



Report of the Croatian Committee of Geodesy and Geophysics on activities carried out between 2019 and 2022

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Introduction

Croatia was admitted to the International Union of Geodesy and Geophysics (IUGG) soon after gaining independence: its membership status had been provisionally granted by the IUGG Executive Committee already in 1992 and the status was ratified by the IUGG Council at the meeting held in Boulder in 1995. From the beginning, the Croatian Academy of Sciences and Arts was the adhering organization, which supervised the election of members of the Croatian Committee of Geodesy and Geophysics. After being admitted to the IUGG, Croatian geodesists and geophysicists took part in the activities of IUGG associations and in the general assemblies. Moreover, they prepared reports on their work, covering five intervals: 1991–1994 (*Geofizika*, **11**, 1994), 1995–1998 (*Geodetski list*, **53**, 1999), 1999–2002 (*Geofizika*, **18/19**, 2001/2002), 2011–2014 (*Geofizika*, **32**, 2015), and 2015–2018 (*Geofizika*, **36**, 2019). With this report, the practice of informing the IUGG community on Croatian geodetic and geophysical measurements and investigations is continued.

In the following pages, the work carried out between the years 2019 and 2022 by Croatian scientists, active in geodesy and in five geophysical disciplines (geomagnetism and aeronomy, hydrology and physical limnology, meteorology, physical oceanography, and seismology), is documented. The work has been shaped by at least three external factors. One of them was COVID-19 pandemic, which, on one hand, has adversely influenced field work in various disciplines, e.g., due to frequent postponements of research cruises, but, on the other hand, has stimulated analysis of data, modeling activities and publication of the results thus obtained. The other factor was a series of earthquakes, the strongest ones being the Zagreb earthquake of 22 March 2020 and the Petrinja earthquake of 29 December 2020. Again, the consequences were twofold. The earthquakes had resulted in a serious damage to numerous buildings housing faculties and institutions in Zagreb, which has led to demanding reconstruction works and even to relocation of several research groups. Still, the Croatian geophysicists and geodesists reacted to the earthquakes in a proper way: the seismological networks were considerably expanded, the earthquakes and the corresponding aftershocks were carefully recorded and studied, the seismological studies were complemented by the remotely sensed data analyzed by geodesists, and a possible influence of earthquake-generated noise on the quality of geomagnetic data was explored. Finally, also important for the shaping of research work were weather- and climate-related extremes in the atmosphere and hydrosphere. Consequently, the relevant observation networks were modernized, extreme events (e.g., heat

waves, droughts, heavy precipitation episodes and consequent flash floods) were analyzed and modeled, and the coastal floods due to the sea level rise and exceptional atmospheric conditions were analyzed by using a decomposition method that had been developed in Croatia but is now increasingly used in other countries. All the findings are documented in some detail in the present report. Also visible from the report is the fact that the expansion of research activities in Croatia received a boost from an access to international scientific projects. It is to be hoped that international collaboration of Croatian scientists will further intensify in the future and that the IUGG-related activities will contribute to the intensification.

Mirko Orlić,

President,

Croatian Committee of Geodesy and Geophysics

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Geodesy in Croatia, 2019–2022

*Report submitted to the International Association of Geodesy
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This report presents a brief overview of research activities in the field of geodesy in Croatia in the period from 2019 till the end of 2022. The activities have been carried out mainly by the Faculty of Geodesy, University of Zagreb, and, to a smaller extent, by the Faculty of Civil Engineering, Architecture and Geodesy, University of Split. Research activities resulted in many scientific and educational projects as well as scientific and educational publications, listed below.

Horizon 2020 projects:

- Twinning Open Data Operational (TODO), Duration: 2019–2023, Project coordinator: Assist. Prof. Ana Kuveždić Divjak, PhD.
- European Solar Telescope Preparatory Phase (PRE-EST), Duration: 2017–2021, Project coordinator: Davor Sudar, PhD.

Croatian Science Foundation scientific projects:

- Interaction of COronal HOles and Solar Storms (ICOHOSS), Duration: 2021–2025, Project coordinator: Mateja Dumbović, PhD.
- Research of recent regional and local geodynamic processes in the Republic of Croatia using modern satellite geodetic methods (GEOMSAT), Duration: 2018–2022, Project coordinator: Prof. Boško Pribičević, PhD.
- Millimeter and submillimeter observations of the solar chromosphere using ALMA (MSOC), Duration: 2018–2022, Project coordinator: Roman Brajša, PhD.

- Geospatial Monitoring of Green Infrastructure by Means of Terrestrial, Airborne and Satellite Imagery (GEMINI), Duration: 2017–2021, Project coordinator: Prof. Damir Medak, PhD.

European Space Agency (ESA) scientific projects:

- Forbush decrease analysis using model fitting to SOHO/EPHIN data (ForbMod), Duration: 2021–2022, Project Coordinator: Mateja Dumbović, PhD.
- Automatic monitoring of narrow-leaved ash (*Fraxinus angustifolia* Vahl) forests by remote sensing methods and Copernicus data (RS4EST), Duration: 2021–2023, Project coordinator: Assoc. Prof. Mateo Gašparović, PhD.

European Regional Development Fund projects:

- Multisenzorsko zračno snimanje Republike Hrvatske (LiDARH), Duration: 2020–2023, Project co-coordinator: Prof. Boško Pribičević, PhD.
- Integrated hydrographic system for sustainable development of the marine ecosystem (HIDROLAB), Duration: 2017–2021, Project coordinator: Prof. Boško Pribičević, PhD.
- Climate cHallenges on coAstal and traNsitional chanGing arEas: WEaving a Cross- Project Adriatic Response (CHANGE WE CARE), Duration: 2019–2021, Project coordinator: Prof. Boško Pribičević, PhD.
- Civil Protection Emergency DSS based on CITIzen Journalism to ENhance Safety of Adriatic Basin (E-CITIJENS), Duration: 2019–2021, Project co-coordinator: Assoc. Prof. Martina Baučić, PhD.

European Education and Culture Executive Agency (EECEA) educational projects:

- Spatial Data Infrastructures and Earth Observation Education and Training for North-Africa (SEED4NA), Duration: 2020–2023, Project coordinator: Assoc. Prof. Vesna Poslončec-Petrić, PhD.
- University Network for Disaster Risk Reduction and Management in Indian Ocean Rim (UN4DRR), Duration: 2020–2023, Project coordinator: Prof. Željko Bačić, PhD.

- Business driven problem-based learning for academic excellence in geoinformatics (GEOBIZ), Duration: 2019–2022, Project coordinator: Prof. Željko Bačić, PhD.
- Towards an innovative strategy for skills development and capacity building in the space geo-information sector supporting Copernicus User Uptake (EO4GEO), Duration: 2018–2021, Prof. Željko Bačić, PhD.

EU programme for education, training, youth and sport (Erasmus+):

- open SPatial data Infrastructure eDucation nEtwoRk (SPIDER), Duration: 2019–2022, Project coordinator: Assoc. Prof. Hrvoje Tomić, PhD.

European Social Fund (ESF) projects:

- Development and formation of profession standards, qualifications and study programs in geodesy and geoinformatics (LABIRINT), Duration: 2019–2022, project coordinator: Prof. Damir Medak, PhD.

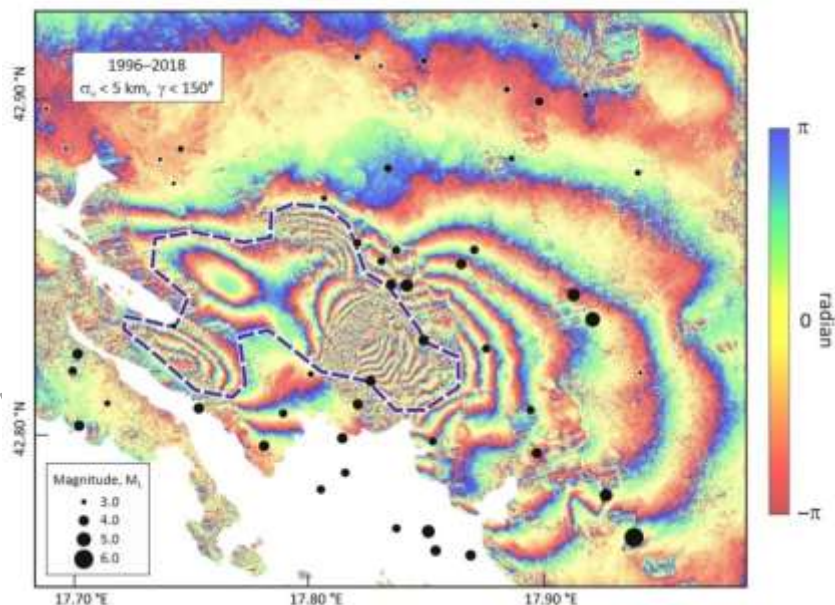


Figure 1. Epicenters of reliably located earthquakes of the Ston-Slano sequence overlain on the ascending orbit interferogram (Govorčin et al., 2020).

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Geomagnetism and aeronomy in Croatia, 2019–2022

Report submitted to the International Association of Geomagnetism and Aeronomy of the International Union of Geodesy and Geophysics

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This report presents an overview of activities in the field of geomagnetism and aeronomy in the four-year period between 2019 and 2022. Scientific, professional and educational activities are carried out mainly at the Department of Geophysics (DG), Faculty of Science and the Faculty of Geodesy (FG), both under the auspices of the University of Zagreb. The report first presents the professional work, as the results of some studies mentioned in this report are closely related to them. A summary of research activities is given next and the report closes with a brief overview of educational activities.

The professional work mostly includes permanent measurements of geomagnetic elements at the Lonjsko Polje (LON) observatory and periodical measurements at the Croatian Geomagnetic Repeat Stations Network (CGRSN), as shown in Figure 1(a). The observatory, established in 2012, works under the auspices of DG, while FG is responsible for the establishment, maintenance and survey at CGRSN since 2004.

The period 2019–2022 was characterized by a series of unfavourable circumstances that adversely affected professional and field work activities. Along with the COVID-19 pandemic, Zagreb was hit by a series of earthquakes. The main shock had a magnitude $M = 5.5$ (on 22 March 2020). Nine months later, 30 km from LON observatory, a series of earthquakes occurred in the area of Petrinja. On 29 December 2020 the main shock hit with a local magnitude $M = 6.2$. Despite these and a larger number of instrumental problems at the observatory, the continuity of measurements was successfully maintained. Upon removal of the instrumental and anthropogenic degradations in the data (simple example is given by Mandić, 2021), the annual datasets submitted to INTERMAGNET contain around 99% of the data. The percentage of missing data per day is shown in Figure 1(b). One-second data from the LEMI-035 magnetometer were continuously delivered to the EMMA network. Operational problems of this magnetometer were solved relatively quickly, so for 2019, 2020, 2021 and 2022 the data availability is 95%, 88%, 84% and 99%, respectively. During 2021 the facility for the LEMI-

018 magnetometer was completed and data processing protocols were modified for processing the data acquired by the new magnetometer. Thus, from 2021 geomagnetic variations are recorded simultaneously with three vector magnetometers at the observatory. This upgrade will ensure better operational reliability and increase data quality. It should be mentioned that at the start of 2020, a new generation of global geomagnetic models was released (P. Alken et al., *Earth Planets Space*, 73 (49), 2021; A. Chuliati et al., *Technical Report, National Centers for Environmental Information, NOAA*, 2020), in which LON data were used for the first time. With this contribution, Croatia is affirmed as an active member of the global geomagnetic community.

Due to the above mentioned circumstances, the survey planned for 2020 at CGRSN was postponed and carried out in 2021. This survey, as well as the one conducted in 2018, was carried out in the framework of the project “2nd Geomagnetic Information Renewal Cycle” at the request of the State Geodetic Administration and Ministry of Defense. Due to destruction or local anthropogenic contamination, two initial repeat stations LOSinj and MEDJimirje were replaced by new ones, PUNta Križ (PUNK) and SVETi Martin (SVEM), shown in Figure 1. The new stations were set up as close as possible to the old ones. In order to perform the measurements in accordance with the recommendations of IAGA and MagNetE, the instrumentation used for the survey was tested at the LON observatory. The mechanical correctness of the non-magnetic theodolite was examined at the Laboratory for Measurements and Measuring Technique of FG. The instrumentation was tested before and after the survey at CGRSN. Currently the “3rd Geomagnetic Information Renewal Cycle” is in progress with the aim to repeat measurements at CGRSN and update the information about geomagnetic field over Croatian territory.

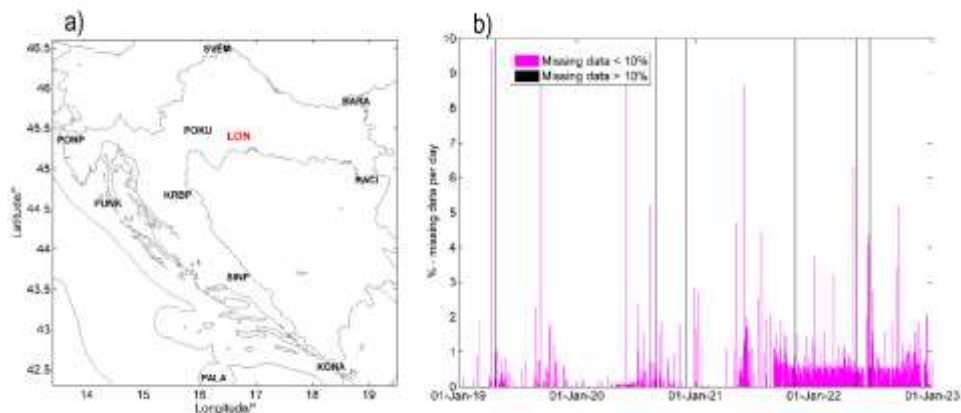


Figure 1. (a) Locations of CGRSN stations and LON observatory. (b) The percentage of missing data (upon removal of degradations) per day in the period 2019–2022. For only five days more than 10% of data is missing.

Published studies in this period are diverse, covering a few topics: investigations of the local geomagnetic field properties, physical processes that occur in the near-Earth space environment, changes in the interplanetary space and on the Sun. Studies are presented in this order according to the topic.

Brkić (2019) emphasized that continuous monitoring the actual Geomagnetic Information (GI) model error is essential, in order to have reliable information about the declination and its annual change over Croatian territory. Partial declination solutions for the 2008.5, 2009.5 and 2010.5 epochs were reduced to the epoch 2018.0, using IGRF12 model and data from neighbouring countries. Data from LON observatory and CGRSN network were used to verify the model solution. Comparison between the final model GI2018v2 declination and observations was found to be $\leq 2.4'$ (arcminutes). The study also recommends using the last 12 months of the observatory quiet day declination means for predicting declination up to the next 6 to 12 months.

Furthermore, the model GI2018v2 was updated to the version GI2020v1 (Brkić et al., 2020). The declination for the epoch 2020.0 over Croatian territory was between 3.7° and 5.4° . The annual change was between $7.6'/\text{yr}$ and $8.7'/\text{yr}$. The maximum GI2020v1 error at CGRSN locations for the epoch 2020.0 is estimated to be $< 3.6'$. This model has been further enhanced, with possibility to model daily declination changes and meridian convergence. Using LON time series and spectral analysis (FFT), harmonic coefficients were determined for 24, 12, 8 and 6 hour period, for each month. In this way, twelve sets of harmonic coefficients were determined and used to model diurnal change of declination (during geomagnetic quiet days).

Possible significance of earthquake-related noise for the geomagnetic information renewal was presented in the study by Brkić et al. (2022). Hypothetically, the noise at the geomagnetic repeat station site (or observatory), far enough from the hypocentre so that the surveyor is not aware of the ongoing earthquake, could affect the quality of measurements. The contribution of earthquake noise in DIF measurements may further propagate into the reduced elements, models and maps. The study aimed to determine whether shallow and nearby earthquakes, comparable to the earthquakes that occurred in the Zagreb area on 22 March 2020, are visible in minute magnetograms. These magnetograms are regularly used in quality control analysis, immediately after the geomagnetic survey, as well in reduction afterwards. By analysing the influence of the selected Zagreb earthquakes on minute magnetograms of the observatories LON and NCK (Nagcyenk, Hungary), the authors found negligible contributions with amounts less than $10''$ for D , $5''$ for I and 0.6 nT for F .

Verbanac et al. (2022) investigated the influence of solar wind high-speed streams (HSSs) on the thermospheric neutral density (ρ) during the declining

phase of solar cycle 23. The investigation of ρ at the latitudinal bins (high, mid and low) in both hemispheres at dayside and nightside showed that ρ values increase/decrease from high to low latitudes at dayside/nightside. Augmentation of ρ from high to low latitudes at dayside caused by solar radiation is most prominent around magnetic local time (MLT) 14 and decreases rapidly with departure from this MLT. The difference between N and S hemispheric ρ values are not the same prior and after the equinox. Quiet time ρ differs among latitudinal bins; ρ contains a clear imprint of solar and geomagnetic activity. The cross-correlation analysis reveals a high degree of correlation between ρ and different ρ indicators employed (based on solar wind parameters and geomagnetic activity measures). Time lags based on all ρ indicators suggest that ρ disturbance occurs about 4 h earlier at higher than at lower latitudes. The disturbance likely propagates faster between polar and mid latitudes at dayside and between mid and low latitudes at nightside. The study provided the most probable characteristics of the ρ variations during the periods in which the magnetospheric-thermospheric system is affected primarily by HSSs.

Different plasmopause structures observed in nature are a sign of the complex processes that cause the formation and evolution of the plasmopause. Bandić et al. (2020) analysed the characteristics of the main plasmopause over a longer period and succeeded to simplify and systemize the global plasmopause behaviour. The study showed that by employing only three types of Kp (planetary geomagnetic activity index) jumps: sharp Kp increase, sharp Kp decrease, short-time burst enhancement in Kp, together with the theory based on interchange instability mechanism, the formation and evolution of the main plasmopause can be statistically explained.

