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

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## Contents

# 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*

# Geodesy in Croatia, 2019–2022

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

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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.

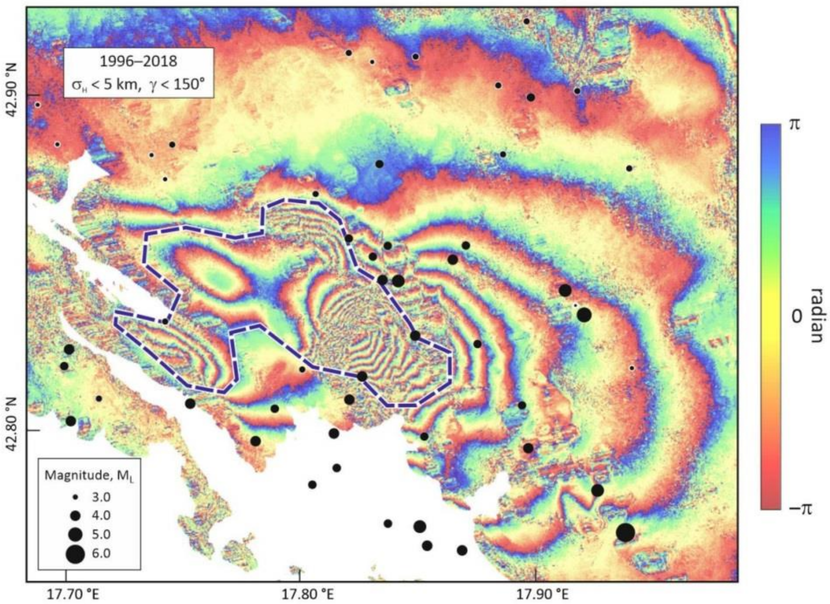


**Figure 1.** Epicenters of reliably located earthquakes of the Ston-Slano sequence overlain on the ascending orbit interferogram (Govorčin et al., 2020).

## *List of publications*


Amerstorfer, T., Hinterreiter, J., Reiss, M., Möstl, C., Davies, J., Bailey, R., Weiss, A., Dumbović, M., Bauer, M., Amerstorfer, U. and Harrison, R. (2021): Evaluation of CME arrival prediction using ensemble modeling based on heliospheric imaging observations. *Space Weather – The International Journal of Research and Applications*, 19 (1), e2020SW002553, 17, doi:10.1029/2020SW002553.

Ančić, M., Pernar, R., Bajić, M., Krtalić, A., Seletković, A., Gajski, D. and Kolić, J. (2020): Spectral signatures (endmembers) some of forest species in the Republic of Croatia. *Šumarski list: znanstveno-stručno i staleško glasilo Hrvatskoga šumarskog društva*, 144 (3-4), 119-127, doi:10.31298/sl.144.3-4.1.

Bačić, S., Tomić, H., Andlar, G. and Roić, M. (2022): Towards integrated land management: The role of green infrastructure. *ISPRS International Journal of Geo-Information*, 11 (10), 513, 14, doi:10.3390/ijgi11100513.

Balenović, I., Jurjević, L., Simic Milas, A., Gašparović, M., Ivanković, D. and Seletković, A. (2019): Testing the applicability of the official Croatian DTM for normalization of UAV-based DSMs and plot-level tree height estimations in lowland forests. *Croatian Journal of Forest Engineering*, 40 (1), 163-174 (https://www.bib.irb.hr/987031).

Banko, A., Banković, T., Pavasović, M. and Đapo, A. (2020): An all-in-one application for temporal coordinate transformation in geodesy and geoinformatics. *ISPRS International Journal of Geo-Information*, 9 (5), 323, 16, doi:10.3390/ijgi9050323.

Baričević, A., Grubor, M., Paar, R., Papastergiou, P., Pilakoutas, K. and Guadagnini, M. (2020): Long-term monitoring of a hybrid SFRC slab on grade using recycled tyre steel fibres. *Advances in Concrete Construction*, 10 (6), 547-557, doi:10.12989/acc.2020.10.6.547.

Baričević, S., Barković, Đ. and Zrinjski, M. (2021): Calibration of precise levelling staffs. *Geodetski list*, 75 (98) (2), 169-188 (https://www.bib.irb.hr/1138547).

Baričević, V., Landek, I. and Šantek, D. (2019): Basic topographic database data in pre-procesind of land consolidation. *Geodetski list*, 73, 129-146.

Barković, Đ. and Zrinjski, M. (2020): Field measurements. Zagreb, Geodetski fakultet Sveučilišta u Zagrebu.

Baučić, M. (2020): Household level vulnerability analysis – Index and fuzzy based methods. *ISPRS International Journal of Geo-Information*, 9 (4), 263, 19, doi:10.3390/ijgi9040263.

Belov, A., Papaioannou, A., Abunina, M., Dumbović, M., Richardson, I.G., Heber, B., Kuhl, P., Herbst, K., Anastasiadis, A., Vourlidas, A., Eroshenko, E. and Abunin, A. (2021): On the rigidity spectrum of cosmic-ray variations within propagating interplanetary disturbances: Neutron monitor and SOHO/EPHIN observations at ~1–10 GV. *The Astrophysical Journal*, 908 (1), 724, 5, doi:10.3847/1538-4357/abd724.

