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Some reflections on tsunami Early Warning Systems and their impact, with a look at the NEAMTWS

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ABSTRACT This paper discusses some features of Early Warning Systems (EWSs), with a particular focus on those dealing with tsunamis. First, a description is presented of what the international organisations have suggested on the matter, starting from the Sendai Framework 2015-2030, in which several useful arguments are outlined. For tsunamis, a wide literature is available, thanks to the efforts of UNESCO-IOC (Intergovernmental Oceanographic Commission) and of many Tsunami Warning Systems (TWSs) operating worldwide since the half of 20th century. Then, some aspects of the recently established Tsunami Alert Centre (CAT) of INGV in Italy are described, focusing on the warning procedures and on the issue of the uncertainties in the real time estimates, which has been recently discussed within the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the north-eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS). Finally, an analysis of the status of the NEAMTWS after almost 15 years of implementation is proposed, underlining the key achievements obtained in the upstream component (the technological part of monitoring and alerting), but also the strong limitations of the downstream part, that in many countries, including Italy, is still the weakest part of the alerting chain, as also seen in recent events affecting the Mediterranean.

Key words: tsunami, early warning system, NEAMTWS.

1. Introduction

Early warning systems (EWSs) are important tools for risk mitigation. However, for earthquakes and tsunamis, the rapidity needed to assess the risk implies that the real time estimates (magnitude, ground shaking, inundation areas, etc.) are often affected by large uncertainties. This is crucial for earthquake EWS (EEWS), in which the alerting time range between a few seconds to a maximum of 1-2 minutes, but also for Tsunami (Early[1]) Warning Systems (TEWSs or TWSs). Although for trans-oceanic tsunamis the travel times of sea waves may exceed 20 hours, for local sources the first waves could strike in less than five minutes after the earthquake occurrence. It happened for instance in the 2018 devastating tsunami in Sulawesi (Indonesia) but also during the seismically

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[1] The use of the word "early" is somehow subjective in the field of warning systems. The meaning of the term changes depending on the type of phenomenon under consideration and the related times of possible action. Early for earthquakes means seconds, for tsunamis minutes, for other phenomena it might refer to hours. In this paper I will use TWS for tsunami (early) warning systems.

induced tsunami that hit Sicily and Calabria in 1908. In recent years, TWSs have started to release alert messages in times that are compatible with this limit, increasing the possibility to enact defensive response and save lives. At the same time, these technological advancements have increased the liability of scientists and engineers, who might be more likely prosecuted in case of damages and fatalities.

A crucial issue for the success of both TEWSs and EEWSs (especially those recently established), is the ability of people to react in the right way. Therefore, besides the technological challenge of being faster and more accurate, two main goals appear to be fundamental today: the first one is the capability of the warning systems to reach people at risk; the second one is the need of raising awareness in the population. The first issue is a hard technological challenge, needs investments and skills; the second one is, perhaps, even more difficult to reach, since it involves human behaviours, perception, and actions. Anyway, if the second component is lacking, the efficiency of an EWS, even a well performing one, would be substantially decreased. This is well known for tsunamis due to tens of events of the past decades in which a wrong behaviour of people at risk has determined an incredibly high number of fatalities.

Also for EEWSs the issue of people's expectations and preparedness is crucial, as demonstrated by the recent, magnitude 7.1 earthquake in Ridgecrest, California (6 July 2019), that raised an interesting debate on EEWS performance, as discussed in several scientific documents and newspapers (see "It worked… and it did not", https://seismo.berkeley.edu/blog/2019/07/10/it-worked-and-it-did-not.html).

In this paper, the general framework of EWS is described first, as outlined in the international documentation, with particular emphasis on the tsunami EWS (see the acronyms in Table 1). For these, a coordinated effort has been put in place in the last decades by UNESCO-IOC (Intergovernmental Oceanographic Commission) that gave some general, broadly adopted regulatory framework. Then, some examples of applications are presented, derived from the experience of the recently established Italian Tsunami Alert Centre of INGV (CAT-INGV) operating in the Mediterranean. Finally, some of the main challenges and criticalities of EWSs are described, with a focus on the NEAMTWS status after almost 15 years of activity from its creation in the UNESCO-IOC framework. In this paper, the focus is on seismically generated tsunamis, the only ones that are currently managed by the TSPs worldwide due to their predictability.

2. EWS for DRR - Generalities

The Sendai Framework (SF2015) outlines the main objectives for Disaster Risk Reduction (DRR, see all acronims in Table 1) in the period 2015-2030, and the tools needed to achieve them. In the Sendai declaration, it is stated that "We call all stakeholders to action, aware that the realisation of the new framework depends on our unceasing and tireless collective efforts to make the world safer from the risk of disasters in the decades to come for the benefit of the present and future generations". The key words here are: unceasing/tireless, collective, future generations. It is recognised the need of thinking and acting in the long run (decades) and without hesitation, it is recommended that everyone makes her/his own part, being aware that it will not be easy. However, it is a necessary effort, for the present and the future generations.

The need to involve, in DRR, not only governmental and international institutions, but all the

Table 1 - List of acronyms used in the paper.

CARIBE TWS:	Tsunami Warning System for the Caribbean region
CAT-INGV:	Centro Allerta Tsunami (Tsunami Alert Center) of INGV
CENALT:	CENtre d'Alerte aux Tsunamis (France)
cTSP:	candidate Tsunami Service Provider
DM:	Decision Matrix
DPC:	Italian National Civil Protection Department
DRR:	Disaster Risk Reduction
EWS:	Early Warning System
EEWS	Earthquake Early Warning System
GNSS:	Global Navigation Satellite System
HF2005:	Hyogo Framework for Action (2005-2015)
ICG:	Intergovernmental Coordination Group
INGV:	Istituto Nazionale di Geofisica e Vulcanologia (Italy)
ISPRA:	Istituto Superiore per la Protezione e la Ricerca Ambientale (Italy)
IOTWS:	Indian Ocean Tsunami Warning and Mitigation System
IOC:	Intergovernmental Oceanographic Commission
IPMA:	Instituto Português do Mar e da Atmosfera (Portugal)
KOERI:	Kandilli Observatory and Earthquake Research Institute (Turkey)
NEAMTWS:	North-Eastern Atlantic, the Mediterranean and connected seas TWS
NOA:	National Observatory of Athens (Greece)
NTWC:	National Tsunami Warning Center
PTF:	Probabilistic Tsunami Forecast
PTHA:	Probabilistic Tsunami Hazard Assessment
PTWS:	Pacific Tsunami Warning System
RMN:	Rete Mareografica Nazionale (Italian National Mareographic Network)
SF2015:	Sendai Framework for Disaster Risk Reduction (2015-2030)
SiAM:	Sistema di Allertamento nazionale per i Maremoti generati da terremoti (Italy)
SOP:	Standard Operational Procedure
S-PTHA:	Probabilistic Hazard Assessment for Tsunamis of seismic origin
TEWS / TWS:	Tsunami (Early) Warning System
TWFP:	Tsunami Warning Focal Point
TSP:	Tsunami Service Provider
UNDRR (formerly UNISDR):	United Nations Office for Disaster Risk Reduction (United Nations International Strategy for Disaster Reduction)

