Institute of Oceanography and Fisheries, Split, Croatia
University of Wisconsin - Madison, WI, USA

BOOK OF ABSTRACTS

The First World Conference on Meteotsunamis

Split, Croatia, 8-11 May 2019

Editors
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THE FIRST WORLD CONFERENCE ON METEOTSUNAMIS

Split, Croatia, 8-11 May 2019

ORGANISED BY:

Institute of Oceanography and Fisheries, Split, Croatia
University of Wisconsin - Madison, WI, USA

MOTIVATION: Research on meteotsunamis - atmospherically generated long-ocean waves in a tsunami frequency band - has proliferated during the last few decades, following strong events observed at numerous coasts of the world oceans, marginal seas and the Great Lakes. The aim of the conference is to share contemporary meteotsunami-related activities (from socio-economic impacts to research and construction of warning systems) and to set up a common platform for promoting future meteotsunami studies.

VENUE: The conference will be held in Hotel Park, Split, Croatia (www.hotel-park-split.hr), from 8 to 11 May 2019.

Split is a living Mediterranean city listed in the UNESCO list of World Heritage Sites, with growing tourism, beautiful landscapes, and welcoming citizens (www.visitsplit.com). The most convenient way to reach Split is through its international airport (code: SPU), which has daily connections to many European cities during May.

PROGRAMME: The conference will comprise a broad range of meteotsunami topics, sorted in several sessions:

1. Meteotsunami observations
2. Atmosphere-ocean modelling for meteotsunamis
3. Atmosphere-ocean interactions and ocean processes
4. Climatology of meteotsunamis
5. Meteotsunamis forecasting and developing early warning system

The conference will close with a round table, during which all aspects of meteotsunami research and meteotsunami-related future activities will be discussed. This will include (i) discussing standards for meteotsunami observations and modelling, (ii) discussing ways for creation of efficient early-warning systems, (iii) creation of a framework (informal/formal network) for future collaborations, (iv) making meteotsunami research more visible in tsunami community and in public, and other.

There will be a full-day excursion on the last day of the conference (11 May 2019).

We plan to have special issue in high-quality peer-review journal, to be announced on the conference, where a collection of papers coming out of the conference presentations (but not restricted to) will be published.

ORGANISING COMMITTEE

1. Ivica Vilibić, Institute of Oceanography and Fisheries, Croatia, vilibic@izor.hr
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CONFERENCE WEBPAGE: http://www.izor.hr/mts2019

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PROGRAMME

Wednesday, 8 May 2019

08:15-09:00	Registration
09:00-09:20	Opening

Overview presentations

Chair: Chin Wu

09:20-09:50	Alexander B. Rabinovich (solicited): *Meteorological tsunamis in the World Ocean: Overview*
09:50-10:10	Ivica Vilibić, Jadranka Šepić, Sebastian Monserrat, Alexander B. Rabinovich: *Meteorological tsunamis in the Mediterranean region: 40 years of studies*
10:10-10:30	Agusti Jansa, Climent Ramis: *Pioneering research on Balearic Islands „rissagues"*
10.30-11:00	Mirko Orlić (solicited): *The great Adriatic flood of 21 June 1978: a continual source of scientific inspiration*
11:00-11:30	*Coffee break*

Session 1: Meteotsunami observations

Chairs: Alexander B. Rabinovich and Eric J. Anderson

11:30-11:50	Begoña Pérez-Gómez, Javier García-Valdecasas, Rafael Molina, Alberto Rodríguez, David Rodríguez, Álvaro Campos, Pablo Rodríguez Rubio, José María Terrés Nicoli, Enrique Álvarez-Fanjul: *Operational tool for characterization of high frequency sea level oscillations at Spanish harbors*
11:50-12:10	Jadranka Šepić, Hrvoje Mihanović: *Preliminary analysis of 1.5 years of sea level and air pressure measurements at the Adriatic meteotsunami hot spots: Stari Grad (Hvar Island) and Vela Luka (Korčula Island)*
12:10-12:30	Havu Pellikka, Hanna Boman, Kimmo K. Kahma, Anu Karjalainen, Terhi Laurila, Ilari Lehtonen, Jenni Rauhala, Jadranka Šepić, Ivica Vilibić: *Recent studies on Baltic meteotsunamis*
12:30-12:50	Charitha Pattiaratchi, Sarath Wijeratne: *Observations of meteotsunamis in Australia*
12:50-14:00	*Lunch break*
14:00-14:20	Emile Okal, Coenaard de Beer, Amir Salaree, Johan Visser, Reza Mansouri: *Dwarskersbos, South Africa, and Bandar Dayyer, Iran: Surveys and simulations of two tsunamis of meteorological origin*

14:20-14:40 Mohammad Heidarzadeh, Jadranka Šepić, Alexander B. Rabinovich: *The 19 March 2017 tsunami-like destructive waves in Dayyer, Persian Gulf analyzed using sea level, air pressure and satellite data*

14:40-15:00 Arnoldo Valle-Levinson, Luming Shi, Maitane Olabarrieta: *Flow velocities related to a meteotsunami*

15:00-15:20 Alex Sheremet, Chunyan Li, Victor I. Shrira: *High-resolution, long time-scale observations of shoreline surface elevation along Louisiana coast*

15:20-15:50 *Coffee break*

Session 2: Atmosphere-ocean modelling for meteotsunamis

Chairs: Jadranka Šepić and Emile Okal

15:50-16:10 Kenji Tanaka: *Meteotsunamis propagating along continental slope in the northwestern Pacific Ocean: a case study of the January 2018 event in Shikoku area*

16:10-16:30 Eric J. Anderson, Greg E. Mann: *Atmospheric and hydrodynamic simulation of a gravity wave induced meteotsunami in Ludington, Michigan*

16:30-16:50 Isaac V. Fine, Richard E. Thomson: *Observation and modeling of the meteotsunami of October 25, 2018 at Port Alberni, Canada*

16:50-17:10 Iael Perez, Walter Dragani, Marcos Saucedo, Alejandro Godoy, Bibiana Cerne: *Numerical simulations of meteotsunamis on the Buenos Aires coast, Argentina*

17:10-17:30 Maitane Olabarrieta, Luming Shi, David Nolan: *Meteotsunamis in the Gulf of Mexico and Eastern United States during hurricane seasons 2016-2017*

17:30-17:50 Ahmet Cevdet Yalçiner, Bora Yalçiner, Alessandro Annunziato, Özge Çabuk, Pamela Probst: *Modeling of storm surge and inundation with respect to pressure and wind fields*

Thursday, 9 May 2019

09:00-09:20 Vasily Titov: *Modeling meteotsunamis with real-time data*

09:20-09:40 Maja Bubalo, Ivica Janeković, Mirko Orlić: *Simulation of flooding and drying in meteotsunami modelling*

09:40-10:00 Baptiste Mourre, Matjaž Ličer, Charles Troupin, Agusti Jansá, Alejandro Orfila, Joaquín Tintoré: *Sensitivity studies of Menorcan meteotsunamis under synthetic gravity wave forcing*

10:00-10:20 David Kristovich, Chin Wu, Alvaro Linares, Adam Bechle: *Convective storm evolution over the Laurentian Great Lakes with respect to meteotsunami-producing conditions*

10:20-10:40	Victor I. Shrira, Alex Sheremet: *How and when solitary edge waves might be a part of a meteotsunami?*
10:40-11:00	Kristian Horvath, Jadranka Šepić, Maja Telišman-Prtenjak, Ivica Vilibić: *Meteorological analysis of an exceptional meteotsunami event of 23-27 June 2014 in the Adriatic and Mediterranean*
11:00-11:30	*Coffee break*
11:30-11:50	Xiaojing Niu, Yixiang Chen, Xingyu Gao: *The growth time required for edge waves generated by atmospheric disturbances moving along coastline*

<u>Session 3: Atmosphere-ocean interactions and ocean processes</u>

Chair: Philip Y. Chu

11:50-12:10	Katsutoshi Fukuzawa, Toshiyuki Hibiya*: The amplification mechanism of the meteo-tsunami originating off the western coast of Kyushu Island in Japan in the winter of 2010*
12:10-12:30	Sota Nakajo: *The propagation characteristics of micro-barometric wave estimated from observational data and the response of meteotsunami in the west Kyushu Island*
12:30-12:50	David Williams, Kevin Horsburgh, David Schultz, Chris Hughes: *Examination of generation mechanisms for an English Channel meteotsunami: Combining observations and modeling*
12:50-13:10	Efim Pelinovsky, Ayse Duha Metin, Andrey Zaitsev, Tatiana Talipova, Gülizar Ozyurt Tarakcioglu, Ahmet Cevdet Yalçiner: *Proudman resonance in the channels of arbitrary cross-section*
13:10-13:30	Chin Wu, Alvaro Linares, Adam Bechle, Eric J. Anderson, Dave Kristovich: *Unexpected rip currents induced by a meteotsunami*
13:30-14:40	*Lunch break*

<u>Session 4: Climatology of meteotsunamis</u>

Chair: Charitha Pattiaratchi

14:40-15:00	Petra Zemunik, Ivica Vilibić, Jadranka Šepić: *A global perspective of nonseismic sea level oscillations at tsunami timescales*
15:00-15:20	Richard E. Thomson, Isaac V. Fine: *Statistics of extreme atmospherically-generated seiches in Port Alberni, British Columbia (2009-2018)*
15:20-15:40	Martijn P.C. de Jong, Bas S. P. Reijmerink: *Meteorologically generated long-period waves and their impact on the primary national flooding protection system of The Netherlands*
15:40-16:00	Viacheslav Gusiakov: *Seismically generated tsunamis, meteotsunamis and rogue waves: problems of identification, parameterization and cataloguing*

Poster session

Chair: Ivica Vilibić

16:00-16:40	2-min presentation of posters
16:40-17:45	Coffee and vine poster discussions
18:00-20:00	*City sightseeing tour*
20:00-23:00	*Conference dinner*

Friday, 10 May 2019

Session 5: Meteotsunamis forecasting and developing early warning system

Chair: David Kristovich and Kenji Tanaka

09:00-09:20	Baptiste Mourre, Albert Buils, Lola Gautreau, Benjamin Casas, Matjaž Ličer, Agusti Jansá, Bernat Amengual, Joaquín Tintoré: *Evaluation of four years of daily predictions of the SOCIB Balearic Rissaga Forecasting System*
09:20-09:40	Romualdo Romero, Maria-del-Mar Vich, Climent Ramis: *A pragmatic approach for the numerical prediction of meteotsunamis in Ciutadella Harbour (Balearic Islands)*
09:40-10:00	Cléa Denamiel, Jadranka Šepić, Damir Ivanković, Ivica Vilibić: *The Adriatic Sea and Coast (AdriSC) meteotsunami forecast system*
10:00-10:20	Anna Dzvonkovskaya: *Ocean radar as a tool for real-time monitoring of meteotsunamis*
10:20-10:40	Myung-Seok Kim, Seung-Buhm Woo, Sung Hyup Yoo, Kun-Young Byun, Hyunmin Eom, Hyunsu Kim, Yoo-Keun Kim, Dong-Hoon Kim: *Accuracy analysis of the real time air-pressure-jump monitoring system in Yellow Sea, Korea: Case study of 2018 March ~ April*
10:40-11:10	*Coffee break*
11:10-11:30	Hyunmin Eom, Kun-Young Byun, Sung Hyup You, Myung-Seok Kim, Seung-Buhm Woo: *Developing an early warning system for meteotsunami in South Korea (KMA)*
11:30-11:50	Michael D. Angove, Lewis Kozlosky: Meteotsunamis: *Working toward an operational forecasting capability for the U.S.*
11:50-12:10	Philip Y. Chu, Eric J. Anderson, Chin Wu, Adam Bechle, Alvaro Linares, Michael Angove, Greg Mann: *Develop a reliable detection and early warning system for meteotsunami events in an operational environment*
12:10-12:30	Greg Mann, Eric J. Anderson: *High amplitude inertia-gravity wave driven meteotsunami across the Lake Michigan basin during the transition season*
12:30-14:00	*Lunch break*

14:00-16:00 Ivica Vilibić (moderator), Philip Y. Chu, Charitha Pattiaratchi, Kenji Tanaka, Alexander B. Rabinovich, Chin Wu (panelists): *Round table: A way to go for meteotsunami research and applications*

16:00-17:00 *Farewell coffee*

Saturday, 11 May 2019

Full-day excursion

Poster session

1. Frano Matić, Stojan Šoša, Ana Radovčić, Jadranka Šepić, Marko Mlinar, Srđan Čupić, Maja Karlović: *Analysis of the Adriatic storm surge and meteotsunami of 29 October 2018* (Session 1)
2. Aldo Drago: *An observing system for the monitoring of seiches in the Maltese Islands* (Session 1)
3. Martina Tudor, Jadranka Šepić, Ivica Janeković, Mario Hrastinski: *Traveling air pressure disturbances in operational meteorological forecast model* (Session 2)
4. Damir Ivanković, Cléa Denamiel: *AdriSC web page - visualization of data from numerical models and real-time stations network in frame of Adriatic Sea and Coast (AdriSC) Meteotsunami Forecast* (Session 2)
5. Sarath Wijeratne, Charitha Pattiaratchi: *Simulating meteotsunamis along the south-west Australian continental shelf* (Session 2)
6. Kenji Tanaka: *The multiscale meteorological processes in the genesis of the atmospheric pressure disturbances in East Asia* (Session 2)
7. Wei Cheng, Richards Sunny, Bill Knight and Juan Horrillo: *Characterization and identification of meteotsunami-physical parameters for the GOM with application to Panama City and other locations in West Florida* (Session 2)
8. Boyko Ranguelov, Orlin Dimitrov: *A comparative study of the tsunami origin (turbidities or meteotsunami)* (Session 3)
9. Cléa Denamiel, Jadranka Šepić, Ivica Vilibić: *Genesis of the atmospheric internal gravity waves (IGWs) driving eastern Adriatic meteotsunamis* (Session 3)
10. Richard E. Thomson, Alexander B. Rabinovich, Jadranka Šepić: *The extreme typhoon "Songda" event of 14 October 2016 on the coasts of British Columbia and Washington State* (Session 3)
11. David Williams, Kevin Horsburgh, Chris Hughes, David Schultz: *Meteotsunamis produced by precipitating atmospheric systems across the north-west Europe* (Session 3)