Bjelotomić Oršulić, O., Markovinović, D., Varga, M. and Bašić, T. (2021): Coseismic ground displacement after the Mw6.2 earthquake in NW Croatia determined from Sentinel-1 and GNSS CORS data. *Geosciences*, 11 (4), 170, 18, doi:10.3390/geosciences11040170.

Bjelotomić Oršulić, O., Markovinović, D., Varga, M. and Bašić, T. (2019): The impact of terrestrial gravity data density on geoid accuracy: case study Bilogora in Croatia. *Survey Review – Directorate of Overseas Surveys*, 2019, 1-10, doi:10.1080/00396265.2018.1562747.

Bjelotomić Oršulić, O., Varga, M., Markovinović, D. and Bašić, T. (2019): LTide – Matlab/Octave software tool for temporal and spatial analysis of tidal gravity acceleration effects according to Longman formulas. *Earth Science Informatics*, 12 (1), 1-10, doi:10.1007/s12145-019-00379-y.

Brajša, R., Skokić, I., Sudar, D., Benz, A., Krucker, S., Ludwig, H., Saar, S. and Selhorst, C. (2021): ALMA small-scale features in the quiet Sun and active regions. *Astronomy & Astrophysics (Berlin)*, 651, A6, 11, doi:10.1051/0004-6361/201936231.

Brajša, R., Verbanac, G., Bandić, M., Hanslmeier, A., Skokić, I. and Sudar, D. (2022): A prediction for the 25th solar cycle maximum amplitude. *Astronomische Nachrichten*, 343 (3), e2113960, 10, doi:10.1002/asna.202113960.

Brkić, I., Miler, M., Ševrović, M. and Medak, D. (2020): An analytical framework for accurate traffic flow parameter calculation from UAV aerial videos. *Remote Sensing*, 12 (22), 3844, 20, doi:10.3390/rs12223844.

Brkić, I., Miler, M., Ševrović, M. and Medak, D. (2022): Automatic roadside feature detection based on lidar road cross section images. *Sensors*, 22 (15), 55100, 17, doi:10.3390/s22155510.

Brkić, M. (2019): Monitoring geomagnetic information in the territory of Croatia. *Geofizika*, 36 (1), 1-15, doi:10.15233/gfz.2019.36.3.

Brkić, M., Grgić, M. and Radović, N. (2022): Zagreb earthquakes on 22nd March 2020 and geomagnetic information. *Tehnički vjesnik: znanstveno-stručni časopis tehničkih fakulteta Sveučilišta u Osijeku*, 29, 652-658, doi:10.17559/TV-20201211131046.

Brkić, M., Varga, M., Grgić, M., Radović, N. and Bašić, T. (2020): Compass working repair model for 2020. *Strategos*, 4 (1), 7-29.

Brož, M., Harmanec, P., Zasche, P., Catalan-Hurtado, R., Barlow, B., Frondorf, W., Wolf, M., Drechsel, H., Chini, R., Nasseri, A., Labadie-Bartz, J., Christie, G., Walker, W., Blackford, M., Blane, D., Henden, A., Bohlsen, T., Božić, H. and Jonák, J. (2022): Towards a consistent model of the hot quadruple system HD 93206 = QZ Carinæ II. *Astronomy & Astrophysics*, 666, A24, 12, doi:10.1051/0004-6361/202243596.

Brož, M., Mourard, D., Budaj, J., Harmanec, P., Schmitt, H., Tallon-Bosc, I., Bonneau, D., Božić, H., Gies, D. and Šlechta, M. (2021): Optically thin circumstellar medium in the βLyr A system. *Astronomy & Astrophysics*, 645, A51, 19, doi:10.1051/0004-6361/202039035.

Bukač, B., Grgić, M. and Bašić, T. (2021): What have we learnt from ICESat on Greenland ice sheet change and what to expect from current ICESat-2. *Geodetski vestnik*, 65 (1), 94-109, doi:10.15292/geodetski-vestnik.2021.01.94-109.

Butorac, K., Maurer, D. and Gajski, D. (2021): Distance decay function optimization model in relation to the spatial patterns of behavior of the perpetrator in the area of the City of Zagreb. *Policija i sigurnost*, 30 (2), 167-180 (https://www.bib.irb.hr/1246265).

Cetl, V., Ioannidis, C., Dalyot, S., Doytsher, Y., Felus, Y., Haklay, M., Mueller, H., Potsiou, C., Rispoli, E. and Siriba, D. (2019): New trends in geospatial information: The land surveyors role in the era of crowdsourcing and VGI. Copenhagen, International Federation of Surveyors (FIG).

Crompvoets, J., Bačič, Ž. and Poslončec-Petrić, V. (2020): Survey report – Academia-business survey on needs and cooperation in field of spatial data infrastructures. Leuven, EuroSDR Secretariat, KU Leuven Public Governance Institute (https://www.bib.irb.hr/1077249).

Čalogović, J., Dumbović, M., Sudar, D., Vršnak, B., Martinić, K., Temmer, M. and Veronig, A. (2021): Probabilistic Drag-Based Ensemble Model (DBEM) evaluation for heliospheric propagation of CMEs. *Solar Physics*, 296 (7), id114, 33, doi:10.1007/s11207-021-01859-5.

de Menezes, P., Santos, K., Laeta, T., Corrêa Martins, F., Fernandes, M., Santos, J. and Lapaine, M. (2021): Map projection analysis of the Nova Lusitania map. *Kartografija i geoinformacije*, 20 (35), 48-69, doi:10.32909/kg.20.35.3.

