European Geosciences Union (EGU) in Vienna, Austria. Hereafter the community agreed on a continuation of the leadership of GFZ (Potsdam, Germany) for the time period of building the new TCS, with the support of a core group including INGV (Rome, Italy), NGI (Oslo), and the University of Bergen (both Norway). Additionally, 12 Institutions sent a letter of interest to cooperate for the construction of the TCS Tsunami. VLIZ (Oostende, Belgium) joined the core group at a later stage, in recognition of the strategic importance of sea level data provision. More recently, in 2021, the core group was extended to representatives of the five accredited NEAM TSPs (CENALT, INGV, IPMA, NOA, KOERI) to emphasise the link between the scientific and risk management components of the tsunami community. The last addition to the core group was the chairperson, from INGV, of the working group dedicated to the construction of the cTCS service delivery.

From the very beginning, the mission of the core group was declared as two-fold:

1) mobilisation of the tsunami community to join the EPOS TCS initiative and
2) undertaking the formal administrative steps towards establishment of an EPOS TCS Tsunami.

A further step in community mobilisation was the joint preparation of the community proposal to the EC Horizon 2020 programme topic “Integrating Activity for Starting Communities (INFRAIA-02-2020)”. In January 2020, twenty-eight partner institutions had entered the consortium with the ultimate goal to foster joint networking, development, and service provision activities to consolidate our community and to prepare the future Tsunami TCS in EPOS. While getting a good score over the threshold, this proposal was not funded, and the community since then has sought for other paths to the self-organisation as a EPOS TCS.

Subsequently, the movement of the tsunami community towards an EPOS TCS was always conducted in close interaction and with the support of the EPOS bodies: the EPOS ERIC management, the Service Coordination Committee (SCC), and the ICS-TCS interaction team. Moreover, our community was involved as an end-user of the currently running EPOS SP (Sustainability Phase) project. One of the goals of Task 4.1 of the EPOS SP deals with the formulation of rules and best practises for the integration of new communities and their services and with guiding the first steps of the new communities. The goals of this task are therefore fully aligned with the ambitions of the tsunami community, and the core group has been in close contact with Task 4.1 receiving support and guidance towards attaining the official status of a Candidate TCS.

In the meantime, in response to the request of the tsunami core group, the EPOS ERIC has started practical steps to involve the tsunami community in the EPOS delivery framework, even prior to attaining official status of a Candidate TCS, based on interim decisions by the SCC. Since the beginning of 2021, representatives of the tsunami community have been invited to attend meetings of the Service Coordination Committee as well as to take an active participation in regular “pitch cycles” organised by the ICS-TCS working group. “Pitches” are short-term projects jointly developed by individual TCSs together with members of the Integrated Core Services (ICS) development team aimed to establish and improve existing community services in the ICS portal. Within the scope of this activity, the two first tsunami services – access to the global sea-level monitoring facility (VLIZ) and access to the NEAMTHM18 tsunami hazard model (INGV) – were prepared to be integrated in the EPOS Service portal in the near future, and are now ready to start the validation process.

In early 2021, the core group prepared a self-assessment report of the readiness of the community and presented it to the SCC to officially start the process for granting the candidate TCS status. The core group appointed a representative of the TCS (GFZ), an alternate representative, further to technical (INGV), scientific (NGI and INGV), and administrative (GFZ) contact points. In the report, the envisaged structure and details of the future TCS service delivery framework was also described.

In July 2021, following several communications between the core group and the community by means of an irregular newsletter and numerous mail exchanges, the core group organised the 1st Community Meeting. During this meeting the core group reported on the activities and work progress, and also presented the concept of further TCS construction introducing the envisaged working groups on services, governance and consortium agreement.

On July 22, 2021, based on the pre-assessment made by the EPOS ERIC Service Coordination Committee and Scientific Advisory Board, the EPOS ERIC General Assembly granted the official status of a Candidate TCS Tsunami. The duration of the Candidate TCS status will be up to three years or until the validation process (governance, technical and financial) has been fulfilled.

4. Envisaged community services

The tsunami community has from its outset transferred science into hazard and risk assessment and tsunami warning operations. This community is also multi-disciplinary and multi-faceted, as it includes a broad range of disciplines such as geophysics, oceanography, engineering, numerical modelling, hazard and risk analysis. The rich spectrum of community activities will be naturally reflected in corresponding EPOS-related products and services that can be roughly systematised by four categories presented in Figure 2.

Correspondingly, the future EPOS Tsunami TCS plans to organise its work within four thematic *Pillars* each representing a specific family of DDSS (Data, Data-products, Services and Softwares, https://www.epos-eu.org/epos-services-list) elements. Figure 3 illustrates the four Pillars, and the four sub-sections below describe the envisaged services in more detail. Considering the multidisciplinarity of the envisaged services, it would be critical to interact with EPOS existing TCSs to remove possible overlaps and identify potential synergies.