12. Ivica Vilibić, Jadranka Šepić, Sebastian Monserrat, Natalija Dunić, Florence Sevault, Gabriel Jorda: *Deriving present and future climate of meteotsunamis from synoptic conditions: the Ciutadella case (the Balearic Islands)* (Session 4)
13. Rachid Omira, Maria Ana Baptista, Alexander B. Rabinovich, Daniela Maxial, Inês Ramalho, Maria Monteiro, Martina Tudor, Pedro Viterbo: *Developing forecast skills for meteotsunamis in the Iberian Shelf – An overview of the FAST project* (Session 5)
14. Chin Wu, Alvaro Linares, Dave Kristovich, Eric J. Anderson, Philip Y. Chu: *Toward the predictability of meteotsunamis in Lake Michigan* (Session 5)
15. Eric J. Anderson, Chin Wu, Alvaro Linares, Philip Y. Chu, Ed Verhamme, Greg Cutrell: *Development of a meteotsunami warning system for the Great Lakes* (Session 5)
16. Dijana Klarić, Lidija Fuštar, Vlasta Tutiš, Igor Horvat: *I-STORMS project and implementation in Croatia* (Session 5)
17. Beatriz Brizuela, Laura Graziani, Alessandra Maramai: *Italian Tsunami Effects Database (ITED): the first database of tsunami effects observed along the Italian coasts* (Session 5)

Overview presentations

METEOROLOGICAL TSUNAMIS IN THE WORLD OCEAN: OVERVIEW

Alexander B. Rabinovich[1,2*]

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ABSTRACT

"Meteorological tsunamis" ("meteotsunamis") are long destructive oceanic waves that have the same temporal and spatial scales as ordinary tsunami waves and can affect coastal areas in a similar hazardous way, but which are generated by atmospheric forcing (atmospheric gravity waves, pressure jumps, frontal passages, squalls, etc.) rather than by seismic activity or submarine landslides. Meteotsunamis have long been considered a very rare and local phenomenon that occurs only in a few specific harbours, such as Ciutadella (Balearic Islands, Spain), Vela Luka and Stari Grad (Croatia), Mazaro dell Vallo (Sicily), Nagasaki Bay (Japan) and other locations, including the Great Lakes. However, observations from around the world over the past decade and the occurrences of several devastating events, including the 2017 meteotsunamis in the Netherlands, Durban (RSA) and Dayyer (Iran), and the 2018 meteotsunamis on the coast of Florida (USA), have demonstrated that meteotsunamis are much more common and widespread than was previously thought. There are two basic types of meteorological tsunamis associated with atmospheric activity: "bad-weather" meteotsunamis and "good-weather" meteotsunamis. Bad-weather waves fall into the "expected" category, as: they are normally associated with large-scale intense meteorological events, such as hurricanes, typhoons, derechos, and strong cyclones (i.e., with storm weather). Typical features of these events include: (1) Impacts of extensive coastal regions (of several hundred kilometers); (2) extreme, long lasting ("ringing") seiches; and (3) concurrence with other hazardous types of sea level oscillations, in particular, with storm surge, infragravity waves and wave setup. This type of meteotsunami is common on the Atlantic coasts of North America and northern Europe. Good-weather meteotsunamis are "mysterious" and "unexpected", frequently occur during beautiful calm weather and are normally generated by atmospheric pressure jumps and trains of atmospheric gravity waves. Such meteotsunamis are more localized, have shorter duration and are not typically concurrent with other long wave phenomena. Data analysis and numerical experiments have shown that "good-weather" meteotsunamis are a resonant phenomenon governed by the Froude number, Fr, which is the ratio of the atmospheric gravity wave speed (U) to the phase speed of long ocean waves (c). Resonance occurs when $Fr = U/c \sim 1.0$. Meteotsunamis can also be strongly amplified by topographic steering and resonance features. This leads to two subtypes of "good-weather" meteotsunamis: "harbour meteotsunamis" and "beach meteotsunamis". "Harbour resonance" and high Q-factor in specific bays, inlets and harbours play critical roles in harbour meteotsunamis. "Harbour meteotsunamis" are common destructive features in Mediterranean

regions, in particular, in the Adriatic Sea, and on the coasts of the Balearic Islands, western Sicily and Malta. Several catastrophic events, including the 6-meter Vela Luka (Croatia) flood of 21 June 1978 and the 1984 and 2006 floods in Ciutadella Harbour (Spain), are spectacular examples of harbour meteotsunamis. Such meteotsunamis lead to steady monochromatic oscillations at the period of the fundamental mode of the corresponding basin. “Beach meteotsunamis” occur on straight beaches and have properties solitary waves (“solitons”). The most famous example of this kind is the “Daytona Beach” (Florida) event of 3 July 1992 when a 3.5-meter tsunami-like ocean wave injured 75 people. Recently, similar destructive events impacted Florida (2012, 2014, 2018), Odessa in the Black Sea (2014) and Dayyer in Iran (2017).

METEOROLOGICAL TSUNAMIS IN THE MEDITERRANEAN REGION: 40 YEARS OF STUDIES

Ivica Vilibić[1*], Jadranka Šepić[1], Sebastian Monserrat[2], Alexander B. Rabinovich[3,4]

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ABSTRACT

Local destructive tsunami-like events have been known for a long time to impact the Mediterranean coastline, being named by local people at different impact areas as: rissaga at the Balearic Islands, šćiga in the Adriatic Sea, marrobbio at the southwestern coast of Sicily, milghuba on Malta. Yet, a common characteristic emerged during research of these phenomena – all events were generated by propagating atmospheric disturbances, in particular by air pressure and internal atmospheric waves, resulting in them being classified as meteorological tsunamis or meteotsunamis. Research has been boosted after the most destructive events, of which the most violent were the šćiga of 21 June 1978 in Vela Luka, Adriatic Sea, and the rissagas of 21 June 1984 and 15 June 2006 in Ciutadella Harbour, the Balearic Islands. All these events were similar to seismically generated tsunami waves, had trough-to-crest wave heights up to 5-6 m and periods of 10-20 min. The accompanying strong currents added to the fact that tides in the Mediterranean are small, and consequently the harbour structures are not designed to accommodate so large oscillations, are the reason why the events are so destructive. The total damage in the affected coastal areas was tens of MEuros. These highly destructive events initiated an intensive research of meteotsunamis in the Mediterranean region. It has been found that the meteotsunami events were associated with a predominant synoptic setting that includes: (i) an exceptionally strong and unstable mid-troposphere jet, (ii) an inflow of dry and warm subtropical air in the lower troposphere, and (iii) weak winds and a weak cyclone at the surface. Such conditions were favourable for ducting of atmospheric gravity waves in the lower troposphere visible in surface air pressure oscillations, through a so-called wave-duct mechanism. During some extreme events, like the recent one of 23-27 June 2014, tsunamigenic synoptic patterns were found propagating from the Western to the Eastern Mediterranean and to the Black Sea, exciting strong seiche oscillations and meteotsunamis along its path. It was also found that meteotsunamis are a resonant phenomenon: the extreme wave heights occur when the Froud number, $Fr = U/c \sim 1.0$, where U is the speed of atmospheric disturbances and c is wave speed of long ocean waves. All of these aspects of meteotsunami investigations in the Mediterranean are overviewed in the presentation, summarizing modern knowledge and problems in understanding of this phenomenon and directions for future research.

PIONEERING RESEARCH ON BALEARIC ISLANDS "RISSAGUES"

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ABSTRACT

"Rissagues" is the local name of large amplitude seiches in the Balearics, particularly in the Ciutadella (Menorca) harbour. The phenomenon is, of course, known since immemorial times, but nothing was described before 1979 regarding its origin, although people talked about "rissaga sky" or "rissaga weather". A direct antecedent of our work, done at the end of the 1970's and during the 1980's, was the paper published by Fontsere (1934), on the simultaneity between large amplitude seiches in Barcelona harbour and local quick pressure oscillations. Analogous relationship was found by us in the late 1970's, after some cases in Ciutadella. An initial description about the meteorological origin of the "rissaga" of Ciutadella was published in a book chapter (Jansa and Jansa 1979). Looking in detail to an important new event, occurred in 1981, permitted the association between "rissaga", quick pressure oscillations, gravity waves and a particular large scale three dimensional meteorological pattern as well as a specific vertical structure of temperature and wind. Our classic work describing this is Ramis and Jansa (1983). The mentioned association permitted the establishment of an experimental "rissaga" forecasting service at the national meteorological service (then named "Instituto Nacional de Meteorologia"). The forecasting service was established after a catastrophic event occurred on 1984, with an estimated tide height of around three meters. The rissaga of 1984 provided additional and new information: the main "rissaga" oscillation was roughly simultaneous with the arrival to Ciutadella of a singular pressure jump associated to an atmospheric convective system. In a paper on this event, Jansa (1986), highlighted the probable existence of the amplification (by Proudman resonance) of the marine response to the atmospheric forcing before the final resonant amplification in the harbour.

THE GREAT ADRIATIC FLOOD OF 21 JUNE 1978: A CONTINUAL SOURCE OF SCIENTIFIC INSPIRATION

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ABSTRACT

On 21 June 1978, a tsunami-like event occurred in the Adriatic Sea. It resulted in the trough-to-crest height reaching 6 m in Vela Luka on the Korčula Island and exceeding 1 m in many locations along both the Croatian and Italian coasts. The event broke the previous Adriatic records and was therefore the subject of a number of scientific and professional papers published over the past four decades. In the lecture, a subjective view of the research activities stimulated by the event is presented. Immediately after the event, a relative value of four possible interpretations was assessed, the distinction was made between two different types of resonance influencing it, and the term Proudman resonance was introduced in order to describe one of the types. However, an attempt aimed at reproducing the event with a numerical model failed at the time. It was only after three decades, during which the power of computers and numerical methods advanced at an unprecedented pace, that numerical modeling of the event could be tackled again. This resulted in an order-of-magnitude reproduction of the event with an oceanographic model, an experimental coupling of the oceanographic model to a meteorological model, and an attribution of the event to a four-phase process capable of transforming a few-hectopascal air pressure perturbation into a few-meter sea level oscillation. The first numerical modeling of the event did not allow for the flooding of Vela Luka and drying of the harbor, which were amply documented by marks on buildings, numerous photos and even some films. Only recently, the flooding and drying option has been included in a numerical simulation and this brought the simulated heights close to the observed values. Therefore, the 1978 Adriatic flood still provides challenges to researchers and may be expected to do so in the future.

Session 1

Meteotsunami observations

OPERATIONAL TOOL FOR CHARACTERIZATION OF HIGH FREQUENCY SEA LEVEL OSCILLATIONS AT SPANISH HARBORS

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ABSTRACT

Port authorities rely on the knowledge of physical forcings (waves, winds, tides) affecting operations and infrastructures life time, and on automatization tools for the daily management of operational risks. High frequency sea level oscillations (HFSLO: infragravity waves, meteotsunamis), and associated currents, may be as well of paramount importance. For this reason, a software for HFSLO characterization has been developed for the 40 tide gauges of the REDMAR Spanish network run by Puertos del Estado (PdE: Spanish Harbors), a significant upgrade to the now in place simple alert system, based on 1-min latency and sampling data. Raw 2Hz data are now transmitted, quality controlled and processed every hour, allowing near-real time interactive and user-friendly display of: high and band pass filtered data, spectrograms and energy content evolution, waves amplitudes and periods, spectral analysis, and additional parameters measured at the station such as 1-min atmospheric pressure data. The user can also display, through an interactive calendar, the same information for historical data. The software makes use of Infinite Impulse Response (IIR) filters and the "rainflow" technique for waves counting. The overall main advantages can be summarized as:

- Comprehensive and operational characterization (amplitudes, periods) for all frequencies (including periods 30-120 seconds, not possible in the initial system)
- Historical raw data and derived products now available in NetCdf in PdE OpenDap server
- Inventory of historical events since 2006, ready to be displayed in a user-friendly way
- Easy access to additional parameters to facilitate source/forcing identification (waves, atmospheric pressure..)
- Statistics of type and number of events observed at the REDMAR ports for more than 12 years from a unique and novel data set
- Refinement of existing alert system based on tide gauge observations and potential contribution to improvement of future meteotsunamis early warning systems.

PRELIMINARY ANALYSIS OF 1.5 YEARS OF SEA LEVEL AND AIR PRESSURE MEASUREMENTS AT THE ADRIATIC METEOTSUNAMI HOT SPOTS: STARI GRAD (HVAR ISLAND) AND VELA LUKA (KORČULA ISLAND)

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ABSTRACT

Destructive meteotsunamis are quite common in the middle Adriatic, especially in Vela Luka (Korčula Island) and Stari Grad (Hvar Island). During the last 88 years, 22 meteotsunamis were observed in the middle Adriatic. The list of the events includes the great Vela Luka flood of 21 June 1978, which is, to this day, the highest meteotsunami observed in the world oceans. Despite of high frequency of hazardous events, until recently, no continuous sea level measurements were available for the most endangered locations. This has changed during 2017, when, as a part of the meteotsunami research project MESSI, three high-resolution tide gauges were installed at Vela Luka, Stari Grad and Sobra (Mljet Island). The latter is located within the Mljet Channel, wherein strong channel seiches are presumably generated during meteotsunamis. The Vela Luka and Stari Grad stations are supplemented by high-resolution atmospheric sensors (measuring air temperature, pressure, humidity and wind velocity). In addition, during the MESSI project nine microbarographs stations were upgraded/installed in the middle Adriatic, with a primary target of tracking tsunamigenic air pressure disturbances.