society components, is not a new concept, indeed. In July 1999, the UN Secretary-General Kofi Annan, speaking at the International Decade for Natural Disaster Reduction (IDNDR) Programme Forum in Geneva, said that "Much has been learnt from the creative disaster prevention efforts of poor communities in developing countries. Prevention policy is too important to be left to governments and international agencies alone. To succeed, it must also engage civil society, the private sector and the media."

The four priorities set by SF2015 are: a) understanding disaster risk; b) strengthening disaster risk governance to manage disaster risk; c) investing in DRR for resilience; d) enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction. The SF2015 also recognises the progress achieved in the previous decade, following the "Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters" (HF2005), but also enhancing gaps that need to be filled. One of the priorities of the HF2005 was to "identify, assess and monitor disaster risks and enhance early warning"; the SF2015 goes further, setting as an expected outcome, to "substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030". In SF2015, the role of people is emphasised, not only as recipients of information and warning, but also as actors of the DRR plan. As mentioned above, the Priority 4 of SF2015 is "Enhancing disaster preparedness for effective response", i.e. the focus is on people, on their involvement, and on the need to make scientific and risk information available and understandable.

In order to provide a comprehensive view of what an EWS should be, and how it should work, it is useful to start from another document released after HF2005, namely the 2006 UN-ISDR document "Developing early warning systems: a checklist". [In: Third International Conference on Early Warning (EWC III), United Nation/International Strategy for Disaster Reduction (UN/ISDR)]. In that document it was already clear that the key actors in the strategy for DRR through EWSs are many: communities; national, regional, local governments; regional institutions and organisations; international bodies; scientific and academic communities; the private sector; non-governmental organisations. The scientific and academic community, in particular, is called to analyse and assess the hazard, to create and improve EWSs, but must also be able to disseminate understandable information and warnings to people.

The four pillars outlined by UNISDR (now UNDRR) for EWS are: a) risk knowledge; b) monitoring and warning service; c) dissemination and communication activities; d) response capability. For each of the four pillars, the UNDDR listed a series of suggestions and questions, most of which are still relevant and open after almost fifteen years of implementation. In the following, the contents of these four pillars and the related open questions are summarised.

a) (Hazard) Risk knowledge (systematic collect data and undertake risk assessment).
   Risks arise from the combination of hazards, exposition, and vulnerabilities at a particular location. Assessments of risk require systematic collection and analysis of data and should consider the dynamic nature of hazards and vulnerabilities that arise from processes such as urbanisation, rural land-use change, environmental degradation and climate change. Risk assessments and maps help to motivate people, prioritise early warning system needs and guide preparations for disaster prevention and responses. The three questions posed in the 2006 UNDRR document were: a) are the hazards and the vulnerabilities well known? b) what are the patterns and trends in these factors? c) are risks maps and data widely available? We will see later the answers that can be given today for Italy and the Mediterranean region. An updated review of global trends in tsunami science for hazard and risk understanding is in Løvholt *et al.* (2019).
b) Monitoring and warning service (developing hazard monitoring and early warning services).
   Warning services lie at the core of the system. There must be a sound scientific basis for predicting and forecasting hazards and a reliable forecasting and warning system that

operates 24 hours a day. Continuous monitoring of hazard parameters and precursors is essential to generate accurate warnings in a timely fashion. Warning services for different hazards should be coordinated where possible to gain the benefit of shared institutional, procedural, and communication networks. The questions posed by UNDRR in 2006 were: a) are the right parameters being monitored? b) is there a sound scientific basis for making forecasts? c) can accurate and timely warnings being generated?

c) Dissemination and communication (communicate risk information and early warnings).
Warnings must reach those at risk. Clear messages containing simple, useful information are critical to enable proper responses that will help safeguard lives and livelihoods. Regional, national and community level communication systems must be pre-identified and appropriate authoritative voices established. The use of multiple communication channels is necessary to ensure as many people as possible are warned, to avoid failure of any one channel, and to reinforce the warning message. The questions here are: a) do warnings reach all those at risk? b) are the risks and warnings understood? c) is the warning information clear and usable?

d) Response capability (Build national and community response capabilities).
It is essential that communities understand their risks; respect the warning service and know how to react. Education and preparedness programmes play a key role. It is also essential that disaster management plans are in place, well practiced and tested. The community should be well informed on options for safe behaviour, available escape routes, and how best to avoid damage and loss to property. The three questions for this pillar are: a) are response plans up to date and tested? b) are local capacities and knowledge made use of? c) are people prepared and ready to react to warnings?

After the 2006 UNISDR document and the 2015 Sendai conference and declaration cited above, in a more recent meeting held in Geneva, Switzerland, in May 2019 (The Second Multi-Hazard Early Warning Conference - MHEWC-II), the importance of making multi-hazard early warning and risk information available to everyone has been emphasised again, spurring national governments to implement and sustain them.