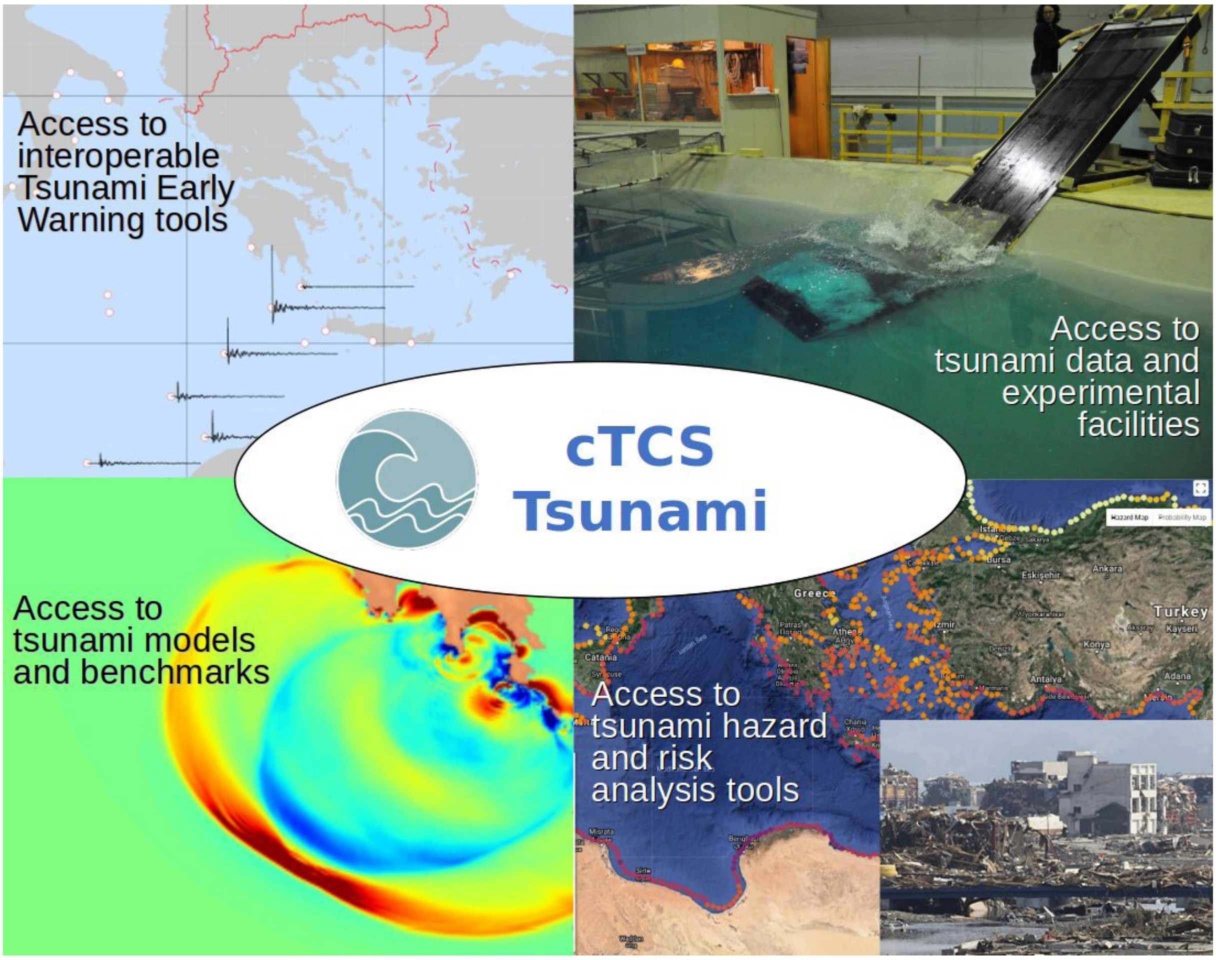

Figure 2. Main categories of the future TCS Tsunami products and services: from Tsunami Early Warning, data, experimental facilities, models and benchmarks, to hazard and risk analysis tools.

4.1 Pillar 1: Support to Tsunami Service Providers

This pillar will incorporate tools, workflows, and workspaces to facilitate interoperability of the official NEAMTWS Tsunami Service Providers (TSP) in their operational (= event processing in real time) but also preparatory

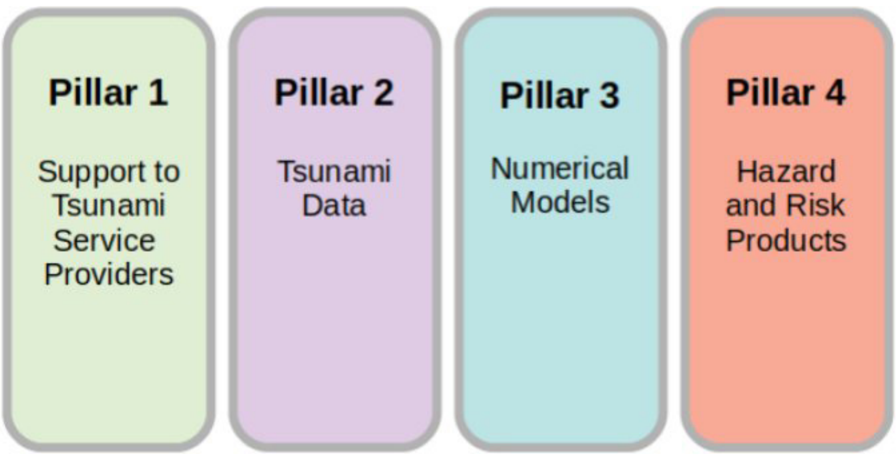

Figure 3. Four thematic Pillars of the future Tsunami TCS.

work. Initially oriented towards the 5 NEAMTWS presently accredited TSPs (in Portugal, France, Italy, Greece, and Turkey), and to the national tsunami warning centres, the services included in this Pillar will be open for further extension. In particular, it is envisaged that the real-time and subsequent rapid characterization of the tsunami events will constitute the basis for further research and understanding of the tsunami and its source.

The first DDSS element in this Pillar will be the so-called "TSP-IOT Interoperability tool": a virtual access (VA) to a web service including a common database (forecast points, sensor locations, bathymetry and topography models, etc.). Tools to enable data exchange (e.g., earthquake parameters and mechanism), warning information and enhanced products (e.g. alert level and tsunami travel time maps) in real-time are also under discussion. TSP-IOT tool will help warning centres to make their early warning operations interoperable and consistent, and to increase redundancy and fall-back solutions during acute event processing. An end-user oriented interface of the tool would allow accredited subscribers to access products and messages from all TSPs through a single point-of-entry. In a second stage of the implementation, additional tools, such as pre-computed scenario and/or earthquake finite fault model databases, will be used by the TSPs for continuous training and to retrospectively analyse past events. The TSP-IOT will be also enhanced with the functionality to access other databases and tools that will be facilitated under the TCS Tsunami such as, in a not too distant future, cloud or HPC simulation capabilities.