Herein, we present the results of preliminary data analysis, with focus on sea level and atmospheric measurements from Stari Grad and Vela Luka. All series were quality checked, and sea level series were de-tided. Series were then filtered to isolate high-frequency ($T < 4$ h) oscillations; the main eigen frequencies of the corresponding basins were determined by spectral analysis. Eigen modes and eigen frequencies of both bays were also estimated by numerical modelling. Cross-spectra of simultaneous sea levels measured at the two bays were estimated to check for coherence between processes at the two locations. Same analysis was repeated for air pressure time series and for simultaneous series of sea level and air pressure. Finally, high frequency air pressure and sea level time series were examined to identify the extreme events; these events were examined in detail.

RECENT STUDIES ON BALTIC METEOTSUNAMIS

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ABSTRACT

This presentation gives an overview of what is known about meteotsunami occurrence in the Baltic Sea. Sporadic mentions of meteotsunamis can be found in old scientific literature and newspaper articles, often using local names (Seebär in German and sjösprång in Swedish), but very little modern research is available on the subject. Coastal residents and seafarers also tell of occasional encounters with such waves.

We further present recent studies of meteotsunamis based on 100 years of high-resolution sea level observations in the Gulf of Finland, as well as eyewitness observations. Before the 1980s, high-resolution data is only available on the original paper charts of the tide gauges, and visual inspection has been used to locate meteotsunamis in the data. Digital 15-min data is available from 1980 onwards and 1-min data from 2004 onwards, and meteotsunamis in these data are detected with automated methods. Air pressure observations are used to confirm the meteorological origin of the waves.

The results reveal that meteotsunamis are not a rare phenomenon in this area, but they are predominantly small, below 0.5 m in height at the tide gauges. Eyewitnesses have reported oscillations exceeding 1 m, but such events seem to be local and very rare. Even small meteotsunamis might create strong currents in inlets and constrictions, however, and endanger the safety of navigation. Studies of atmospheric conditions during the meteotsunami events have shown that meteotsunamis in Finland occur practically always in connection with thunderstorms and are predominantly a summertime phenomenon.

OBSERVATIONS OF METEOTSUNAMIS IN AUSTRALIA

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ABSTRACT

Meteorological tsunamis (meteotsunamis) are water level oscillations which are similar to waves generated by seismic activity ('tsunami waves'), except they have a meteorological origin. In recent papers we have identified that south-western Australia is a global hot-spot for meteotsunamis with the occurrence of ~25 events annually. In this paper we extend the analysis to include 13 tide gages around Australia that all have sampling periods of 1 minute. These included: Spring Bay, Tas; Burnie, Tas; Portland, Vic; Thevenard, SA; Esperance, WA; Hillarys Harbor, WA; Cape Cuvier Wharf, WA; Broome, WA; Darwin, NT; Groote Eylandt, NT; Cape Ferguson, Qld; Rosslyn Bay, Qld; Port Kembla, NSW. At each of these sites the analysis covered a period of 5 years from December 2009 to December 2014. In addition, some events were captured by moored instruments located offshore that included high resolution pressure sensors and current profilers. A total of 214 events were identified that could be classified as meteotsunami events. Majority of the events coincided with the meteorological events with small changes (~2-3hPa) in atmospheric pressure and/or associated strong wind events including tropical cyclones. Some were associated with the passage of cold fronts. A large event in Cape Cuvier was attributed the passage of atmospheric gravity waves through the region. There were no events recorded in the tropical regions (Broome and Darwin), most likely due to the high tidal range and absence of travelling pressure systems. The largest number (in terms of events and highest amplitude) occurred in Western Australia (Cape Cuvier, Hillarys and Esperance). There were also a number of events with amplitudes > 0.40m in south-east Australia: Burnie, Portland and Port Kembla.

DWARSKERSBOS, SOUTH AFRICA, AND BANDAR DAYYER, IRAN: SURVEYS AND SIMULATIONS OF TWO TSUNAMIS OF METEOROLOGICAL ORIGIN

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ABSTRACT

(i) The Dwarskersbos event of 27 August 1969 was surveyed more than 40 years later, based on the interview of elderly witnesses still residing in the community; it documented a maximum runup of 2.9 m, concentrated on an extremely short segment of coastline, less than 2 km in length. It occurred in the absence of any felt or recorded seismic source, and we could not simulate a legitimate landslide source reproducing the concentration of the wave at Dwarskersbos. By contrast, the wave can be explained as a “meteo-tsunami” resulting from Proudman resonance between a meteorological squall propagating at 18 m/s in the azimuth N101E and a gravity wave propagating in the shallow waters off the eastern shore of St. Helena Bay.

(ii) In the Persian Gulf, the Bandar Dayyer tsunami of 19 March 2017 resulted in six presumed deaths and more than $10 million in damage. The post-tsunami survey documented runup reaching 3 m and inundation of 600 m. Again, no seismic activity was either felt or recorded, and we fail to simulate the distribution of run-up along the coast from possible landslide sources. We prefer the model of a meteorological tsunami, triggered by Proudman resonance with a hypothetical weather front moving at 10 m/s in a NNW azimuth, which could be an ancillary phenomenon to a major shamal wind system present over the Persian Gulf on that day.

THE 19 MARCH 2017 TSUNAMI-LIKE DESTRUCTIVE WAVES IN DAYYER, PERSIAN GULF ANALYZED USING SEA LEVEL, AIR PRESSURE AND SATELLITE DATA

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ABSTRACT

We present results of a comprehensive study of the source of the tsunami-like waves observed on 19 March 2017 in Dayyer, the Persian Gulf (PG), which killed 5 people and caused multi-million dollars damage. Post-event field surveys revealed that the destructive waves reached the maximum height of >3 m and inundation distances of ~1 km along the coast of the Dayyer region, South Iran. We examined a dataset of 12 sea-level records from inside and outside of the PG and 47 high-resolution air pressure records. This dataset was supplemented by satellite images over the PG region for the period of the event. Maximum trough-to-crest wave heights of 197 and 234 cm were recorded at the two near-field cities of Dayyer and Assaluyeh, respectively, while tide gauges located outside of the PG registered wave heights of 5-33 cm. The wave periods were 10-40 min, whereas the dominant periods of extreme waves were 15-20 min. The event was identified as a meteotsunami. The atmospheric processes in the PG area were found to be very active for the period of 18-22 March 2017: ten distinctive pressure disturbances were identified crossing the gulf. The entire atmospheric situation was very similar to the conditions over the Mediterranean Sea region on 23-27 June 2014, which produced a number of strong meteotsunamis in various parts of the sea. The atmospheric status in the PG region was very prone to generate such destructive tsunami-like waves. In addition, the Froude number, $Fr = U/c$, where U is the speed of atmospheric disturbance and c is the long wave speed, was found to be 0.9-1.1 in the area of Dayyer, which is the most favorable for meteotsunami generation.

FLOW VELOCITIES RELATED TO A METEOTSUNAMI

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ABSTRACT

Current velocity profiles recorded the influence of meteotsunami waves at the entrance to Barataria Bay, in the Gulf of Mexico. Profiles were recorded at a frequency of 2 Hz from April 9th to May 7th, 2017 at two inlets that communicate the bay to the gulf. On May 4th, a meteotsunami was triggered in the northern Gulf of Mexico by a barometric pressure jump of nearly 8 hPa accompanied by a wind speed increase of 8 m/s over 30 minutes, as measured in Grand Isle, Louisiana. The jump in atmospheric pressure and wind speed was followed by a water level increase of 0.8 m over the same 30 minutes and a drop of 0.95 m over 2.8 hrs. After this initial pulse, the water level displayed 4 damped oscillations with periods of 3-4 hrs that approximately followed changes in wind speed. The water level drop associated with the initial tsunami pulse caused outflows of 1.8 m/s followed by inflows of 1.7 m/s: a change of 3.5 m/s in 48 minutes. The response was consistent in both inlets that had flow measurements. Most remarkable were the upward vertical velocities. They were in phase with the outflows and attained values of 0.12 m/s near the bottom, increasing to 0.40 near the surface. Acoustic backscatter suggested marked sediment suspension throughout the water column during the first wave and in subsequent oscillations. An in-depth exploration of the flows associated with the meteotsunami will be executed with the results of a Coupled Ocean-Waves-Atmospheric model.

HIGH-RESOLUTION, LONG TIME-SCALE OBSERVATIONS OF SHORELINE SURFACE ELEVATION ALONG LOUISIANA COAST

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ABSTRACT

Despite an increasing number of studies, the class of processes included in the definition of meteotsunami phenomenon remains poorly constrained. We present the results of a field experiment designed to collect high-resolution, long-time observations of sea-surface displacement. The deployed array of pressure and velocity sensors has recorded at 4 Hz continuously since Winter 2018 along the Louisiana Coast, USA. The observations resolve time scales ranging from wind waves with the periods of the order of a few seconds to storm surges lasting several days. Plausible meteotsunami events are identified in the pressure anomaly (detided surface elevation) as oscillations with a characteristic time scale in the order of hours, that show significant correlation with atmospheric perturbations. We present preliminary numerical simulations of the generation of the identified meteotsunami events. If classified as meteotsunamis, the observations suggest that this phenomenon occurs at the selected stretch along the Louisiana coast with a frequency of a few events every winter month, and may be associated with a wide variety of atmospheric perturbations.

ANALYSIS OF THE ADRIATIC STORM SURGE AND METEOTSUNAMI OF 29 OCTOBER 2018

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ABSTRACT

During night hours of 29-30 October, a north-eastward propagating cyclone which originated in the western Mediterranean crossed the Adriatic. An associated pressure drop and strong sirocco winds resulted in flooding of the middle and northern Adriatic: 4th highest Aqua Alta of the measurement period was recorded in Venice (Venice Municipality, 30/10/2018), 1st highest sea level of the measurement period was recorded in Bakar (GFZ, 2018), many harbours and boats suffered material damage and extreme waves were observed and recorded throughout the Adriatic. Although there were no public meteotsunami reports, available tide gauge data reveals that a weak meteotsunami occurred in Vela Luka between 20:00-24:00 UTC of 29 October. Maximum meteotsunami wave at tide gauge location had a height of 94.0 cm. Associated to this wave was maximum sea level of 63.4 recorded at 20:32 UTC, which was also time of a high tide. Mean period of Vela Luka waves was ~12 min. Increased high frequency sea level activity, but of lower intensity, was recorded at other middle Adriatic tide gauge stations as well, including Stari Grad (Hvar Island), Sobra (Mljet Island), and Split. Air pressure measurements reveal that numerous potentially tsunamigenic high-frequency atmospheric disturbances propagated over the middle Adriatic during the event. These disturbances were especially strong over Vela Luka area, where several consecutive oscillations of up to 5-min duration, and crest-to-through heights of ~1 hPa were measured.

Synoptic setting leading to the event is analysed in detail using ERA5 reanalysis dataset and available air pressure and wind measurements. It is shown that during October the Adriatic Sea was on the front side of a 500 mb trough, and that a low pressure trough on 850 mb was located over the western Mediterranean. This pattern was supporting warm air advection from the SW, and preconditioning generation of the Mediterranean cyclone. Available tide gauge records are analysed to estimate contribution of different processes to the flooding, including tides, storm surges, and meteotsunamis.

AN OBSERVING SYSTEM FOR THE MONITORING OF SEICHES IN THE MALTESE ISLANDS

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ABSTRACT

Long period waves with periodicities up to several tens of minutes are observed throughout the year along the northern and south-eastern coastal area of the Maltese Islands. These coastal seiches, locally known as 'milghuba', resemble closely tsunamis in character, but result from meteorological forcing rather than seismic events. These waves are present uninterrupted on the sea level trace as 'background' oscillations, occasionally intensifying to large amplitude fluctuations reaching up to 1m in extent. These events have been studied extensively in the past, and are believed to be related to mesoscale atmospheric gravity waves which occur in association to the passage of frontal disturbances or during particular synoptic settings characterised by an inversion near the surface, and by dynamic instability and vertical wind shear in the middle troposphere.

A new network of real-time meteorological stations with barometric measurements, seven in Malta and Gozo, and three on the southern Sicilian coast, together with five sea level monitoring stations with high temporal data acquisition, will be set up in the region within the Interreg Italia-Malta CALYPSO South project. These observations will provide the setting to tackle some unresolved questions. Further insight on the long wave oscillations in the central areas of the Strait of Sicily is needed as opposed to those on the shelf area. The position of the islands close to the shelf break presents a very interesting case of an island system with a very asymmetric surrounding bathymetry. A better understanding of the phenomenology of atmospheric waves and their correlation to the sea waves needs longer term simultaneous measurements of sea level and surface pressure at a set of stations both on land and offshore. There is also still much speculation about the occurrence of impulse type larger amplitude seiches during summer, manifesting in short bursts often lasting only a few cycles.