Verbanac and Bandić (2021) conducted an exhaustive study on the origin and characteristics of the southward component (B_s) of the interplanetary magnetic field (IMF). In this analysis, 28 years (1990–2017) of hourly values of the IMF data were used. Two important steps were made in this study. First, the IMF data ordered in Geocentric Solar Magnetospheric System (GSM) are transformed to Geocentric Solar Equatorial System (GSEQ). Second, B_s fields are separated according to the IMF polarity – toward/away from the Sun. The obtained results showed that B_s fields exist also in fall/spring when the IMF points toward/away from the Sun. In these unfavourable seasons, the field is reduced, but it is not zero. Thus, in unfavourable seasons, geomagnetic activity can be due to reduced B_s and not because the field is pointing northward. The authors showed that patterns of the experimental B_s fields are not in agreement with the well-known Russell-McPherron model of B_s . The obtained results open a way to correctly interpret variations seen in the IMF components and geomagnetic indices.

Heinemann et al. (2019) investigated the evolution of 16 long-living Coronal Holes (CH) between 2010 and 2019 with the aim to reveal processes

that drive the observed changes in the corona hole parameters and the associated properties of the high speed solar wind streams (HSSs) peak velocity at 1 astronomical unit (AU). They find that the CH area evolution shows a general trend of growing to a maximum followed by a decay. This study suggests independence between the CH area evolution and the evolution of the signed magnetic flux (and flux density) enclosed in the projected CH area. The derived CH area changes show a reasonable anti-correlation with the solar activity, approximated by the amounts of sunspots. The signed magnetic flux and the signed mean magnetic flux density change rates were found to be dependent on solar activity rather than on the individual CH evolution. Relation between CH area HSS peak velocity is valid over each individual CH evolution with varying correlation coefficients and varying slopes of the linear regression line.

A prediction of the 25th solar cycle maximum amplitude (A_{\max}) is presented in the work presented by Brajša et al. (2022). A modified version of the minimum-maximum method is used considering not only the minimum activity years, but also years before and after the epoch of the solar minimum activity. The solar parameter used in this work was the sunspot number. The input data were the 13-month smoothed monthly total sunspot numbers for the period from 1794 to March 2020, from Sunspot Index and Long-term Solar Observations/SIDC. The first aim of this work was to check whether the assumption that 3 years before the activity minimum is the best epoch to predict the next solar maximum is true. The second aim was to make a prediction of the amplitude of the next solar cycle maximum, using the modified minimum-maximum method. The last aim was to check reliability of the method by reproducing the maxima of the last four solar cycles using the proposed modified minimum-maximum method. The reliability of the “3 years before minimum” predictor is experimentally justified by the largest correlation coefficients (CCs) and sufficiently explained by two empirical well-known findings: the extended solar cycle and the Waldmeier effect. The proposed method predicts maximum $A_{\max} = 121 \pm 33$ for the solar cycle 25. Finally, the solar maxima of solar cycles 21–24 calculated with the proposed method are preferred over those obtained by the simple minimum-maximum method, since the proposed method implies higher CCs and lower statistical errors.

Finally, the education engagement is briefly presented here. The education is actively performed at DG through several university undergraduate and graduate courses (*Planetology, Geomagnetism, Aeronomy, Geophysical Practicum*) and an university doctoral course (*Planetary Magnetism*). Within the course *Geophysical Practicum*, the students' visit to the LON observatory is organized. There, the students have an opportunity to gain some practical experience with geomagnetic measurements, which help them to better adopt the theoretical knowledge provided by other regular

courses. Furthermore, at FG the education is performed in the framework of two university courses (*Geomagnetic Survey, Geomagnetic Networks*). During the period of the COVID-19 pandemic, classes took place in accordance with the regulations and recommendations of the Civil Protection Headquarter of the Republic Croatia.

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Hydrology and physical limnology in Croatia, 2019–2022

*Report submitted to the International Association of Hydrological Sciences
of the International Union of Geodesy and Geophysics*

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This report presents the main activities in the field of hydrology in the Republic of Croatia for the period from 2019 to 2022. The main state institutions responsible for hydrological research and measurements are the Croatian Meteorological and Hydrological Service and the Croatian Waters, as well as university faculties throughout the country (Faculty of Civil Engineering, Faculty of Mining, Geology and Petroleum Engineering, Faculty of Science and Faculty of Geotechnical Engineering from University of Zagreb; Faculty of Civil Engineering, Architecture and Geodesy at the University of Split; Faculty of Civil Engineering at the University of Rijeka; Faculty of Civil Engineering at the University of Osijek). Scientific research within the framework of various research projects has intensified due to the increasing use of EU funds. In addition to scientific projects, the Croatian Waters is also involved in professional projects for flood protection in endangered areas. The results of scientific research in the field of hydrology have been published in national and international journals (*Journal of Hydrology, Catena, Science of the Total Environment, Hydrological Sciences Journal, Water Science and Technology, Water, Geosciences, Sustainability, Hydrology, Hydrology and Earth System Sciences, Theoretical and Applied Climatology, Acta Hydrotechnica, Journal of Hydrology and Hydromechanics, Journal of Hydroinformatics, Water Supply, Rudarsko-geološko-naftni zbornik, Geofizika, Geologia Croatica, Hrvatske vode*) and at numerous scientific and professional conferences.

Projects from different institutions are listed below:

1. CroClimGoGreen – Croatian climate variability and change – From global impacts to local green solutions.
2. AdriaMORE – Adriatic decision support system exploitation for integrated MONitoring and Risk management of coastal flooding and Extreme weather.
3. DriDanube – Drought risk in the Danube region.
4. UKV – Carstic coastal water management endangered by climate changes.

5. VEPAR Project – Improvement of non-structural measures of flood risk management in the Republic of Croatia.
6. Development and implementation of a regional Flash Flood Guidance System (FFGS) in southeastern Europe region.
7. Flood risk Slovenia-Croatia operations – Strategic project 1 – Nonstructural measures FRISCO 1.
8. Programme for improving national early warning system and flood prevention in Albania PRO NEWS.
9. SeCure – Saltwater intrusion and climate change: monitoring, countermeasures and informed governance.
10. NATURAVITA – Demining, restoration and protection of forests and forest land in protected and Natura 2000 areas in the Danube-Drava River region.
11. WACOM – Water management in emergency situations in the Sava River basin.
12. CROSScade – Cross-border cascading risk management for critical infrastructure in Sava River basin.
13. DAREFFORT – Danube River basin enhanced flood forecasting cooperation.
14. ForMURA – Upgrade and development of the Mura River warning system and prognostic model.
15. ASTERIS – Adaptation to saltwater intrusion in sea level rise scenarios.
16. WATERCARE – Water management solutions to reduce the microbiological impact on the environment in coastal areas.
17. MoST – Monitoring saltwater intrusion in coastal aquifers and testing pilot projects to mitigate saltwater intrusion.
18. SIMONA – Sediment-quality Information, MONitoring and Assessment system to support transnational cooperation for joint Danube basin water management.
19. Hydrodynamic modeling of Plitvice Lakes system.

Two of the projects are addressed here in more detail.

Project 4: Carstic coastal water management endangered by climate changes:

The UKV project is focused on researching the consequences of climate change in coastal karst aquifers – increasing salinity and water temperature and deteriorating water quality – and on finding measures of climate change adaptation in the water resources, tourism, agriculture and health sectors. One of the most important factors that amplify the impacts of climate change on water resources is excessive seasonal exploitation of aquifers for water supply purposes, especially during the summer when water needs are greatest. The project will establish monitoring of groundwater and surface water in three pilot areas (Zadar, Korčula and Cres) for which the quality and quantity of surface and groundwater will be analyzed and projections will be made to

the end of the 21st century using meteorological and hydrological models. Some preliminary findings are shown in Figs. 1 and 2.

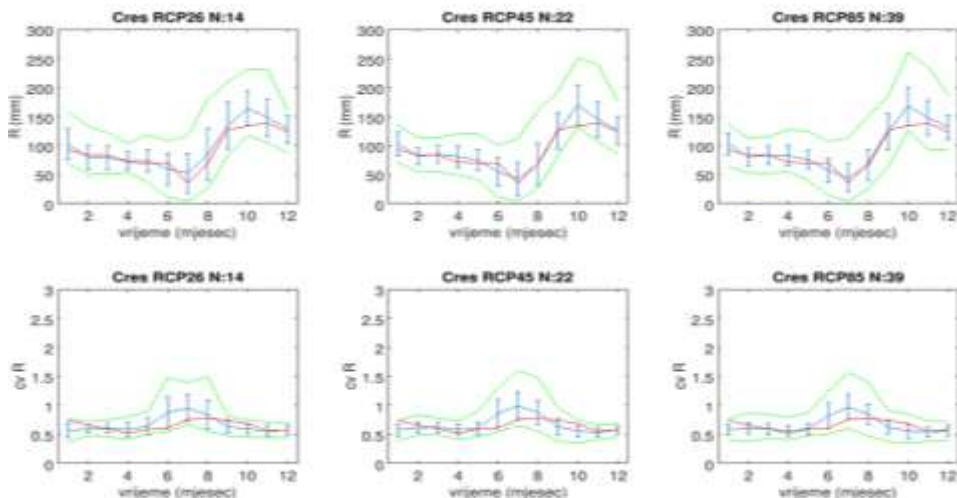


Figure 1. Annual cycle of the mean monthly precipitation (mm; first row) and annual cycle of the coefficient of variation of the monthly precipitation amount (dimensionless; second row). First column: models included in the RCP2.6 scenario; second column: models included in the RCP4.5 scenario; third column: models included in the RCP8.5. scenario; blue: mean and standard deviation within the RCM ensemble; green: range within the RCM ensemble; red: measurements. Period: 1981–2010 Source: DHMZ measurements and original simulations of regional climate models (Biondić, 2023). Location: Cres.

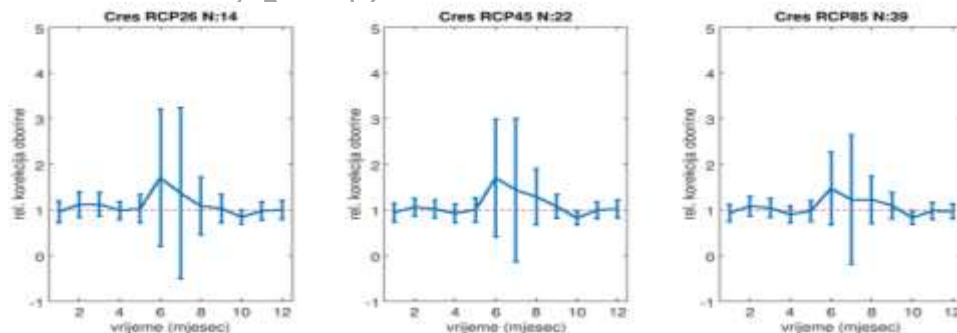


Figure 2. Annual cycle of relative correction of mean monthly precipitation (dimensionless). The mean and standard deviation of monthly corrections within the RCM ensemble are presented for models included in the scenarios RCP2.6 (first column), RCP4.5 (second column) and RCP8.5 (third column). Period: 1981–2010. Location: Cres (Biondić, 2023).

Project 19: Hydrodynamic modeling of Plitvice Lakes system:

Physical limnology topics were mainly investigated within an interdisciplinary project encompassing meteorology, hydrology, physical limnology and hydrogeochemistry (Hydrodynamic modeling of Plitvice Lakes system). The project was collaborative between three institutions: Department of Geophysics (Faculty of Science, University of Zagreb), Faculty of Civil Engineering (University of Rijeka), and Faculty of Geotechnical Engineering (University of Zagreb), and, it was funded by the Plitvice Lakes National Park, Croatia. Within the project activities, a multi-year lake-temperature measurements were performed at multiple depths of the two largest lakes (Kozjak and Prošće). Analyses of these measurement data provided an insight into differences between the two lakes in stratification, internal seiching (Fig. 3, left) and fine-scale internal oscillations (Fig. 3, right) (Klaić et al., 2020a, 2020b). Furthermore, lake-temperature experimental data served as a basis for the development of a simple 1-D energy budget model (SIMO) for the prediction of the vertical temperature profiles in small monomictic lakes (Fig. 4, Šarović et al., 2022).

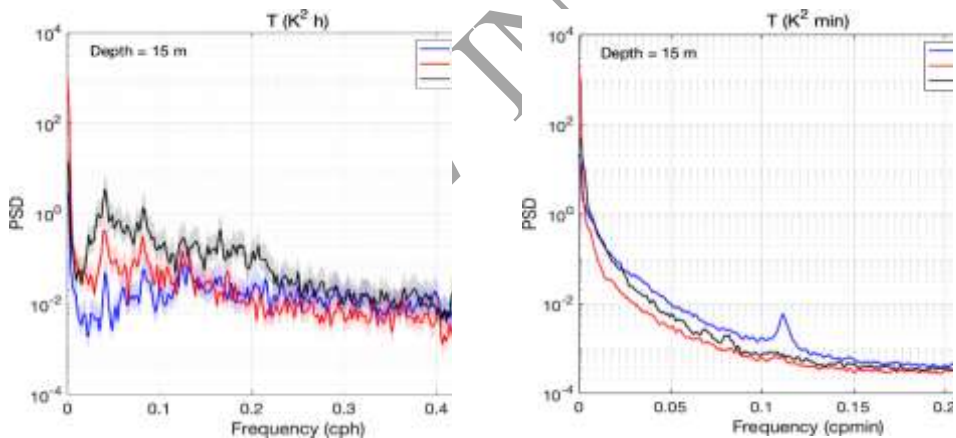


Figure 3. Power spectral densities (PSDs) computed from the 1 h and 2 min mean lake temperatures at the two points in Kozjak Lake (K1 and K2) and one point in Prošće Lake (P1) at the depth of 15 m for the period from 6 July 2019 to 4 November 2019 (Klaić et al., 2020a, 2020b). Full lines and shaded areas show the PSDs and 95% confidence intervals, respectively.

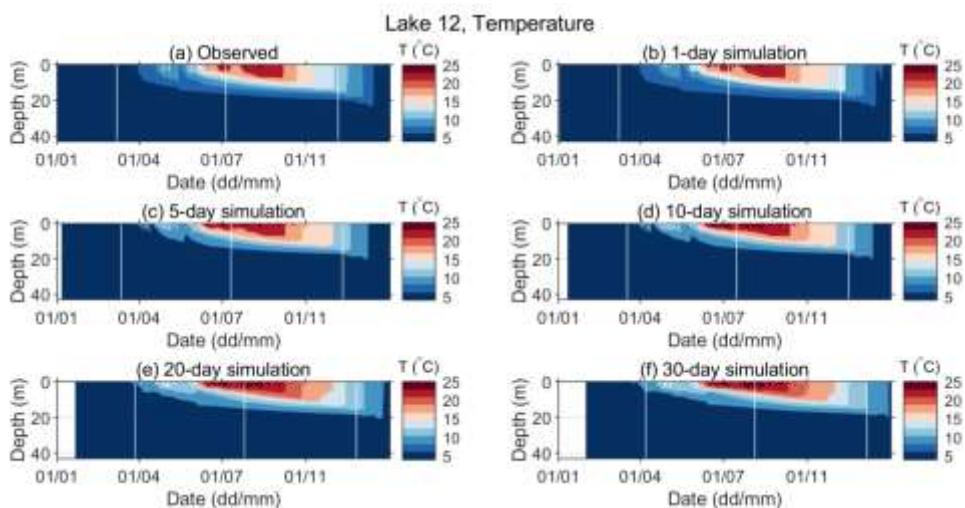


Figure 4. Observed and predicted water temperatures of Kozjak Lake for different simulation lengths for 2019. Periods with 425 missing data are seen as white vertical stripes (adopted from Šarović et al., 2022).

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Meteorology in Croatia, 2019–2022

Report submitted to the International Association of Meteorology and Atmospheric Sciences of the International Union of Geodesy and Geophysics

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In Croatia, the research in the field of meteorology has been performed at the following institutions: Department of Geophysics, Faculty of Science, University of Zagreb (hereafter, DG), Croatian Meteorological and Hydrological Service (DHMZ), the Physics Department, Faculty of Science, University of Split (PDS), and the Institute of Oceanography and Fisheries (IOF) in Split. The research at these institutions spans a wide range of a state-of-the-art topics including numerical weather prediction, severe weather, climatology and climate change, agrometeorology, extreme weather and extensive activities on the intermediary among meteorology and closely related disciplines such as hydrology, air quality, oceanography, energy, forestry, and similar. During the 2019–2022 period, at the above four institutions in total thirty projects (completed and still ongoing) were implemented. As listed in the Appendix, three of them were funded by the Croatian Science Foundation, twenty six by different funds of the European Union, and one by other sources. In addition, three Young Researchers' Career Development projects funded by the Croatian Science Foundation and a number of professional projects funded by various sources (not listed here) were carried out.

A number of the implemented projects addressed various aspects of climate change, namely, the climate change adverse impacts (*e.g.*, droughts and other extreme weather phenomena), assessments of resilience, hazards and risks, and adaptation strategies (including designs of appropriate warning systems). As geosystems interact, some of these projects were multidisciplinary, and they dealt with the air-sea interactions and resulting phenomena (*e.g.*, meteotsunamis and coastal flooding, upwelling and downwelling, etc.). To better understand the role of the air-sea interactions in dynamic properties of a sea, a network of automatic meteorological-oceanographic stations has been established by IOF under the framework of several projects (Fig. 1). Interactions of atmosphere and freshwater bodies (*e.g.*, internal seiches in lakes, lake-land breezes, and meteorologically forced

establishments of a lake stratification) and related issues (such as, flood risk management and prevention of flood disasters, optimal management of coastal karstic aquifers, etc.) were also in the focus of some projects. Other multidisciplinary projects dealt with the: 1) air pollution (where both expansion and modernization of the National Network for Continuous Air Quality Monitoring and modeling activities addressing the long-range transport of pollutants and the role of the traffic in urban air quality were performed); 2) adaptability of agricultural cultivars to climate change and particularly to drought conditions; and 3) improvement of maritime transport efficiency and safety in the Adriatic. Finally, the remaining projects addressed the development of training material based on satellite data and its combination with other meteorological data, and the applicability of geostatistical and machine learning methods to spatial and temporal interpolation of meteorological data.