3. TEWS - Brief historical perspective

One of the first examples of "early warning" for tsunamis comes from Japan, and it became a legend. At the end of the 20th century, a popular story came out about an old man living in the mountains who saw a huge wave coming in, and set "the fire of rice" to warn people living in the Ansei coastal village below that a tsunami was coming. The tale emphasises the importance of warning systems when earthquakes hit, and is reported in textbooks in Japan. The legend was based on a real event in the life of Hamaguchi Goryo, a man living in the village. Goryo's action really helped to warn people in the area of an upcoming tsunami, saving many lives. It was 5 November 1854, and that day is now celebrated yearly as the World Tsunami Awareness Day (WTAD).

Modern EWSs for tsunamis date back to the middle of the 20th century, after a large earthquake (magnitude 8.6) occurred in 1946 in the Aleutians Islands. The earthquake triggered a powerful tsunami that killed more than 100 people in the Hawaii islands, several hours later. The first TWS was, then, established in Hawaii. Years later, after the 1960, magnitude 9.5 Chilean earthquake, the Pacific Tsunami Warning System (ICG/PTWS) was established in 1968 under the coordination of UNESCO-IOC. Since then, several warnings were released in the following decades for large earthquakes along the Pacific ring of fire, contributing to save lives and reduce damage. However, more than half a century later in the Indian Ocean, the 2004, magnitude 9.3 earthquake in Sumatra triggered a powerful tsunami that caused more than two hundred thousands of victims in the Indian Ocean. Such a heavy toll was mostly due to the lack of a TWS in the region, and to unpreparedness of residents and tourists. The tsunami killed even a few hundreds people in Somalia, on the other side of the ocean, despite the waves arrived several hours after the earthquake. An updated review of recent large tsunamigenic earthquakes worldwide is in Romano *et al*. (2020).

Today, several tsunami warning centres are operating in all the hazardous areas of the world, organised and coordinated by UNESCO-IOC in four ICGs (Intergovernmental Coordination Groups), namely the Pacific (PTWS), Indian Ocean (IOTWS), Caribe (CARIBE TWS), and the North-East Atlantic, Mediterranean and connected seas (NEAMTWS). This latter ICG operates in areas of large tsunamis occurred in historical times (such as those occurred in 365 A.D. and 1303 A.D. in Crete, in 1755 in the Portuguese off-shore, in 1908 in Sicily-Calabria, among many others). However, since no large events have occurred in recent years, the tsunami risk is underrated in many countries of the NEAM region, both by authorities and by people living or travelling in the coasts at risk. It is worth recalling that the exposure along the Mediterranean coasts has grown dramatically in the last century, and even more compared to the times of the large historical tsunamis. Nonetheless, all the warning systems operating in the NEAM region rely only on sea level stations installed on the coasts (generally in harbours) since there are no "tsunameters" and buoys operating in the region. This is a strong limitation to the capacity of confirming quickly the tsunami occurrence after a strong earthquake, as well as to real time modelling of tsunami propagation and inundation (Angove *et al*., 2019; Fry *et al*., 2020).

4. Recent developments

During the decades of operation of PTWS and of the other ICGs, many documents have been published by the different centres and by IOC to describe the strategy, the implementation process and the operational procedures of the TWS. These documents are important not only because they define the procedures to be followed by regional and national TWS, but also as they describe the uncertainties and the limits of the warning and alerting procedures. Among the most recent documents published in this framework, this paper describes the main outcomes of the most recent meeting of all the TWSs, namely the "Symposium on advances in tsunami warning to enhance community response". Scientists, Civil Protection (CP) officers, authorities, met in Paris on February 2018 to: a) review the latest and potential new technologies and procedures for estimating tsunami threat; b) consider ways of estimating uncertainties associated with threat assessments and optimal ways of conveying these uncertainties to decision-makers; c) examine ways of utilising enhanced tsunami threat information in making decisions with regards to emergency responses; d) provide information on the latest technologies for disseminating tsunami warning information to responders and communities; e) formulate roadmaps for developing and implementing new technologies, procedures, and their application to enable more effective community responses to tsunami threats. As far as the current trends in tsunami science for hazard and risk assessment, including a suite of examples of disaster reduction measures worldwide, we refer to a recent review by Løvholt *et al*. (2019) and references therein.

Starting from the lessons learnt from past events and the efforts put in place to improve tsunami warning and mitigation systems, the symposium identified the future needs and suggested developments in the following areas: i) detection and warning; ii) emergency management; iii) community awareness and preparedness; iv) national initiatives; and v) international initiatives.

For all these areas, the summary statement of the symposium reports the challenges and the improvements needed, including both scientific/technological goals and social issues. The latter include goals as "educating the media", "meeting public and political expectations", "establishing and maintaining public trust".

Among the many scientific and technological improvements suggested, some general concepts that were recognised as important at the symposium are discussed here. One is the need to provide decision makers with more accurate and timely tsunami forecasts with an appropriate measure of uncertainty. The explicit reference to "appropriate measure of uncertainty" is important because scientists recognise the limitations inherent in the hazard estimates and in the real time assessment of a tsunami threat, and feel the need to convey this information to decision makers (I would add also to the media and to the public). As well, the need that stakeholders and end users acknowledge this limitation and accept its consequences (including false alarms, under- or over-estimates, etc.) is recognised.

As far as detection and warning are concerned, the symposium has emphasised the need of: i) improving observational networks, especially through off-shore systems (tsunameters, etc.); ii) a "more rapid and accurate assessment of earthquake source characteristics for near-source events, to enable timely and appropriate community responses, limit unnecessary disruption and enhance public trust", also through GNSS data; iii) explore new techniques of modelling the source characteristics and inundation assessment; iv) explore the Probabilistic Tsunami Forecasts (PTF); v) investigate ways of dealing with non-seismic potential sources of tsunamis.

Apart from very few exceptions on well monitored volcanoes or landslides, the TWSs worldwide focus on seismically generated tsunamis both because they are the most common source of tsunamis, especially the big ones, and because they are the only ones that can be forecasted after large, shallow earthquakes off shore or on the coasts. Efforts are ongoing in the scientific community and more specifically in the global community of TWS's experts, to find tools and techniques for monitoring other potential sources of tsunamis such as active volcanoes and landslides. This task is far from being reached, and will probably require many years of research and technological developments. Hopefully, this will happen also for the NEAM region, where several active volcanoes and landslide-prone areas are present.