4.2 Pillar 2: Tsunami Data

Pillar 2 will provide services both via Virtual Accesses (VA) and Trans National Accesses (TNA). It will include VA to real-time sea-level monitoring facilities as well as to catalogues of historical and paleotsunamis. VA to datasets on submarine landslides, bathymetry- topography models, in accordance with FAIR principles, will also assist tsunami researchers and modellers. A link to potential earthquake sources, such as crustal faults and subduction systems, already offered in the TCS Seismology [Haslinger et al., 2022] will be provided, and collaborations will be sought to enhance the existing services for seamless use within the tsunami community. This Pillar also incorporates access to large experimental hydrodynamic experimental facilities as TNAs.

The sea level monitoring facility (SLMF) (Figure 4, http://www.ioc-sealevelmonitoring.org/) collects and processes in real time data from 1028 sea level measuring stations operated by 164 institutes (station operators) world wide. The system was built and is operated by Flanders Marine Institute (VLIZ) for UNESCO as part of the GLOSS (Global Sea Level Observing System) program of the Intergovernmental Oceanographic Commission. The station operators push the raw data to the SLMF using different data protocols: WMO GTS (Global Telecommunication System), FTP push, HTTP and even Email. Data is parsed in real-time and stored in the database. SLMF redistributes the parsed real time data through a series of interfaces: web-pages, rest-API, or GTS to the different users, including tsunami warning centers, station operators and scientific community. SLMF database contains sealevel data coupled with metadata, contact information and configuration data for sea-level stations and their sensors. Access to the SLMF data is one of the two cTCS-Tsunami pilot services to be integrated into the EPOS ICS Data Portal.

The distribution of historical tsunami data, and other services related to the Euro Mediterranean Tsunami Catalogue [EMTCv2, Maramai et al., 2021] will be available on the TCS portal. Information on historical tsunamis generated in the NEAMTWS area is classified by the generating cause, tsunami intensity, and reliability. A general description of the tsunami, related parameters, and bibliographic references are linked to each event. In addition, a second database, the Italian Tsunami Effects Database (ITED), documenting the tsunami effects observed along the Italian coasts will be provided. The description of the effects and quantitative data (local intensity, run-up, inundation, sea retreat, etc.), as well as the respective bibliographic references are indicated for each site in the database. The distribution of tsunami intensities over time (tsunami history) is available for each locality. Both databases are already available as OGC (Open Geospatial Consortium) services. An additional database about the Greek Tsunami Effects Database (GTED), which is under construction will be also provided by the Dept. of Geology, National and Kapodistrian University of Athens.

The ASTARTE Paleotsunami Deposits database is a relational geographic database on paleotsunami deposits. It comprises a total of 151 sites and 220 tsunami evidence (events) recorded for the whole North-East Atlantic and Mediterranean Sea region. Extending in the past the tsunami catalogues may help constrain or validate at least large event recurrence [Behrens et al., 2021]. The database has been implemented with the purpose to be the future information repository for tsunami research in Europe, integrating the existing official scientific reports and peer reviewed papers on these topics. The database is regularly updated.

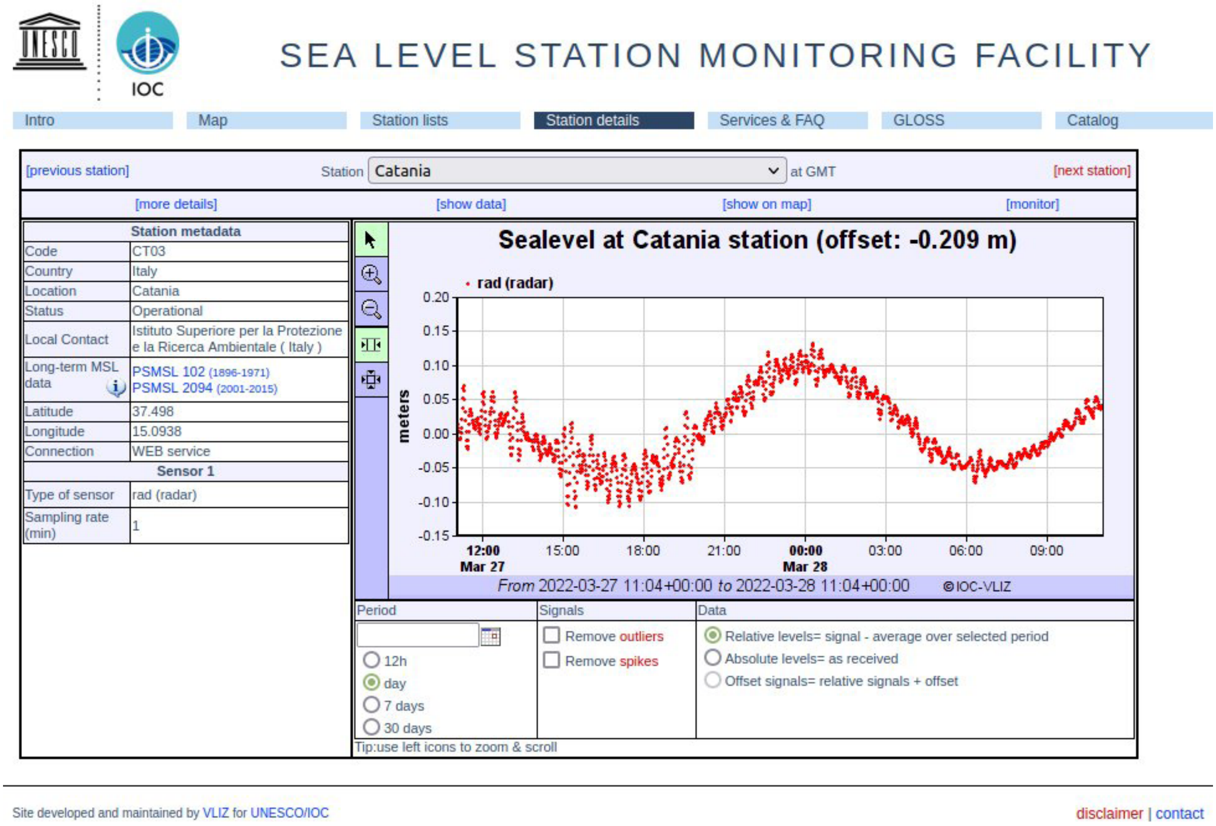

Figure 4. Screenshot of the Sea-Level Monitoring Facility at VLIZ (Oostende) displaying real time records of the March 4, 2021 Raoul Is. tsunami (Romano et al., 2021). Virtual Access to the SMLF facility is one of the two pilot services of cTCS Tsunami.