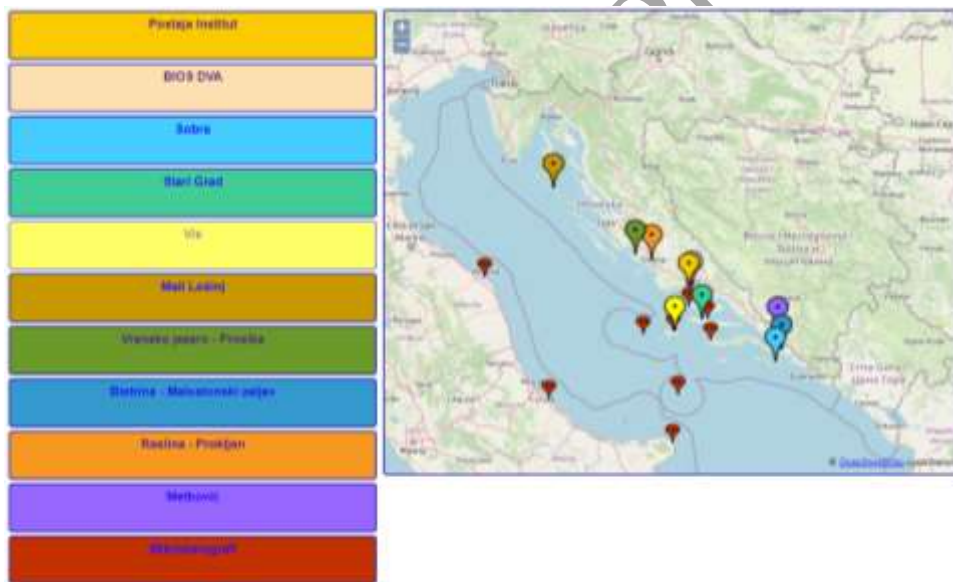


Figure 1. Automatic meteo-ocean stations of the Institute of Oceanography and Fisheries (IOF).

DHMZ conducted the largest modernization of its observation networks in its history through structural projects funded by the EU Operational Programme Competitiveness and Cohesion 2014–2020. Modernization of national weather observation network through implementation of the project METMONIC (KK.05.1.1.01.0001) includes: (1) around 400 surface automatic weather stations, (2) six C-band Doppler dual-polarization radars with full national coverage, (3) five meteorological-oceanographic buoys, (4) two

stations with profiling measurements (lidar, wind profiler and microwave radiometer), and (5) calibration laboratories. Modernization also included a major upgrade of supercomputing facilities for improvement of weather and air quality predictions and climate projections (Atos BullSequana XH2000 with 12.288 cores and 373 teraflop capacity). Furthermore, air quality and hydrological networks were modernized through implementation of the AirQ (KK.06.2.1.02.0001) and VEPAR (KK.05.2.1.07.0001) projects. This modernization, as a whole, is an unprecedented step forward in supporting current and future members of meteorological research community in Croatia with meteorological infrastructure and observation data. On average around 25 researchers and 8 PhD students at DHMZ, together with their colleagues, lead applied research and bring research results to operations in topics covering numerical weather prediction including data assimilation, ensemble forecasting, verification and postprocessing, climate monitoring, regional climate modelling, process studies of extreme geophysical events (dry spells, droughts, heavy precipitation, fire, fog, hail, winds, meteorological tsunamis, etc.), agrometeorology, biometeorology and other.

Research efforts resulted in eleven PhD theses, three books, twelve book chapters and eighty-nine international peer-review scientific papers (full details are given in the List of publications). Overall, published items addressed a wide variety of meteorological, climatological and multidisciplinary topics. Some of these are: ensemble modeling of regional climate at kilometer-scale resolution (Fig. 2); studies of bora events based on high-resolution wind observations and high-resolution meteorological model

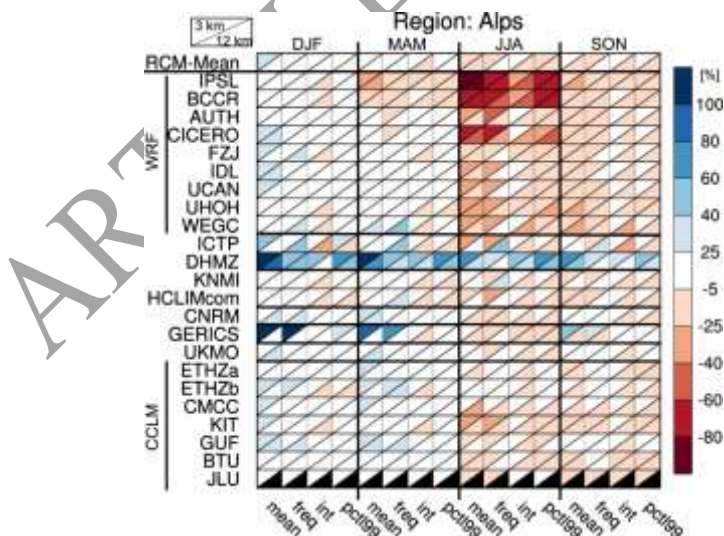


Figure 2. Relative bias of a daily precipitation in winter, spring, summer, and fall. White colour indicates an acceptable bias range which accounts for the uncertainties in the observations due to the systematic rain gauge under-catch (~20%) (Ban et al., 2021).

simulations (Fig. 3); investigation of lake-land breezes produced by a small, elongated lake (Fig. 4); mesoscale modeling of the background particulate matter concentrations over Europe by two coupled atmosphere-air chemistry models, namely, the Weather Research and Forecast with Chemistry module (WRF-Chem) and the European Monitoring and Evaluation Programme (EMEP) model (Fig. 5); identification of diverse air pollution sources in urban environment based on positive matrix factorization and conditional bivariate polar plots (Fig. 6); and studies of the observed, wind-forced internal seiches in lakes (Fig. 7).

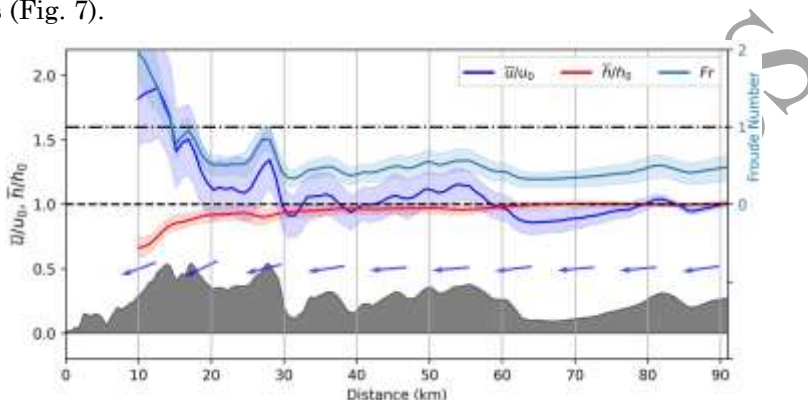


Figure 3. Median normalized layer-mean wind speed u/u_0 , median normalized inversion-top height h/h_0 , and barotropic Froude number Fr (solid lines) for several cross-sections along the very long lasting bora flow over Kvarner region. Shaded areas represent the 10–90% quantile span. The dot-dashed line represents $Fr = 1$. The dashed line represents the unit normalized layer-mean wind speed and inversion-top height. The layer-mean wind direction is shown as blue arrows (Golem et al., 2022b).

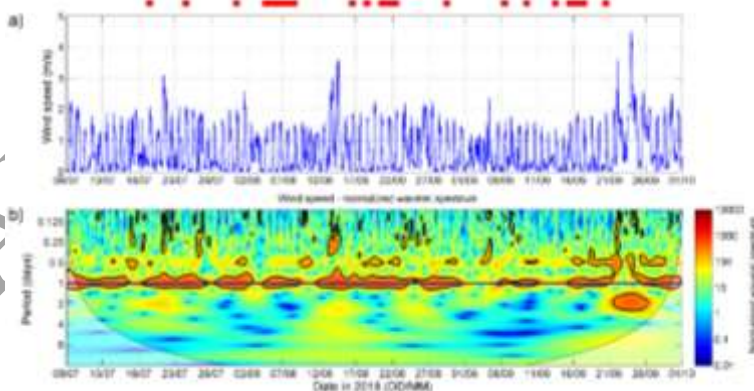


Figure 4. Observed wind speed (a) and the corresponding normalized wavelet spectrum (b) in the vicinity of Kozjak (Plitvice Lakes, Croatia) for summer 2018. Time intervals with lake-land breezes are indicated in red above panel a. The horizontal blue line in panel b corresponds to a period of 24 h. The thick black line indicates the 95% confidence level, with red noise as the background spectrum. Lighter shadings on both ends in panel b denote regions where edge effects become important (Staver et al., 2022).

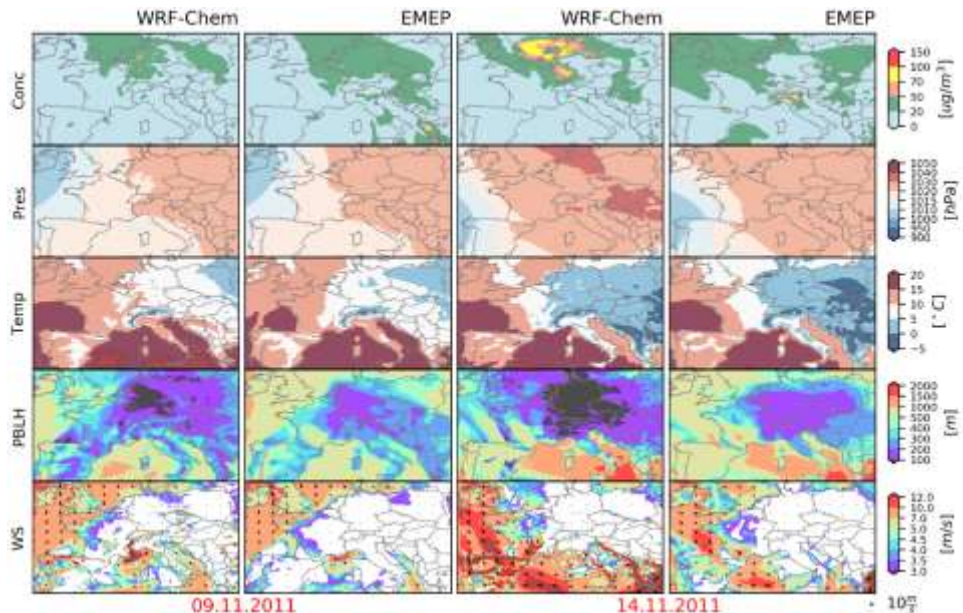


Figure 5. Daily mean values of PM₁₀ concentrations (Conc), sea level pressure (Pres), temperature at 2 m (Temp), planetary boundary layer height (PBLH), and wind speed and direction (WS) for two days in November 2011, obtained by the WRF-Chem and EMEP models (Gašparac et al., 2020).

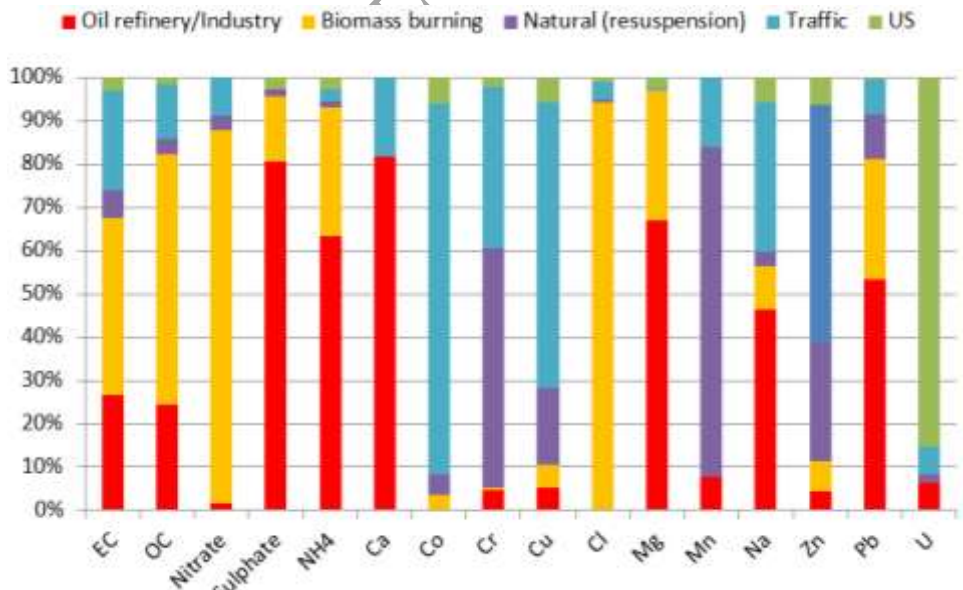


Figure 6. Contribution of five different emission sources and unidentified sources (US) to species concentrations in PM_{2.5} (%) determined from positive matrix factorization analysis for Slavonski Brod, Croatia, during 2015 (Jeričević et al., 2019).

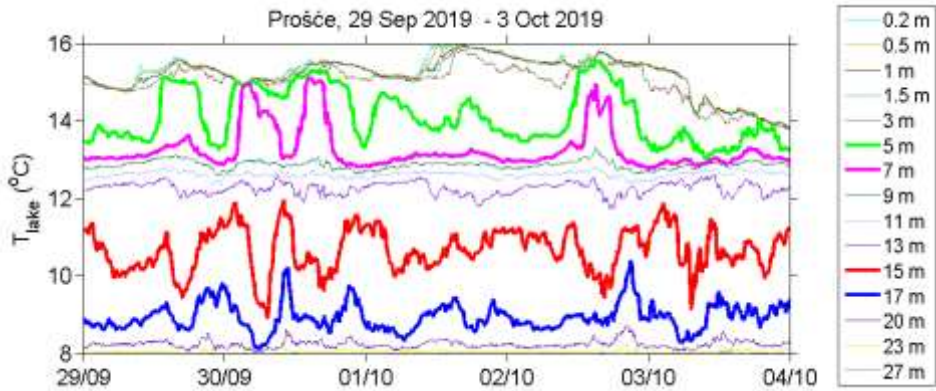


Figure 7. Prominent lake temperature oscillations observed in Prošće (Plitvice Lakes, Croatia) at depths of 5, 7, 15 and 17 m. These oscillations point to the second vertical, first horizontal (V2H1) seiche mode. They are produced by along-basin stronger southern winds, which are associated with sirocco flow over the Adriatic (Klaić et al., 2020b).

Here, we presented only a few results of conducted research while additional information can be found at the web sites of individual institutions: <http://www.pmf.unizg.hr/geof/en> (DG), https://meteo.hr/index_en.php (DHMZ), <https://www.pmfst.unist.hr/odjel-za-fiziku/?lang=en> (PDS) and <https://galijula.izor.hr/en/> (IOF). At the end, we conclude that meteorological community was very active during the reporting period. Furthermore, international and national inter-institutional cooperation was intense, observational networks were expanded and modernized, up-to-date field experiments were performed and state-of-the-art methodologies were used.

List of publications

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Appendix: List of projects

a) Croatian Science Foundation

Adaptability assessment of maize and soybean cultivars of Croatia in the function of breeding for drought tolerance (AGRO-DROUGHT-ADAPT) (Project Leader: Ivan Pejić, 2017–2019).

Climate change and variability in Croatia - from global impacts to local green solutions (CroClimGoGreen) (Project Leader: Herceg-Bulić, I.; HRZZ UIP-2017-05-6396, 2018–2023).

Middle Adriatic Upwelling and Downwelling (MAUD) (Principal investigator: Mirko Orlić, 2018–2023).

b) EU funding

A resilience information platform for Adriatic cities and towns (AdriAdapt) (DHMZ Team Leader: Lidija Srnec, 2019–2021).

Adaptation of the viticultural zones of the Republic of Croatia to climate changes (CroViZone) (DG Team Leader: Telišman Prtenjak, M.; European Structural and Investment Funds, 2020–2023).

Adaptation-oriented Seamless Predictions of European Climate (ASPECT) (DG Team Leader: Telišman Prtenjak, M.; Horizon-EUROPE Framework Programme, 2022–2026).

Adriatic decision support system exploitation for integrated MONitoring and Risk management of coastal flooding and Extreme weather (AdriaMORE) (DHMZ Team Leader: Krešo Pandžić, 2018–2019).

Climate cHallenges on coAstal and traNsitional chanGing arEas WEaving a Cross-Adriatic REsponse (CHANGE WE CARE) (IOF Team Leader: Ivica Vilibić, Hrvoje Mihanović, INTERREG project IT-HR, 2019–2021).

Climate change information, monitoring and management tools for adaptation strategies in Adriatic coastal areas (AdriaClim) (IOF Team Leader: Gordana Beg Paklar, INTERREG Project IT-HR, 2020–2023).

Climate REsponses for the AdriaTic rEgion (CREATE) (IOF Team Leader: Natalija Dunić, 2022–2023).

Climate vulnerability of Croatia and adaptation possibilities of urban and natural environments (Klima-4HR) (Project Leader: Herceg-Bulić, I.; 1 Jun 2020–1 Dec 2022, European Regional Development Fund (ERDF) and Environmental Protection and Energy Efficiency Fund).

Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe (EMEP) (DHMZ Team Leader: Jadranka Škevin-Sović, continuous as of 1981).

Destination Earth On-Demand Extremes Digital Twin – Phase 1 (DHMZ Team Leader: Kristian Horvath, 2022–2024).

Drought Risk in the Danube region (DRIDANUBE) (DHMZ Team Leader: Ksenija Cindrić Kalin, 2017–2019).

Expansion and Modernisation of the National Network for Continuous Air Quality Monitoring (AIRQ) (Project Leader: Jadranka Škevin-Sović, 2017–2023).

EUMeTrain - International training project sponsored by EUMETSAT to support and increase the use of meteorological satellite data (DHMZ Team Leader: Dunja Plačko-Vršnak, continuous as of 2004).

EUMETNET Climate Programme (DHMZ Team Leader: Melita Perčec Tadić, 2019–2023).

Flood Risk Slovenia-Croatia Operations – Strategic Project 1 – Nonstructural Measures (FRISCO 1) (DHMZ Team Leader: Borivoj Terek, 2016–2019).

Improving Maritime Transport Efficiency and Safety in the Adriatic (INTESA) (DHMZ Team Leader: Dijana Klarić, 2019–2022).

Carstic Coastal Water Management Endangered by Climate Changes (UKV) (DHMZ Team Leader: Melita Perčec Tadić, 2020–2023).

Improvement of Non-Structural Measures of Flood Risk Management in the Republic of Croatia (VEPAR) (DHMZ Team Leader: Dario Kompar, 2019–2023).

Integrated Sea sTORM Management Strategies (I-STORMS) (DHMZ Project Manager: Dijana Klarić, 2018–2020).

Modernisation of the National Weather Observation Network in Croatia (METMONIC) (Project Leader: Stjepan Ivatek-Šahdan, 2017–2023).

Severe Weather over Alpine-ADRIatic region in a Changing Climate (SWALDRIC) (Croatian Team Leader: Telišman Prtenjak, M.; Swiss National Science Foundation and Croatian Science Foundation, 2019–2022).

South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A) (DHMZ Team Leader: Kristian Horvath, 2019–2020).

South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A) – Phase 2.5 (DHMZ Team Leader: Kristian Horvath, 2021–2022).

Space-time interpolation of daily meteorological variables at 1 km resolution (WorldDailyMeteo) (DHMZ Team Leader: Melita Perčec Tadić, 2015–2020).

Strategies to adapt to climate change in Adriatic regions (RESPONSe) (INTERREG Project IT-HR, DHMZ Team Leader: Ivan Güttler, IOF Team Leader: Branka Grbec, 2019-2022).

Traffic model for better Air Quality policies in cities (LIFE CityTRAQ) (DHMZ Team Leader: Darijo Brzoja, 2022-2026).

Viticulture and climate change in Croatia (VITCLIC) (Project Leader: Telišman Prtenjak, M.; Croatian Science Foundation, HRZZ PKP-2016-06-2975, 2017–2019).

c) Other funding

Hydrodynamic Modeling of Plitvice Lakes System (Project Leader: Klaić, Z. B., Plitvice Lakes National Park, Croatia 7989/16, 2016–2021).



Physical oceanography in Croatia, 2019–2022

Report submitted to the International Association for the Physical Sciences of the Ocean of the International Union of Geodesy and Geophysics

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Research in the field of physical oceanography in Croatia in the period 2019–2022 has been carried out mainly in five institutions: Geophysical Department of Faculty of Science at University of Zagreb (FS-UniZG); Institute of Oceanography and Fisheries (IOF), Split; Faculty of Science at University of Split (FS-UniST); Hydrographic Institute of the Republic of Croatia (HIRH), Split and at Ruđer Bošković Institute (RBI) – its Division for Marine and Environmental Research in Zagreb, and Center for Marine Research in Rovinj. The research covered a wide range of topics and included data acquisition, empirical studies, theoretical analyses and numerical modelling.

Oceanographic infrastructure

Field work encompassed permanent or long-term measurements, targeted short-term measurements and intense high-resolution measurements during cruises. Measurements at sea were performed from research vessels *Bios Dva* (owned by IOF), *Vila Velebita* (RBI) and *Palagruža* and *Hidra* (both from HIRH) and several smaller boats.

Oceanographic equipment used to study hydrographic properties included several types of Seabird CTD probes. High-resolution measurements were performed with CTDs mounded onto a towed undulating vehicle (Sea Science). Sono.Vault acoustic recorders manufactured by Develogic GmbH Subsea Systems were used to monitor acoustic emissions along the eastern Adriatic coast. Sea currents were measured with a number of current meters, both bottom and vessel mounted (mainly RDI ADCPs), and high frequency radars (WERA). A set of directional waveriders were used for measuring wave height, period and direction of the waves. A meteo-ocean buoy was maintained by RBI to be operational in the northern Adriatic, off Rovinj. Sea level measurements were performed for studying processes on a wide range of temporal scales.

Permanent tide-gauge stations at Rovinj, Bakar, Zadar, Split (Luka and Marjan), Ploče and Dubrovnik, are mostly equipped with classical chart recorders which work aside float-operated instruments with A/D converters; in addition, a radar tide gauge has been operating in Bakar since 2004 and a new one was installed in Rijeka in 2021; all instruments were manufactured by Ott GmbH. Atmospheric conditions were also measured at Split-Marjan while the stations at Split-Luka and Zadar were lately upgraded with a microbarograph. Most of the permanent stations are operated by HIRH, while Bakar is maintained by FS-UniZG and Split-Marjan by IOF. A detailed review of sea-level monitoring at Croatian tide gauge network can be found in Pérez Gómez et al. (2022). In addition to the above mentioned standard equipment, small bottom-mounted data loggers were used to obtain continuous measurements of temperature, pressure (*i.e.* sea level) and dissolved oxygen.

Nine automatic meteo-oceanographic stations were installed, initially for studying meteotsunamis in the Adriatic, and maintained by IOF at: Stari Grad (island of Hvar), Vela Luka (island of Korčula), Sobra (island of Mljet), Vis (island of Vis), Mali Lošinj (island of Lošinj), Prosika (Lake Vrana), Bistrina (Mali Ston Bay), Raslina (Krka River estuary) and Metković (Neretva River estuary; Fig. 1). All stations were equipped with radar tide gauges and meteorological sensors, while stations at Bistrina, Raslina, Lake Vrana and Metković were also equipped with CTD sensors. Atmospheric pressure was recorded with microbarographs: six were located along the eastern Adriatic



Figure 1. Meteo-oceanographic station being installed at Metković in the Neretva River estuary, in November 2022 (photo by Stipe Muslim).

coast at Ražanj (island of Brač), Vis (island of Vis), Svetac Island, Palagruža Island, Vrboska (island of Hvar), Vela Luka (island of Korčula), while three microbarographs were in Italy, at Ancona, Ortona and Vieste.

As to the computing resources, the RBI numerical modelling group had access – in order to conduct high-resolution atmosphere-ocean-wave simulations in both operational and climate/reanalysis models – to the ATOS supercomputer at the European Centre for Middle-range Weather Forecast (ECMWF) and to the Slovenian VEGA high-performance facility, while storing the processed data at the local data server with ca. 50 TB in capacity. The ocean modelling with the POM, ROMS and Ichtyop models was also conducted at IOF, using local servers.

Field work

During the four-year interval considered, the previously established long-term measurement programs were maintained. Sea level was continuously measured at the above mentioned network of permanent tide-gauge stations. Međugorac et al. (2022a) gave a detailed description of measurements that have been carried out for nearly 100 years by FS-UniZG at the tide-gauge station Bakar and the dataset itself has been published in SEANOE database (Međugorac et al., 2022b). Long-term measurements of thermohaline, chemical and biological properties were performed on a monthly or seasonal basis all along the east Adriatic coast, as well as along three cross-shore transects (Split-Gargano, Šibenik-Ortona, Rovinj-Po delta) within the framework of national projects and studies.

Continuous measurements of various physical parameters were maintained or established. Sea level measurements continued at previously established stations (Vela Luka, Stari Grad, Sobra) and started at new ones (Vis, Mali Lošinj, Prosika, Bistrina, Raslina, Metković) installed mainly within projects funded by Interreg Italy-Croatia Programme. Previously established high-frequency air pressure measurements at Vis, Vela Luka, Vrboska, Ražanj, Svetac Island, Palagruža Island, Ancona, Vieste and Ortona were sustained. Waves were continuously measured near the towns of Rijeka, Split, Ploče and Dubrovnik. Surface currents and waves were measured with a pair of high-frequency radars installed in the middle Adriatic at Cape Ražanj on the island of Brač and Cape Stončica on the island of Vis, until November 2019. Temperature along the water column, pressure and dissolved oxygen were continuously recorded with small data loggers at the islets of Jabuka and Blitvenica (middle Adriatic) between 2019 and 2022.

Among others, five research cruises were performed to document hydrographic properties of an upper layer (0–45 m) using towed undulating vehicle with mounted CTD. Profiling took place in the northern and in the

middle Adriatic with high spatial resolution of ~ 200 km in the horizontal and ~ 10 cm in the vertical; during the profiling in the middle Adriatic, also measured were currents, with vessel mounted ADCP. The northern Adriatic cruises (March 2019, 2020) were aimed to record mesoscale variability and dense water formation in the area. The cruises in the middle Adriatic (June 2019, August 2020, May 2021) were organized to document upwelling in the wider area of Jabuka and Blitvenica islands and the connecting region (Fig. 2). Several campaigns of high-frequency CTD measurements were also conducted in the Rogoznica Lake, with temperature, salinity and water level sensors installed inside the lake and in the nearby sea.



Figure 2. Deployment of towed undulating vehicle for high-resolution CTD profiling along a transect between Jabuka and Blitvenica (eastern middle Adriatic), in June 2019 (photo by Hrvoje Mihanović).

Projects and meetings

The research was done within framework of a number of international and national projects. The ERC funded project SHExtreme, for which FS-UniST serves as a host institution, is aimed to estimate contribution of sub-hourly sea level oscillations to overall sea level extremes in a changing climate. International project CBIOMES, funded by the Simon foundation, deals with computational biogeochemical modelling of marine ecosystems. Croatian scientists also participated in the project FATIMA, supported by the U.S. Department of Defense – Office of Naval Research, where the main objective

is to investigate formation, evolution and dissipation of coastal and open-ocean fog.

Majority of national scientific projects were funded by Croatian Science Foundation (CSF), many of which were interdisciplinary. Project StVar-Adri is dedicated to research of strength and variability of the Adriatic sea level extremes in present and future climates. The major objective of the ADIOS project is to investigate and to quantify processes driving interannual to decadal thermohaline variations in the Adriatic-Ionian basin. Within project MAUD, upwelling and downwelling (U/DW) of water masses in the middle Adriatic is investigated from physical and biological aspects. Project ISLAND is focused on island-trapped waves and their impact on pycnocline movements and related vertical mixing. SSA@EDAL deals with software sensor augmentation at an environmental data analysis laboratory, with a large part of research dedicated to ocean processes. Many of the CSF funded projects (MARRES, MARIPLAN, EcoRENA, BivACME and SCOOOL, ESamar, BenthicNIS) are focused on changes in the ecosystem. A national project (Project Hydrodynamic Modeling of Plitvice Lakes System) financed by the Plitvice Lakes National Park is aimed to develop a hydrodynamic forecast model for the system of lakes. Demanding numerical modelling performed within several of these projects required access to the high-performance computing facilities which was secured through three ECMWF Special Projects.

Research was performed also within several projects funded by Interreg Italy-Croatia Programme: ChangeWeCare, RESPONSE, AdriaClim, CREATE, ECOSS and SOUNDSCAPE. The CAAT and HIDROLAB projects were funded by European Structural and Investment Funds, the QUIETMED 2 project was supported by the DG Environment programme while BLUEMED was supported within Horizon 2020 initiative. In addition to the scientific work, the researchers also participated in a series of professional studies dealing with physical parameters relevant to ecosystem analysis and categorization of water within the European directives.

Physical oceanographers from Croatia took part in the IOC assemblies, MedGOOS, EuroGOOS and COST Action AGITHAR meetings, and presented their results at a number of international conferences and workshops, among others at IUGG (2019), EGU (2019–2022), CIESM (2019), THEMES Workshop (2019, 2022), Ocean Sciences Meeting (2020, 2022), Challenges in Meteorology (2020, 2022), EuroSea (2021), AGU (2022), AMS Symposium on Meteorological Observation and Instrumentation (2022), MedGU (2022), ICPAE (2022), Ocean Carbon from Space Workshop (2022). Aside from presenting, they were also part of science and/or organization committees for the 1st (2019) and 2nd (2022) World Conference on Meteotsunamis, HyMEX Workshop (2019), Challenges in Meteorology (2020) and special Adriatic session at the ECSA 59 Conference (2022).

Scientific results

Results were published in scientific papers listed at the end of the report. The list also contains doctoral theses defended and a university textbook (Orlić, 2022) published in the period 2019–2022. Here is a short account of the main results.

The main scientific research was carried out in the following fields: (A) sea level variability, (B) changes of thermohaline properties and thermohaline circulation, (C) different aspects of numerical modelling, including operational, climate and stochastic modelling at high resolutions, (D) bio-optical modelling of primary production and bio-physical interactions in the ocean, focusing on the photosynthesis-light relationship, (E) atmosphere-ocean interaction, (F) use of machine learning for increasing understanding of the main concepts that drive ocean processes, and (G) diverse interdisciplinary ocean studies.

A. Sea-level research was focused on several topics: (1) climatology of the Adriatic sea level extremes and their occurrence in expected future climate conditions; (2) numerical modelling and forecasting of coastal floods in the northern Adriatic, (3) high-frequency sea level oscillation, with special emphasis on meteorological tsunamis; the latter includes coastal flooding in the northern Adriatic caused by interaction of a storm-surge and a meteotsunami, and specific extreme events in remote parts of the world caused either by a hurricane or by an eruption-generated tsunami.

Climatology of the Adriatic sea level extremes (for 1956–2019/2020 period) was analysed in detail by Šepić et al. (2022) with respect to seven sea level components. It was shown that positive extremes dominantly occur due to superposition of tide, 6 h – 10 d, and 10–100 d components, and negative extremes dominantly occur due to superposition of tide and 10–100 d component. Trend analysis points to shortening of negative and prolonging and strengthening of positive extremes. Ferrarin et al. (2022) carried out a similar analysis of Venice floods in the period 1872–2019 and found that storm surges were the main driver of the most intense events, while tides and longer period contributors mostly determined recurrent nuisance flooding. Intensity of non-tidal contribution to floods increased in the last three decades which led, along with relative sea-level rise, to an increase in the frequency of floods. Duration and intensity of the northern Adriatic floods will likely continue to increase through this century, mainly due to mean sea-level rise (Lionello et al., 2021), while winds that favor flooding will probably stay unchanged (Međugorac et al., 2021).

Numerical modelling of storm surges in the Adriatic (Bajo et al., 2019) showed that reproduction of episodes influenced by pre-existing seiches can be improved by assimilation of residual sea-level series (based on the Ensemble Kalman Filter) and that simulated seiche decay time approaches the

empirically obtained one if bottom friction was defined using hybrid linear-quadratic formulation. A review of challenges in prediction of floods in the northern Adriatic and potential improvements was given by Umgiesser et al. (2021).

Regarding high-frequency sea level oscillation, simulations of several historic meteotsunami events in the Adriatic (Bubalo et al., 2019, 2021) proved that modelling of wave heights with flooding and drying included, an algorithm not commonly implemented in experiments, was more realistic than with cut-off depth. Croatian researchers were engaged in several empirical studies of high-frequency sea level oscillation observed at tide gauges over the world oceans. This includes quantification of severe meteotsunami events in the Persian Gulf occurring in March 2017 (Heidarzadeh et al., 2020; Kazeminezhad et al., 2021) and marrobbio events occurring in 2007 along the southwestern Sicilian coastline (Zemunik et al., 2021a), and analysis of spatial and temporal changes in Finnish meteotsunamis between 2004 and 2015, where two types of events have been quantified (Pellikka et al., 2022). Many of the results were published in a special issue of journal *Natural Hazards* and afterwards reprinted as a book (Vilibić et al., 2021a). With an attempt to go toward objective analysis of nonseismic sea level oscillations at tsunami timescales (NSLOTTs), Minute Sea Level Analysis dataset has been created (Zemunik et al., 2021b) and analyzed (Zemunik et al., 2022a), connecting NSLOTTs with the atmospheric synoptic patterns (Zemunik et al., 2022b). A doctoral thesis: ‘Climatology of high-frequency sea-level oscillations in the World Ocean’ was defended at the Faculty of Science of the University of Zagreb in 2022 (Zemunik, 2022).

A study of the great flood that hit Venice on 12 November 2019 (Ferrarin et al., 2021) established that occasionally meteotsunami can have an important impact in creating the flood; the particular eventy was preconditioned by a low-frequency disturbance of air pressure and wind, the main contribution came from a storm surge but it was largely reinforced by occurrence of a meteotsunami. Analysis of destructive sea level oscillations generated in September 2020 in the Sea of Japan by Typhoon Mysak (Medvedev et al., 2022) showed that, depending on prevailing atmospheric forces, ocean bathymetry, and coastal topography, sea level oscillations of various types (storm surges, seiches and meteotsunamis, infragravity waves) have the strongest impact on the coast. Studies of the Hunga Tonga-Hunga Ha’apai eruption deal with tsunami waves related to the atmospheric Lamb waves (Kulichkov et al., 2022; Haiderzadeh et al., 2022) and tsunami waves related to initial displacement of water surface due to the underwater volcano eruption (Haiderzadeh et al., 2022). The latter was manifested in waves reaching maximum amplitudes of up to 90 m (at Hunga Tonga) and up to 3 m along the distanced coasts of the Pacific Ocean (Haiderzadeh et al., 2022),

while the former resulted in waves of less than 0.5 m amplitude but observed along most of the coasts of the World's oceans (Kulichkov et al., 2022).