Deur, M., Gašparović, M. and Balenović, I. (2020): Tree species classification in mixed deciduous forests using very high spatial resolution satellite imagery and machine learning methods. *Remote Sensing*, 12 (23), 3926, 18, doi:10.3390/rs12233926.

Deur, M., Gašparović, M. and Balenović, I. (2021): A review of satellite missions and forest cover classification methods using high resolution satellite imagery. *Geodetski list*, 75 (98) (2), 143-168 (https://www.bib.irb.hr/1140064).

Deur, M., Gašparović, M. and Balenović, I. (2021): An evaluation of pixel- and object-based tree species classification in mixed deciduous forests using pansharpened very high spatial resolution satellite imagery. *Remote Sensing*, 13 (10), 1868, 19, doi:10.3390/rs13101868.

Dianjun Zhang, Jie Zhan, Lifeng Tan, Yuhang Gao and Robert Župan (2020): Comparison of two deep learning methods for ship target recognition with optical remotely sensed data. *Neural Computing and Applications*, 1 (1), 1-11, doi:10.1007/s00521-020-05307-6.

Divić, V., Galešić, M., Di Dato, M., Tavra, M. and Andričević, R. (2020): Application of open source electronics for measurements of surface water properties in an estuary: A case study of River Jadro, Croatia. *Water*, **12**, 209, 29, doi:10.3390/w12010209.

Dobrinić, D., Gašparović, M. and Medak, D. (2021): Sentinel-1 and 2 time-series for vegetation mapping using random forest classification: A case study of Northern Croatia. *Remote Sensing*, 13 (12), 1-20, doi:10.3390/rs13122321.

Došlić, T., Martinjak, I. and Škrekovski, R. (2019): Total positivity of Toeplitz matrices of recursive hypersequences. *ARS Mathematica Contemporanea*, 17 (1), 125-139, doi:10.26493/1855-3974.1526.b8d.

Downs, C., Warmuth, A., Long, D., Bloomfield, D., Kwon, R., Veronig, A., Vourlidas, A. and Vršnak, B. (2021): Validation of global EUV wave MHD simulations and observational techniques. *The Astrophysical Journal*, 911, 118, 18, doi:10.3847/1538-4357/abea78.

Dumbović, M., Čalogović, J., Martinić, K., Vršnak, B., Sudar, D., Temmer, M. and Veronig, A. (2021): Drag-Based Model (DBM) tools for forecast of coronal mass ejection arrival time and speed. *Frontiers in Astronomy and Space Science*, 8, id58, 14, doi:10.3389/fspas.2021.639986.

Dumbović, M., Veronig, M., A., Podladchikova, T., Thalmann, K., J., Chikunova, G., Dissauer, K., Magdalenic, J., Temmer, M., Guo, J., and Samara, E. (2021): 2019 International Women's Day event two-step solar flare with multiple eruptive signatures and low Earth impact. *Astronomy & Astrophysics (Berlin)*, 652, A159, 20, doi:10.1051/0004-6361/202140752.

Dumbović, M., Vršnak, B., Guo, J., Heber, B., Dissauer, K., Carcaboso, F., Temmer, M., Veronig, A., Podladchikova, T., Möstl, C., Amerstorfer, T. and Kirin, A. (2020): Evolution of coronal mass ejections and the corresponding Forbush decreases: Modeling vs. multi-spacecraft observations. *Solar Physics*, 295 (7), article id.104, 33, doi:10.1007/s11207-020-01671-7.

Dumbović, M., Vršnak, B., Temmer, M., Heber, B. and Kühl, P. (2022): Generic profile of a long-lived corotating interaction region and associated recurrent Forbush decrease. *Astronomy & Astrophysics (Berlin)*, 658, A187, 13, doi:10.1051/0004-6361/202140861.

Duplančić Leder, T. and Leder, N. (2019): Usporedba algoritama za kartiranje obalne crte satelitskim metodama. *Hrvatske vode*, 27, 110, 295-304.

Duplančić Leder, T., Leder, N. and Baučić, M. (2020): Application of satellite imagery and water indices to the hydrography of the Cetina River basin (Middle Adriatic). *Transactions on Maritime Science*, 9, 2, 374-384, doi:10.7225/toms.v09.n02.020.

Duplančić Leder, T., Leder, N. and Peroš, J. (2019): Satellite derived bathymetry survey method – Example of Hramina Bay. *Transactions on Maritime Science*, 8, 1, 99-108, doi:10.7225/toms.v08.n01.010.

Đapo, A., Pavasović, M., Pribičević, B. and Prelogović, E. (2020): Combined space–time analysis of geodetic and geological surveys for evaluation of the reliability of the position of points in the geodynamic network of the City of Zagreb. *Geosciences*, 10 (12), 498, 19, doi:10.3390/geosciences10120498.

Ertunç, E., Muchová, Z., Tomić, H. and Janus, J. (2022) Legal, procedural and social aspects of land valuation in land consolidation: A comparative study for selected central and eastern Europe countries and Turkey. *Land*, 11 (5), 11050636, 22, doi:10.3390/land11050636.

Flego, V., Roić, M. and Benasić, I. (2021): LADM extensions to maritime domain in multi-register environment – Case study Croatia. *Land Use Policy*, 102, 105247, 11, doi:10.1016/j.landusepol.2020.105247.