As far as the emergency management is concerned, several indications were provided, mostly aimed at: promoting "improvements to community warnings and advisories, so they are increasingly relevant, timely, accurate, clear and trusted"; simplifying the end-to-end warning chain, with clear messages and considering language and culture; using "multiple public alerting systems (traditional and social media) insuring consistent information"; addressing "community expectations and misunderstandings with regards to the duration and cancelation of warnings".

The symposium also emphasised the importance of more realistic real time assessment of threat levels. Presently, the most diffuse approaches are either the adoption of a Decision Matrix

(DM) based mostly on earthquake magnitude, depth, distance from the coasts (as for instance in the NEAMTWS), or a scenario approach, where the most likely fault is used for modelling the tsunami and predicting its impact. Recently, thanks to the increased computing power and improved knowledge on seismogenic sources, a PTF approach has been proposed (Selva *et al.*, 2019, 2020) and is presently in test at the Italian TSP (CAT-INGV). Another current challenge of TWSs is to investigate ways of dealing with non-seismic potential sources of tsunamis. This has been a topic of discussion for many years, but it has recently re-emerged after the December 2018 Anak Krakatau volcano eruption and landslide, that triggered a huge tsunami in Indonesia. A special working group has been recently established within the UNESCO-IOC framework to investigate possible defense systems against tsunamis induced both by non-subduction earthquakes and by non-seismic sources.

Finally, at the 2018 symposium a particular care has been given to the issue of community awareness and preparedness. Several recommendations have been reported in the Summary Statement, all oriented towards the increase of awareness. The emphasis is on school programs, especially for very young children; on the need to increase quantity and quality of information available to citizens; to implement and monitor performance of national tsunami readiness programs. At national level, it is suggested to include tsunami risk management in multi-hazard legislative and policy frameworks; to ensure a strong working relationship between the scientific and emergency management component in order to get well-defined national tsunami warning plans.

Also the international cooperation is strongly recommended, not only of the scientific components but also of emergency managers. Of particular importance is the suggestion of continuous "review of international guidelines and manuals to ensure simplicity and clarity of instructions that involve the community".

Although TWSs are able to provide alerts within few minutes from the occurrence of large marine and coastal earthquakes, in many countries the alert messages do not reach the citizens yet, due to the challenge in implementing the "Last Mile" with broadcast and social media, as well as with local warning systems (such as sirens, speakers, etc.). Furthermore, the lack of awareness, both of the authorities and of people potentially affected by the tsunami risk, limits the efficiency of current warning systems. The emphasis on the "Last Mile" issue is shared among all the TWSs, but is really crucial in the areas where tsunamis are rare and the most recent events occurred many decades or centuries ago.

Along with the increasing capability of seismic and sea level monitoring, and the consequent improved performance of EWSs, also the expectations from authorities, media and citizens have grown and will continue to grow. Any technological achievement in EWSs, although at an experimental stage, might be seen as a requirement by the authorities, and even by prosecutors and judges in the event of a deadly tsunami or earthquake. The risk for scientists and emergency managers of being prosecuted for a "late" or underestimated alert, or even for a false alarm, must be seriously taken into account. In the long and complex chain of duties and responsibilities, scientists operating in real time risk reduction and communication are the first (and probably the weakest) ring of the chain.

For this reason, it is important for scientists and institutions to be able to assess and communicate limits and uncertainties inherent in any real-time estimate. In order to avoid to put EW science in the dock, it is important to establish clear, transparent, effective standard operational procedures which delineate roles and duties of all the operators (Valbonesi *et al.*, 2019).

Moreover, since EWSs' goals include both automatic actions (mainly for EEWSs) and self protective behaviours (for both EEWS and TEWS), it is crucial that citizens are correctly informed and prepared to an alert. Assessing and improving people's risk perception is a fundamental step towards risk mitigation and require contributions obtained by social science studies.

5. The CAT-INGV

The CAT-INGV has been established in 2013 at the INGV headquarters in Roma (Michelini *et al*., 2016). The centre was created after some years of preparation and discussion within the ICG/NEAMTWS framework. The CAT-INGV started to operate as a NEAM candidate Tsunami Service Provider (cTSP) in October 2014, taking advantage of the already existing 24/7 seismic monitoring room of the National Earthquake Centre (now National Earthquake Observatory) of INGV and of its personnel's ultra-decennial experience in the earthquake monitoring service. Most of this personnel have been trained and selected to fulfill the new 24/7 tsunami-expert duty shift. CAT-INGV has become an official TSP for NEAM countries in 2016, after being accredited by a special commission of ICG/NEAMTWS. Since then, it has been sending information and alert messages to several countries and agencies of the European and Mediterranean areas. It started the official operations at national level in January 2017, sending messages to the Italian national civil protection system through the Prime Minister Civil Protection Department (DPC). The CAT-INGV area of competence is the whole Mediterranean basin, from 100 km west of Gibraltar to eastern Mediterranean.

The service is based on the real time analysis of seismic data from a virtual seismic network composed by about 400 stations distributed worldwide, that CAT-INGV receives from international agencies and through bilateral agreements. The seismic data analysis for locating earthquakes and computing magnitudes is performed with Early-Est, a software jointly developed by ALomax Scientific and INGV (Lomax and Michelini, 2012; Bernardi *et al*., 2015 and references therein; http://early-est.rm.ingv.it/warning.html). The in-house developed software, called JET (Java Estimate of Tsunami; Bono *et al*., 2019), allows to automatically produce "Information" and "Alert" messages (of two levels: Advisory or Watch) that are defined by a DM based on magnitude, depth, location of the earthquake. Personnel on duty verifies the hypocentral solutions, the magnitude estimates, the completeness of the information, and sends the messages to a pre-defined list of recipients [i.e. Euro-Mediterranean countries which subscribed to the service, the DPC, international institutions, and the other NEAM TSPs]. For confirming the presence of a tsunami or cancelling the threat, subsequent messages (ongoing, cancellation, etc.) are issued by the personnel on duty, after analysis of data from sea level measuring instruments, including the Italian National Mareographic Network [RMN, managed by the Istituto Superiore per la Protezione e la Ricerca Ambientale, (ISPRA)], and other tide gauges belonging to different countries of the Mediterranean.