Resonance-driven topographic amplification as found for meteotsunami waves has been quantified also for the Adriatic tides (Medvedev et al., 2020), showing its substantial growth when a tidal period is close to the period of an eigenmode of the basin.

B. Thermohaline CTD profiles measured in September for the period 2005–2020 covering most of the Adriatic Sea were used to analyze the physical properties of the sea surface layer based on the depth of the mixed layer, depth of the isothermal layer, heat storage, potential energy anomaly, surface barrier layer and wind types, and air-sea energy exchange (Matić et al., 2022).

Substantial changes in the Adriatic thermohaline properties occurring in recent years have been detected (Vilibić et al., 2019; Mihanović et al., 2021; Fig. 3), having potential to substantially influence biogeochemical and biological properties of the Adriatic Sea. These changes were found to be driven dominantly by changes in river loads and by BiOS oscillations (Ciglonečki et al., 2020; Vilibić et al., 2020).

Circulation reversals of the Northern Ionian Gyre (NIG) were investigated in the two studies carried by Rubino et al. (2020) and Gačić et al. (2021). It was demonstrated, performing experiments in the Coriolis rotating tank (Grenoble) and using numerical simulations, that reversals of polarity of the near-surface circulation in the NIG are mainly induced by internal forcing, *i.e.* injection of dense water on a sloping bottom. Similarities in temporal evolution and vertical structure of laboratory and oceanic conditions revealed that overflow of the Adriatic dense water formed in 2012, as a result of harsh winter, was a trigger for sudden switch from cyclonic to anticyclonic basin-wide circulation. Also, thermohaline circulation of inland basins was studied by analytical model setting different density distributions in vertical and horizontal (Lazar et al., 2022). Results revealed different types of circulation (cyclonic and anticyclonic) stretching through the entire column or limited to the surface/bottom layer.

C. Great effort was spent on high-resolution numerical modelling. To that end, the Adriatic Sea and Coast (AdriSC) modelling suite was set up. It consists of Weather Research and Forecasting (WRF) and Regional Ocean Modeling System (ROMS) at resolutions of 15 and 3 km in the atmosphere and 3 and 1 km in ocean, respectively, in which the SWAN wave and Advanced Circulation (ADCIRC) models are embedded, the latter being two-dimensional and going to ten meter in resolution in coastal regions (Denamiel et al., 2019a).

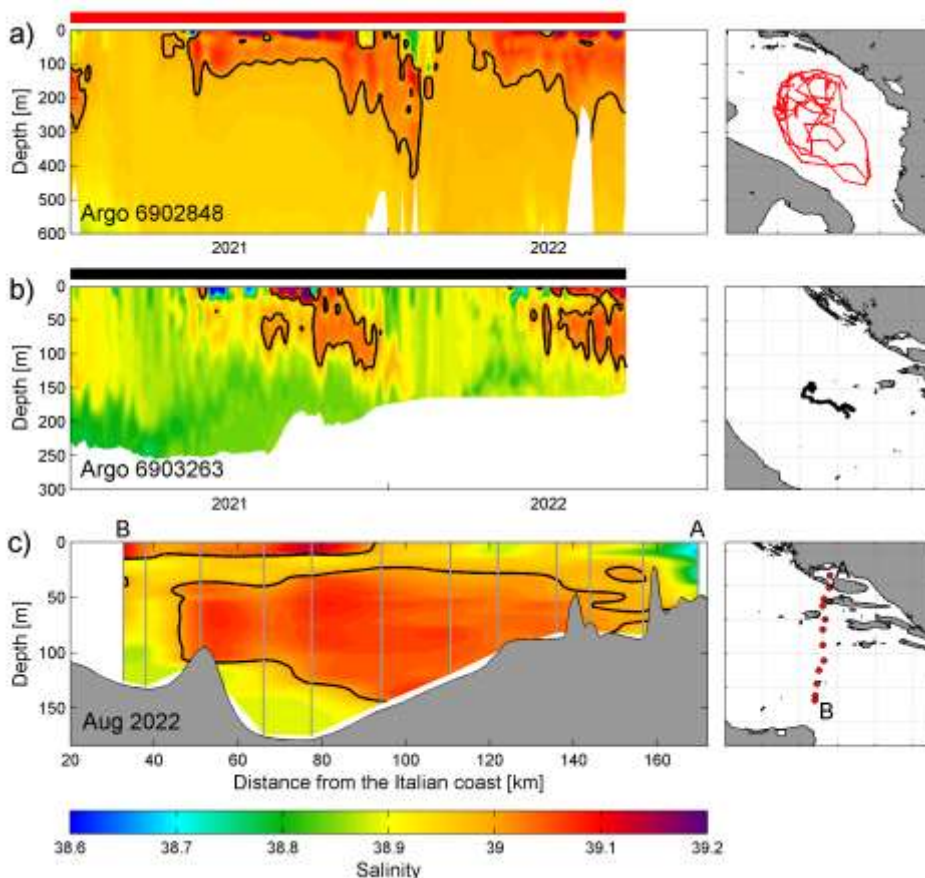


Figure 3. a) Hovmöller diagram of salinity data for the Argo float 6902848 in the first 600 m in the period 2021–2022 (left panel) with corresponding float trajectory (right panel). (b) As in panel (a) except for the Argo float 6903263 between the surface and the bottom. Note that the vertical scale in panel (b) is between 0 and 300 m. (c) Salinity profile at the Palagruža Sill transect in August 2022 (left panel), with the map of CTD stations (right panel). Argo trajectories are colored depending on the location of the float (black–middle Adriatic, red–southern Adriatic). The same color notation is used in horizontal bars above left panels, indicating periods during which Argos were profiling in respective areas. Thick black line in left panels denotes 39.0 salinity contour. Vertical gray lines in left (c) panel denote CTD casts. The figure was prepared by Hrvoje Mihanović.

High-resolution modelling has been used to quantify a number of processes and their behavior in the present and future climates and to address some other issues: (1) changes in surface waves in the future climate (Denamiel et al., 2020a), (2) changes in air-sea heat fluxes and their consequences on the dense water formation (Denamiel et al., 2020b), (3) assessing the effects of resolution on reproduction of bora events in the northern Adriatic (Denamiel et al., 2021a), (4) evaluation of reliability of the Croatian meteotsunami early

warning system (Tojčić et al., 2021), (5) changes in meteotsunamis in the future climate (Denamiel et al., 2022a), and (6) reproducibility of the Adriatic-Ionian Bimodal Oscillating System (BiOS) in the present climate (Denamiel et al., 2022b). All except the last application is based of short-term (3-day) reproduction of extreme events, while full present climate (1987–2017) and future climate (2070–2100, RCP 8.5) runs have been conducted as well and fully evaluated (Denamiel et al., 2021b; Pranić et al., 2021). Further, one-year long run with 4D-Var data assimilation of all available remote and *in situ* data has been performed to assess enhancement of the ocean model toward the data-driven dynamic solutions (Janeković et al., 2020). In addition, proxy-based circulation index has been constructed and verified in regional climate models, providing an insight into the circulation regimes in the northern Adriatic in the future climate (Dunić et al., 2022). As it stands now, it seems that these models are not quantifying properly some of the Adriatic processes, mostly due to their coarseness, set up and inappropriate atmospheric forcing (Dunić et al., 2019). Stochastic surrogate modelling has been applied to meteotsunami forecast, optimized by using polynomial chaos expansion methodology, to obtain probabilistic assessment of meteotsunami hazard in endangered areas (Denamiel et al., 2019b, 2020c). Such methodology was conceptually proposed for its application in extreme sea level early warning systems (Denamiel et al., 2021c). Regarding the wave model developments, new numerical schemes and algorithms have been implemented to the WW3 wave model (Abdolali et al., 2020), with special emphasis on wave-vegetation interaction (Abdolali et al., 2022). Numerical modelling by ROMS and several other models has also been applied to elucidate the impact of various physical processes in a number of interdisciplinary problems which are briefly described further below.

D. Research on bio-optical modelling of primary production resulted, among all else, in a solution to a problem posed 70 years ago. In his 1953 paper, Harald Sverdrup argued that the development of a spring bloom in the ocean depends on the juxtaposition of two depth horizons: the mixed-layer depth and the critical depth. Mixed-layer depth shallower than the critical depth favours phytoplankton growth in the layer and vice versa. However, mathematically, Sverdrup left the problem unsolved in the form of a transcendental equation. Despite the high number of citations that this paper has garnered, the solution to this equation has not been found, until Kovač et al., (2021) finally presented an analytical solution for the critical depth, as originally defined by Sverdrup.

Further on, Croatian scientists have done research: on stability in marine phytoplankton biomass revealing that causes of stability are shading and nutrient limitation (Kovač et al., 2020); and on ecosystem fragility. Ecosystem fragility is an often-used term in oceanography, yet it lacked a precise and widely accepted definition. With this aim the concepts of marginal production

and fragility, which are defined for marine photosynthesis, were introduced to the oceanographic literature by Kovač and Sathyendranath (2022). It is demonstrated that marine photosynthesis is always fragile with respect to light, implying variability in surface irradiance that acts unfavourably on biomass; but also, that marine photosynthesis can be both fragile and antifragile with respect to the mixed-layer depth, implying variability in mixed-layer depth that can act both favourably and unfavourably on biomass.

E. A study of atmosphere-ocean interaction resulted in publication of the first global-scale comprehensive climatology of marine fog (Dorman et al., 2019). It is based on ICOADS ship present weather observations for the period 1950–2007. In general, the median marine fog occurrence away from the polar oceans is low (0.2%). Substantially greater marine fog occurrences are, in addition to the polar region, limited to: the western side of the subpolar ocean gyres where fog occurs during the warm season and over the shelf; seven marginal seas; and over five wind-driven coastal upwelling zones. A special attention was given to the northeast Pacific marine fog (Li et al., 2022). The atmospheric circulation and marine atmospheric boundary layer structure associated with marine fog over the northeast Pacific in winter were classified, showing that fog mostly occurs when the eastern flank of the Aleutian low and the northwestern flank of the Pacific subtropical high jointly contribute to a northward air flow over the NEP, resulting in advection of warm and moist air over a cooler ocean surface. In another study, relationship between hemispheric indices and air temperature and precipitation patterns has been analyzed by Matić et al. (2019).

F. Regarding the use of machine learning in oceanography, the research was focused on overcoming obstacles related to gaps in records, which are, for example, common for satellite measurements (Kalinić et al., 2021; Kalinić et al., 2022). One way to deal with the gaps is via various reconstruction methods. Different approaches related to optimal sensor placement were studied and it was shown that an optimal sensor location can be selected using unsupervised learning methods such as self-organising maps, neural gas or the K-means algorithm. It was shown, using wind data over the Mediterranean Sea, that a small fraction of the data is sufficient to reconstruct wind data over a larger geographic area with an error comparable to that of a meteorological model.

G. A number of papers resulted from the collaboration of physical oceanographers with their colleagues from other closely related oceanographic disciplines: chemists, geologists, biologists and fisheries scientists (e.g. Talijančić et al., 2019; Ninčević Gladan et al., 2020; Šantić et al., 2020; Šolić et

al., 2020; Paliaga et al., 2021; Šantić et al., 2021; Džoić et al., 2022; Šolić et al., 2022; Vrdoljak Tomaš et al., 2019; Živković et al., 2019; Žužul et al., 2019). Here are some details of the interdisciplinary studies conducted. Satellite-based SST measurements were used to study the influence of environmental factors on phenotypic traits of gilthead seabream (Talijančić et al., 2019). The Lagrangian dispersal model Ichthyop, with temperature, salinity and 3D velocity input fields from hydrodynamical model ROMS, was used to investigate the dynamics of the gilthead sea bream ichthyoplankton stage (Žužul et al., 2019). A non-linear method belonging to the artificial neural network class called Growing Neural Gas Network analysis was used to explain the multiple dependencies between the abundances of early life stages of anchovy (eggs/m²; larvae/m²) and environmental variables such as salinity, sea surface temperature and chlorophyll (Džoić et al., 2022). Great efforts have been made in studying the microbial community and its relation to environmental parameters (Beg Paklar et al., 2020; Šantić et al., 2020; Šolić et al., 2020; Paliaga et al., 2021; Šantić et al., 2021; Šolić et al., 2022; Vrdoljak Tomaš et al., 2019; Živković et al., 2019). Variations in seasonal structure and abundance of bacterial assemblages in an eutrophic marine lake and a more oligotrophic coastal area of the adjacent middle Adriatic Sea with respect to environmental conditions were studied by Čanković et al. (2022). Impact of physical conditions and circulation in the northern Adriatic on spreading of plankton species and large organic production of the region was analyzed by Budiša et al. (2021), Ciglencečki et al. (2021) and Malej et al. (2022). A dispersive model was developed by Paliaga et al. (2021) for tracing the paths of allochthonous potentially harmful zooplankton species *Mnemiopsis leidyi*. Further, the connectivity between bivalve growth, its chemical properties and



Figure 4. Coarse-clast deposit on the island of Mana (NP Kornati, Central Adriatic) brought by storm sirocco waves (photo by Ivica Vilibić).

ocean dynamics has been analyzed having as a base either long-term observations or ocean numerical models (Markulin et al., 2019; Peharda et al., 2019a, b; Vilibić et al., 2020; Ezgeta-Balić et al., 2022). Numerical models have also been used to quantify the changes in the European lobster abundance in the eastern Adriatic (Matić-Skoko et al., 2022). Various pollution problems were analysed by Kraus et al. (2019) and Picciulin et al. (2022). Finally, impact of severe storms on dynamics of coastal boulders (Fig. 4) in different regions of the Adriatic was assessed by Biolchi et al. (2019a, b) and Korbar et al. (2022).

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ARTICLE IN PREP



Seismology in Croatia, 2019–2022

Report submitted to the International Association of Seismology and Physics of the Earth's Interior of the International Union of Geodesy and Geophysics

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The development, activities and areas of research in seismology in Croatia in the period 2019–2022 were significantly affected by the intense earthquake activity in 2020. The Zagreb area was first activated by the earthquake that occurred on 22 March 2020, with a magnitude of 5.5, and the location of the epicenter in the vicinity of Markuševac and Čučerje, about 7 km north of the center of Zagreb (Markušić et al., 2020). Both epicentral area and many buildings across wider city center suffered a significant damage. (Fig. 1). The main earthquake was followed by a large number of aftershocks.

This event activated awareness of the danger of earthquakes and vulnerability to it. Therefore, numerous activities were started with the aim of better monitoring of seismic activity and studying the mechanisms that caused increased seismic activity, thus attempting to prevent significant extent of damage in the future (through quality assessment of seismic hazard and risk).

At the end of the year, on 28 December 2020, the Petrinja epicentral area was activated, where an earthquake of magnitude 5.8 occurred in 1909. The latter earthquake is known for the fact that Andrija Mohorovičić discovered a discontinuity between the crust and the mantle based on the analysis of its records. First, the M5 earthquake occurred and a day later the main M6.2 event followed. These earthquakes damaged almost 35,000 buildings and caused significant ground failures as karst sinkholes, visible ruptures at the surface, landslides and liquefaction. In less than three days after the main earthquake, more than 2,000 aftershocks occurred (Markušić et al., 2021). The seismic activity of this area is still increased, more than two years after the mainshock (Fig. 2).



Figure 1. Photos of damage in Zagreb caused by the 22 March 2020 earthquake (from Markušić et al, 2020).

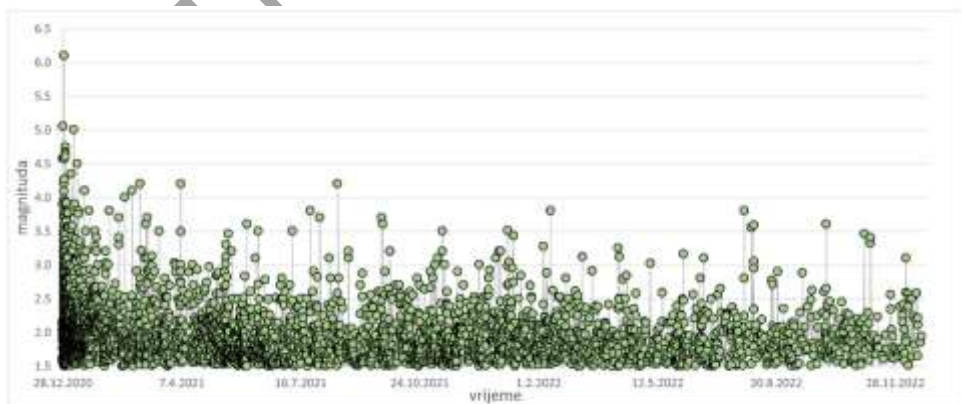


Figure 2. Temporal distribution of the magnitudes of the Petrinja series of earthquakes – magnitudes greater than 1.5 (URL 1).

After strong earthquakes in 2020, employees of the Croatian Seismological Survey (I. Ivančić, I. Sović and T. Fiket) participated in the preparation of two strategic reports: Croatia Earthquake – Rapid Damage and Needs Assessment 2020 (URL 2) and Croatia December 2020 earthquake – Rapid Damage and Needs Assessment (URL 3), both prepared by the Government of Croatia with the support of the World Bank.

As a result of the mentioned seismic events and extensive large damage, there was a significant development of operational seismology – investment in seismological infrastructure (from intervention state funds and the funds within the National Resilience and Recovery Plan, financed by the EU), as well as the approval of several scientific research seismological projects – two funded by the Croatian Science Foundation (CSF) and one (international) financed from the Norwegian Financial Mechanism (NFM).