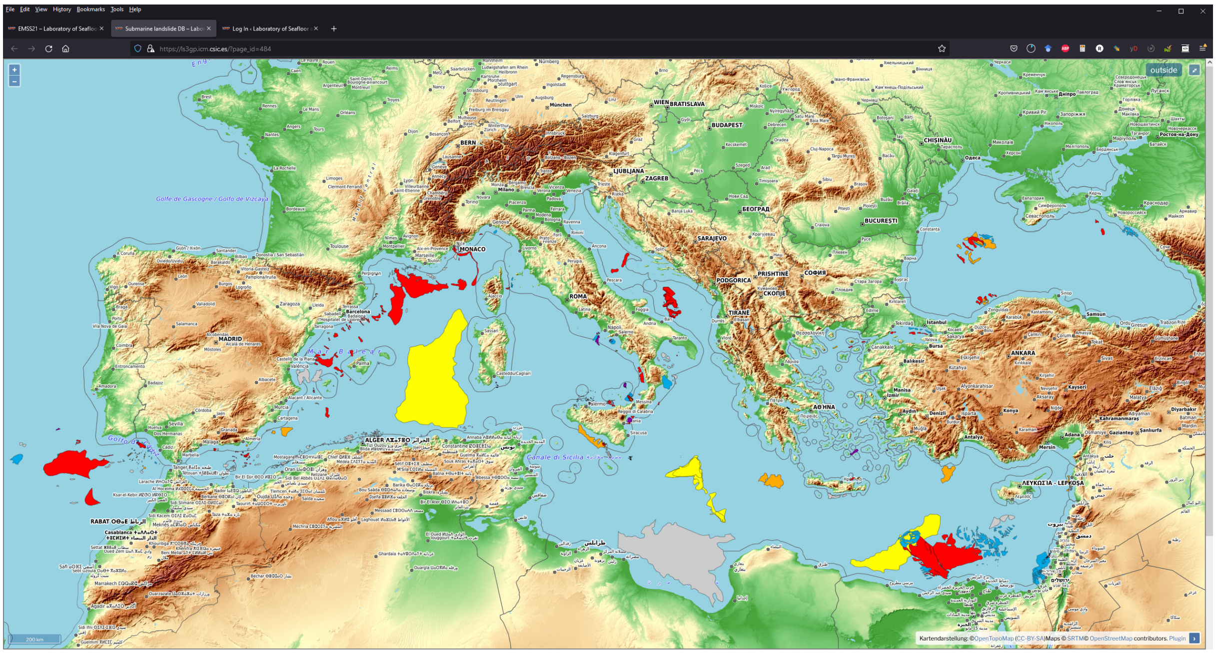

Figure 5. Screenshot of the web-mapper portal of the Euro-Mediterranean Submarine landSlide database (EMSS21) with submarine landslides color coded according to typology (yellow polygons- megaturbidites; red- debris flows; blue- slumps; orange- glides; purple- coastal failures; grey- generic mass transport deposits).

The Euro-Mediterranean Submarine landSlide database [EMSS21; Urgeles et al., 2021; see Figure 5] will provide services allowing scientists to derive information relative to the source and subsequent dynamics, which can be useful for Probabilistic Tsunami Hazard Assessment (PTHA) from submarine landslides. The relevant information to construct individual landslide tsunami scenarios will also be available. The dataset includes polygons and polylines for the landslide deposits, source areas and scars as well as information relative to age, volume, area, runout, thickness, typology, scar elevation, depth, and slope as well as the bibliographic information relative to each event amongst others. This dataset will be augmented with information from the recently compiled submarine landslide open-access database in the south and southwest Iberia Margin [Gamboa et al., 2021a]. The latter incorporates more than 1500 events, including their morphic features and the spatial and morphometric relationships between them [Gamboa et al., 2021b].

Currently, two experimental facilities have expressed their interest in the TNA program within the EPOS Delivery framework.

The HR Wallingford's Froude Modelling Hall (Figure 6) has a total extent of approximately 14,400m^2. These physical laboratory test facilities provide a global service to support water related engineering projects, including the installation offered for TNA: the Fast Flow Facility (FFF) with Tsunami Simulator. HR Wallingford's state-of-the-art Tsunami Simulator is the outcome of 10 years of collaboration between HRW and UCL [see Chandler et al., 2021]. It is situated within the FFF and data acquisition systems are backed up by a range of instrumentation that enables detailed measurements to be made. The facilities and instrumentation are supported by a dedicated electronics laboratory, workshops (for handling metal, plastics, wood and other materials), a sediment/rock preparation laboratory and a specialist building team. A single deployment of the Tsunami Simulator in the FFF is being offered with the expectation that multiple projects will be undertaken consecutively by one or more research groups.

The Coastal Engineering, Oceanography and Hydraulics Laboratory of IH Cantabria performs physical model testing in which phenomena related to the generation and propagation of waves, wave-wave interaction and wave-structure, stability and behaviour of coastal protection structures, breakwaters and marine structures, behaviour of floating structures, operation of valves and hydraulic machine and device testing marine energy generation are studied. The lab offers the Cantabria Coastal and Offshore Basin (CCOB) and the Wave-Current-Tsunami Flume (CoCoTsu), being among the largest and most advanced hydraulic facilities in Europe and worldwide. Services offered by the infrastructure include 2D and 3D physical modelling of a variety of different scenarios, an applied toolbox for post-processing tasks, and Model Manufacturing: building and/or modifying of hydraulic tailored scale models and a wide range of systems and equipment for measurement and instrumentation both in laboratory tests and field measurement campaigns.