The monitoring of earthquakes and tsunamis is carried out at CAT-INGV also for events outside its area of competence, i.e. all around the world. Although for these cases the warning messages are sent only to an internal list of recipients, a regular procedure is adopted by CAT personnel for these events, in order to keep personnel on duty constantly trained and the procedures tested almost daily.

Besides the tsunami surveillance, another important task of CAT-INGV is the hazard assessment for seismically induced tsunamis. In the last few years, INGV has coordinated the first (seismic) tsunami hazard assessment in the NEAM region through the EU-funded project TSUMAPS-NEAM, that led to the realisation of a Probabilistic Hazard Assessment for Tsunamis of seismic origin (S-PTHA) for the region (Basili *et al.*, 2019). The results have been used by the DPC to establish the inundation areas to be evacuated in the event of an Advisory or Watch alert.

Among the current developments at CAT-INGV one of the priorities is a more detailed S-PTHA for the Italian coastal regions. The huge suite of tsunami models computed for the NEAM S-PTHA will be also used for the real time assessment of tsunami forecast, following an original approach that is currently under test at CAT-INGV, namely the Probabilistic Tsunami Forecast [PTF: Selva *et al.* (2019)]. The PTF will substitute the currently used DM, with the result of more accurate real time estimates of tsunami threat/alert levels. It must be acknowledged that the determination of alert levels using the DM is very fast and somehow conservative, with a tendency to over-alerting. Applying this method to worldwide earthquakes at CAT-INGV for 2017 and 2018, it came out that for the Advisory (orange) level, only in about 10-20% of events the alert has been confirmed by sea level readings, whereas this percentage raises to 50-75% for Watch (red) alerts (these confirmations include even very small tsunamis observed at one or more tide gauges).

As recommended by the documents described in previous sections (SF2015, UNISDR2006), it is important that also scientists and monitoring centres contribute to increment knowledge and raise awareness of people living or travelling in areas at risk. For this reason, in 2018 CAT-INGV has started a research on tsunami risk perception in two sample regions in southern Italy, where the tsunami hazard is high. The results of this study, on a stratified sample of more than 1,000 residents representing more than 3 million citizens (Cerase *et al.*, 2019), confirm that the perception of tsunami risk is low, particularly in areas where the latest events occurred a long time ago. Also, it appears that people’s idea of tsunamis is strongly conditioned by the TV images of huge events such as the 2004 Sumatra and the 2011 Japan tsunamis, thus leading to underestimate the risk posed by small, more frequent tsunamis. Other interesting results of the survey are relative to people’s sources of knowledge and expectations about wave heights and warning messages (Cerase *et al.*, 2019). The outcome of this study (and of other ongoing analyses) is contributing in the definition of the communication strategy of CAT-INGV, both on the web, in campaigns and drills.

5.1. Performance of CAT-INGV in recent potential tsunamigenic earthquakes

During the past few years, the CAT-INGV has released a number of information and alert messages for the Mediterranean. Fortunately, none of the earthquakes that triggered the tsunami alerts were strong enough to be harmful to people, although one in 2017 did actually generate a small tsunami in Greece and Turkey; another one in 2018 determined an alert in Greece (Watch level), Albania and Italy (Advisory). Finally, another earthquake which occurred offshore the island of Crete in May 2020 (M_W 6.6) triggered a local Watch alert according to CAT-INGV.

Table 2 reports the main events of the last few years in the Mediterranean for which CAT-INGV issued at least one message, showing an average of about three events per year above the activation threshold (M 5.5), and at least one Advisory or Watch message per year.

As shown in Table 2, none of the events that occurred in the last few years in the Mediterranean had magnitude equal to, or greater than, 7.0. However, in the magnitude range 6.5-7.0 the DM

Table 2 - Earthquakes which activated the CAT-INGV between 2017 and 2020 (May). The magnitude values are those determined in real time at CAT-INGV. EE-loc is the number of Early-Est solution used for the message (002 is 2 minutes after the first location, 005 after 5 minutes).

Origin Time UTC	Region	Mag CAT (USGS)	Lat.	Lon.	Depth	Early-Est solution	Alert level max	Initial message issued at	Delay (minutes)
02/05/2020 12:51	Greece	6.7 (6.6)	34.12	27.51	20	002	Watch	02/05/20 12:59	8
21/03/2020 00:49	Greece	5.9 (5.7)	39.42	20.51	13	005	Information	21/03/20 00:57	8
30/01/2020 11:21	Greece	5.9 (5.7)	35.11	27.83	11	005	Information	30/01/20 11:30	9
27/11/2019 07:23	Greece	5.8 (6.0)	35.78	23.11	15	002	Information	27/11/19 07:30	7
26/11/2019 02:54	Albania	6.5 (6.4)	41.35	19.43	20	002	Advisory	26/11/19 03:01	7
26/09/2019 10:59	Turkey	5.9 (5.7)	40.85	28.22	10	005	Information	26/09/19 11:08	9
21/09/2019 14:04	Albania	5.9 (5.6)	41.36	19.45	10	005	Information	21/09/19 14:13	9
20/03/2019 06:34	Turkey	6.0 (5.7)	37.40	29.54	10	002	Information	20/03/19 06:41	7
30/10/2018 15:12	Greece	5.9 (5.7)	37.60	20.52	10	002	Information	30/10/18 15:20	8
25/10/2018 22:54	Greece	6.8 (6.8)	37.49	20.54	19	002	Watch	25/10/18 23:02	8
20/07/2017 22:31	Turkey	6.8 (6.6)	36.90	27.46	10	005	Watch	20/07/17 22:41	10
12/06/2017 12:28	Greece	6.5 (6.3)	38.87	26.34	16	005	Advisory	12/06/17 12:38	10

adopted by CAT-INGV predicts a local Watch (expected run-up>1 m) within 100 km from the epicentre, and Advisory (expected run-up<1 m) up to 400 km. Due to the proximity of epicentres to the coasts, the maximum alert level (= Watch) was issued for two earthquakes (20 July 2017 and 25 October 2018) in the vicinity of the epicentres. In the last column of Table 2 the time delays of initial message issuance from earthquake origin times are reported. For all events after the start of CAT activity as official NEAM TSP (the fall of 2016) the response has been between 7 and 10 minutes, which is below the maximum time (14 minutes) expected according to the NEAM accreditation and the threshold dictated by the 2017 Italian Prime Minister Directive instituting the national system "SiAM".