Seismological infrastructural and scientific research projects

In the following, more is said about the mentioned investments in seismological infrastructure as well as about the goals of active scientific research seismological projects.

Mobile pool of seismological instruments

Shortly after the Petrinja main earthquake, state intervention funds (amounting approx. to 4.5 million HRK) financed the purchase of the mobile pool of instruments for monitoring the seismic activity of the currently active fault zone (URL 4). Twenty seismometers with data acquisition system and twenty accelerometers were acquired. It was the first significant national investment in the seismological network in the last 20 years. The map of the current locations of seismological stations of the mobile network is displayed in Fig. 3.

The data collected by this mobile network will: enable a better determination of earthquake locations, define the subsoil structure in the wider vicinity of the active fault zone, and provide valuable information for seismic hazard assessment, earthquake design and construction. The locations of earthquakes, even the small ones that were not previously recorded at the stations of the state seismological network, will enable the determination of the position and geometry of the currently active part of the Pokupsko fault. As strong earthquakes occur relatively rarely in Croatia, the data collected in this way will be extremely valuable for the study of geological structures in central Croatia. Accelerograph records are an indispensable part of engineering-seismological and construction analyzes related to earthquake-resistant design and construction.

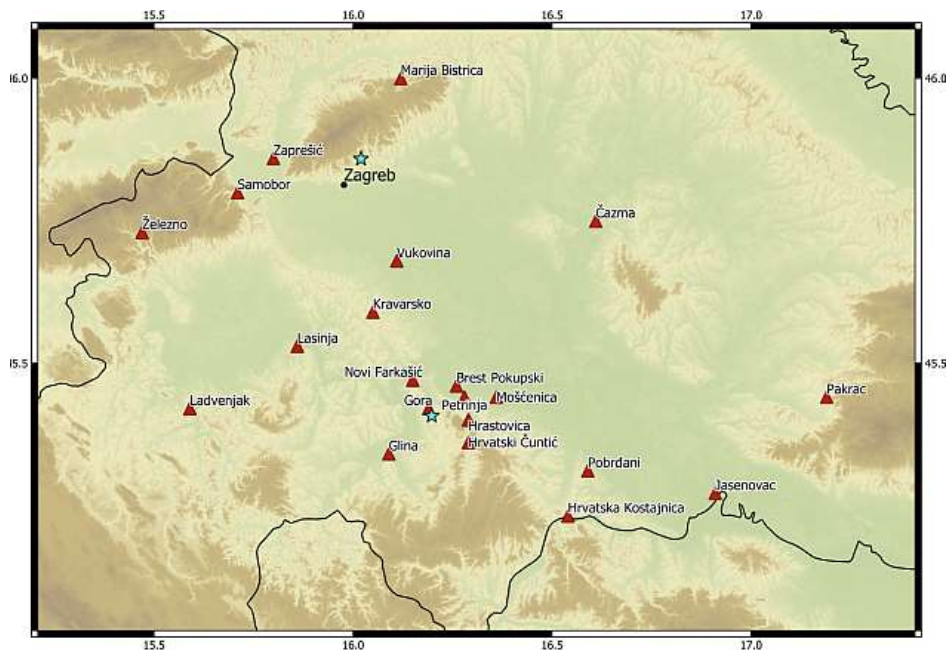


Figure 3. Map of currently active seismological stations of the mobile network (red triangles) and the locations of the epicenters of the main Zagreb and Petrinja earthquakes (blue stars) (URL 4).

Project CROSSNET – Development of a Seismological Data Network

The Croatian Seismological Survey at the Department of Geophysics at the Faculty of Science started with the implementation of the project "CROSSNET - Development of a Seismological Data Network" (URL 5) at the end of 2021. The aim of the CROSSNET project is to strengthen the infrastructural and organizational capacities of the Croatian Seismological Survey in order to increase the quality of collection, processing and application of seismic data necessary for the processes of reconstruction of buildings, planning the construction of new buildings and monitoring public infrastructure, as well as strengthening Croatia's resistance to earthquakes and related risks. In the scope of the project, 95 permanent seismological stations will be installed. The installation of new stations will create basic prerequisites for modern collection and analysis of seismological data.

Project „Investigation of Seismically Vulnerable Areas in Croatia and Seismic Ground Motion Assessment – CRONOS“

The project "Investigation of Seismically Vulnerable Areas in Croatia and Seismic Ground Motion Assessment - CRONOS" (URL 6) is financed by the

Norwegian Financial Mechanism for the period 2014–2021. The project started in January 2022, with duration of 27 months. The main goal of the CRONOS project is to make Croatian society more resistant to the impact of strong earthquakes. This implies the development and modernization of earthquake risk assessment as well as the acquisition of knowledge and the development of tools for reducing earthquake vulnerability. The aforementioned is planned through the improvement of the scientific infrastructure, the increase of capacity and the transfer of knowledge, including communication with decision-makers at the state, regional and local level, and international research cooperation. The project will help improve the seismological scientific community in Croatia and strengthen bilateral cooperation between Croatia and Norway.

The project consists of two components:

Component 1 deals with the assessment of the seismogenic potential and the characterization of the seismic fault system, the aim of which is to describe the seismicity in as much detail as possible, determine the 3D structure of the Earth's crust (seismic velocities, density and damping) and the anatomy of the fault system, and to understand the tectonic relations in the area of interest.

Component 2 aims to develop a hybrid-empirical attenuation relation for earthquake-sampled ground motion prediction (Ground Motion Prediction Equation – GMPE), based on combining empirical data from earthquakes recordings and stochastic modeling using characteristic regional seismic parameters for the investigated area.

Both components are focused on the area of northern and central Dalmatia, one of the most seismically vulnerable areas in Croatia (Fig. 4).

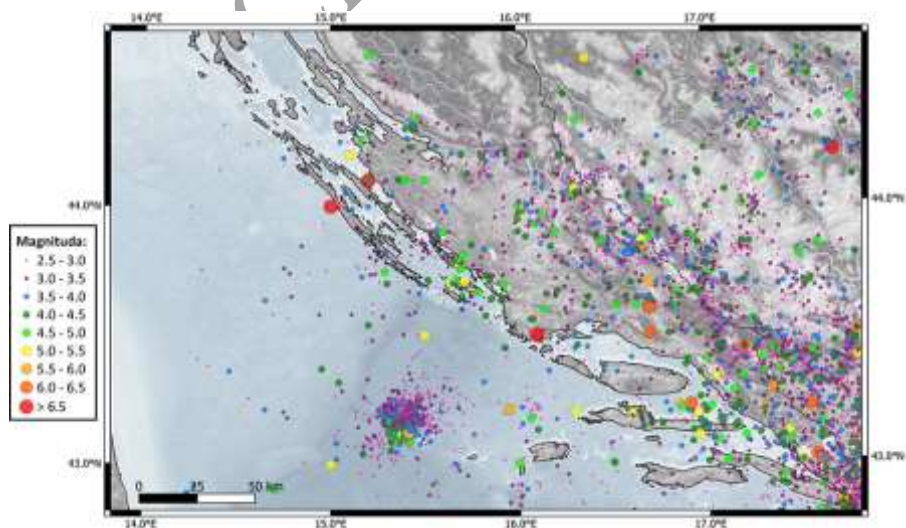


Figure 4. The research area of the CRONOS project (URL 6).

Their activities complement each other and are equally important in the process of better assessment of the seismic hazard and thus the reduction of the seismic risk.

Project „Seismic Risk Assessment of Cultural Heritage Buildings in Croatia – SeisRICHerCRO“

The primary objective of the proposed research in the SeisRICHerCRO project (URL 7), funded by the Croatian Science Foundation, is development of ready transferable methodology and practical procedure for assessing the seismic risk to cultural heritage which include seismic risk assessments on urban scale (macro approach) and for individual monuments (micro approach), based on the quantitative and qualitative analyses of selected cultural heritage buildings and locations.

Characteristic locations were selected according to the highest level of seismicity criteria. Chosen as target locations are the following: the old city center of Dubrovnik (comprising a multitude of churches, monasteries, palaces, etc.), the most significant architectural achievement of the 15th and 16th century in Croatia – the cathedral St. Jakov in Šibenik, and one of the most attractive castles in Croatia – Trakošćan Castle. The first two sites are listed on the UNSECO World Heritage list.

Project „Characterization and monitoring of the Dubrovnik fault system – DuFAULT“

The goal of the DuFAULT project (URL 8), financed by the Croatian Science Foundation, is to investigate the wider Dubrovnik area, one of the most seismically active areas in Croatia and one of the more active areas in Europe. Analyzes of previous geophysical and geological research and application of new seismological and geological methods will enable the definition of fault systems, the creation of a high-resolution lithosphere model and the simulation of earthquake tremors, which will indicate locations with strong tremors and help in understanding the propagation of seismic waves through this area.

Seismological research and its results

The most important seismological research and its results published in the period 2019–2022 can be grouped as follows:

a) Determining the structure of the lithosphere under the Dinarides and surrounding areas

Structural investigations of the Vinodol Valley area (Northwestern Adriatic, Croatia) were performed by Palenik et al. (2019) based on new geological and structural data addressing the tectonic evolution of the area. Structural measurements of the fault planes in the study area generally correspond to the existing structural model of the tectonic evolution of the Dinarides. Cross-cutting relationships suggest that transpressional and extensional features are structurally concurrent or younger than the reverse faults, suggesting a change in the palaeostress field during the Neogene–Quaternary, with prevalent transpression and radial extension.

Kapuralić et al. (2019) proposed the crustal structure model of the northern Dinarides and southwestern part of the Pannonian basin based on local earthquake tomography. The velocity model reveals crustal thickening beneath the Dinarides and significant crustal thinning beneath the Pannonian basin. Relatively high velocities were observed below the northern Dinarides at shallow depths (< 10 km), with low velocities caused by deep local depressions in the Pannonian basin (Fig. 5). A very pronounced high-velocity body is present in the transitional part between the Dinarides and the Pannonian basin at a depth range of 5–15 km. The strong velocity increase at depth of about 20 km indicates that the Dinaridic crust could be interpreted as two-layered, while the Pannonian crust is probably one-layered.

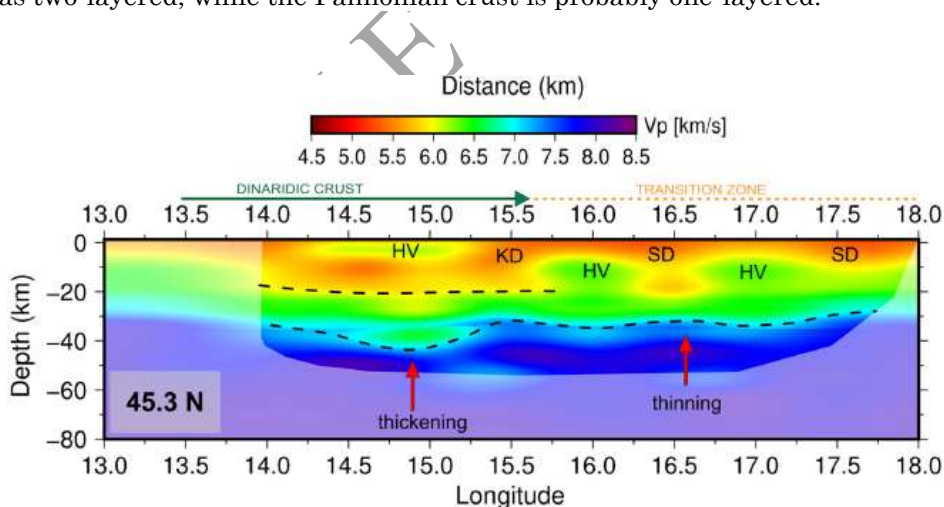


Figure 5. Section along 45.3 N across the P-wave inversion model (from Kapuralić et al., 2019). HV – high-velocity anomalies, KD – Karlovac depression, SD – Sava depression. Black dashed lines represent an intra-crustal discontinuity and the Moho discontinuity.

Crustal thickness beneath the Dinarides and surrounding areas was also obtained based on research performed by Stipčević et al. (2020). A new Moho depth map is presented, encompassing wider Dinarides region (Fig. 6). The resulting Moho topography fits well within a structural framework that includes a thicker crust under the Dinarides, which gradually becomes thinner toward the Pannonian and Adriatic domains. The Mohorovičić discontinuity lies deepest in the central and southern Dinarides, at depths of over 55 km. Similarly to the northwestern segment, a jump in the crustal thickness was observed when transitioning toward the Internal Dinarides, which hints at possible underthrusting (or subduction) of the Adria plate in this region. Moho depths in the transition zone toward the Pannonian basin and in the Pannonian basin proper vary between 25 and 35 km. In the Adriatic domain, crustal thickness ranging from 30 km to more than 45 km around the Central Adriatic islands was observed.

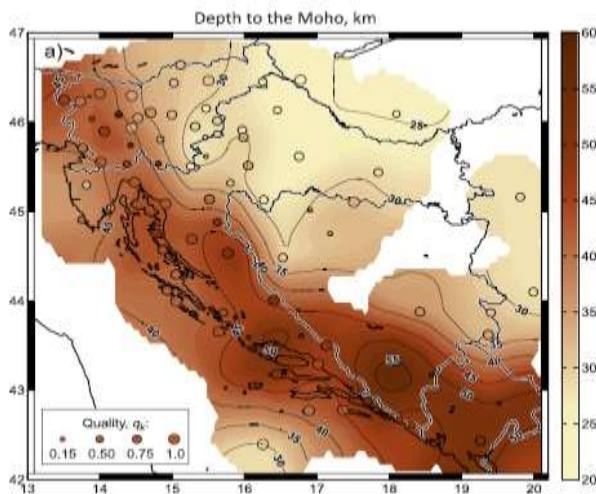


Figure 6. Depth to the Mohorovičić discontinuity below each of the stations is shown by the colored circles according to the color scale on the right (from Stipčević et al., 2020). The interpolated Moho surface was spatially smoothed with a smoothing kernel of the radius of 41.5 km.

Belinić et al. (2021) defined shear-wave velocity structure beneath the Dinarides from the inversion of Rayleigh-wave dispersion. Resulting velocity model reveals a robust high-velocity anomaly present under the whole Dinarides, reaching the depths of 160 km in the north to more than 200 km under southern Dinarides. These results do not agree with most of the previous investigations and show continuous underthrusting of the Adriatic lithosphere under Europe along the whole Dinaric region. The geometry of the down-going slab varies from the deeper slab in the north and south to the shallower underthrusting in the center. On-top of both north and south slabs there is a low-velocity wedge indicating lithospheric delamination which could explain

the 200 km deep high-velocity body existing under the southern Dinarides (Fig. 7).

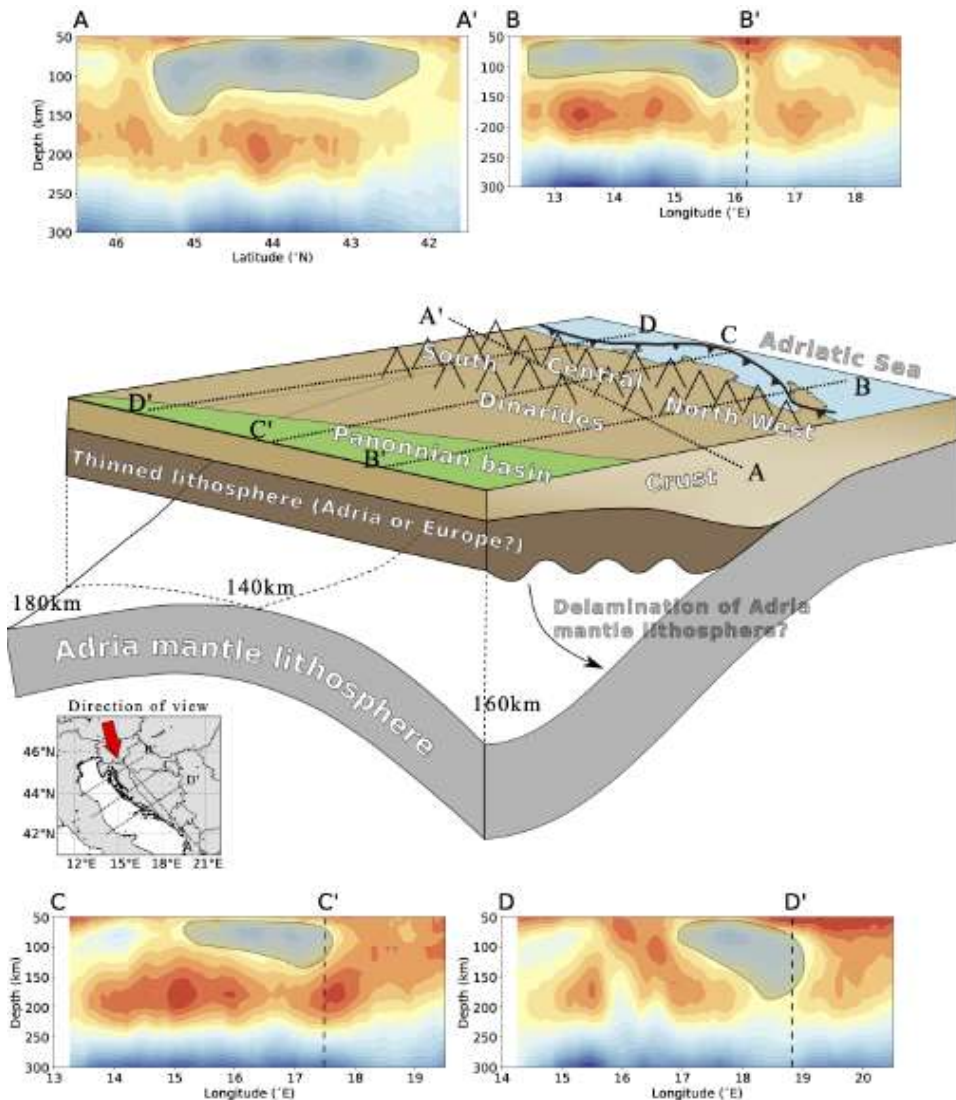


Figure 7. Schematic interpretation of the Dinarides lithospheric structure (not to scale) from the new 3-D shear-wave velocity model (from Belinić et al., 2021). Subimages a) to d) are the cross-sections through the new shear-wave velocity model with shaded areas marking the location and shape of the underthrusting Adriatic lithosphere. Tectonic sketch in the central image depicts the subducted Adria lithosphere beneath the Dinarides. Dark brown color denotes the thinned lithosphere of uncertain origin, either thermo-chemically thinned European or possibly Adriatic, thinned due to delamination.