Frangeš, S., Šantek, D. and Fudurić, D. (2019): New model and guidelines for the evalution of different cartographic products. *Tehnički vjesnik: znanstveno-stručni časopis tehničkih fakulteta Sveučilišta u Osijeku*, 26 (5), 1205-1210, doi:10.17559/TV-20170314091115.

Freiherr von Forstner, J., Guo, J., Wimmer- Schweingruber, R., Dumbović, M., Janvier, M., Demoulin, P., Veronig, A., Temmer, M., Papaioannou, A., Dasso, S., Hassler, D. and Zeitlin, C. (2020): Comparing the properties of ICME-induced Forbush decreases at Earth and Mars. *Journal of Geophysical Research*, doi:10.1029/2019JA027662.

Fuštar, B., Lukačević, I., Skejić, D. and Gašparović, M. (2022): Fatigue tests of as-welded and HFMI treated S355 details with longitudinal and transverse attachments. *Welding in the World*, 66 (12), 2549-2561, doi:10.1007/s40194-022-01357-7.

Gašparović, I. and Gašparović, M. (2019): Determining optimal solar power plant locations based on remote sensing and GIS methods: A case study from Croatia. *Remote Sensing*, 11 (12), 1481, 18, doi:10.3390/rs11121481.

Gašparović, I., Gašparović, M., Medak, D. and Zrinjski, M. (2019): Analysis of solar potential spatial data for Croatia. *Geodetski list*, 73 (96) (1), 25-44 (https://www.bib.irb.hr/995829).

Gašparović, M. (2020): Urban growth pattern detection and analysis. In: Verma, P., Singh, P., Singh, R. and Raghubanshi, A. (Eds) Urban ecology. Amsterdam, Elsevier, pp. 35-48.

Gašparović, M. and Dobrinić, D. (2020): Comparative assessment of machine learning methods for urban vegetation mapping using multitemporal Sentinel-1 imagery. *Remote Sensing*, 12 (12), 1952, 22, doi:10.3390/rs12121952.

Gašparović, M. and Dobrinić, D. (2021): Green infrastructure mapping in urban areas using Sentinel-1 imagery. *Croatian Journal of Forest Engineering*, 42 (2), 859, 20, doi:10.5552/crojfe.2021.859.

Gašparović, M. and Klobučar, D. (2021): Mapping floods in lowland forest using Sentinel-1 and Sentinel-2 data and an object-based approach. *Forests*, 12, 553, 26, doi:10.3390/f12050553.

Gašparović, M., Dobrinić, D. and Medak, D. (2019): Geometric accuracy improvement of WorldView-2 imagery using freely available DEM data. *Photogrammetric Record*, 34 (167) (1), 266-281, doi:10.1111/phor.12292.

Gašparović, M., Rumora, L., Miler, M. and Medak, D. (2019): Effect of fusing Sentinel-2 and WorldView-4 imagery on the various vegetation indices. *Journal of Applied Remote Sensing*, 13 (3), 036503, 18, doi:10.1117/1.JRS.13.036503.

Gašparović, M., Zrinjski, M. and Gudelj, M. (2019): Automatic cost-effective method for land cover classification (ALCC). *Computers, Environment and Urban Systems*, 76 (4), 1-10, doi:10.1016/j.compenvurbsys.2019.03.001.

Gašparović, M., Zrinjski, M., Barković, Đ. and Radočaj, D. (2020): An automatic method for weed mapping in oat fields based on UAV imagery. *Computers and Electronics in Agriculture*, 173 (6), 105385, 12, doi:10.1016/j.compag.2020.105385.

Gizdavec, N., Gašparović, M., Miko, S., Lužar-Oberiter, B., Ilijanić, N. and Peh, Z. (2022): Discrimination of rock units in karst terrains using sentinel-2A imagery. *Remote Sensing*, 14 (20), 1-27, doi:10.3390/rs14205169.

Gou, T., Veronig, A., Liu, R., Zhuang, B., Dumbović, M., Podladchikova, T., Reid, H., Temmer, M., Dissauer, K., Vršnak, B. and Wang, Y. (2020): Solar flare-CME coupling throughout two acceleration phases of a fast CME. *Astrophysical Journal Letters*, 897 (2), id.L36, 14, doi:10.3847/2041-8213/ab9ec5.

Govorčin, M., Herak, M., Matoš, B., Pribičević, B. and Vlahović, I. (2020): Constraints on complex faulting during the 1996 Ston-Slano (Croatia) earthquake inferred from the DInSAR, seismological, and geological observations. *Remote Sensing*, 12 (7), 1157, 23, doi:10.3390/rs12071157.

Govorčin, M., Pribičević, B. and Wdowinski, S. (2019): Surface deformation analysis of the wider Zagreb area (Croatia) with focus on the Kašina fault, investigated with small baseline InSAR observations. *Sensors*, 19 (22), 4857, 12, doi:10.3390/s19224857.

Govorčin, M., Wdowinski, S., Matoš, B. and Funning, G. (2020): Geodetic source modeling of the 2019, Mw 6.3 Durrës, Albania earthquake: partial rupture of a blind reverse fault. *Geophysical Research Letters*, 47, 47, 17, doi:10.1029/2020gl088990.

Grgac, I. and Paar, R. (2020): Quality assessment of Locata positioning system. *Journal of Applied Geodesy*, 14 (1), 95-112, doi:10.1515/jag-2019-0036.