For the July 2017 earthquake in the eastern Aegean Sea, a local Watch alert was issued, as described above; the initial message was delivered by CAT-INGV 10 minutes after the earthquake origin time. Indeed, a local tsunami with run-up as high as 2 metres was recorded in Bodrum peninsula and Kos island (Yalciner *et al*., 2017; Dogan *et al*., 2019; Papadopoulos *et al*., 2019). The first inundations in these two areas occurred after about 13-14 minutes, as witnessed by webcam recording the event. Moreover, in Kos the highest run-up was recorded during the second tsunami wave, after about 21 minutes. Therefore, both inundations occurred some minutes after the potential warning released by CAT-INGV. It must be mentioned that a sea recede has been reported in the Gumbet Bay area (Bodrum) 5 minutes after the shock (Papadopoulos *et al*., 2019). Moreover, it must be noticed that none of the warnings released by the three TSPs operating in the area (NOA, KOERI, CAT-INGV) have reached the citizens in the coastal areas, due to the lack of a complete chain of information to the downstream components of the system (residents, tourists, local operators, etc.). This is a problem that still needs to be solved for several countries of the NEAM region, and is a top priority for the next few years.

For the October 2018 event in the Ionian Sea [Zakynthos island: Cirella *et al*. (2020)], a local Watch was issued by CAT-INGV for a 100 km-radius area around the epicentre (in Greece), and an Advisory warning was delivered for a 400-km radius area around the epicentre. The Advisory area included Albania and Italy. In Italy, although the CAT-INGV sent out a message after 8 minutes (Table 2) and this message was suddenly forwarded by the DPC to the local authorities, no warning has reached the population, since the warning system is still in the development phase. Municipalities are updating their emergency procedures including tsunami risk, but having all the steps arranged down to the "last mile" is not straightforward and will take several months (if not years). Even more time is needed to raise people's (and local authorities') awareness and preparation. Luckily, the 2018 Zakynthos earthquake occurred with a predominant strike-slip mechanism and did generate only a very small tsunami (less than 20-30 cm have been observed at tide gauges), with no impact neither in Greece nor in Italy. Fig. 1 is a screen shot of the interface JET used at CAT-INGV for managing the tsunami alert in real time, and shows the map of the area potentially affected by the tsunami, with alert levels at the forecast points and the isochrones of the first wave. For Italy, an alert delay time lower than 10 minutes, as the one obtained for this event, would be short enough to guarantee more than 20 minutes for evacuating areas at risk.

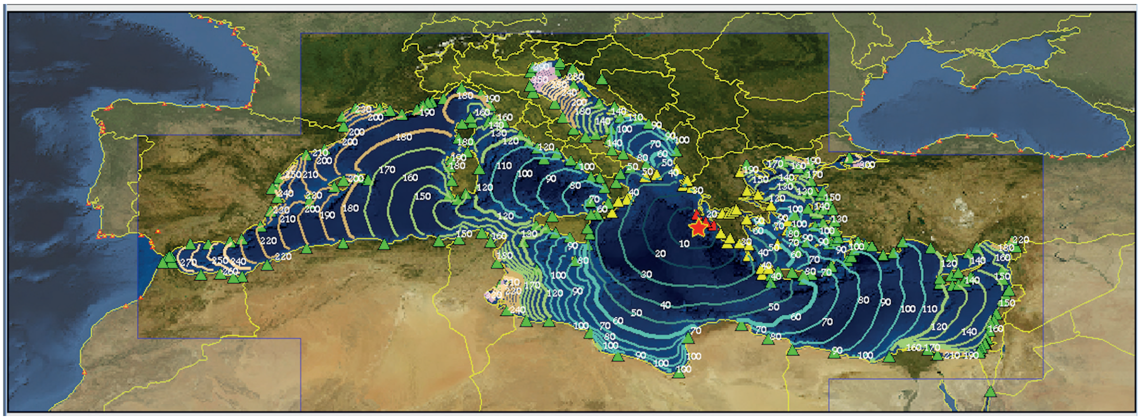

Fig. 1 - Screen shot of the software JET used at the CAT-INGV during the 24 October 2018 alert for the earthquake in Zakynthos. Map of the Mediterranean with the epicentre of the earthquake (red star), surrounded by some red forecast points (within 100-km radius) and yellow ones (within 400 km), corresponding to Watch and Advisory level, respectively. For the remaining regions of the Mediterranean, a green (= Information) message was issued. Coloured lines are the isochrones of the first tsunami wave (number are minutes from origin time).

Nonetheless, for local response after a strong earthquake very close to a coastal town, an initial warning after 7-10 minutes may not be fast enough to allow people to escape. In such cases, the importance of people's awareness of "natural warnings" like a strong and long shaking, the sea retreat, the rumble, etc. is well known. All TSPs in the NEAM region are trying to improve their ability to respond more quickly, decreasing the time needed for the assessment of earthquake parameters and alert levels. For instance, CAT-INGV decided to rely on automatic solutions, instead of reviewing waveforms and re-computing hypocentres and magnitudes, thus gaining some minutes. Still, CAT-INGV goes on investigating the opportunity of releasing warnings based on faster solutions. From a preliminary analysis of Early-Est accuracy vs. rapidity, it is evident that in some regions of the Mediterranean the adoption of faster automatic solutions warrants sufficiently good estimates, whereas this is not the case for areas with poor seismic network coverage, like the northern African coasts. For this reason, some of the initial messages have been sent after solution no. 002 instead of no. 005 (Table 2), as suggested in the CAT-INGV Standard Operational Procedure. It must be considered, however, that communicating a “wrong” parameter (for instance the magnitude, and as a consequence the alert levels)) to authorities and to the public may generate an immediate response which could turn out to be inappropriate, which would be very difficult (if not impossible) to correct with subsequent messages.