Figure 6. HR Wallingford's Froud Modelling Hall. The picture shows the 4m wide Fast Flow Facility during tests conducted for URBANWAVES, with the Tsunami Simulator seen at the far end of the flume.

For meteorological tsunamis (also known as meteotsunamis), a global 1-min sea-level dataset named MISELA has been recently published [Zemunik et al., 2021] and will be accessible in EPOS. It encompasses quality-checked records of non-seismic sea-level oscillations at tsunami timescales, that is with periods below 2 h, obtained from 331 worldwide tide-gauge sites. To account for historical events, EPOS will make accessible information from the global scale meteotsunami catalogues that have been recently compiled [e.g., Gusiakov et al., 2021], suggesting 235 events as confirmed or suspected meteotsunamis.

4.3 Pillar 3: Numerical Models

Pillar 3 will provide access to all kind of software and simulation data resources including:

- Software repositories with source codes (e.g. GitHub);
- Simulation-data repositories (e.g., amplification factors or pre-calculated Green's functions);
- Virtual accesses (VA) to online tsunami simulation tools;
- Virtual and Transnational Accesses (VA/TNA) to HPC Workflows as a Service (WaaS).

Since tsunami science is mostly simulation-oriented, this Pillar will be broadly relevant. Some examples are described in the following.

The representation of earthquakes as tsunamigenic sources is a major component in tsunami simulations. Spatial variation of slip, particularly at shallow depths, can have a large impact on tsunami wave height, particularly in the near field [Geist et al., 2002; Ulrich et al., 2019] which can influence tsunami hazard assessment [Scala et al., 2020; Basili et al., 2021] and the probabilistic tsunami forecasting [Selva et al., 2021b]. cTCS Tsunami will provide services for generation of earthquake source scenarios, based on stochastic and physics-based, depth-dependent slip distributions, representative of the earthquake rupture history on planar and non-planar geometries of the subduction zones. These distributions obey the k-square fractal law in the definition of the slip asperities and are implemented in the K223d software [Herrero and Murphy, 2018; Murphy and Herrero, 2020].

Tsunami propagation modelling suite will include the flagship *Tsunami-HySEA* code designed for quake generated tsunami simulations [Macías et al., 2017, 2020a,b]. *Tsunami-HySEA* is a fully nonlinear shallow water model implemented in multi-GPU architectures. Thanks to the GPU acceleration, a numerical simulation of a tsunami on a relatively high-resolution domain can be simulated much faster than the evolution of a real tsunami. *Tsunami-HySEA* was initially developed to be integrated in early warning systems. Two-way telescopic nested meshes can be used for high-resolution inundation simulations, and a dispersive version of the code is also available. The code was extensively tested and validated against prescribed benchmarks for operational use.

Another tsunami simulation code that will be made available is *TsunAWI* [Rakowsky et al., 2013], a model for wave propagation and inundation based on finite elements. It operates on triangular meshes which allow great freedom with respect to the discretization of complicated coastlines and bathymetric features. Different versions of advection and run-up schemes are implemented. The model was developed in the framework of the GITEWS project and is currently used for the determination of warning products for the tsunami database of the Indonesian Tsunami Early Warning System (InaTEWS) as described in Harig et al. [2020].

An alternative to high-resolution local inundation modelling is the application of amplification factors. In EPOS, a set of amplification factors will be provided for two datasets, either global [Løvholt et al., 2012] or related to the NEAM region [Glimsdal et al., 2019]. Amplification factors relate the maximum offshore wave amplitude at a given reference depth to the maximum inundation height plus its uncertainty. Being computed along transects assuming linear non-breaking waves implies that the amplification factors involve a much higher uncertainty than local inundation models do. Some of this uncertainty stems from the local inundation height variability in a local inundated area. The strength of this method, while carrying large uncertainties, is that it is able to estimate inundation heights for use in for instance PTHA over large areas.

The cTCS Tsunami simulation suite will also include the *Tsunami Toolbox*, a suite of codes and data enabling approximate tsunami modelling based on linear combinations of pre-calculated elementary tsunami scenarios. The suite will be geographically expandable, allowing interested users to include their own regions, based on the *Tsunami-HySEA* code. This tool will be interoperable with both the stochastic slip modelling tools and the amplification factors, to allow users to build their own computationally effective simulation workflows in any part of the world.

Simulation of landslide-generated tsunamis will be represented by a number of tools. Landslide dynamics are often important for determining the tsunamigenic strength and the details of the tsunami generation. Characteristics of tsunami generation can be very different depending on whether the landslide is subaerial or submarine. Subaerial landslides are well characterised by the landslide size and impact [e.g. Rauter et al., 2021] while submarine landslides are determined by the landslide evolution and in particular the acceleration phase, water depth, and slope [e.g. Løvholt et al., 2015; Snelling et al., 2020]. For submarine landslides, the rheology will control the dynamics of the landslide, which in turn affects tsunami-genesis [Kim et al., 2019]. Most submarine landslides are clay dominated, implying that their dynamics can be described using cohesive models. In EPOS, we will provide a service related to modelling cohesive landslide dynamics using the *BingClaw* model [Løvholt et al., 2017; Kim et al., 2019]. This model has been used extensively over the last few years for modelling landslide dynamics, and the coupling to tsunami generation. *BingClaw* is a two-layer depth averaged landslide model based on the Hershel-Bulkley rheology. It offers the opportunity to link tsunamigenesis to the material properties of the sediments.