Using forward seismic modelling based on new tomographic models Šumanovac (2022) researched lithosphere structure of the southern Dinarides and continuity of the Adriatic lithosphere slab beneath the Northern Dinarides. The results indicate a continuous lithospheric slab along the entire Dinarides in the shallow mantle, but it is not continuous vertically. In the Northern Dinarides, the shallow lithospheric slab extends at least to a depth of 150 km. In the Southern and Central Dinarides, there is a deep high velocity anomaly that can be interpreted in two ways (Fig. 8), due to the weak vertical resolution of teleseismic tomography. The first model suggests a steeply dipping continuous Adriatic lithospheric slab whereas the second model shows that the slab consists of two separate blocks, meaning that the deeper block was formed by delamination of the Adriatic lithospheric slab.

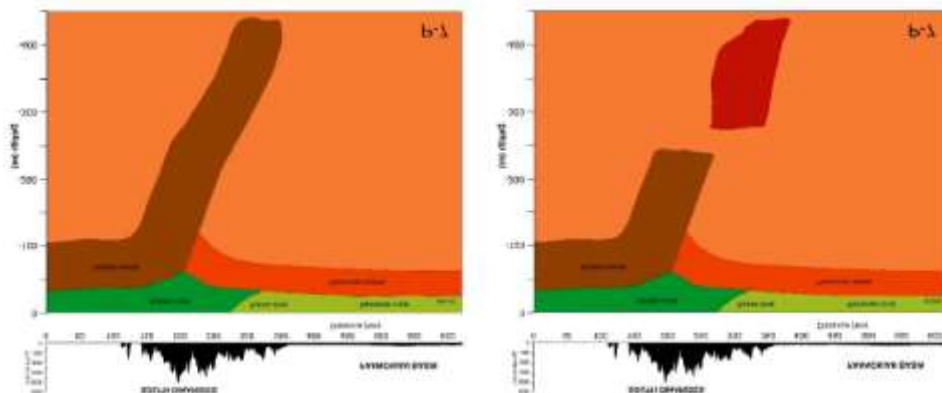


Figure 8. Two possible structural models of the lithosphere in the Southern Dinarides (from Šumanovac, 2022). The first model (on the left) assumes a steeply dipping continuous Adriatic lithospheric slab. The second model (on the right) presumes that the Adriatic slab consists of two separate blocks, with the deeper block resulting from delamination of the Adriatic lithosphere in a previous subduction.

b) Investigations of local soil conditions, seismic site amplification and attenuation

Stanko et al. (2019a) evaluated the site amplification factors (AFs) estimated by equivalent linear site response analysis using time series (TS) and random vibration theory (RVT) based approaches. Results showed that the AFs estimated by the TS-approach are systematically higher than the AFs estimated by the RVT based method in the short period range ($T < 0.5$ s), especially when the bedrock peak ground acceleration is higher than 0.2 g. On the other hand, the AFs calculated in this study match the empirical AF models utilized in recent ground motion models well, indicating that the RVT-

based AF models may be preferred in the future to cover a larger range of scenarios than the empirical datasets.

Seismic site amplification in the city of Ivanec using HVSr and equivalent-linear site response analysis was assessed by Stanko et al. (2019b). The city of Ivanec (northwestern Croatia) is located between valley of the Bednja River and Mt. Ivanščica and this area can be prone to significant seismic site amplification due to local site characteristics. The results are presented in the amplification maps (Fig. 9) at fundamental/predominant peak frequencies. They indicate two microzones – one with high amplification in the central part of the city due to soft soil characteristics, and the other with small amplification in the transitional zone from alluvial basin towards the foothills of Mt. Ivanščica. They also provide significant information about potential resonance effects for structures of certain heights that can be correlated with the local ground shaking characteristics.

Also, the high-frequency attenuation parameter kappa was estimated for the tectonically complex contact area of the northwestern External Dinarides and the Adriatic foreland (Markušić et al., 2019) and for the wider Zagreb area (Stanko et al., 2020). First research (Markušić et al., 2019) showed that regional near-surface attenuation distribution and modelled macroseismic fields point to the conclusion that attenuation properties of rocks in the northwestern External Dinarides are far from isotropic. The most likely anisotropy sources are the preferential orientations of cracks and fractures under the local tectonic stress field, trapping of waves along major faults (waveguides), and/or attenuation within the fault zones (Figure 10).

In the second research (Stanko et al., 2020) estimation of the high-frequency attenuation parameter kappa for the Zagreb seismic stations was performed. The results confirm the effect of local structures on local attenuation and of deep structures on the attenuation at long distances. Actually, spatial distribution of kappa within the Zagreb seismic zone shows that it is not isotropic, with high-frequency attenuation anisotropy probably being affected by local and regional geological variability, regional active faults and a complex tectonic structure in each direction (Fig. 11).

Stanko and Markušić (2020) derived an empirical relationship between resonance frequency, bedrock depth and V_{S30} for Croatia based on HVSr forward modelling. This relationship is important for several reasons – it can be used to map sedimentary subsurface structure for geological cross section and bedrock mapping; it provides relatively good estimates of bedrock depth as well its geometry; the results are important for site characterization. Presented results are important for developing nonlinear site amplification model for the seismic ground motion based on numerical site response analysis.

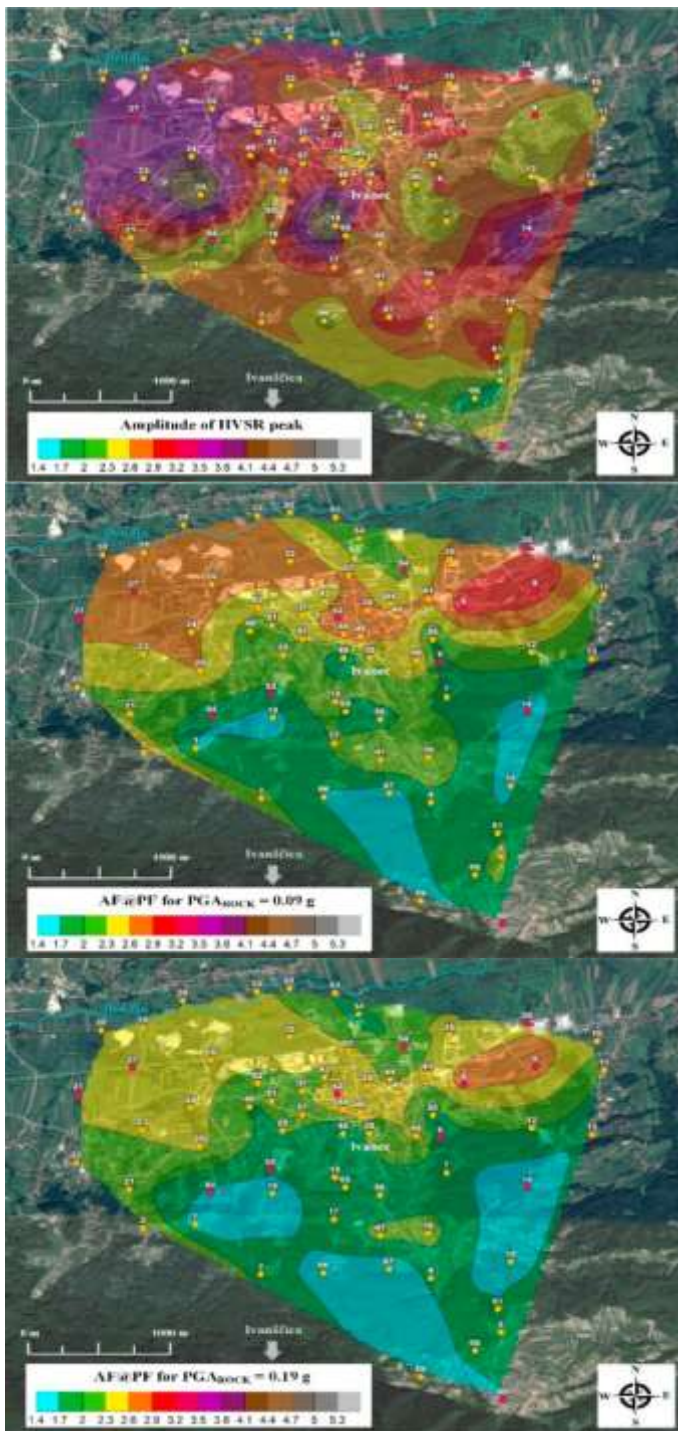


Figure 9. *Up:* Map of the amplitude of HVSR peak at fundamental HVSR frequency. *Middle:* Map of site response amplification factor at predominant frequency for input $PGA_{ROCK} = 0.09\text{ g}$ (95yrp). *Bottom:* Map of site response amplification factor at predominant frequency for input $PGA_{ROCK} = 0.19\text{ g}$ (475yrp) (from Stanko et al., 2019b).

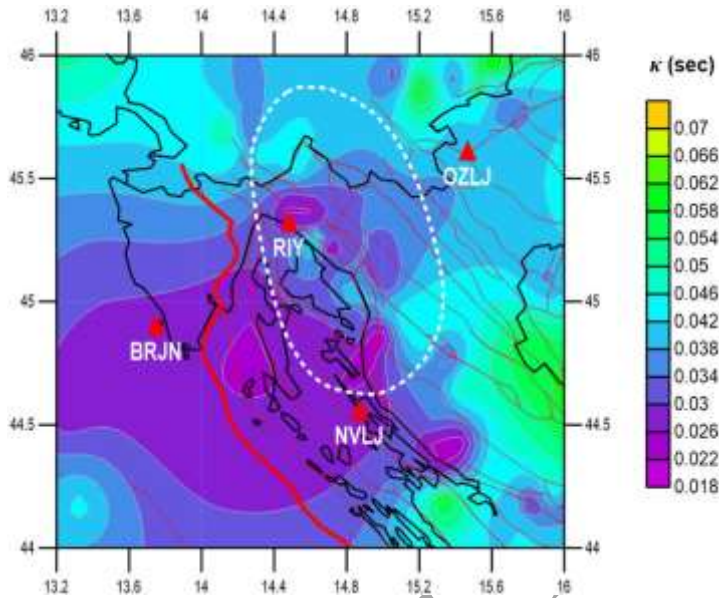


Figure 10. Spatial distribution of kappa parameter – high-frequency attenuation parameter (from Markušić et al., 2019). Red lines represent the possible seismogenic surface faults, red triangles mark the locations of seismic stations, thick white dashed line marks the contours of the northern Dinaric (ND) fast-velocity anomaly.

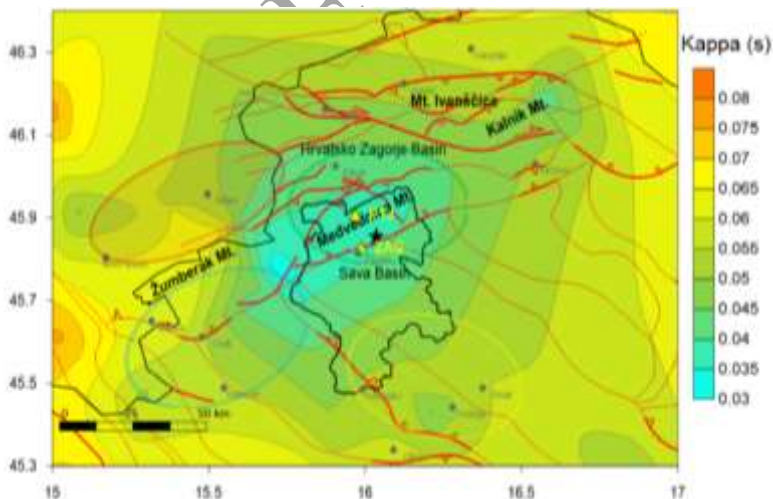


Figure 11. Regional kappa dependence around the PTJ and ZAG seismological stations shown as a spatial distribution of individual kappa values (from Stanko et al., 2020). Red lines represent the possible seismogenic surface faults in Croatia and possible active faults are marked with thick lines. The Zagreb city area is marked with a thick black polygonal line. Seismic zones Novo Mesto-Krško, Karlovac-Metlika, Pokupsko-Petrinja and Zagreb are marked with colours (red, blue, yellow and green). The M5.5 earthquake of 22 March 2020 is marked with a black star.

A semi-empirical estimation of the Zagreb $M_L5.5$ earthquake (2020) ground motion amplification by 1D equivalent linear site response analysis was also carried out (Uglešić et al., 2021). This research is a contribution to better understanding of the Zagreb $M_L5.5$ earthquake effects and of the significance of local site effects in the damage extent.

Local soil conditions in northern Croatia (Međimurje region) were analyzed using the microtremor Horizontal-to-Vertical Spectral Ratio (HVSr) method for subsurface characterization (Stanko et al., 2022). Based on the obtained results, a microzonation map for the Međimurje region was prepared. Its aim is to better understand the behavior of ground motion and the influence of local site conditions in comparison to macroseismic intensities and past damage observations (Fig. 12).

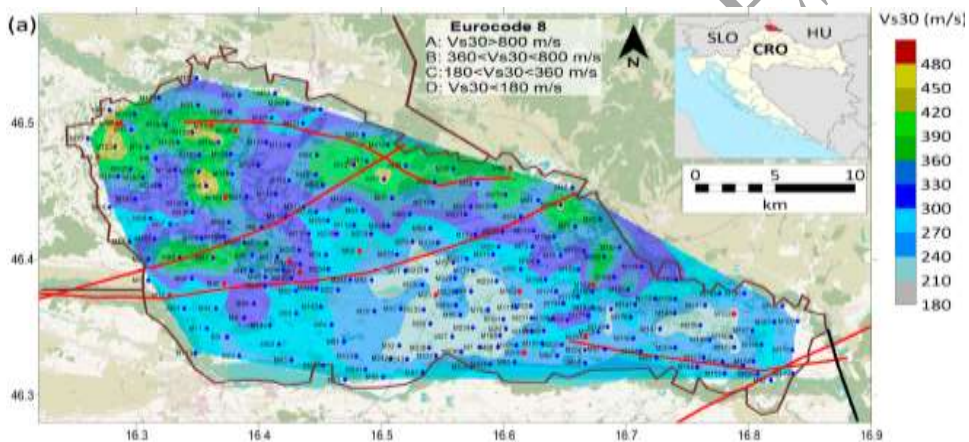


Figure 12. Map of estimated V_{S30} values of the Međimurje region (from Stanko et al., 2022). The most important seismogenic faults are shown with red lines.

c) Reanalysis and update of the Croatian Earthquake Catalog through homogenization of magnitude and research of historical earthquakes

The conversion relations between the local magnitude (M_L) and the moment magnitude (M_W) for earthquakes in the Croatian Earthquake Catalogue was derived (Herak, 2020) and historical earthquakes of 1838 and 1839 in the Slovene Hills (Slovenia) – Međimurje (Croatia) area were re-analyzed (Herak et al., 2021).

d) Multidisciplinary research after the earthquakes in Ston in 1996 and in Zagreb and Petrinja in 2020

Korbar et al. (2020) applied an alternative approach based on focused geological mapping, 3D seismological data, and shallow seismic imaging data in the Kvarner region. Reverse, normal, and strike-slip orogen-parallel (longitudinal) to transverse faults were identified (Fig. 13), but there is no clear evidence of their mutual relations and possible recent activity. The 3D spatial and temporal distribution of recent earthquake hypocenters indicate their clustering along predominantly subvertical transversal and steeply NE-dipping longitudinal planes. High-resolution shallow seismic geoaoustical survey (subbottom profiler) of the Quaternary sediments in the Rijeka Bay revealed local tectonic deformations of the stratified Late Pleistocene deposits that, along with overlaying mass-transport deposits, could imply prehistorical strong earthquake effects. Neotectonic faults onshore are tentatively recognized as highly fractured zones characterized by enhanced weathering, but there is no evidence for its recent activity. It seems that the active faults are blind and situated below the thin-skinned and highly deformed early-orogenic tectonic cover of the Adria.