6. Asset and limitations of a multi-TSP system: the NEAMTWS case

In the ICG/NEAMTWS region, the discussion after Sumatra 2004 brought to a system consisting of several tsunami warning centres acting as TSPs for their own countries and for others, which have subscribed to their services (IOC, 2017). For recently established TSPs, like the one run by INGV in Italy (CAT-INGV) and the others in the NEAM region (CENALT in France, NOA in Greece, KOERI in Turkey, IPMA in Portugal), moving in an international framework as the one coordinated by UNESCO-IOC is important since there are well established procedures, guidelines, and best practices to follow. On the other side, a regulatory framework does not exist neither at global nor at the European level, so there is room for different interpretations and ambiguity in the national legal systems (Valbonesi *et al.*, 2019). It is desirable that such a framework will be designed, in analogy to what exists for the World Meteorological Organization (WMO). However, this latter is a United Nations specialised agency, which is the UN authoritative voice on the state and behaviour of the Earth’s atmosphere, its interactions and effects. No such body is currently running the tsunami community worldwide, therefore a different route has to be found in order to reach a general regulatory framework.

Even if all the NEAM TSPs follow the best scientific practices and international standards, and all have been accredited by a special commission established on purpose by the NEAMTWS ICGs, each of them operates with specific procedures, software, thresholds, timelines, etc. Although they all share the basic criteria, they differ in several details, thus resulting in different real time assessments.

This may be regarded as a valuable situation since it guarantees redundancy, but it may generate confusion in the event of discrepant solutions. This is what happened in some recent events in the Mediterranean, fortunately without a strong impact, as described below.

This delicate issue has been discussed within the ICG-NEAMTWS, particularly after an earthquake that occurred in the Aegean Sea on 20 July 2017. The earthquake had magnitude 6.6 and generated a small local tsunami, which affected both Greece and Turkey, with observed maximum run-up of about 2 m (Yalciner *et al.*, 2017). It happened that this earthquake occurred in the competence area of three TSPs, namely the Greek NOA, the Turkish KOERI, and the Italian INGV[2]. The warning messages released by the three TSPs turned out to be somehow different, and they were issued at different times after the earthquake. Some of the NTWCs of the Mediterranean, which receive messages by all three TSPs, received the three messages between 10 to 20 minutes after the event, and with different alert levels.

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[2] The competence areas of the former two TSPs include the eastern Mediterranean and the Aegean (for KOERI also the Marmara and the Black Sea), whereas INGV monitors the whole Mediterranean.

Possible ways of dealing with different estimates and different warnings have been discussed by Behrens (2017), one of the chairs of WG1 of the NEAM at that time. He notes that in case of seismically generated tsunamis, the complexity of the phenomenon is such that "an accurate assessment of source parameters, wave shape and, thus, impact is often only possible after months of investigation". For this reason, Behrens informs National Tsunami Warning Centres (NTWCs) and Tsunami Focal Points (TFPs, i.e. the receivers of bulletins) that any early warning estimate is necessarily and inherently uncertain, and advises them on how to deal with diverging messages. He argues that, if receiving diverging information might be unacceptable for decision makers, from another point of view this might be seen as a strength, possibly bringing to more adequate measures for disaster reduction. Such divergence is an asset because it gives a measure of the "true" uncertainty. Having different estimates available (in almost the same time frame) allows NTWCs to choose how to react. A possibility is to adopt the worst case, as recommended by Behrens, although he also recognises that there may be reasons to deviate from this advice, for instance if one wants to avoid "over-warning". An argument against this choice is that since also the message timing is different, the "worst case" could be defined as such only after the latest message has arrived, thus slowing down the whole procedure.

By the way, it is important that any decision is agreed beforehand, and clearly reported in the Standard Operational Procedures (SOPs) of any tsunami warning authorities. This is important first of all for the good functioning of the service (including automatic decisions and personnel on duty's behaviour), and for the best success of the warning procedure. Moreover, following SOPs is crucial for minimising the risks of being prosecuted in the unfortunate event of a missed (or delayed) alert, or for an underestimation of an event, which generates fatalities and/or injuries.

Although SOPs and protocols are "low rank" regulations in any legal system, they would be important in case of a legal dispute to ascertain the responsibility of the personnel involved in the risk management during an emergency.

7. Concluding remarks

Going back to the questions posed in the 2006 UNDRR document on EWS (see Chapter 3), and looking at the efforts made in the NEAM area by the national systems with the coordination of UNESCO-IOC in the following years, some considerations on the present state of the art can be made. Some of the 2006 goals have been achieved, some others have not, indicating the main areas of improvements needed for the future. The next section refers mostly to the Italian TEWS, but some discussions with colleagues operating in other areas of the NEAM region suggest that other countries are in similar conditions.

7.1. (Hazard) Risk knowledge (systematic collect data and undertake risk assessment)

a) Are the hazards and the vulnerabilities well known? b) What are the patterns and trends in these factors? c) Are risks maps and data widely available?

It is widely accepted that tsunami risk assessment needs Probabilistic Tsunami Hazard Assessment (PTHA) as input. In the last few years, a recent effort supported by the European Commission has brought to the first long-term probabilistic assessment of the tsunami hazard for earthquake-induced tsunamis (S-PTHA) in the NEAM region (TSUMAPS-NEAM, Basili *et* *al.*, 2018). The project has used historical data on earthquakes and tsunamis, as well as available knowledge of seismogenic sources for the NEAM region. Assumptions have been made about potential sources of large earthquakes in subduction areas, whereas a distributed seismicity approach was adopted for most of the other areas. Of course, the knowledge of potential tsunami sources is necessarily incomplete, but is (slowly) increasing thanks to off-shore investigations in some of the active areas of the NEAM region. Due to the high degree of uncertainty of the problem, the best way to deal with the hazard assessment is certainly through a probabilistic approach, in which the different uncertainties can be treated in a satisfactory way. These include the details of fault parameters (e.g. the heterogeneous slip distribution on the faults - which has a relevant effect on tsunami generation), of tsunami propagation and coastal inundation, which is strongly controlled by the three-dimensional coastal topo-bathymetry,

Tsunami vulnerability and risk maps/data are not widely available for most of the NEAM countries, probably because there is a general underrating of the problem, both by politicians and by citizens. In Italy, this is proved by the fact that the 2017 Prime Minister Directive which established the National Tsunami Warning System (SiAM) has not allocated specific resources for it ("without new or larger public financial burden"). Nonetheless, a big effort has been undertaken since then by the three institutions involved (DPC, INGV, and ISPRA) to find the human and financial resources needed for the construction of the national system. As far as people's perception is concerned, both Cerase *et al.* (2019) and previous studies in the NEAM region have shown a general underestimate of the risk. Efforts are needed in order to improve hazard and risk knowledge, and even more to make the current knowledge accessible and understandable to decision makers, media, and citizens.