Guo, J., Wimmer-Schweingruber, R., Dumbović, M., Heber, B. and Wang, Y. (2020): A new model describing Forbush decreases at Mars: combining the heliospheric modulation and the atmospheric influence. *Earth and Planetary Physics*, 4 (1), 62-72, doi:10.26464/epp2020007.

Harmanec, P., Božić, H., Koubský, P., Yang, S., Ruždjak, D., Sudar, D., Šlechta, M., Wolf, M., Korčáková, D., Zasche, P., Opluštilová, A., Vršnak, D., Ak, H., Eenens, P., Bakiş, H., Bakiş, V., Otero, S., Chini, R., Demsky, T., Barlow, B., Svoboda, P., Jonák, J., Vitovský, K. and Harmanec, A. (2022): V1294 Aql = HD 184279: A bad boy among Be stars or an important clue to the Be phenomenon? *Astronomy & Astrophysics*, 666, A136, 15, doi:10.1051/0004-6361/202244006.

Heinemann, S., Jerčić, V., Temmer, M., Hofmeister, S., Dumbović, M., Vennerstrom, S., Verbanac, G. and Veronig, A. (2020): A statistical study of long-term evolution of coronal hole properties as observed by SDO. *Astronomy & Astrophysics (Berlin)*, 638, A68, 11, doi:10.1051/0004-6361/202037613.

Husak, M., Brajša, R. and Špoljarić, D. (2021): On the determination of the solar rotation elements i, Ω and period using sunspot observations by Ruđer Bošković in 1777. *Rudarsko-geološko-naftni zbornik (The Mining- Geological-Petroleum Bulletin)*, 36 (54), 77-98, doi:10.17794/rgn.2021.3.6.

Husak, M., Brajša, R. and Špoljarić, D. (2021): Solar rotation elements i, **Ω** and period determined using sunspot observations by Ruđer Bošković in 1777. *Central European Astrophysical Bulletin (CEAB)*, 45 (1), 1-7 (https://www.bib.irb.hr/1133458).

Jajac, N., Kilić, J. and Rogulj, K. (2019): An integral approach to sustainable decision- making within maritime spatial planning – A DSC for the planning of anchorages on the Island of Šolta, Croatia. *Sustainability*, 11, 1, 1-27, doi:10.3390/su11010104.

Jajac, N., Marović, I., Rogulj, K. and Kilić, J. (2019): Decision Support Concept to selection of wastewater treatment plant location – the case study of town of Kutina, Croatia. *Water*, 11, 4, 1-16, doi:10.3390/w11040717.

Jogun, T., Lukić, A. and Gašparović, M. (2019): Simulation model of land cover changes in a post-socialist peripheral rural area: Požega- Slavonia County, Croatia. *Hrvatski geografski glasnik*, 81 (1), 31-59, doi:10.21861/HGG.2019.81.01.02.

Jurišić, M., Radočaj, D., Krčmar, S., Plaščak, I. and Gašparović, M. (2020): Geostatistical analysis of soil C/N deficiency and its effect on agricultural land management of major crops in Eastern Croatia. *Agronomy*, 10 (12), 1996, 18, doi:10.3390/agronomy10121996.

Jurjević, L., Gašparović, M., Liang, X. and Balenović, I. (2021): Assessment of close-range remote sensing methods for DTM estimation in a lowland deciduous forest. *Remote Sensing*, 13 (11), 2063, 14, doi:10.3390/rs13112063.

Jurjević, L., Gašparović, M., Simic Milas, A. and Balenović, I. (2020): Impact of UAS image orientation on accuracy of forest inventory attributes. *Remote Sensing*, 12 (3), 404, 19, doi:10.3390/rs12030404.

Jurjević, L., Liang, X., Gašparović, M. and Balenović, I. (2020): Is field-measured tree height as reliable as believed – Part II, A comparison study of tree height estimates from conventional field measurement and low-cost close-range remote sensing in a deciduous forest. *ISPRS Journal of Photogrammetry and Remote Sensing*, 169, 227-241, doi:10.1016/j.isprsjprs.2020.09.014.

Karabin, M., Kitsakis, D., Koeva, M., Navratil, G., Paasch, J., Paulsson, J., Vučić, N., Janečka, K. and Lisec, A. (2020): Layer approach to ownership in 3D cadastre in the case of underground tunnels. *Land Use Policy*, 98, 104464, 12, doi:10.1016/j.landusepol.2020.104464.

Kilić Pamuković, J., Ivić, M., Rogulj, K. and Jajac, N. (2020): Decision support to sustainable parking management – Investment planning through parking fines to improve pedestrian flows. *Sustainability*, **12** (22), 1-19, doi:10.3390/su12229485.

Kilić Pamuković, J., Rogulj, K. and Jajac, N. (2021): Assessing the bonitet of cadastral parcels for land reallocation in urban consolidation. *Land*, 10, 1, 9, 31, doi:10.3390/land10010009.

Kilić Pamuković, J., Rogulj, K. and Jajac, N. (2022): Towards sustainable management of anchoring on Mediterranean islands – Concession Support Concept. *Journal of Marine Science and Engineering*, 10, 1, 1-28, doi:10.3390/jmse10010015.

Kilić Pamuković, J., Rogulj, K., Dumanić, D. and Jajac, N. (2021): A sustainable approach for the maintenance of asphalt pavement construction. *Sustainability*, 13 (1), 109, 18, doi:10.3390/su13010109.