Session 2

Atmosphere-ocean modelling for meteotsunamis

METEOTSUNAMIS PROPAGATING ALONG CONTINENTAL SLOPE IN THE NORTHWESTERN PACIFIC OCEAN - A CASE STUDY OF THE JANUARY 2018 EVENT IN SHIKOKU AREA

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ABSTRACT

In early January 2018, a series of meteostunamis was observed in the wide area of west Japan. According to the in situ observations, the wave maximum height was as high as 1.0 - 1.6 m in south Kyushu. In this event, the large amplified oscillation also recorded at Tosa-Shimizu and Muroto of Kochi prefecture along the coast of the Pacific Ocean. Since there runs Nankai Trough with the depth of 9000 m, the path of the pressure disturbance is very limited for multiple resonance.

In the present study, the propagation mechanism along the northwestern Pacific Ocean was investigated using numerical models. The propagation term of the atmospheric forcings are embedded in the tsunami model, TUNAMI-N2. An idealized atmospheric wave pattern written by sinusoidal function was given with the amplitude of 1.0 hPa, continuous 20 waves. It is assumed that the atmospheric pressure wave speed of 35 m/s with the azimuth of 220-240 degrees according to the wind profiler observations. The following results were obtained after the numerical experiments: 1) the propagation direction nearly 225-230 degrees enhanced the resonance effect along the continental shelf (depth around 150-250m) just the north of the Nankai Trough 2) the resonance across the wide mouth of the bay played an important role, 3) the reflectance across the wide channels would help the train of the waves more amplified.

ATMOSPHERIC AND HYDRODYNAMIC SIMULATION OF A GRAVITY WAVE INDUCED METEOTSUNAMI IN LUDINGTON, MICHIGAN

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ABSTRACT

On Friday, April 13, 2018, a significant meteotsunami event (~2 m amplitude) occurred on Lake Michigan. A high amplitude atmospheric inertia-gravity (IG) wave packet with surface pressure perturbations exceeding 10 hPa and wind speeds approaching gale force crossed the lake at a propagation speed that neared the long-wave gravity speed of the lake, likely producing Proudman resonance. The meteotsunami struck the shores near Ludington, Michigan, a coastal community along the sandy dunes of Lake Michigan. During the event, harbor walls were overtopped, damage occurred to shoreline homes and boat docks, and water intake pumps were impacted due to the large change in water level. To fully understand the generation of this event and the impacts to the coastal community, we have carried out atmospheric and hydrodynamic model simulations of the storm and meteotsunami wave. Atmospheric simulation of the inertia-gravity waves weas carried out using a high-resolution WRF model for the Great Lakes region, in which weather conditions are validated against coastal measurements and outputs provided to the hydrodynamic model. The Finite Volume Community Ocean Model (FVCOM), which is the basis for NOAA's operational forecast models of the Great Lakes, was used to simulate the meteotsunami event. In this work, the results of the simulation are compared to measured water level fluctuations as well as eye witness reports wave height. This research helps understand the generation of a meteotsunami wave in the Great Lakes from IG, and supports evaluation of NOAA's existing and proposed operational infrastructure as it pertains to meteotsunami forecasting.

OBSERVATION AND MODELING OF THE METEOTSUNAMI OF OCTOBER 25, 2018 AT PORT ALBERNI, CANADA

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ABSTRACT

A pronounced negative water level pulse with an amplitude about 33 cm was recorded by the Port Alberni tide gauge at 01:15 UTC on October 25, 2018. Prior to the event, seiches recorded at the site had typical amplitudes of around 5 cm. The strong pulse was followed by long duration oscillations with amplitudes of about 10 cm. An analysis of atmospheric pressure records from 9 microbarograph stations on Vancouver Island reveals that the sea level event was coincident with strong (1.5-1.9 mb) falls in air pressure at all sites that were associated with an atmospheric pulse propagating to the northeast at a speed of 29 m/s. A numerical model of the sea level event was formulated using modeled atmospheric pressure and a high-resolution bathymetric grid. The simulated sea level oscillations closely agree with observation. The model results further show that long waves, generated on the shelf by the moving atmospheric disturbance, radiate into the open ocean and should be strong enough to be recorded by offshore Bottom Pressure Recorders (BPRs). This finding is confirmed by comparing the model results with high resolution data recorded at ~2700 m depth in Cascadia Basin by BPRs in the Ocean Network Canada cabled observatory network.

NUMERICAL SIMULATIONS OF METEOTSUNAMIS ON THE BUENOS AIRES COAST, ARGENTINA

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ABSTRACT

Previous investigations have shown that meteotsunamis are forced by atmospheric gravity waves (AGW) on the coast of the Buenos Aires Province (Argentina). Recently, the Weather Research and Forecasting (WRF) Model was employed to simulate AGW in this region. The results indicated that the WRF model is able to reproduce high-frequency atmospheric pressure fields associated with AGW. AGW outputs, simulated with WRF model, were used to drive a vertically integrated ocean model and meteotsunamis can be successfully simulated along the coast of the Buenos Aires Province. High-resolution sea level measurements were used to validate the numerical results in Mar del Plata. By means of wavelet analysis it was found that the ocean model is able to represent the spectral structure of the meteotsunamis. The main conclusions of this numerical study are: (1) maximum wave heights are detected at the coastal area, close to Mar del Plata (38°S); (2) meteotsunami wave propagates along the Buenos Aires coast, predominantly from South to North; (3) meteotsunami celerity is around 10 m/s; (4) amplitudes decrease from the coast to open ocean, reaching very small amplitudes (< 0.01 m) near the continental slope; (5) heights are negligible in the outer Río de la Plata; and (6) amplitudes depend on the celerity and propagation direction of the AGW.

METEOTSUNAMIS IN THE GULF OF MEXICO AND EASTERN UNITED STATES DURING HURRICANE SEASONS 2016-2017

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ABSTRACT

Tropical cyclones are one of the most destructive natural hazards. Flood-related damages represent a large portion of losses and casualties. Characterizing and predicting total water levels during extreme storms is important to increase the resilience of coastal communities.

Numerical simulation and prediction of coastal water levels during extreme storms is still challenging, despite the latest scientific and computational advances. Total water levels in the nearshore are usually computed as the superposition of the astronomic tide, storm surge, gravity wave setup, water level changes due to infragravity waves, wave runup, and swash motions. However, there is enough observational evidence of the existence of other types of water level oscillations, such as meteotsunamis, during tropical cyclones. Despite the potential hazard associated with these types of waves, the generation and propagation mechanisms of meteotsunamis during tropical cyclones remain elusive.

In this study, we analyze the meteotsunami events along the Gulf of Mexico and U.S. East coast during the hurricane seasons 2016 and 2017. This period includes hurricanes Maria (2017), Irma (2017), Harvey (2017), Matthew (2016), and Hermine (2016). For the duration of each hurricane, we analyzed the free surface elevation measurements from the National Oceanic and Atmospheric Administration (NOAA) tidal gauge network. We complemented the analysis with atmospheric radar reflectivity, sea level atmospheric pressure, wind speed and wind gust, and air temperature measurements (when available). Results indicate the presence of meteotsunamis with maximum water level anomalies of up to 0.8 m. In three of the five analyzed hurricanes maximum meteotsunami elevations were higher than 0.45 m. Most of these events were triggered by spiral rainbands. We used the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modelling system to identify which types of spiral rainbands have a higher potential to trigger meteotsunamis. We used atmosphere-ocean coupled idealized simulations to untangle the main generation and propagation mechanisms.

MODELING OF STORM SURGE AND INUNDATION WITH RESPECT TO PRESSURE AND WIND FIELDS

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ABSTRACT

Evolution of storm surge and related inundation is dependent on the spatial and temporal change of atmospheric pressure and wind fields. A numerical model is developed to solve nonlinear shallow water equations using the forcing function as pressure and wind fields. The model has been built up on tsunami numerical model NAMI DANCE GPU version and therefore, have the capability of computing spatial and temporal distribution of water level throughout the study domain and respective inundation related to either tsunamis or tropical cyclones. Therefore, the code has gained the capacity of solving storm surge.

Since the code is originally structured for Graphical Processing Unit (GPU) using CUDA API, its process time decreased tremendously. The tsunami solver module of the code has already been applied to different (analytical, experimental and field) benchmark problems of tsunamis for tests. The accuracy of the results is compared with the measurements and fairly well agreements are obtained. The storm surge module of the model computes possible water level changes due to the forecasted pressure and wind fields and provides the information to the decision makers in advance. Fastest simulation time of the code provides repeated simulations to the users due to the forecasted (pressure and wind) data during the evolution of the tropical cyclones and help to early accurate assessment of the situation before warning.

The code, NAMI DANCE GPU T-SS (Tsunami-Storm Surge) is validated by applying to regular shaped basins under circular static and dynamic pressure fields separately and also different wind fields. The wave generation with respect to the combinations of pressure and wind fields are also tested in validation. Furthermore, the code is also applied to recent events in the Mediterranean and Caribbean. The results are presented and compared with the observations.

MODELING METEOTSUNAMIS WITH REAL-TIME DATA

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ABSTRACT

On June 13, 2013, tsunami-like waves were observed at the New Jersey and southern Massachusetts coasts. In Barnegat Inlet, New Jersey, three people were injured when a six-foot wave swept them off a jetty and into the water. The waves were recorded by many coastal water-level stations from Puerto Rico to New England as well as a Deep-Ocean Assessment and Reporting of Tsunamis (DART) buoy 150 miles offshore. This was one of many meteotsunamis recorded at the East Coast gages each year.

A proof-of-concept modeling study has been conducted to investigate the June 13, 2013 event to investigate potential of meteotsunami modeling based on real-time observation data. The preliminary tsunami model based on MOST has been constructed using the radar reflection data as a proxy for pressure field temporal evolution. The tsunami wave generated by the propagating pressure field has been modeled, and simulated time-series were compared with the sea-level coastal gages and DART records. The model is able to reproduce the recorded sea-level changes in deep ocean and at the coast. The study shows promise for developing meteotsunami model forecast capability based on available measurement data.

SIMULATION OF FLOODING AND DRYING IN METEOTSUNAMI MODELLING

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ABSTRACT

Meteotsunamis, sea level oscillations of meteorological origin with periods similar to those of tsunamis, can, in extreme cases, reach significant wave heights and cause large damage to property and even a loss of life. In this study we have taken four historic meteotsunamis in the Adriatic, the largest of which had a wave height of 6 meters, and attempted to improve upon previous numerical simulations (or to compute them for the first time) in order to model the events as accurately as possible. First, a set of simulations was done using a minimum depth of 4 m. Results for Vela Luka (21 June 1978), Široka (22 August 2007) and Mali Lošinj (15 August 2008) showed significant sea level oscillations in the bays but the amplitudes were, at best, 50% of the observed ones. In the case of Stari Grad (19 February 2010) the modelled oscillations were smaller, up to 30% of the observed ones. The situation in Stari Grad was specific that day – sea level was already elevated due to a storm surge and it is assumed that without the storm surge the meteotsunami that hit the bay would not have caused flooding on its own. The next set of simulations included flooding and drying of grid nodes. Grid resolution was enhanced in the entire Adriatic but especially in the four bays where the spatial resolution was several tens of meters and topography was included in order to allow for wave runup. All modelled wave heights were larger than in previous simulations, by up to a 100%. Even though some of the modelled wave heights were still lower than the observed ones, this result is a clear indication that modelling extreme wave heights of destructive meteotsunamis can benefit from a flooding and drying methodology incorporated into the model.

SENSITIVITY STUDIES OF MENORCAN METEOTSUNAMIS UNDER SYNTHETIC GRAVITY WAVE FORCING

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ABSTRACT

The oceanic model component of the Balearic RIssaga Forecasting System (BRIFS, run at SOCIB, the Balearic Islands Coastal Observing and Forecasting System) is used to investigate the sensitivity of meteotsunamis affecting Ciutadella harbor and Platja Gran (Menorca Island) to different factors including atmospheric gravity wave characteristics and the presence of Son Blanc dike. These synthetic atmospheric forcing experiments allow us to both validate the physical soundness of the high-resolution nested ocean modelling system used for BRIFS operational daily predictions, and investigate propagation and amplification mechanisms under varying conditions.

The ocean model is first forced by synthetic gravity wave trains with varying speeds and directions. The variation of the propagation paths in the Menorca Channel according to the atmospheric forcing velocities indicates that the bathymetry serves as a converging lens for meteotsunamis waves, whose paths are constrained by the forcing direction and the Proudman resonance. Isolating the atmospheric pressure forcing over either Mallorca shelves or the Menorca Channel shows that the Channel is the key built-up region determining the amplitude of meteotsunamis in Ciutadella.

Single pressure wave forcing with varying periods is then used to investigate the impact of the forcing period on the amplification of the meteotsunamis. The sea level range in Ciutadella properly shows the two maxima corresponding to the two main oscillation modes of the harbor. Surprisingly, while the model properly represents the maximum amplification for the fundamental period of 10.5min, this situation is obtained for an atmospheric forcing period of 12.5min. This shift is found to be related to the specific shape of the sea level response to the atmospheric wave under Proudman resonance conditions.

Finally, the impact of Son Blanc dike, which was built in 2011 close to the entrance of Ciutadella inlet, is also evaluated numerically under this synthetic forcing framework.

CONVECTIVE STORM EVOLUTION OVER THE LAURENTIAN GREAT LAKES WITH RESPECT TO METEOTSUNAMI-PRODUCING CONDITIONS

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ABSTRACT

Previously-recorded meteotsunami events over the Laurentian Great Lakes (heights of at least 0.3 m) are most frequently accompanied by convective storm systems associated with strong surface winds and large barometric pressure perturbations. However, it has been observed that convective storms usually weaken in terms of precipitation rates as they cross the lakes. It may be expected that such weakening storms are less likely to produce intense pressure and surface wind perturbations, especially when they overlie stable over-lake atmospheric boundary layers (OLBL). This presentation will highlight the state of knowledge of interactions between convective storms and stable OLBLs, with respect to their ability to produce meteotsunami-producing conditions.