7.2. Monitoring and warning service (developing hazard monitoring and early warning services)

a) Are the right parameters being monitored? b) Is there a sound scientific basis for making forecasts? c) Can accurate and timely warnings being generated?

This is probably the area in which the best progress has been made, at least in terms of seismically induced tsunamis. Until ten years ago, no warning system was operating in the NEAM region. Today, as described above, five TSPs are providing warnings for the NE Atlantic, the Mediterranean and the connected seas. The response times have been shortened to less than ten minutes. Although all the TSPs are still working with a simple DM that has strong limitations, current developments are going on to move towards a PTF. This is now possible thanks to increased computing power, which in the future will be more and more effective in making accurate real time estimates. Also, the time needed for the first alerting message could probably be lowered down to 5-7 minutes. As described above, this time delay might not be short enough for reaching people in case of tsunamigenic earthquakes very close to the coasts.

A strong limitation in tsunami monitoring in the NEAM region is the lack of offshore monitoring devices (such as tsunameters). This implies that today the confirmation (or cancellation) of the tsunami generation can be made only with tide gauges positioned in the harbours, therefore after the first wave has reached some coast. Also, the availability of offshore data on tsunami propagation would improve our ability to model the scenario propagation in real time and make more accurate prediction of the expected impact. A strong cooperation among all the countries at risk and with the international organisations could probably solve this problem.

7.3. Dissemination and communication (communicate risk information and early warnings)

a) Do warnings reach all those at risk? b) Are the risks and warnings understood? c) Is the warning information clear and usable?

In most of the NEAM countries warnings today would not reach those at risk. The “downstream component” is probably the most critical part of the warning systems in the region. Recent experience in Greece (2017 earthquakes and small tsunamis in Lesvos and in Kos) have shown that many people did not react in the right way after a potentially tsunamigenic earthquake, not leaving the coasts, but rather staying in the area at risk for taking pictures and movies. In a recent event affecting also Italy [the M 6.8 earthquake occurred in the Ionian island Zakynthos and related (small) tsunami potentially affecting Apulia and Calabria] the warning reached the local authorities but not the people for the lack of a clear information flow to the citizens (and apparently also for incorrect evaluations by the mayors who received the warning messages).

In several countries participating to the activity of the ICG-NEAM (not only those hosting the TSPs, but also those receiving the messages), educational activities are going on at various levels, with campaigns, drills, web sites, etc. It seems however that we are still far from a widespread awareness of the risk and knowledge on how to behave.

The main problems are likely the low perception of this risk, due to the rarity of tsunami events, and the weak action of the decision makers (including national and local authorities) in facing this risk. About the public understanding of risk and warnings, at least in Italy, the goal is far from being reached, not only with citizens but also with local authorities. A long way is still needed for making the warning information clear and usable. The NEAM TSPs do not generate public bulletins but only messages to the authorities (generally a national CP agency or department), which in turn disseminates them to the public and the media. In Italy, a discussion on how to better reach the citizens at risk is going on within the national system SiAM, including the use of cell-broadcast technology.

7.4. Response capability (build national and community response capabilities)

a) Are response plans up to date and tested? b) Are local capacities and knowledge made use of? c) Are people prepared and ready to react to warnings?

This probably differs significantly from country to country. In Italy, the national system for tsunami risk reduction has been established only in 2017, and in 2018 the DPC Head has released the guidelines to local authorities and all the components of the CP system. These include the indications for defining the evacuation zones, that were designed starting from the hazard maps. Following these 2018 guidelines, response plans are being prepared in some regions of Italy, both by municipalities and by other stakeholders, but for most of them there is still a long way to go. Once the response plans are prepared, their implementation will take more time, several months to a few years, depending on the complexity of the territory and the will of the administration to take seriously into account this risk. Unfortunately, the DPC guidelines do not contain strict rules that must be observed, but rather general indications and a high degree of freedom in the tools to be implemented.

Local communities have some capacities to face natural risks, but not specifically the tsunami risk. Experience from other more frequent emergency situations, such as severe weather, floods, earthquakes, could be used to increase people awareness and preparedness on tsunamis.

People in Italy are not ready and prepared to react to tsunami warnings. In the already mentioned study in two pilot regions of southern Italy (Cerase *et al*., 2019), it came out that the population's tsunami risk perception is low, probably due to the long time elapsed since the last big tsunami in Italy (more than one century ago). In other countries, similar studies have found analogous results and have suggested the adoption of specific actions for increasing people's awareness (Papageorgiu *et al*., 2015; Liotard *et al*., 2017). In a specific region of Norway, it was found that the local population has a clear perception of the tsunami hazard, but that warning and evacuation conditions are not well known, despite the local and national communication work (Goeldner-Gianella *et al*., 2015). These studies demonstrate that there is a lot to do in order to reach the goal of a TWS, that is, to reduce the tsunami risk by releasing warnings that are timely and effective in terms of reducing life loss and damages. As described above, the most critical part is in the downstream component.

Recent activities were promoted first in the U.S.A. for adopting common guidelines aimed at recognising "Tsunami Ready" communities. From 2015, the UNESCO-IOC Intergovernmental Coordination Group (ICG) for Tsunamis and other Coastal Hazards for the Caribbean and Adjacent regions recommended the approval of the Tsunami Ready guidelines, and the IOC General Assembly approved this recommendation. The goal of the Tsunami Ready program is to improve coastal community preparedness for tsunami emergencies and to minimise the loss of life and property, through a collaborative effort allowing to reach a standard level of tsunami preparedness (UNESCO-IOC, 2019). The discussion has started also in the NEAM region, and hopefully in the next decade it will bring to an improved resilience of people living in risky areas.

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