Kilić, J., Jajac, N., Rogulj, K. and Mastelić-Ivić, S. (2019): Assessing land fragmentation in planning sustainable urban renewal. *Sustainability*, 11 (9), 1-24, doi:10.3390/su11092576.

Kilić, J., Rogulj, K. and Jajac, N. (2019): Fuzzy expert system for land valuation in land consolidation processes. *Croatian Operational Research Review*, 10, 1, 89-103, doi:10.17535/crorr.2019.0009

Kirin, A., Vršnak, B., Dumbović, M. and Heber, B. (2020): On the interaction of galactic cosmic rays with heliospheric shocks during Forbush decreases. *Solar Physics*, 295 (2), 28, doi:10.1007/s11207-020-1593-5.

Klarić, L., Pribičević, B., Đapo, A. and Žeger, L. (2022): Integrated hydrographic system for sustainable development of the marine ecosystem. *Geodetski list*, 76 (99) (3), 213-226.

Kljajić, I. and Lapaine, M. (2019): 100th anniversary of the Glasilo geometara Journal. *Geodetski list*, 73 (96) (4), 361-379.

Kordić, B., Gašparović, M., Lužar Oberiter, B., Đapo, A. and Vlastelica, G. (2020): Spatial data performance test of mid-cost UAS with direct georeferencing. *Periodica Polytechnica – Civil Engineering*, 64 (3), 859-868, doi:10.3311/PPci.15619.

Kordić, B., Lužar-Oberiter, B., Pikelj, K., Matoš, B. and Vlastelica, G. (2019): Integration of terrestrial laser scanning and UAS photogrammetry in geological studies: Examples from Croatia. *Periodica Polytechnica – Civil Engineering*, 63 (4), 989-1003, doi:10.3311/PPci.14499.

Koubský, P., Harmanec, P., Brož, M., Kotková, L., Yang, S., Božić, H., Sudar, D., Frémat, Y., Korčáková, D., Votruba, V., Škoda, P., Šlechta, M. and Ruždjak, D. (2019): Properties and nature of Be stars 31. The binary nature, light variability, physical elements, and emission-line changes of HD 81357. *Astronomy & Astrophysics*, 629, 105, 14, doi:10.1051/0004-6361/201834597.

Kovačić, B., Toplak, S., Paar, R. and Lubej, S. (2022): Application and comparison of non-contact vibration monitoring methods for concrete railway sleepers. *Applied Sciences (Basel)*, 12 (24), 12875, 19, doi:10.3390/app122412875.

Kranjčić, N. and Medak, D. (2020): Evaluating different machine learning methods on RapidEye and PlanetScope satellite imagery. *Geodetski list*, 74 (97) (1), 1-18.

Kranjčić, N., Medak, D., Župan, R. and Rezo, M. (2019): Machine learning methods for classification of the green infrastructure in city areas. *ISPRS International Journal of Geo-Information*, 8 (463), 1-15, doi:10.3390/ijgi8100463.

Kranjčić, N., Medak, D., Župan, R. and Rezo, M. (2019): Support vector machine accuracy assessment for extracting green urban areas in towns. *Remote Sensing*, 11 (6), 655, 13, doi:10.3390/rs11060655.

Križanović, J., Pivac, D., Tomić, H. and Mastelić-Ivić, S. (2021): Review of land administration data dissemination practices: Case study on four different land administration system types. *Land (Basel)*, 10 (11) (1175), 1175, 21, doi:10.3390/land10111175.

Krtalić, A. and Bajić, M. (2019): Development of the TIRAMISU advanced intelligence decision support system. *European Journal of Remote Sensing*, 52 (1), 40-55, doi:10.1080/22797254.2018.1550351.

Krtalić, A., Bajić, M., Ivelja, T. and Racetin, I. (2020): The AIDSS module for data acquisition in crisis situations and environmental protection. *Sensors*, 20 (5), 1267, 29, doi:10.3390/s20051267.

Krtalić, A., Gajski, D. and Maltarski, M. (2019): Digital three-dimensional representations of the scene and stereo satellite photogrammetry. *Geodetski list*, 73 (96) (2), 147-164.

Krtalić, A., Linardić, D. and Pernar, R. (2021): Framework for spatial and temporal monitoring of urban forest and vegetation conditions: Case study Zagreb, Croatia. *Sustainability*, 13 (11), 1-22, doi:10.3390/su13116055.

Krtalić, A., Miljković, V., Gajski, D. and Racetin, I. (2019): Spatial distortion assessments of a low-cost laboratory and field hyperspectral imaging system. *Sensors*, 19 (19), 4267, 19, doi:10.3390/s19194267.

Kurečić, T., Bočić, N., Wacha, L., Bakrač, K., Grizelj, A., Tresić Pavičić, D., Lüthgens, C., Sironić, A., Radović, S., Redovniković, L. and Fiebig, M. (2021): Changes in cave sedimentation mechanisms during the Late Quaternary: an example from the Lower Cerovačka Cave, Croatia. *Frontiers in Earth Science*, 9, 672229, 26, doi:10.3389/feart.2021.672229.

Kuveždić Divjak, A., Đapo, A. and Pribičević, B. (2020): Cartographic symbology for crisis mapping: A comparative study. *ISPRS International Journal of Geo-Information*, 9 (3), 142, 20, doi:10.3390/ijgi9030142.