HOW AND WHEN SOLITARY EDGE WAVES MIGHT BE A PART OF A METEOTSUNAMI?

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ABSTRACT

The first observations of solitary edge waves of anomalously large amplitude seemingly linked to a meteoevent were reported in the fifties (Munk et al, 1956). However, to this day it remains unclear under what conditions solitary edge waves can occur and how they could be generated by atmospheric anomalies.

Here we present a theoretical model of edge waves' nonlinear dynamics and their generation by atmospheric disturbances. The theory is derived for a simplified model of topography and takes into account the longshore current. The edge waves can be generated through the linear Proudman resonance between the longshore projection of the atmospheric front velocity and the phase velocity of an edge wave. The resonant condition is simultaneously satisfied for all edge wave modes having the same phase speed, although usually the generation of the fundamental mode is the most efficient. We derive nonlinear evolution equations describing dynamics of such edge waves. The main question we focus upon is whether/when solitary edge waves are possible.

METEOROLOGICAL ANALYSIS OF AN EXCEPTIONAL METEOTSUNAMI EVENT OF 23-27 JUNE 2014 IN THE ADRIATIC AND MEDITERRANEAN

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ABSTRACT

Meteotsunamis are long sea surface waves caused by propagating weakly dissipative atmospheric pressure perturbations formed by ducted internal atmospheric gravity waves and/or convection. Several strong meteotsunamis occurred in the northern Mediterranean countries during a major meteotsunami period of 23-27 June 2014. The largest sea level oscillations were observed in the morning of 25 June 2014 in Vela Luka Bay, Croatia, where sea level oscillations reached height of 3 m. Sea level oscillations reaching more than 1 m were also observed at the Balearic Islands (Spain), Sicily (Italy), and Odessa (Ukraine). The large-scale synoptic setting during the meteotsunami period was characterized by an incoming upper-level trough as well as the upper-level jet aloft and warm low-level advection from the African continent. Such environment, combined with Froude number values of ~1.0, is conducive to meteotsunamis, which was the case during this event in areas where meteotsunami occurred.

The numerical analysis of the atmospheric component of the event was carried out using the Weather and Research Forecasting (WRF) mesoscale non-hydrostatic model. The model simulations were configured with several telescoping domains reaching 0.5 km grid spacing over the Adriatic and 1 km grid spacing over the Mediterranean. In the Adriatic, the dynamically unstable mid-troposphere with Richardson number smaller than 0.25 capped the warm statically stable air in the lower troposphere. Concurrently with pressure perturbations, both convection and internal gravity waves were at play, with both wave-CISK and wave-duct promoting maintenance and intensity of pressure perturbations over the Adriatic. Furthermore, similarities and differences between generation mechanisms over the Mediterranean and along the U.S. East Coast are briefly discussed. Finally, simulations performed in this event reproduced meteotsunami-related pressure perturbations at the adequate time and approximate locations several days ahead, which is a step forward demonstrating the ability of atmospheric models to assist early warning meteotsunami systems.

THE GROWTH TIME REQUIRED FOR EDGE WAVES GENERATED BY ATMOSPHERIC DISTURBANCES MOVING ALONG COASTLINE

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ABSTRACT

It has been observed and theoretically proved that edge waves can be generated by an atmospheric pressure disturbance moving along the coastline. Edge waves propagate along coastline in a packet form and are confined within a certain distance in cross-shore direction. The occurrence of edge waves relies on the spatial scale, translational speed and trajectory of atmospheric disturbance as well as the beach slope. Furthermore, the generation of edge wave takes time, so the growth time or the fetch length for edge waves is also an important factor for the occurrence of notable edge waves. Based on the nonlinear shallow water wave model, a set of numerical cases are conducted to study the evolution of edge waves under an atmospheric pressure disturbance moving along coastline in an idealized coast area. The growth time required for edge waves becoming notable from a calm sea is defined and investigated. Associating with the analytical solution of Greenspan, the effects of dominant factors in the case of a Gaussian pressure disturbance, such as disturbance spatial scale, translational speed and beach slope, are discussed. Other factors including the length of coastline and the shape of pressure disturbance are also discussed numerically. Critical conditions for the occurrence of notable edge waves are provided to assist the observation of edge wave phenomenon.

TRAVELING AIR PRESSURE DISTURBANCES IN OPERATIONAL METEOROLOGICAL FORECAST MODEL

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ABSTRACT

Atmospheric numerical weather prediction models represent one of the main components of any meteotsunami warning system. The non-hydrostatic 2km resolution ALADIN System forecast running operationally in Meteorological and Hydrological Service of Croatia is an obvious candidate. Preliminary analyses of its operational outputs, which have been available since July 2011, reveal the presence of travelling small-scale pressure disturbances capable to excite meteotsunamis. However, the comparison of forecast pressure evolution to the measured data shows that the intensity of the observed pressure disturbances is simulated fairly by the model, but at a slightly different position and time, and propagate with slightly different speed and direction. Meteotsunamis are known to be highly sensitive to these parameters. The recent meteotsunamis are investigated using available atmospheric data and meso-scale atmospheric model ALADIN with ALARO physics package for reproduction of travelling air pressure disturbances during the Adriatic meteotsunami events. Spatial, temporal and spectral properties of the travelling air pressure disturbances are assessed. Here we analyse if using more realistic SST, such as from the ROMS ocean model, and more realistic physiography of the terrain surrounding the Adriatic Sea, can improve the forecast of intense small-scale pressure disturbances that can generate meteotsunamis. One-minute model time-step is used for reproducing the disturbances. This allows for an accurate estimate of the error in the position, shape, variability in space and time, as well as speed and direction of the model disturbances with respect to those know to have generated meteotsunamis. Supplementary, the improvement of the operational forecast is documented, based on the use of more realistic SST, e.g. coming from the ROMS ocean model, and more realistic physiography of the terrain surrounding the Adriatic Sea.

ADRISC WEB PAGE - VISUALIZATION OF DATA FROM NUMERICAL MODELS AND REAL-TIME STATIONS NETWORK IN FRAME OF ADRIATIC SEA AND COAST (ADRISC) METEOTSUNAMI FORECAST

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ABSTRACT

AdriSC web page is available at http://www.izor.hr/adrisc. Every day since the 15th of April 2018, the following forecast data are published:

- 48h forecast of hourly atmospheric fields from the WRF model: air temperature at 2m (°C), air temperature at 850 mbar (°C), mean sea level air pressure (hPa), wind at 10m (m/s) and wind at 500mbar (m/s). The WRF results presented in the website have a spatial resolution of 3km.
- 48h forecast of hourly ocean fields from the ROMS model: sea surface elevation (m, including tides), sea surface ocean currents (cm/s), barotropic ocean currents (cm/s, averaged value of the currents over the depth), sea surface ocean temperature (°C) and salinity. The ROMS results presented in the website have a spatial resolution of 1km.

There is two type of layers available: scalar layers and vector layers. Both types of layers can be switched on and off. Vector layer can be combined with one of the scalar layers.

On the AdriSC web page stations can be shown. Station are locations where model results are extracted for each minutes and some of them are paired with actual real-time measurement stations.

For the better understanding of environment, various measuring systems and models with output as gridded fields of values are developed. At this moment there are two types of visualizations used for presenting model results on the Internet: generated static images and generated a georeferenced image used as an overlay with a zoomable map. This paper describes the third type of solution: dynamically created scenes at client side using JavaScript.

SIMULATING METEOTSUNAMIS ALONG THE SOUTH-WEST AUSTRALIAN CONTINENTAL SHELF

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ABSTRACT

Field data from coastal tide gauges and meteorological stations located along the south-west coast of Western Australia and a depth-averaged barotropic unstructured grid numerical model were used to investigate the sensitivity of meteotsunamis to atmospheric disturbances in south-west Western Australian coast. In this region, the occurrence of meteotsunamis is a regular phenomenon particularly during the summer months with different atmospheric forcing (e.g. thunderstorms, low pressure systems and tropical cyclones) generating meteotsunamis at coastal stations up to 500 km apart. Analysis of the field measurements indicated that meteotsunamis generated by thunderstorms, passage of low pressure systems and tropical cyclones each consisted of unique waveforms. A numerical model, validated using field measurements of meteotsunamis, was used to examine characteristics of two large meteotsunami events associated with supercell thunderstorms. Southward propagating air pressure jumps of 2–4 hPa were associated with both events, but with different propagating speeds and directions. The predicted sea level and current oscillations for both events were in good agreement with observations. Generating mechanisms of meteotsunamis were then explored through numerical simulations with synthetic air pressure jumps. The results indicated that the initial meteotsunami waves at the coast were sensitive to the propagation speed, magnitude, direction and bandwidth of the pressure jump. The maximum initial wave heights along the coastline were due to topographic influences leading to a combination of different resonance conditions. The results indicated that both the forced and free edge waves were generated along the coast with the relatively larger meteotsunamis generated via Greenspan resonance.

THE MULTISCALE METEOROLOGICAL PROCESSES IN THE GENESIS OF THE ATMOSPHERIC PRESSURE DISTURBANCES IN EAST ASIA

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ABSTRACT

The present study investigates the genesis of the atmospheric pressure disturbance at sea level with the multiscale meteorological analysis from Asian monsoon scale to mesoscale. I used the reanalysis data set of JRA-55 provided by Japan Meteorological Agency to investigate monsoon scale atmospheric circulation. Weather Research and Forecast (WRF) model was also used to analyze the 3-dimensional wind circulation and trace the particles backward to find the air particle origin. One of the important mechanism to cover the pressure disturbances over the East China Sea is the lifting of the low level moist air above LFC along the mountain range of the South China or Taiwan Island. The mixing of the lifted moist air and dry air mass from south of the Himalaya mountain range made the middle troposphere unstable. The band of unstable air covered with the East China Sea by subtropical subject. According to the backward trajectory analysis, the origin of the lifted moist air came from the South China Sea, Indochina Peninsula, and Bay of Bengal. Indeed, in the severe cases such as March 1979 or February 2009 events, anomalously massive flow of lowlevel moist (below 850hPa isosurface) air was analyzed across the coastal area at 15 N of the South China.

CHARACTERIZATION AND IDENTIFICATION OF METEOTSUNAMI-PHYSICAL PARAMETERS FOR THE GOM WITH APPLICATION TO PANAMA CITY AND OTHER LOCATIONS IN WEST FLORIDA

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ABSTRACT

In the US, conditions for destructive meteotsunamis are common in the Gulf of Mexico (GOM). Atmospheric pressure and wind anomalies associated with the passage of squalls create the majority of the observed meteotsunami events. The most intense meteotsunamigenic periods seem to occur during El Nino years, but some also have been observed in years characterized by unusually intense tropical cyclone. On average, 1 to 3 meteotsunamis with wave heights greater than 0.5 m occur each year in this region, (Olabarrieta, et al., 2017). To unveil and gain an understanding of this phenomenon, we developed a simple (depth integrated) web-based numerical model tool. This simplified numerical tool allows us to rapidly create several plausible scenarios, helping us to identify energy focusing locations and resonance mechanisms (Proudman, Greenspan, shelf, etc.). We aim to obtain worst-case meteotsunami-physical parameters (squall transects, speed, atmospheric pressure signal, etc.) to specific locations. We have chosen Panama City, Clearwater Beach and Naples, FL as prime locations for the pilot study and thus gain a better understanding of the meteotsunami phenomenon in the west coast of Florida. Our final goal is to identify meteotsunami-physical parameters that could help emergency manager to assess and mitigate the hazard.

Reference:

Olabarrieta, M., Valle-Levinson, A., Martinez C., Pattiaratchi, C., Shi, L., 2017. Meteotsunamis in the northeastern Gulf of Mexico and their possible link to El Nino Southern Oscillation. Nat Hazards (2017) 88:1325–1346 DOI 10.1007/s11069-017-2922-3

Session 3

Atmosphere-ocean interactions and ocean processes

THE AMPLIFICATION MECHANISM OF THE METEO-TSUNAMI ORIGINATING OFF THE WESTERN COAST OF KYUSHU ISLAND IN JAPAN IN THE WINTER OF 2010

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ABSTRACT

A meteo-tsunami is a tsunami-like phenomenon excited by a travelling atmospheric disturbance. In Japan, meteo-tsunamis are frequently observed along the western coast of Kyushu Island during winter–spring and are called Abiki. One of the largest Abiki occurred on March 3, 2010, where the maximum amplitude of water level oscillations exceeded 1 m in various bays including Nagasaki Bay and Makurazaki Bay. At the same time, triangular-shaped atmospheric pressure changes with amplitudes of ~1 hPa were recorded at various weather stations along the western coast of Kyushu Island.

In this study, we carry out a numerical simulation of this meteo-tsunami to show that it can be reproduced very well assuming that a simple atmospheric pressure disturbance consisting of several triangular-shaped pressure changes in 10-20 minutes propagated east-southeastward at a speed of ~ 30 ms-1 over the East China Sea.

Over a wide area of the shallow continental shelf in the East China Sea, oceanic waves are amplified through a resonant coupling (Proudman resonance) to the travelling atmospheric disturbance. After leaving the shallow continental shelf in the East China Sea, the amplified oceanic waves propagate faster getting out of the influence of the atmospheric disturbance. Then, they propagate eastward as free-waves while being further amplified through reflection and refraction under the complicated topographic and configuration constraints in the coastal area and excite meteo-tsunamis along the western coast of Kyushu Island. Of special interest is the fact that the resonant coupling between the oceanic waves and the traveling atmospheric disturbance occurs again over the elongated shallow continental shelf extending westward from Cape Kaimondake, which contributes to the long-term water level oscillations in Makurazaki Bay.