Landslide-HySEA is a numerical model of the HySEA family designed for landslide generated tsunami simulations [Macías et al., 2015; González-Vida et al., 2019]. This code implements a 2D coupled system composed of two models, one for the slide material represented by a Savage-Hutter type of model and the water dynamics model is represented by the fully non-linear shallow-water equations. A dispersive, weakly coupled version of the model is also available. The *Multilayer-HySEA* [Macías et al., 2021a, b] is a more recent model of the HySEA family implemented to consider a richer vertical structure in simulated solutions. This code represents an efficient hybrid finite-volume–finite-difference implementation on GPU architectures of a non-hydrostatic multilayer model and has been specifically benchmarked.

Another landslide modelling approach is presented in the model *CaLypSo*. This model is based on Navier-Stokes equations for a three-layer (landslide-water-air) boundary-value problem in an arbitrary 3-D domain. It is developed for the computation of the generation and propagation of tsunami waves under the impact of underwater/surface landslide [Androsov et al., 2014; Voltzinger and Androsov, 2015]. The problem is solved in curvilinear boundary-fitted coordinates. The numerical method is realized by splitting in coordinate directions using the module of the nonhydrostatic pressure computation for the water layer. The numerical method uses a switcher to approximate advection to third-order accuracy, a TVD procedure (Total Variation Diminishing), a wetting and drying algorithm, and algorithms for layer friction parameterization.

For meteotsunamis, modelling involves the use of (sub-)kilometre-scale atmospheric models capable of reproducing the atmospheric disturbances (or internal gravity waves) that trigger the tsunami-like ocean waves ideally represented with unstructured ocean models up to 10 m resolution near the coasts. In the Adriatic Sea, such a numerical tool was designed to forecast meteotsunamis operationally: the Adriatic Sea and Coast (*AdriSC*) modelling suite [Denamiel et al., 2019a]. In EPOS, domains (including atmospheric and ocean grids and unstructured mesh), workflow (including bash scripts) and model codes will be provided for the *AdriSC* modelling suite version used to forecast meteotsunamis in the Adriatic Sea (i.e. the *AdriSC* meteotsunami forecast component). Additionally, the major uncertainties of the forecast reside on the capacity of the atmospheric models to reproduce the atmospheric disturbances (i.e. geographic location, intensity, speed, period, etc.) that trigger the meteotsunami waves. To account for these uncertainties a stochastic surrogate model has been implemented within the *AdriSC* modelling suite, the *AdriSC MTsurrogate* model [Denamiel et al., 2019b, 2020]. The surrogate model is based on a generalised Polynomial Chaos Expansion (gPCE) methodology that propagates the uncertainties linked to the atmospheric disturbance to the extreme sea-level forecast at sensitive harbour locations along the Adriatic Sea. The developed surrogate model has been successfully applied for several meteotsunami events in the Adriatic Sea. It provides conservative extreme sea-level forecasts even for events missed with the deterministic *AdriSC* model [Denamiel et al., 2019b; Tojčić et al., 2021]. In EPOS, the polynomial coefficients, the Matlab scripts and the user interface of the *AdriSC MTsurrogate* model will be provided.

An innovative aspect of the TCS Tsunami delivery framework will be the provision of both VAs and TNAs to Workflows as a Service (WaaS), based on HPC resources, in cooperation with the ChEESE Centre of Excellence (ChEESE CoE) for Exascale supercomputing in the area of solid Earth. Numerical services and workflows were developed during several European projects (e.g. ChEESE, eFlows4HPC) and initiatives, and tested with PRACE awarded simulation campaigns. For both VAs and TNAs, it is foreseeable that the TCS will be offering a training, a project design and a project execution phase. The users will be trained for the usage of the softwares and of the computational infrastructure, and accompanied in the development of new experiments exploiting the TCS workflows. One example is the probabilistic tsunami forecasting based on large ensembles of high-resolution tsunami simulations [Gibbons et al., 2020; Selva et al., 2021b]. Another examples are innovative and efficient numerical techniques to model physics-based tsunami-earthquake interaction [Wirp et al., 2021; Krenz et al., 2021].

While this manuscript was in the revision phase, two new projects were funded by the Horizon Europe program 2021 call funding Research Infrastructures: Geo-INQUIRE and DT-GEO, both launched by the broader geo-hazard community. Among other EPOS RI strengthening activities, Geo-INQUIRE will in particular facilitate long-term sustainable access to computationally-based services stemming from the efforts of the tsunami community members within the ChEESE CoE project. In turn, DT-GEO will be operating within the framework of the new European flagship Destination Earth initiative (see Section 2.3) and will develop a prototype *Digital Twin on Geophysical Extremes* consisting of interrelated components dealing with geohazards including earthquakes (both natural and anthropogenic), volcanoes, and earthquake/landslide-triggered tsunamis.

4.4 Pillar 4: Hazard and Risk Products

The last Pillar will incorporate access to data repositories, codes, and online tools aimed at generating and presenting hazard and risk results. Datasets on existing tsunami exposure and vulnerability models will be made accessible, together with methodological guidelines, engineering assessment tools and statistical codes for future exposure capture and vulnerability model development. Whenever possible, data will be published through open standard web services like those described by the Open Geospatial Consortium. Existing and future hazard, exposure, and vulnerability models will be harmonised with those of the seismic community (to foster multi-hazard risk assessment) and made available to different end-users: researchers, civil protection authorities, decision and policy makers, and the general public. The European NEAMTHM18 probabilistic hazard model [Basili et al., 2021; Figure 7] will be the first focus for this harmonisation. Local case studies like risk assessment in terms of building replacement cost [Triantafyllou et al., 2018] will be presented as well.