Lapaine, M. (2019): Cartography in Croatia 2015–2019. *Kartografija i geoinformacije: časopis Hrvatskoga kartografskog društva*, 18 (32), 100-165.

Lapaine, M. (2019): Companions of the Mercator projection. *Geoadria*, 24 (1), 7-23 (https://www.bib.irb.hr/1102290).

Lapaine, M. (2019): Geodesy in Croatia. *Annual of the Croatian Academy of Engineering*, 2019, 235-250.

Lapaine, M. (2019): Geodesy. In: Polić Bobić, M. (Ed.) Sveučilište u Zagrebu, 1669.-2019. Zagreb, Sveučilište u Zagrebu, pp. 397-399.

Lapaine, M. (2019): Secant parallels in azimuthal projections. *Геодезия и картография*, 80 (4), 39-54, doi:10.22389/0016-7126-2019-946-4-39-54.

Lapaine, M. (2021): Gauss-Krüger projection as a double mapping. *Geodetski list*, 75 (98) (2), 85-102.

Lapaine, M. (2021): Geodetic foundations of cartography in Europe in 19th century. *Геодезия и картография / Geodesy and Cartography = Geodezia i Kartografia*, 82 (11), 51-64, doi:10.22389/0016-7126-2021-977-11-51-64.

Lapaine, M. (2021): Local linear scale factors in map projections of an ellipsoid. *Geographies*, 1, 238-250, doi:10.3390/geographies1030014.

Lapaine, M. and de Menezes, P. (2020): Standard, secant and equidistant parallels. *Kartografija i geoinformacije*, 19 (34), 40-62.

Lapaine, M. and Frančula, N. (2021): Web Mercator projection – One of cylindrical projections of an ellipsoid to a plane. *Kartografija i geoinformacije: časopis Hrvatskoga kartografskog društva*, 20 (35), 30-47.

Lapaine, M. and Frančula, N. (2022): Approximately conformal, equivalent and equidistant map projections. *Journal of Geodesy and Geoinformation Science*, 5 (3), 33-40.

Lapaine, M. and Frančula, N. (2022): Map projections classification. *Geographies*, 2 (2), 274-285, doi:10.3390/geographies2020019.

Lapaine, M., Frančula, N. and Tutek, Ž. (2021): Local linear scale factors in map projections in the directions of coordinate axes. *Geo-Spatial Information Science*, 24 (4), 630-637, doi:10.1080/10095020.2021.1968321.

Lapaine, M., Usery, E. and Nyrtsov, M. (2020): To the 20th anniversary of the Commission on Map Projections of the International Cartographic Association (2003–2023). *Геодезия и картография*, 81 (9), 44-52, doi:10.22389/0016-7126-2020-963-9-44-52.

Latinčić, A., Bačić, Ž. and Nevistić, Z. (2022): Open access on GNSS permanent networks data in case of disaster. *Interdisciplinary Description of Complex Systems: INDECS*, 20 (2), 210-221, doi:10.7906/indecs.20.2.11.

Leder, N., Duplančić Leder, T. and Lončar, G. (2020): Measurements and numerical modelling of surface waves in front of the Port of Split. *The Transaction of Navigation*, 14, 1, 192-197, doi:10.12716/1001.14.01.24.

Lénárt, I., Radović, N., Rybak, A., Brkić, M. and Mladinić, P. (2022): Comparative geometry teaching with accessories. Zagreb, Hrvatska udruga nastavnika istraživača.

Linker, J., Heinemann, S., Temmer, M., Owens, M., Caplan, R., Arge, C., Asvestari, E., Delouille, V., Downs, C., Hofmeister, S., Jebaraj, I., Madjarska, M., Pinto, R., Pomoell, J., Samara, E., Scolini, C. and Vršnak, B. (2021): Coronal hole detection and open magnetic flux. *The Astrophysical Journal*, 918 (1), 21, 18, doi:10.3847/1538-4357/ac090a.

Lisjak, J., Roić, M., Tomić, H. and Mastelić Ivić, S. (2021): Croatian LADM profile extension for state-owned agricultural land management. *Land (Basel)*, 10 (2), 10020222, 19, doi:10.3390/land10020222.

Lončar, G., Krvavica, N., Šepić, J., Bekić, D., Gašparović, M. and Kulić, T. (2022): Potentials for implementing publicly available databases for coastal flood hazard assessment in coastal towns of the Republic of Croatia. *Hrvatske vode*, 30 (121), 185-200.

Lončar, G., Leder, N., Duplančić Leder, T. and Carević, D. (2019): Wave energy disbalance as generator of extreme wave occurrence in semi-enclosed coastal waters (Example of Rijeka Bay—Croatia). *Journal of Marine Science and Engineering*, 7, 420, 1-15, doi:10.3390/jmse7110420.

Malić, B. and Frangeš, S. (2019): The Map of the Bosnia or Đakovo and Syrmia Diocese. *Tehnički vjesnik/Technical Gazette*, 26 (3), 801-806, doi:10.17559/TV-20170310083225.

Marasović, S., Crompvoets, J. and Poslončec-Petrić, V. (2019): State and development of local spatial data infrastructures in Croatia. *Journal of Spatial Science*, 64 (3), 405-422, doi:10.1080/14498596.2018.1429331.