THE PROPAGATION CHARACTERISTICS OF MICRO-BAROMETRIC WAVE ESTIMATED FROM OBSERVATIONAL DATA AND THE RESPONSE OF METEOTSUNAMI IN THE WEST KYUSHU ISLAND

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ABSTRACT

The estimation of the trigger of meteotsunami is very difficult problem in general. In some meteotsunami cases, a single pressure bump is measured and it would be considered as a reliable external force of the event. However, in other cases, the variation of pressure wave was complicated because various atmospheric disturbances are included. In this study, the trigger of meteotsunami in the west coast of Kyushu Island was analyzed from observational data. The micro-barometric wave components at some distant stations extracted from observational data of atmospheric pressure were similar. The propagation property of micro-barometric wave, speed and direction, were estimated. The propagation processes of micro-barometric wave of two representative events were different although the transfer of synoptic low pressure looked like each other. The development and propagation process of meteo-tsunami was simulated by solving of the nonlinear longwave equation. The translation process of external force of meteotsunami, micro-barometric waves, were simulated by move of simple sine function. In the simulation, the sensitivity analysis of some parameters of micro-barometric waves were conducted because the objective decision of these parameters is difficult. The results overestimated or underestimated the actual oscillation of water surface. Even the very small micro-barometric waves comparing to measurement precision limit could induce significant increase of water level according to the condition of pressure waves. Besides, the number of pressure waves and the wave length affected the maximum water level and the beats phenomena.

EXAMINATION OF GENERATION MECHANISMS FOR AN ENGLISH CHANNEL METEOTSUNAMI: COMBINING OBSERVATIONS AND MODELING

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ABSTRACT

On the morning of 23 June 2016, a 0.70-m meteotsunami was observed in the English Channel between the United Kingdom and France. This wave was measured by several tide gauges and coincided with a heavily precipitating convective system producing 10m/s wind speeds at the 10-m level and 1–2.5-hPa surface pressure anomalies. A combination of precipitation rate cross correlations and NCEP–NCAR Reanalysis 1 data showed that the convective system moved northeastward at 17–21 m/s. To model the meteotsunami, the finite element model Telemac was forced with an ensemble of prescribed pressure forcings, covering observational uncertainty. Ensembles simulated the observed wave period and arrival times within minutes and wave heights within tens of centimeters. A directly forced wave and a secondary coastal wave were simulated, and these amplified as they propagated. Proudman resonance was responsible for the wave amplification, and the coastal wave resulted from strong refraction of the primary wave. The main generating mechanism was the atmospheric pressure anomaly with wind stress playing a secondary role, increasing the first wave peak by 16% on average. Certain tidal conditions reduced modeled wave heights by up to 56%, by shifting the location where Proudman resonance occurred. This shift was mainly from tidal currents rather than tidal elevation directly affecting shallow-water wave speed. An improved understanding of meteotsunami return periods and generation mechanisms would be aided by tide gauge measurements sampled at less than 15-min intervals.

PROUDMAN RESONANCE IN THE CHANNELS OF ARBITRARY CROSS-SECTION

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ABSTRACT

Tsunami waves of meteo-origin are amplified if the atmospheric disturbance moves with the celerity of the water waves. This Proudman effect is well-known and confirmed by the observations and numerical modeling. Our paper deals with study of the features of the Proudman resonance in the channels of arbitrary cross-section. Firstly, we develop the analytical theory of this phenomenon using 1D linear shallow-water equations averaged on the cross-section. Secondary, we perform a set of numerical simulations within 2D nonlinear shallow-water equations using software NAMI-DANCE which solves the nonlinear shallow water equations. In the simulations we inputted the moving high pressure band with a constant velocity over a flat bottom water basin. The constant velocity of pressure band is selected slower, equal and faster than the group velocity of the water waves in the basin. Therefore, we considered various scenario of interaction including sub-critical and super-critical regimes and taking into account the variability of basin depth along the propagation path. The applicability of the developed theory is discussed comparing the analytical and numerical results.

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UNEXPECTED RIP CURRENTS INDUCED BY A METEOTSUNAMI

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ABSTRACT

A tragic drowning event occurred along southeastern beaches of Lake Michigan on a sunny and calm July 4, 2003, hours after a fast-moving convective storm had crossed the lake. Data forensics indicates that a moderate-height (~0.3 m) meteotsunami was generated by the fast-moving storm impacting the eastern coast of the lake. Detailed Nearshore Area (DNA) modeling forensics on a high-resolution spatial O(1 m) grid reveals that the meteotsunami wave generated unexpected rip currents, changing the nearshore condition from calm to hazardous in just a few minutes and lasting for several hours after the storm. Cross-comparison of rip current incidents and meteotsunami occurrence databases suggests that meteotsunamis present severe water safety hazards and high risks, more frequently than previously recognized. Overall, meteorological tsunamis are revealed as a new generation mechanism of rip currents, thus posing an unexpected beach hazard that, to date, has been ignored.

A COMPARATIVE STUDY OF THE TSUNAMI ORIGIN (TURBIDITIES OR METEOTSUNAMI)

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ABSTRACT

Extreme sea level changes have been documented with a lot of photographs, movies and clips recorded by the eyewitnesses during the water surface oscillations to the North Bulgarian Black Sea coast at the morning of 7th May, 2007. Short time after the event (less than a week) a field expedition have been organized and explored the consequences on the sea coast. The data about the debris on the coastal line, the moved tetrapodes in walls of the wave breakers, as well as boats disturbed and partially damaged and stories of the eyewitnesses have been collected Not so many in situ ocean and meteorological measurements along the western Black Sea coastline were available during the tsunami event of 7th May 2007, especially concerning high-frequency (a minute timescale) data. Sea observations were available at a number of locations, including tide gauge measurements conducted at Ahtopol and Varna as well as at Iraklly and eyewitnesses' reports. The possible sources of tsunami in the area are earthquakes, on land and in the sea landslides and possible atmospheric disturbances. As no earthquakes and on land landslides activity have been registered, two hypotheses have been explored - the tsunami have been produced by a submarine landslide or by atmospheric pressure pulses – both reasonable and suggested by researchers even in the first days after the tsunami event. The numerical simulations of the both possible sources – turbidities and atmospheric pressure pulses gave quantitative results which are under a comparative analysis in this study. It is very important to identify the real origin of this significant event. Both explored methods presented the acceptable results, but the comparison with the observations are still not enough to be considered as real confirmation of the source origin of the case of 7th May, 2007.

GENESIS OF THE ATMOSPHERIC INTERNAL GRAVITY WAVES (IGWS) DRIVING EASTERN ADRIATIC METEOTSUNAMIS

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ABSTRACT

During the last decades, meteotsunami events occurring along the eastern Adriatic coastal areas and islands have been intensively studied and modelled. That also applies to the propagation of meteotsunamigenic atmospheric internal gravity waves over the ocean, normally ascribed to the synoptic setup that favours its propagation over long distances. However, little is still known concerning the genesis of the atmospheric IGWs, including the mechanism and source area driving the meteotsunami events in this region. Recently, a dedicated high resolution operational model – the AdriSC Meteotsunami component, has been implemented and validated part of the Croatian Meteotsunami Early Warning System funded by the project MESSI. In order to perform a process oriented analysis of the generation and propagation mechanisms of the atmospheric IGWs during meteotsunamis, the AdriSC modelling suite was used in re-analysis mode for four well-documented meteotsunami events (25th & 26th of June 2014, 28th of June 2017 and 1st of July 2017) which occurred in the recent years. The validation of the different model used as well as the preliminary results of the analysis of the modelled atmospheric IGWs are presented in this study.

THE EXTREME TYPHOON "SONGDA" EVENT OF 14 OCTOBER 2016 ON THE COASTS OF BRITISH COLUMBIA AND WASHINGTON STATE

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ABSTRACT

Typhoon "Songda" formed in the central Pacific Ocean on 2 October 2016. "Songda" subsequently passed along the coast of Japan and then turned eastward, crossed the Pacific Ocean and arrived on the coast of British Columbia (BC) on 12-16 October. In this study, reanalysis data and satellite images have been used to define the development and trajectory of the typhoon. Results show that the interaction of the typhoon with a northward moving atmospheric low generated hazardous sea level oscillations along the BC-Washington coast, involving a superposition of strong storm surge, seiches and infragravity waves. On the southern BC and northern Washington (WA) coasts, surge heights were greater than 80 cm. The maximum storm surge of 117 cm was observed at La Push (WA), while New Westminster in the Fraser River recorded a surge height of 101 cm. A particularly remarkable feature of the event was the sharp, knife-like 40-cm increase in sea level that peaked at 07:01 UTC on 14 October at Tofino on the west side of Vancouver Island. Similar, but weaker, sharp sea level peaks were also observed at Bamfield, Port Alberni and Port Renfrew. At Tofino, Bamfield and Port Alberni, the peaks were related to specific shapes of the air pressure variations (the minimum atmospheric pressure at Tofino was 971.4 hPa). In addition, the sea level responses were 1.5-2.5 times greater than expected from the inverted barometer effect, suggesting that topographic sea level amplification was a factor in these areas. The concurrent sea level oscillations observed at Tofino and surrounding region clearly have the form of a "meteorological tsunami" that, in this specific case, has the character of a forced solitary wave. For each tide gauge record, we isolated several types of recorded oscillations - storm surge, meteotsunami (local seiches) and infragravity waves - and estimated their role in the formation of the extreme sea level heights.

METEOTSUNAMIS PRODUCED BY PRECIPITATING ATMOSPHERIC SYSTEMS ACROSS THE NORTH-WEST EUROPE

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ABSTRACT

There have been several meteotsunami case-study reports in north-west Europe generated by precipitating, convective storms between May–August. However, there has not been a meteotsunami climatology in north-west Europe. We address this issue and present two main results, showing the size-frequency distribution of meteotsunamis around north-west Europe and the seasonal occurrence patterns.

We analysed 72 tide gauges in north-west Europe between 1 January 2010 – 31 December 2017. A non-seismic sea-level oscillation at tsunami timescales (NSLOTT) was classified as a non-tidal sea-level oscillation with period below 2 hours, with a wave height that is greater than 6 standard deviations of the non-tidal residual, which was detected by at least two tide gauges within 2 hours. For the purposes of this climatology, a meteotsunami is an NSLOTT with > 0.3 m recorded wave height. Records were cleaned with automatic peak detection algorithms and then visual inspection. To determine an atmospheric forcing for the meteotsunamis, we used the Met Office radar-network derived precipitation covering 70/72 of the analysed tide gauges.

Preliminary results show that 378 meteotsunamis occurred in north-west Europe over 8 years (47.3 meteotsunamis/year). At least 100 NSLOTTs per year exceeded 0.18 m, 10 meteotsunamis per year exceeded 0.60 m, and one meteotsunami per year exceeded 0.97 m. However, tide gauges with 5–15-minute sampling intervals may have under-predicted size-exceedance rates.

Preliminary results also suggest that most meteotsunamis occurred in winter (DJF, 52.1%), and least in summer (JJA, 7.9%). This suggests that previous north-west European studies have neglected case studies that represent over half of meteotsunamis. The average meteotsunami wave height in JJA is 0.43 m (30 events) and in DJF is 0.51 m (197 events); this over-representation is not because meteotsunamis are larger in summer than winter. Future work should focus on winter-time meteotsunami case studies and their associated atmospheric forcings.

Session 4

Climatology of meteotsunamis

A GLOBAL PERSPECTIVE OF NONSEISMIC SEA LEVEL OSCILLATIONS AT TSUNAMI TIMESCALES

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ABSTRACT

Sea level extremes are consequences of a variety of processes operating on different time and space scales. Tides, seasonal cycles, global sea level rise and many other contributors to extremes have been investigated for a long time due to availability of long-term sea level time series measured with temporal resolution of 1 hour or lower. Yet, processes at tsunami timescale, i.e. from a few minutes to a few hours, have been only sparsely and locally analyzed, as these require higher resolution data unavailable in quality-checked research form for the World Ocean. Fortunately, the UNESCO IOC Sea Level Station Monitoring Facility website (http://www.ioc-sealevelmonitoring.org) provides not quality-checked global 1-min sea level data for more than 1000 world stations. These data have been downloaded for the period from June 2006 to June 2018 and analysed for high frequencies ($T < 2$ h). To get reliable results, time series shorter than one year and containing more than 10% data gaps have been excluded from the analyses, while the rest of the time series have been passed through several steps of quality control that included various automatic procedures (e.g. detection of data spikes and shifts, tidal analysis), as well as visual inspection (manual removal of spikes and other low-quality data). Tsunami events registered in NGDC/WDS Global Historical Tsunami Database have been removed from the analysis. The series have then been filtered with a 2-h Kaiser-Bessel high-pass filter. Preliminary results of these analysis will be presented. After obtaining quality-controlled high-frequency sea level data, various further studies will be conducted, including global and regional statistical analysis, spectral properties, mapping of coherent regions, conjunction of high-frequency oscillation with atmospheric processes, and other. The proposed research will allow for more accurate assessment of high-frequency oscillations and forecasts of future extreme events, which have already been found to contribute up to 50% to sea level range in certain regions and basins.