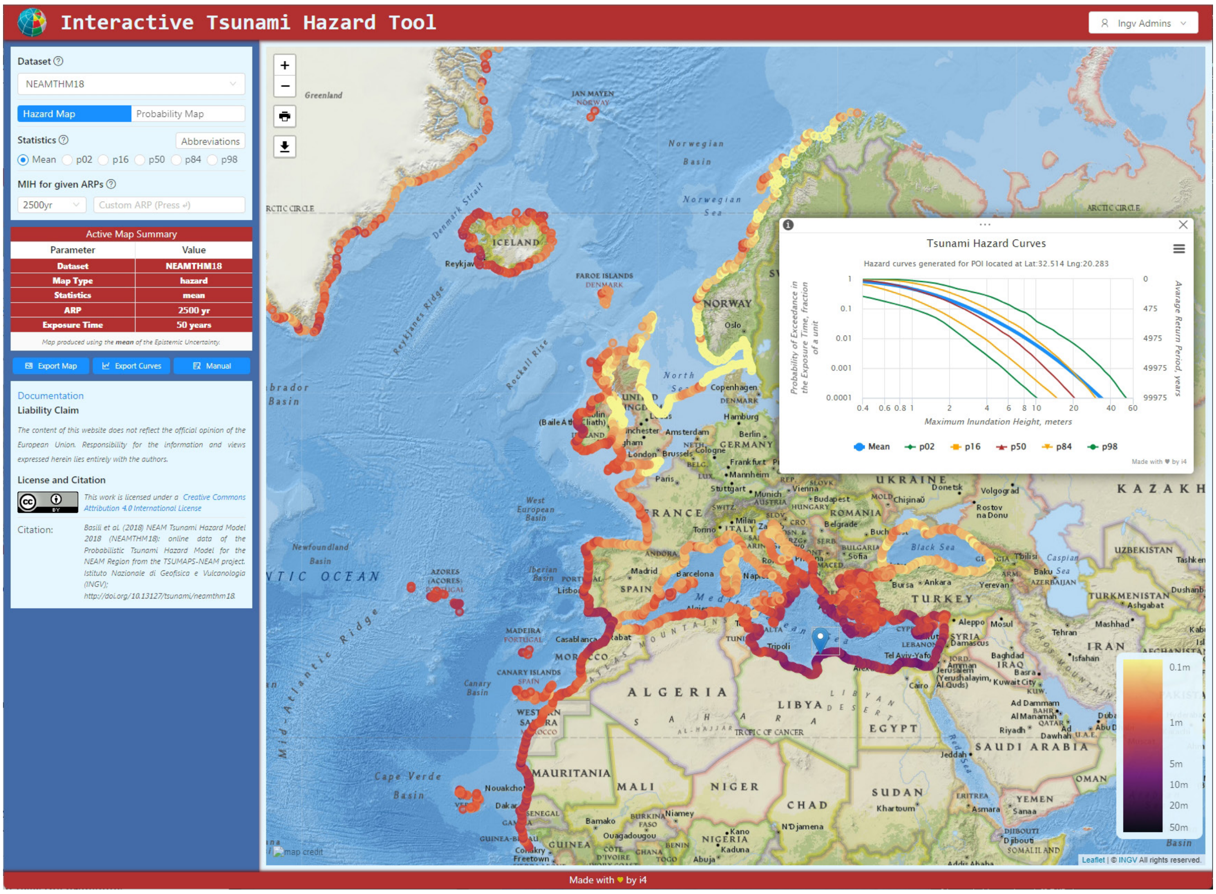

Figure 7. Interactive web-mapper showing the European NEAMTHM18 probabilistic hazard model [Basili et al., 2021] data and navigation tools. Virtual Access to this tool is another pilot service of cTCS Tsunami.

In a similar way to the WaaS provision foreseen for the simulations, several WaaS for hazard assessment based on HPC will be provided. One of these services relates to the local probabilistic tsunami hazard analysis (PTHA), facilitating workflow and software for carrying out numerous (in the order of tens to hundreds of thousands) high-resolution simulations and integrating these results into probabilistic outputs. This workflow has been developed during the H2020 ChEESE project, and is set up for use in the NEAM region. To this end, it uses the probabilistic outputs of the NEAMTHM18 model [Basili et al., 2021; TSUMAPS-NEAM project] as input to set up local PTHA analysis on high resolution grids. The core HPC part uses *Tsunami-HySEA* with telescopic grids, and the setup has been successfully tested on the Tier-0 machine Marconi100 [Tonini et al., 2021; Gibbons et al., 2020].

The Tsunami Structural Engineering Analysis Hub (TSEA-Hub, https://www.tseahub.net) brings together the latest tsunami engineering analysis and assessment tools from across the globe. TSEA-Hub is contributed to by a number of international institutions with strong research track records in tsunami engineering. The service directly hosts or provides links to a range of tools and codes that can be used to assess or design single assets for tsunami loading, to analyse classes of buildings for fragility analysis, or to assess assets at a network or urban level using vulnerability and risk index-based approaches. It hosts survey forms for exposure capture pre-tsunami that specifically account for attributes that reduce or increase an asset's vulnerability to this hazard. It also provides access to post-tsunami damage data collection tools for use in reconnaissance missions. The service will provide training materials on the use of the different tools, developed by the TSEA-Hub community of international contributors. Under the framework of the new cTCS, TSEA-Hub will link with the European Tsunami Risk Service, developing shared taxonomies and ensuring data is interoperable.

The European Tsunami Risk Service (ETRiS) provides DDSS useful for performing tsunami risk analysis. This service, for the most part, collects the available vulnerability and risk-related datasets and models and ensures that they adhere to FAIR principles. More specifically, it includes a tsunami consequence database collecting available datasets reporting impacts, incurred damages and societal consequences of past tsunami events. It also features selected available tsunami fragility models (empirical and analytic), vulnerability, and consequence models in the literature. The service provides software tools useful for statistical post-processing of the consequence datasets to derive fragility and vulnerability models, estimate the uncertainties in a given model, and select the most suitable one considering both the goodness of fit and model parsimony. ETRiS will link with the PTHA-related datasets and services (e.g., European NEAMTHM18 Model and local PTHA workflows) and the Tsunami Structural Engineering Analysis Hub to ensure interoperability, in hazard, exposure and vulnerability models. The service also strives to provide access to tools in diverse forms, e.g., as raw code, live notebooks, web services, and containerized applications to provide users with the possibility of running them across different platforms.