In order to explain the geodynamic processes that caused the Zagreb M5.5 earthquake in 2020, Markušić et al. (2020) performed an extensive

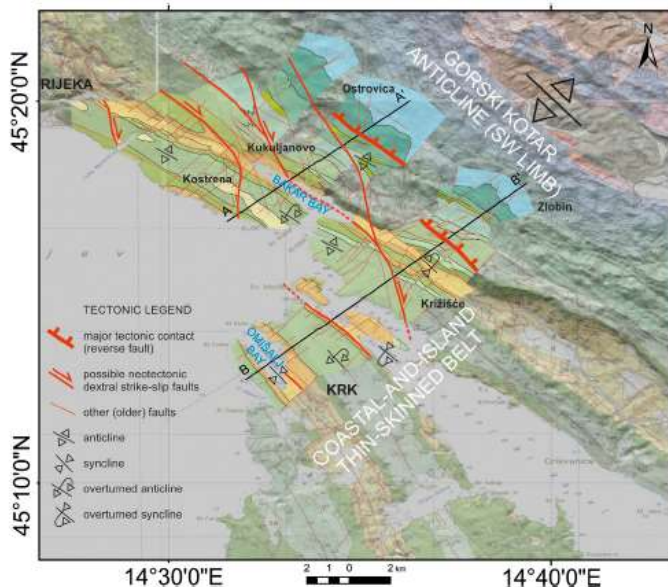


Figure 13. Simplified new geological map of the area of focused fieldwork (from Korbar et al., 2020). The major fault (the thickest red lines) delineates the Gorski Kotar anticline and the coastal-and-island thin-skinned belt. Possible neotectonic dextral strike-slip faults on the surface are marked by medium-thick red lines and arrows.

seismological, geological, geodetic and structural engineering surveys immediately after the mainshock. The first-order assessment of seismic amplification (due to site conditions) in the Zagreb area for the M5.5 earthquake shows that ground motions of approximately 0.16–0.19 g were amplified at least twice (if standard deviation is taken into account, the amplification factor can reach 3 at some locations) in the Podsljeme and city center zones where the greatest extent of damage was reported. Based on Sentinel-1 interferometric wide-swath data, the most affected area (with an uplift of about 3 cm) was identified, covering approximately 20 km². The spatial and temporal analyses of the 22 March 2020 Zagreb earthquake indicate that the mainshock and the first aftershocks occurred in the subsurface of the Medvednica Mountains along a deep-seated southeast-dipping thrust fault, recognized as a primary fault (Fig. 14). The co-seismic rupture propagated during the first half-hour of the earthquake sequence along the thrust towards the northwest. Most of the aftershocks recorded during the first 24 h occurred along a south-dipping, east-west striking secondary fault that is probably superimposed on the thrust fault. Other aftershocks occurred on unidentified faults that probably form a complex fault system.

Govorčin et al. (2020) researched complex faulting during the 1996 Ston-Slano (Croatia) earthquake inferred from the DInSAR, seismological, and

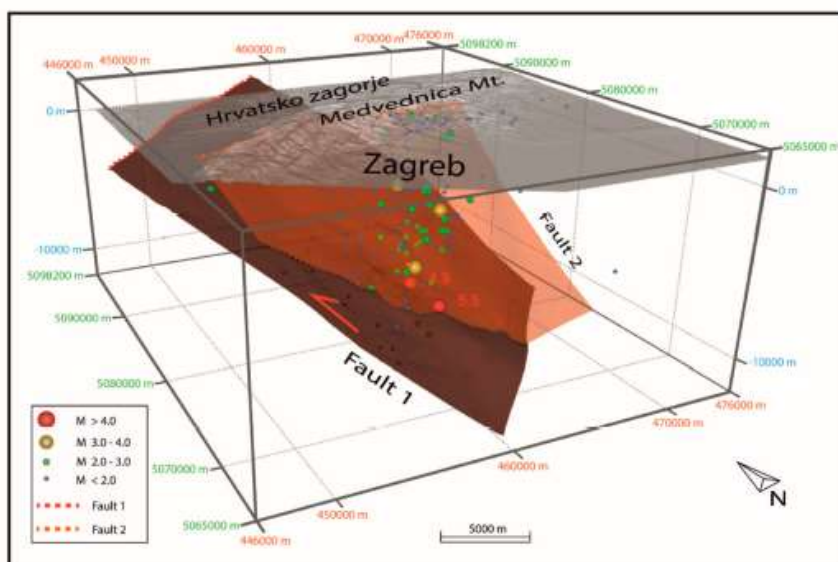


Figure 14. Preliminary structural 3D model of the Zagreb 2020 earthquake sequence (from Markušić et al., 2020). Coordinates are shown in HTRS96/TM coordinate system, and the elevation is in meters (no vertical exaggeration). Fault 1 is interpreted as a primary thrust fault, and Fault 2 is interpreted as a secondary (reverse?) fault.

geological observations. The observed DInSAR interferogram fringe patterns could not be explained by a single fault rupture. Geological investigations assigned most of the interferogram features either to previously known faults or to those newly determined by field studies. Relocation of hypocentres and reassessment of fault mechanisms provided additional constraints on the evolution of stress release during this sequence. Available data support the scenario that the mainshock started with a reverse rupture with a left-lateral component on the Slano fault, 4.5 km ESE of Slano, at the depth of about 11 km. The rupture proceeded unilaterally to the NW with the velocity of about 1.5 km/s for about 11 km, where the maximum stress release occurred. DInSAR interferograms suggest that several faults were activated in the process (Figure 15). The rupture terminated about 20 km away from the epicentre, close to the town of Ston, where the maximum DInSAR ground displacement reached 38 cm. Such a complicated and multiple rupture has never before been documented in the Dinarides.

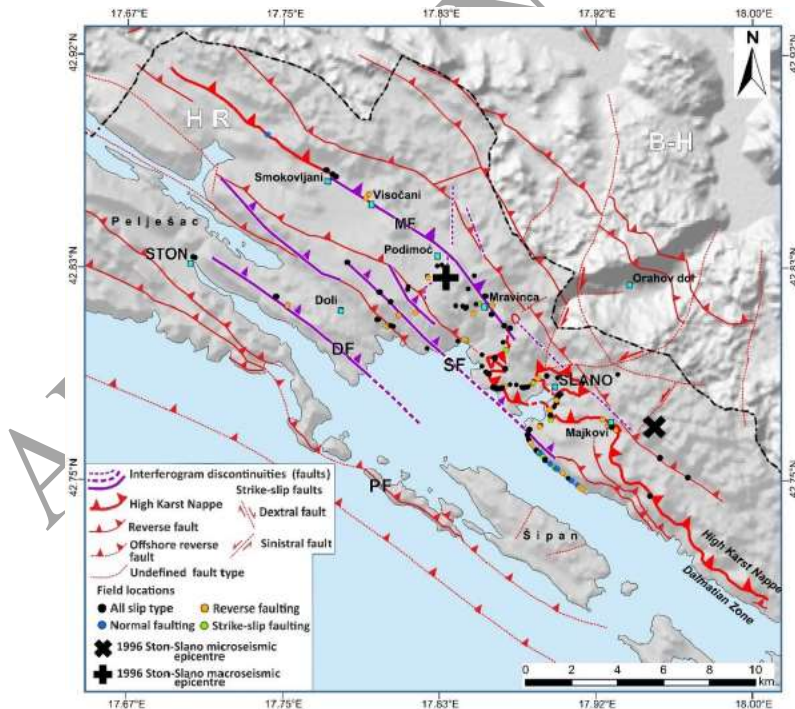


Figure 15. Simplified structural map of the Ston–Slano area with faults mapped onshore and offshore (from Govorčin et al., 2020). Fault measurements conducted at the 127 locations are indicated with multicolour dots in accordance to the measured fault’s kinematic properties.

Locations of microseismic and macroseismic epicentres of the 1996 Ston-Slano earthquake are marked, whereas purple lines are the fringe discontinuities interpreted based on interferograms. Abbreviations: PF: Pelješac fault; DF: Doli fault; SF: Slano fault; MF: Mravinca fault.

Shortly after the destructive M6.2 (M_w 6.4) Petrinja earthquake in 2020 Markušić *et al.* (2021) performed a multidisciplinary research. Outcomes of preliminary seismological, geological and SAR image analyses indicate that the foreshocks, mainshock and aftershocks were generated due to the (re)activation of a complex fault system – the intersection of longitudinal NW-SE right-lateral and transverse NE-SW left-lateral faults along the transitional contact zone of the Dinarides and the Pannonian Basin (Figure 16). A preliminary analysis of the earthquake ground motion showed that in the epicentral area, the estimated peak ground acceleration PGA values for the bedrock ranged from 0.29 to 0.44 g. In the close Petrinja epicentral area that is characterized by the superficial deposits, significant ground failures were reported within local site effects. Based on that finding and building damage (approximately 15% of buildings were very heavily damaged or collapsed), we assume that the resulting peak ground acceleration (PGA_{site}) values were likely between 0.4 and 0.6 g depending on the local site characteristics and the distance from the epicentre.

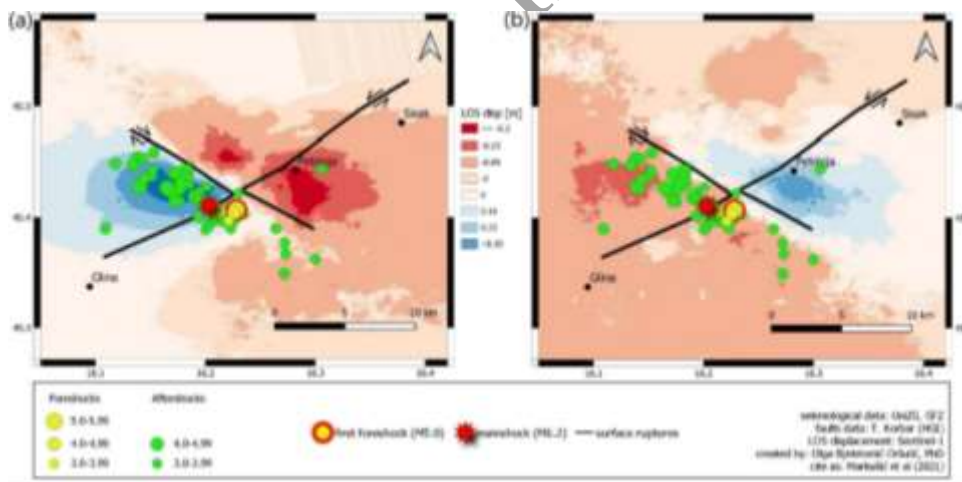


Figure 16. Line of sight (LOS) displacements for (a) Sentinel-1A ascending orbit T146, which has an amplitude of 74 cm and (b) Sentinel-1B descending orbit T124, which has an amplitude of 53 cm (from Markušić *et al.*, 2021).

Šugar *et al.* (2021) performed a geodetic and seismological analysis of the CROPOS (Croatian Positioning System) Zagreb station (ZAGR) kinematics

during the Zagreb 2020 M_L 5.5 earthquake. For the first time, motion of one of the CROPOS stations during an earthquake shake was analysed by the PPK (Post-Processed Kinematic) method using all available GNSS signals (GPS – Global Positioning System, GLONASS – GLObalnaya NAVigatsionnaya Sputnikovaya Sistem, Galileo, Bei-Dou) and seismologically interpreted. The ZAGR station is situated about 9 km to the south-southeast of the earthquake's epicentre location. The analysis showed the following station's movements: approx. 13 cm in the N-S direction and approx. 6 cm in the E-W direction. The seismological analysis showed that the ZAGR station recorded the onset of SV- and surface waves. The results of the PPK method have pointed out the usefulness of the method in earthquake observations.

Rapidly after mainshock, a team of European researchers performed the extensive field work to map the evidence of coseismic environmental effects (Baize et al., 2022). In the epicentral area, a surface deformation was observed, such as tectonic breaks along the earthquake source at the surface, liquefaction features (scattered in the fluvial plains of Kupa, Glina and Sava rivers), and slope failures, all caused by strong motion. The surface rupture appears discontinuous, consisting of multi-kilometre *en échelon* right stepping sections (Figure 17), along a NW-SE striking fault (Petrinja-Pokupsko Fault). The observed deformation features, in terms of kinematics and trace alignments, are consistent with slip on a right lateral fault. The surface rupture is observed over a length of ~13 km from end-to-end, with a maximum displacement of 38 cm and an average displacement of ~10 cm. Moreover, the liquefaction extends over an area of nearly 600 km² around the epicentre.



Figure 17. Aerial view (drone survey) of a ~20-m-long surface rupture on alluvial fan gravels mapped southwest of Križ Hrastovački (from Baize et al., 2022). Surface faulting occurred as a continuous rupture, striking 120°, or as a set of left-stepping *en échelon* ruptures. The maximum coseismic offset, measured between well-preserved piercing points, is ~15 cm.

e) Analysis and explanation of surface manifestations (such as sinkholes, liquefaction, etc.) after the Petrinja series of earthquakes

The preliminary inventory of coseismic ground failures, including subsidence dolines, liquefaction and landslides, related to December 2020 – January 2021 Petrinja earthquake series, was prepared by Pollak et al. (2021). The aim of the inventory is not only to provide data for the development of susceptibility maps and more detailed exploration for possible remediation measures, but also to define the priorities for immediate action.

Tomac et al. (2022) performed geotechnical reconnaissance of an extensive cover-collapse sinkhole phenomena (Figure 18) of the Petrinja earthquake sequence (2020–2021). They collected data about geological background, seismic sequence information, sinkhole geometric characteristics, rainfall data, and results of detailed geotechnical subsurface investigation for 122 new and 49 historical cover-collapse sinkholes in Petrinja area. Clayey cover, 4–10 m thick, with sporadic gravel lenses overlying cavernous, intensely karstified carbonate rocks, characterizes the sinkhole area. The observed vertical walls that accompanied sinkholes opening can occur in the overconsolidated cohesive cover clay layer with varying degree of saturation. Geotechnical, geological, seismic, and precipitation data generally indicate that the formation of cover-collapse sinkholes in the study area is a consequence of a specific local geological setting but is significantly expedited by earthquake-induced dynamic loading and complemented by multiple hydro-mechanical factors.

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Figure 18. The largest sinkhole in Mečenčani village (diameter is 24.55 m) (from Tomac et al., 2022).

f) Investigations of damage after an earthquake and analysis of the response of characteristic buildings to earthquake excitation

Šavor Novak et al. (2020) prepared an extensive preliminary report on seismological aspects and damage to buildings after the Zagreb 2020 earthquake.

Seismic performance of an existing RC wall building with irregular geometry was assessed by Uroš et al. (2020). The study presents a comprehensive methodology for the seismic performance assessment of individual buildings, applied to an existing reinforced concrete (RC) hospital, located in the seismically active region of Croatia: assessment of seismic hazards on the location, ambient noise measurements, experimental determination of structural modal parameters (Figure 19), creation of a detailed numerical model calibrated with experimental data, and a seismic performance assessment using various analysis methods. As a result, the building collapse mechanisms were determined and critical structural elements identified, which is the basis for future actions directed to the reduction of its risk (e.g., applications of specific measures for a target retrofit, proposal of evacuation routes and safe places inside the building, etc.).

Markušić et al. (2021) prepared the observations of earthquake damage on historical Trakošćan castle after the Zagreb and Petrinja 2020 earthquakes. The damage was assessed by visual inspection accompanied by ambient vibration measurements. The slight cracks that appeared on masonry arches were found to be critically positioned, and can likely lead to the arches' collapse if their spreading is not prevented. Ambient vibration measurements, which were compared to pre-earthquake ones, revealed the decrease in the fundamental frequencies of the castle's central tower unit and the second floor, thus possibly indicating the loss of structural stiffness as a consequence of the earthquake damage.

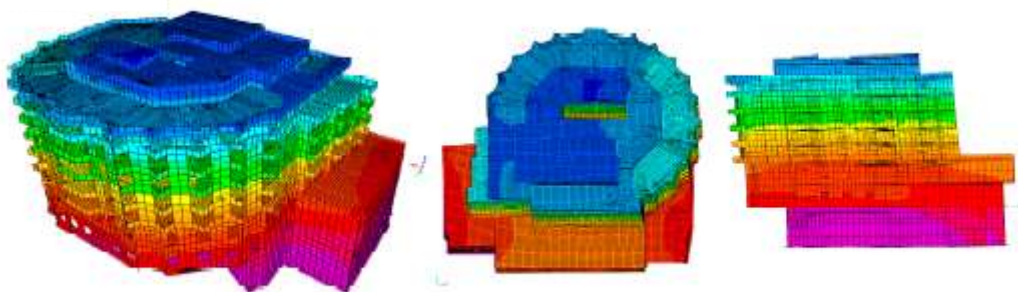


Figure 19. Three-dimensional view of mode shapes of the initial numerical model of the General Hospital Dubrovnik – first mode (from Uroš et al., 2020).

The engineering analysis and correlation of earthquake damage after earthquakes in Albania (2019) and Croatia (2020), both of $M_w 6.4$, was done by Abrahamczyk et al. (2022). The causes of the damage as well as the consequences for rapid response to earthquake are discussed in close relation to the standardization in low to moderate seismic regions in Europe.

g) Analysis of strong motion (SM) registrations, creation of SM database, derivation of GMPE relation for the area of Croatia

Prevolnik et al. (2020) did analysis of the strong ground motion records of the Zagreb earthquake which occurred on 22 March 2020.

Regionally adjusted ground motion model based on the existing BSHAP database for the empirical estimation of the response spectrum using the Fourier Amplitude Spectrum (FAS) and the duration of ground motion (D_{gm}) was estimated by Uglešić et al. (2022). It was observed that estimated model is comparable with the other GMPEs for Petrinja M_L6.2 scenario (chosen as case study). Model is applicable for magnitudes up to M_w6.5 and Joyner-Boore distances up to 200 km with usable frequency range between 0.4 and 33 Hz. Adjustment of the GMPE to the different seismological environments and site conditions using D_{gm} and FAS models, constructed for predicting the response spectral ordinates using Random Vibration Theory approach, is applicable GMPE candidate for the PSHA studies in the Western Balkan area. This is particularly important for the Croatian territory since there is a lack of SM recordings and current attenuation relation is derived only for the rock conditions.

Sinadinovski et al. (2022) analyzed the near-field seismic records of two moderate sized earthquakes: the Skopje 2016 (M_L5.3) and the Zagreb 2020 (M_L5.5) earthquakes. Such recordings at close epicentral distances are rare and are thus very useful for testing some of the theoretical assumptions used in modelling earthquake risk. By combining only the results of the strong motion analysis and the Nakamura method, the authors proved that the site substructure can be fairly inferred to the first degree, which is very useful in evaluation of the regional velocity models.

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