STATISTICS OF EXTREME ATMOSPHERICALLY-GENERATED SEICHES IN PORT ALBERNI, BRITISH COLUMBIA (2009-2018)

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ABSTRACT

Port Alberni, located at the head of the 40-km long Alberni Inlet on the west coast of Vancouver Island, British Columbia, Canada, is known for having a marked resonant response to oceanic tsunamis and for having recorded the highest tsunami wave heights in Canada. Resonance-enhanced waves reached a maximum amplitude of 4 m during the Alaska earthquake and tsunami of March 1964. For this study, we analysed digital time series data from the Port Alberni tide gauge to determine statistics of the fundamental mode (period, about 105 min) of water level amplitudes during the period 2009-2018. The highest seiches occurred during the 2011 Tohoku tsunami (up to 0.70 m in amplitude) and the 2010 Chilean tsunamis (up to 0.49 m in amplitude). Unexpectedly, the next group of several tens of high amplitude seiches had no relationship to earthquakes. An analysis of the 12 strongest events after the Tohoku and Chilean tsunamis shows that the events had amplitudes of up to 0.35 m and were all associated with rapid changes in atmospheric pressure. Most of these meteotsunamis were directly attributable to pressure changes associated with large-scale atmospheric fronts, confirming that regionally-forced meteotsunamis are important factors in the generation of extreme seiches in the inlet. The extreme statistics of all seiche amplitudes in the inlet, including those arising from meteotsunami, are well-defined by Gumbel Type-I distributions.

METEOROLOGICALLY GENERATED LONG-PERIOD WAVES AND THEIR IMPACT ON THE PRIMARY NATIONAL FLOODING PROTECTION SYSTEM OF THE NETHERLANDS

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ABSTRACT

Long-period water level oscillations occur on the North Sea during storms. The meteorological generating mechanisms of these events are known to a large extent and include pulse-like events and events of longer duration (De Jong, 2004). Under these conditions seiching occurs in the ports along the Dutch North Sea coast. These need to be taken into account for the height criteria that apply to the dunes, dikes and other barriers that protect the western part of the Netherlands from flooding. These height criteria correspond to a return period of 10000 years or longer, since these barriers protect the most densely populated areas in the Netherlands, which are below mean sea level. Over the last years, extensive work on the climatology of seiching has been performed at Deltares. Results served for updating the height criteria of the barriers inside the Port of Rotterdam, but also as input to the design and construction of two large new sea locks within other coastal ports in The Netherlands - one further north, near Amsterdam, and one in the South of the Netherlands, near the city of Terneuzen. These new large sea locks will be integrated into the national primary flooding protection system and therefore need to meet the same strict criteria for the protection against flooding. The presentation and the paper will describe the different port locations considered (stretching a large portion of the national coastline), the analyses of local measurements, the modelling of local responses to incoming long waves and how results were translated into seiche statistics based on a consistent understanding of the physics involved in meteorologically generated long-period waves in this area. The resulting insights and data have been used for deriving the normative values of long-wave responses (seiching) to be included in the law on the Dutch primary flooding barriers.

SEISMICALLY GENERATED TSUNAMIS, METEOTSUNAMIS AND ROGUE WAVES: PROBLEMS OF IDENTIFICATION, PARAMETERIZATION AND CATALOGUING

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ABSTRACT

Meteorological tsunamis (meteotsunamis) are usually defined as anomalous sea level oscillations in the long-period band (2 to 60 min) resulted from atmospheric forcing. In the Global Historical Tsunami Database (GHTD) maintained by the NCEI/NOAA, which covers almost 4000 years and contains about 2450 events, meteotsunamis constitute very small fraction (less than 2%). For the 20th century, where the database is more complete, their fraction is slightly higher (2.4%). For the same period, the database contains 51 events (5.1%) of unknown origin (source type). Even in the beginning of 21st century (2001-2018), when digital instruments for sea-level recording became widely available, the identified meteotsunamis constitute only 4.4% of all catalogued tsunami events. For example, the strongest ever reported meteotsunami, which occurred in Vela Luka (Croatia) on June 21, 1978, is included into the database with only 0.6 m height and with CC (Cause Code)=0 (unknown source). Other well-known case of meteotsunami (March 25, 1995, western Florida, US) is absent in the database at all. It shows that there are problems in cataloguing this phenomenon. At the same time, there are many regions in the World Ocean (Spain, Croatia, Sicily, Malta, US East coast and the Great Lakes), where meteotsunamis dominate over seismically generated tsunamis. Their deficiency in other regions is partly explained by the absence of clear definition of this phenomenon and by problems of their discrimination from other hazardous sea level oscillations, resulted from extreme tides, storm surges, pressure jumps, squalls, frontal passages, etc., as well as from rogue waves, which are mainly observed in the open sea but sometimes affect coastal areas. Even in cases of reporting such phenomena in mass media and in scientific publications, their cataloguing faces the problems because the adopted format of the GHTD was developed for description and parameterization of tectonic tsunamis (seismogenic, volcanogenic and slide-generated), that in sum constitute more than 90% of the GHTD content. As a result, many of already included in the database "meteotsunamis" lack some basic parameters, like time of origin and source coordinates as well as run-up values. The paper discusses these problems and possible ways for their resolution. Several well-known cases of recent meteotsunamis are considered from the point of view of their parameterization and hazard.

DERIVING PRESENT AND FUTURE CLIMATE OF METEOTSUNAMIS FROM SYNOPTIC CONDITIONS: THE CIUTADELLA CASE (THE BALEARIC ISLANDS)

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ABSTRACT

At a number of places in the World Ocean, meteotsunamis are known to occur under specific atmospheric conditions. In the Mediterranean, these conditions include: (i) exceptionally intense and unstable mid-troposphere jet, (ii) an inflow of warm and dry air masses in the lower troposphere, (iii) near-surface temperature inversion, and (iv) a weak surface cyclone and winds. We quantified connection between synoptic variables and meteotsunami occurrence probability for the meteotsunami hot spot Ciutadella (the Balearic Islands) by constructing synoptic atmospheric index for the present and future climates. ERA Interim reanalysis has been used to derive present meteotsunami climate estimates, while outputs from evaluation, historical, and three scenario MED-11_CNRM Med-CORDEX regional atmospheric climate runs have been used for assessment of future meteotsunami climatology. For the present climate, there exists an index threshold below which the meteotsunamis are very unlike to occur. Similarly, threshold-exceeding values indicate a potential for meteotsunami occurrence (i.e. increased probability of occurrence). For the future climate, no significant changes in the index are projected under RCP2.6 and RCP4.5 scenarios by year 2100. Under the RCP8.5 scenario, the yearly number of days potentially favourable for meteotsunami occurrence is expected to increase by 34% by the year 2100, dominantly during the summer season (May-August). The developed methodology might be used in any world location that exhibit a strong connection between high-frequency sea level oscillations and synoptic atmospheric patterns.

Session 5

Meteotsunamis forecasting and developing early warning system

EVALUATION OF FOUR YEARS OF DAILY PREDICTIONS OF THE SOCIB BALEARIC RISSAGA FORECASTING SYSTEM

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ABSTRACT

The Balearic RIssaga Forecasting System (BRIFS, run at SOCIB, the Balearic Islands Coastal Observing and Forecasting System) is an atmosphere-ocean numerical modelling system aiming to quantitatively reproduce the high frequency sea level oscillations associated with meteotsunamis (rissagues) in the Spanish port of Ciutadella (Menorca Island). The system is executed every morning, generating 48-hour sea level predictions which are made available on SOCIB website www.socib.es/?seccion=modelling&facility=rissagaforecast). These predictions provide a complementary support to the Spanish Meteorological Agency (AEMET) which is responsible for the delivery of official warnings, primarily based on the analysis of the synoptic conditions in the atmosphere.

BRIFS employs WRF as atmospheric model to simulate the high-frequency variability of surface pressure with a 4km spatial resolution. WRF outputs are then used to force the ROMS ocean model covering the Balearic shelves with 2 nested grids to reach a 10m resolution in Ciutadella inlet. Accurate evaluation of this modelling system is possible thanks to a very valuable network of fixed stations recording high-frequency atmospheric pressure variations and sea level oscillations.

In this presentation we will describe the modelling system and evaluate the results of the daily BRIFS predictions over the last 4 years, as well as its capacity to reproduce significant past events in 2006, 2008 and 2014, when the system is run in hindcast mode. We will examine specific cases of rissagues to understand model strengths and limitations, which are mainly related to the capacity of the atmospheric model to accurately represent the small scale disturbances at the origin of the meteotsunamis. Finally, the sensitivity of model results to WRF parameterizations will also be discussed.

A PRAGMATIC APPROACH FOR THE NUMERICAL PREDICTION OF METEOTSUNAMIS IN CIUTADELLA HARBOUR (BALEARIC ISLANDS)

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ABSTRACT

The long and narrow inlet of Ciutadella (Menorca, Spain) is well known for the frequent occurrence of highly amplified seiches (periods of about 10.5 min) during the warm season. These atmospherically driven oscillations (locally referred to as “rissagas”) might occasionally reach extreme wave heights, in the range 1.5 – 4 m, disrupting the port activities and inflicting damages on vessels up to catastrophic limits. Any step towards a better prediction of Ciutadella meteotsunamis has the potential to help anticipating these effects hours or days in advance and thus the adoption of proportional measures of protection.

We devise a pragmatic (and computationally inexpensive) numerical approach aimed at predicting the occurrence and magnitude of this phenomenon. The idea is to retain exclusively the responsible physical mechanisms pointed out by Šepić et al. (2015) and the consideration of contexts as simple as possible (e.g. initialization with a single observed or forecasted radiosounding and use of 2D geometries and flat bottom topography). The method involves the application of the nonhydrostatic fully compressible equations for the atmospheric step (generation and propagation of gravity waves) and the adaptation of the shallow water equations to simulate the subsequent oceanic response (Proudman resonance, shoaling effects and harbour resonance). We propose this strategy as an effective and affordable alternative to the application of full 3D high-resolution atmosphere-ocean coupled models.

The prognostic system is successfully tested for the available set of 128 rissaga events and for a complementary set of 600 ordinary situations. Our approach is able to recognize the rissaga prone situations and tends to correctly categorize the meteotsunami events among weak, moderate or strong cases. The method is now in operation, running daily driven by the GFS forecasted soundings for the next 3 days and providing probabilistic predictions (see http://meteo.uib.es/rissaga).

THE ADRIATIC SEA AND COAST (ADRISC) METEOTSUNAMI FORECAST SYSTEM

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ABSTRACT

The Adriatic Sea and Coast (AdriSC) modelling suite is a research product (funded by Croatian projects MESSI and ADIOS) that was developed with the aim to accurately represent the coastal and nearshore processes driving the atmospheric and oceanic Adriatic Sea circulation, in particular during extreme weather conditions. Within the framework of a pilot meteotsunami early warning system, a special attention was paid to the capability of the modelling system to reproduce and forecast the Adriatic meteotsunamis. A meteotsunami research and warning network, consisting of three radar tide gauges, two meteorological stations and nine microbarograph stations, was also installed within the MESSI project. The modelling strategy for the warning system is twofold: (1) the deterministic generation and propagation of meteotsunamis is forecasted with an operational atmosphere-ocean model, and (2) the coastal hazard (maximum elevation) is statistically given via the application of the Pseudo-Spectral Approximation method. This study presents the capabilities of such a modelling suite to forecast the meteostunami events occurring along the Croatian coast and islands.

OCEAN RADAR AS A TOOL FOR REAL-TIME MONITORING OF METEOTSUNAMIS

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ABSTRACT

High-frequency ocean radar is known to deliver measurements of ocean surface current far beyond the horizon. An ocean radar system doesn't provide a direct estimation of the wave height of an approaching tsunami; however, it measures the surface current velocity generated when the tsunami enters the continental shelf. An unusual change of the surface current can be detected and tracked by a phased-array radar system in real-time. The remote observations of real meteotsunami events have shown a good applicability of ocean radar for offshore tsunami monitoring as a valuable tool to support tsunami early warning.

One of WERA ocean radar systems was installed as a part of the Ocean Networks Canada's Tsunami Project, the initiative to develop a near-field tsunami alert network consisting of different sensors. On 14 October 2016, the 13-MHz WERA system on Vancouver Island, Canada, automatically detected strong changes in measured currents at distances up to 60 km off the coast and triggered an automatic tsunami alert immediately. The system tracked the unusual current pattern for 1.5 hour in real-time following the wave propagation coincided with an atmospheric frontal passage. A jump in surface current velocity was observed simultaneously with air pressure development and compared with tide gauge measurements.

On 29 May 2017, a meteotsunami was generated in the North Sea by an air pressure disruption and reached the southwestern coast of the Netherlands where two 16-MHz WERA systems are installed. They are operated in a standard non-tsunami mode. After re-processing the acquired raw radar measurements from both systems, the original WERA tsunami detection software identified tsunami-like currents more than 40 km offshore. The observations were compared with local tide gauge information and an available video record of the event. One can observe that the wave front had a similar slope to the coastline as seen in video.

ACCURACY ANALYSIS OF THE REAL TIME AIR-PRESSURE-JUMP MONITORING SYSTEM IN YELLOW SEA, KOREA: CASE STUDY OF 2018 MARCH ~ APRIL

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ABSTRACT

The accuracy of the Real-time Air-Pressure-jump Monitoring System (RAPMS) was analyzed from the viewpoint of Propagation Pattern of Atmospheric Instability (PPAI) and its correlation with local tsunami-like surge event. This tentative analysis period is from March to April 2018. One of the observation data we used in the analysis is radar imagery (rain rate ≥ 10 mm/h) selected in the event case. This data is used for the accuracy check of PPAI by inspecting if atmospheric instability indeed happened on the day of the forecast. The accuracy of the forecast is further investigated if there is a correlation between the propagation pattern of air-pressure-disturbance and the atmospheric instability. As a result, the accuracy of the real-time pressure jump monitoring system from the viewpoint of PPAI, was about 83.3%. The propagation pattern of 5 cases among the total 6 pressure jump cases was consistent with the atmospheric instability in radar imagery.