5. Outlook

The next steps for the development of the new EPOS cTCS Tsunami will be implemented by several dedicated working groups (WGs). Up to now, four working groups have been established, each covering specific responsibilities towards construction of a full-fledged TCS within the next three years of candidacy.

1) WG-Core is a core team coordinating all TCS capacity building activities.
2) WG-Governance: this group will develop the TCS Tsunami Governance model: structure, composition of boards, roles of service and data providers, liaisons with other TCSs and external organisations.
3) WG-Consortium Agreement has an ultimate goal to organise compilation, discussion, dissemination, and finally signature of the TCS Consortium Agreement by all TCS partners.
4) WG-Services is the largest working group. This WG will organise integration of DDSS elements into both community and EPOS Integrated Core Services (ICS) data portals. In particular:
   - assess candidate products and services for their feasibility to be integrated into the EPOS DDSS granularity database;
   - develop a roadmap for integration of individual services;
   - provide technical support along the roadmap (e.g., by following blueprint solutions);
   - provide support for the TCS Tsunami entry into the EPOS Cost-Book.

The two pilot community services -- (i) Global sea-level monitoring facility presented by Flanders Marine Institute (Oostende, Belgium) and (ii) European probabilistic tsunami hazard model NEAMTHM18 presented by INGV

(Rome, Italy) – have already undergone EPOS ICS data portal integration efforts during 2021 TCS-ICS development pitches, and, after the final validation and performance testing activities, will be soon available through the Service Delivery portal. These two pilot services will open the door, as blueprints, for the further integration of community data and products (see Section 4) under the support of WG-Services.

Besides the integration into the main EPOS ICS (Integrated Core Service) cross-community data portal, tsunami community resources will be also presented in a harmonised way through the new Community Portal (Figure 8) (http://www.tsunamidata.org).

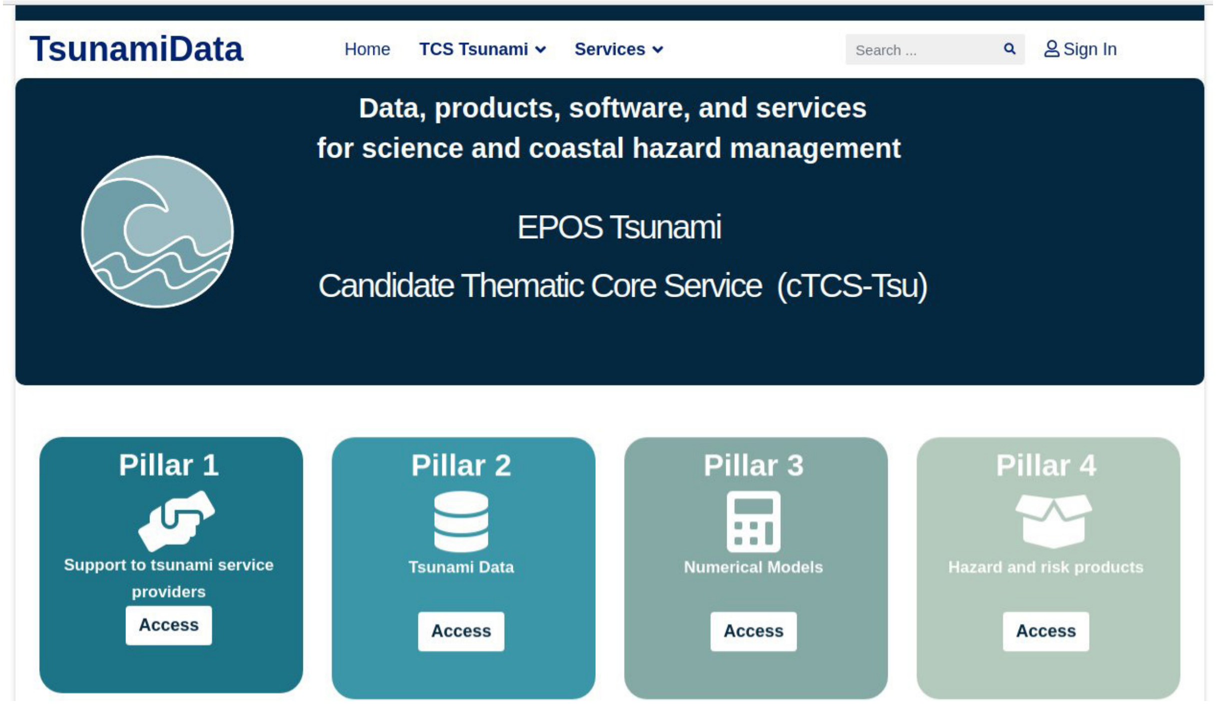

Figure 8. Screenshot of the homepage of the Tsunami Data portal (https://tsunamidata.org).

Due to its natural affinity to the rapidly developing HPC-technologies, cTCS Tsunami will contribute to the planning and development of future EPOS ICS-D (Distributed Integrated Core Services) elements. Specifically, by presenting use cases dealing with HPC-computing requiring mobilisation of external HPC-resources. cTCS representatives already take part in correspondent TCS-ICS development pitches. One potential contribution to the ICS-D is also exemplified by current efforts towards participation in the above mentioned European flagship program Destination Earth (see Section 2.3), in particular towards the creation of a *Digital Twin on Geophysical Extremes* including tsunamis (project DT-GEO, Section 4.3).

Last but not least, at a broader scope, the Tsunami Community considers participation in EPOS also as an integration point for community development. The existence of a TCS:

- may become a community "meeting point", a permanent alternative to large (but intermittent) international projects;
- motivates and provides practical support in bringing research outcomes (data, software) to high technology readiness level and, as a consequence, "closer" to less-specialised end-users;
- may push researchers to create synergies and to make their products interoperable (e.g., to develop community standards for data and models);
- fosters joint participation in fund-raising programs (e.g., EU-Projects).

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