Additionally, the correlation between the forecasted day by RAPMS and the day of actual tsunami-like surge occurred is investigated. The day of occurrence of the surge is extracted through the criteria (above 2-sigma and 3 points simultaneously) from the local tidal measurement data. Comparisons from this point of view shows an accuracy of about 50%. Another interesting aspect found in this study is that the tsunami-like surge only occurred in the case of certain PPAI. From the radar imagery data, we classified the PPAI according to the storm structure classification (Adam J. Bechle et al., 2015) and found that only the propagation patterns of linear and bow type are strongly correlated with the surge occurrences.

DEVELOPING AN EARLY WARNING SYSTEM FOR METEOTSUNAMI IN SOUTH KOREA (KMA)

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ABSTRACT

The Korea Meteorological Administration (KMA) has developed the meteotsunami early warning system which includes coastal observations and prediction systems. The KMA has improved real-time observation networks to measure water level, sea level pressure, and wind at intervals of 1-min at 18 stations nationwide since 2011. The meteotsunami prediction system consists of the high resolution (1.5km) atmospheric model (UM) and the ocean model (FVCOM) with 50 m resolution. FVCOM is running with every 10-min meteorological data from UM out to 36 hours. KMA is operating the experimentally meteotsunami prediction system since March 2017. This study verifies the operational results of the system with observational data.

On March 31, 2007, 2 people were injured, 4 were killed and more than $ 2 million of property damage including flooding of houses, loss of fish farms, ship overturning, and inundation of nuclear coolant pumps was caused by meteotsunami. And 15 people were injured and 9 were killed by meteotsunami near Boryung breakwater on the 1st weekend of May 2008. After that, we conducted an analysis of meteotsunami in terms of seasonality and occurrence frequency through the analysis of long-term water level records. The majority of the observed meteotsunamis over Korea happen between March and May associated primarily with fast moving weather systems such as pressure jump. Statistical analysis shows that about 6 cases annually happen based on the observational data for 18 years (2001-2018) in Korea. The KMA also watches observational data such as air pressure measurements and wave height to detect the propagation of meteotsunami over Yellow sea especially for the every spring season(from March to May). Meteotsunami warning system by sending an automatic mobile text message to forecasters of KMA and the staff of the KCG and KHNP based on the observation network has been constructed since 2013.

METEOTSUNAMIS: WORKING TOWARD AN OPERATIONAL FORECASTING CAPABILITY FOR THE U.S.

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ABSTRACT

Recent research has shown that meteotsunamis are more common in the United States than previously thought, and suggests that some past events may have been mistaken for other types of coastal floods, such as storm surges or seiches. There have been two meteotsunami events detected by the Deep-ocean Assessment and Reporting of Tsunamis (DART) system off the US east coast. The most notable was on June 13, 2013, when, in Barnegat Inlet, New Jersey, three people were injured when a six-foot wave swept them off a jetty and into the water. The other was on May 15, 2018, also off the coast of New Jersey, where the National Tsunami Warning Center coordinated with National Weather Service Forecast Offices to issue warnings to the public.

The United States is in the early stages of developing a meteotsunami forecast and warning capability. Led by NOAA, these efforts include combining our traditional tsunami modelling and detection network including DART buoy systems and tsunami-capable coastal tide gauges with efforts to developing a process that outlines when, where, and how meteotsunami form based on high resolution numerical weather prediction models, in-situ data sources such as sea-level pressure measurements and Doppler weather radar. Once detected, we than forecast meteostunami coastal impacts using operational tsunami forecast models. We provide this information to National Weather Service Coastal Forecast offices for public alerting.

This paper will investigate the current state of the U.S. meteotsunami detection, and forecast capability and will summarize the most recent science, technology, research, and development efforts—as well as remaining challenges to be overcome—that we hope will lead to a robust meteotsunami alerting system.

DEVELOP A RELIABLE DETECTION AND EARLY WARNING SYSTEM FOR METEOTSUNAMI EVENTS IN AN OPERATIONAL ENVIRONMENT

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ABSTRACT

The establishment of an operational detection and early warning system for meteotsunamis remains a challenging task due to the observational and modeling difficulties of capturing the small-scale features of tsunamigenic atmospheric disturbances. As a result, reliable operational meteotsunami warning systems are still lacking.

NOAA's National Weather Service (NWS) goal is to build a weather-ready nation to protect residents from hazardous weather events and property damages. There's a strong need to develop operational capabilities to detect, monitor and predict meteotsunamis. Collaboration efforts have been made among NOAA, academia, and private industry to understand drivers and processes that form and amplify meteotsunamis as well as to determine the frequency of occurrence in certain regions. In this presentation, author will describe examples of academic researchers and private industry's effort in advancing the scientific knowledge and technical instrumentations that improve meteotsunami forecasting capabilities, and summarize NOAA's progress and requirements that involves the multiple line offices such ad NWS Tsunami program office, the National Center for Tsunami Research center and local Weather Forecast Offices (WFO) towards building an operational early warning protocol and procedures for meteotsunamis.

HIGH AMPLITUDE INERTIA-GRAVITY WAVE DRIVEN METEOTSUNAMI ACROSS THE LAKE MICHIGAN BASIN DURING THE TRANSITION SEASON

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ABSTRACT

A significant meteotsunami event (~2 m amplitude) occurred across the Lake Michigan basin on April 13, 2018. The episode was driven by high amplitude atmospheric inertia-gravity (IG) wave packet with surface pressure perturbations exceeding 10 hPa and wind speeds approaching gale force. The IG wave packet also generated an accompanying elevated convective line - which allowed for continuous tracking via the regional radar network.

The phase speed of the IG wave packet optimally matched the Proudman resonant speed for the central basin of Lake Michigan and presented two distinct periods of meteotsunami excitation. Given this class of atmospheric forcing has not been readily explored in the context of meteotsunami generation, a brief synopsis of the event observations will be presented. Moreover, the results of a demonstration using potentially quick response atmospheric modeling capabilities leveraging relatively coarse spatial resolution (order 5-10 km grid spacing) with fine temporal resolution (order 1-2 minutes) is offered. This initial work highlights the importance of scaling atmospheric modeling to diagnose meteotsunami forcing and explicitly inform hydrodynamic models to carry out near-realtime and ultimately operational simulations of resultant water body behavior.

DEVELOPING FORECAST SKILLS FOR METEOTSUNAMIS IN THE IBERIAN SHELF – AN OVERVIEW OF THE FAST PROJECT)

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ABSTRACT

Meteotsunamis are atmospherically induced high-energy ocean waves in the tsunami frequency band. Along the Iberia coast, at least four meteotsunamis were recorded/observed in the last ten years: June 2006, July 2010, June 2011, and July 2018. Several of these meteotsunamis caused destructive coastal damage. Observations made during these events offer a unique opportunity to more thoroughly study meteotsunamis on this coast, a challenging phenomenon still lacking a reliable forecast, even in the most sophisticated tsunami warning systems around the world. The Iberian coast is prone to both tsunami and meteotsunami threat; therefore, the regional tsunami warning centre (IPMA, Portugal), confronts the problem of integrating meteotsunami warning into the general alarm strategy. The IPMA monitoring and forecasting facilities of atmospheric and oceanic processes may promote further development in the meteotsunami science and new skills to effectively forecast meteotsunamis for the Iberian coast. To achieve such inspiring objectives, we need to answer a set of questions: 1) What is the nature of meteotsunami events instrumentally recorded along the Iberian coast? 2) What are the precursor meteorological conditions leading to the formation of these events? 3) Could an effective coupled atmosphere-ocean numerical model be developed to reproduce these meteotsunamis? 4) What are the required improvements in the IPMA's observing system to forecast meteotsunamis? 5) How can these improvements be operationally implemented for an end-to-end meteotsunami forecast system?

In the frame of the FAST project, we hope to answer these questions and to reach the main objective of the project (developing forecast skills) and the operational strategy of the leading institution (IPMA). Here, we present an overview of the FAST project and a preliminary version of the meteotsunami catalogue for the Iberian coast that includes the main parameters of the events and associated atmospheric processes. This work was supported by the FCT-funded project FAST (PTDC/CTA-MET/32004/2017).

TOWARD THE PREDICTABILITY OF METEOTSUNAMIS IN LAKE MICHIGAN

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ABSTRACT

Predictability of meteotsunami heights remains challenging due to the uncertainty in the predictions associated with the high spatial and temporal variability of the atmospheric sources. To date, predictions of meteotsunami heights can be achieved using coupled atmospheric and hydrodynamic models. Uncertainty of meteotsunami predictability is largely dependent on the uncertainty of the small-scale O(1 km) features of the atmospheric disturbances. Different storm types can also associated with distinct perturbation types (i.e. pressure-, wind-, or both pressure and wind-dominated). Nevertheless, the uncertainty in meteotsunami prediction for different storm types remains unknown. In this talk, we systematically examine the predictability of meteotsunamis in Lake Michigan with distinct meteotsunami causes and formation processes. Specifically, we employ a heuristic approach based on the classification of storm types, characterization of atmospheric perturbation strength and velocity, numerically-derived meteotsunami height potential, and assessment of predictions by comparison with meteotsunami height observations over a 12-year period. The uncertainties in meteotsunami predictions caused by the uncertainty in the atmospheric sources are calculated and assessed. Overall, meteotsunami formation processes in Lake Michigan with distinct atmospheric and bathymetric conditions can be captured by the heuristic approach, thus having the potential to provide early meteotsunami warning in the Great Lakes.

DEVELOPMENT OF A METEOTSUNAMI WARNING SYSTEM FOR THE GREAT LAKE

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ABSTRACT

Meteotsunamis impact the Great Lakes several times each year, however a reliable detection and warning system is not available to warn the public of potential danger from these storms. In recent years, significant strides have been made in understanding the generation of meteotsunamis in the Great Lakes, including documenting historical events and developing a climatology based on water level records. Recent work from Linares et al., 2016 detailed the potential for a heuristic approach to relate meteotsunami wave height to coastal meteorological observations. In this study, we expand on this work to develop a real-time warning system for the Great Lakes through the combination of a high-temporal weather observation network and the Linares heuristic model. Through a collaboration between NOAA, University of Wisconsin, University of Michigan, and Limnotech, several real-time observation stations were enhanced or initiated in Lake Michigan and Lake Erie, two documented hot-spots for meteotsunami activity in the Great Lakes. Using these observations, we are developing a warn-on-detection system that will predict potential meteotsunami conditions based on near real-time pressure changes, wind speed, and other storm characteristics. This experimental system is the first effort to provide warnings of meteotsunami conditions in the Great Lakes.

I-STORMS PROJECT AND IMPLEMENTATION IN CROATIA

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ABSTRACT

I-STORMS (Integrated Sea sTORm Management Strategies) project – Adriatic-Ionian (ADRION) project on early warning system for storm surge and other meteo oceanographic phenomena that caused coastal flooding. I-STORMS is a project of regional cooperation in the exchange of knowledge, data and forecasts, for early warning of sea surges and sea flooding. Through joint infrastructure, joint risk response strategies, I-STORMS plans common interoperable information platform tools for data sharing of observations and model products, joint early warning guidelines for the public and rescue and rescue services, a transnational strategy for reducing the risk of flooding, and establishing a permanent forum for partner co-operation in the project and national participants and users. Till the end of 2019, project will produce: ADRION Sea Storm Atlas - atlas of sea flooding risks, I-STORMS network of partners and stockholders, I-STORMS early warring platform and establish a common ADRION strategy for more effective response, management and protection of coastal areas.

The DHMZ is a national meteorological and hydrological service and a licensed state body for maritime meteorology, and publishes meteorological bulletins and alerts for the Adriatic Sea and Croatian territorial waterways on a daily basis. DHMZ actively participate in the achievement of all goals, share knowledge of specific marine and coastal phenomena in the Adriatic (e.g. storm surge, sea level anomalies due to extreme local winds, meteo-tsunamis), observations and forecasts for sea conditions. During 2018, a first year of I-STORMS Project, Croatian I-STORMS Network has reached 34 members (3 national public authorities, 2 regional public authorities, 3 higher education and research centers, 15 local public authorities, 11 SME and interest groups). The voices of Network partners will contribute to ADRION common strategy in the coastal storm risk management in the Adriatic-Ionian area.

ITALIAN TSUNAMI EFFECTS DATABASE (ITED): THE FIRST DATABASE OF TSUNAMI EFFECTS OBSERVED ALONG THE ITALIAN COASTS

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ABSTRACT

The Italian Tsunami Effects Database (ITED), realized in ArgGis environment, is the first database dealing with the tsunami effects observed along the Italian coasts from historical times. ITED was compiled starting from the Euro Mediterranean Tsunami Catalogue (EMTC) and it focuses on the propagation effects observed along the Italian coasts, providing information on how each locality was interested by tsunamis effects over time. The Italian tsunamis contained in the EMTC were excerpt, analyzed and updated according to recent studies published in literature.

Starting from the description of Italian tsunamis in EMTC, for each "observation point" the description of tsunami effects found in literature is given, accompanied by the corresponding bibliographic references and the estimate of the intensity of the phenomenon at each point is also provided, according to both the Sieberg-Ambraseys and the Papadopoulos-Imamura scales. All the ITED data, including quantitative data such as runup, inundation, withdrawal, number of waves observed and first sea movement, can be retrieved by accessing online the database through the web application that was expressly designed and built for this purpose.

Currently, ITED contains about 300 observations of tsunami effects referred to 184 localities of the Italian coasts and related to the 70 Italian tsunami events present in EMTC. Whenever a place experienced a tsunami effects more than once, details of each observation is supplied to allow the user to build the tsunami-history of the locality.

ITED was specifically built to meet the needs of the tsunami hazard community, thus providing useful information that can improve the knowledge of the tsunami exposition of the national territory. From this perspective, we are now collecting data on meteo-tsunami occurred along the Adriatic coasts in order to evaluate the possibility to devote a specific section of ITED to meteo-tsunami data.