Maričić, D., Vršnak, B., Veronig, A., Dumbović, M., Šterc, F., Roša, D., Karlica, M., Hržina, D. and Romštajn, I. (2020): Sun-to-Earth observations and characteristics of isolated Earth-impacting interplanetary coronal mass ejections during 2008 - 2014. *Solar Physics*, 295 (7), 91, 24, doi:10.1007/s11207-020-01658-4.

Martinić, K., Dumbović, M., Temmer, M., Veronig, A. and Vršnak, B. (2022): Determination of coronal mass ejection orientation and consequences for their propagation. *Astronomy & Astrophysics*, 661, 155, 10, doi:10.1051/0004-6361/202243433.

Mayer, P., Harmanec, P., Zasche, P., Brož, M., Catalan-Hurtado, R., Barlow, B., Frondorf, W., Wolf, M., Drechsel, H., Chini, R., Nasseri, A., Pigulski, A., Labadie-Bartz, J., Christie, G., Walker, W., Blackford, M., Blane, D., Henden, A., Bohlsen, T., Božić, H. and Jonák, J. (2022): Towards a consistent model of the hot quadruple system HD 93206 = QZ Carinæ. *Astronomy & Astrophysics*, 666, A23, 19, doi:10.1051/0004-6361/202142108.

Mićunović, M., Faivre, S. and Gašparović, M. (2021): Assessment of remote sensing techniques applicability for beach morphology mapping: A case study of Hvar Island, Central Adriatic, Croatia. *Journal of Marine Science and Engineering*, 9 (12), 1407, 24, doi:10.3390/jmse9121407.

Mladenov, V., Fotopoulos, V., Kaiserli, E., Karalija, E., Maury, S., Baranek, M., Segal, N., Testillano, P., Vassileva, V., Pinto, G., Nagel, M., Hoenicka, H., Miladinović, D., Gallusci, P., Vergata, C., Kapazoglou, A., Abraham, E., Tani, E., Gerakari, M., Sarri, E., Avramidou, E., Gašparović, M. and Martinelli, F. (2021): Deciphering the epigenetic alphabet involved in transgenerational stress memory in crops. *International Journal of Molecular Sciences*, 22 (13), 7118, 20, doi:10.3390/ijms22137118.

Mladinić, P. and Radović, N. (2019): The geometry of nature. Zagreb, PROVEN Grupa d.o.o.

Mlinarić, D. and Kljajić, I. (2020): Early modern Dalmatian landscape and demographic changes in the multiple borderland area: cartographic vs. statistical data. *Hrvatski geografski glasnik*, 82 (1), 35-58, doi:10.21861/HGG.2020.82.01.02.

Mulahusić, A., Kljajić, I., Tuno, N., Topoljak, J. and Điđelija, M. (2021): Bosnia and Herzegovina's convents, madrasas and monasteries represented on the analog cadastral plans of old and new cadastral surveys. *Geodetski list*, 75(98) (2), 117-142.

Mulahusić, A., Kljajić, I., Tuno, N., Topoljak, J. and Kulo, N. (2021): Medieval fortresses represented on analog cadastral maps of the old and new surveys of Bosnia and Herzegovina. *Geodetski list*, 75 (98) (4), 345-364.

Mulahusić, A., Nedim, T., Dubravko, G. and Jusuf, T. (2020): Comparison and analysis of results of 3D modelling of complex cultural and historical objects using different types of terrestrial laser scanner. *Survey Review – Directorate of Overseas Surveys*, 52 (371), 107-114, doi:10.1080/00396265.2018.1528758.

Nevistić, Z. and Bačić, Ž. (2022): Improving the availability of space research spatial data. *Interdisciplinary Description of Complex Systems: INDECS*, 20 (2), 64-77, doi:10.7906/indecs.20.2.1.

Nevistić, Z. and Špoljarić, D. (2019): Web GIS in mountaineering in Croatia. *GeoScape*, 13 (2), 114-124, doi:10.2478/geosc-2019-0011.

Nikçi, R. (2019): Land consolidation for the future regulation of the Kosovo's land. *Journal of Natural and Technical Sciences*, 2 (47), 333-344.

Odak, I., Tomić, H., Redovniković, L. and Mastelić Ivić, S. (2022): Analysis of agricultural parcel shapes. *Geodetski list*, 76 (99) (2), 135-152.

Paar, R. (2019): Carl Ritter von Ghega – 2018 surveyor of the year. *Kartografija i geoinformacije: časopis Hrvatskoga kartografskog društva*, 18 (32), 64-78, doi:10.32909/kg.18.32.5.

Paar, R., Ante, M., Ivan, J. and Igor, G. (2021): Vibration monitoring of civil engineering structures using contactless vision-based low-cost IATS prototype. *Sensors*, 21 (23), 7952, 22, doi:10.3390/s21237952.

Paar, R., Roić, M., Marendić, A. and Miletić, S. (2021): Technological development and application of photo and video theodolites. *Applied Sciences-Basel*, 11 (9), 3893, 29, doi:10.3390/app11093893.

Paouris, E., Čalogović, J., Dumbović, M., Mays, M., Vourlidas, A., Papaioannou, A., Anastasiadis, A. and Balasis, G. (2021): Propagating conditions and the time of ICME arrival: A comparison of the effective acceleration model with ENLIL and DBEM models. *Solar Physics*, 296 (1), 12, 18, doi:10.1007/s11207-020-01747-4.

Pavasović, M. and Đapo, A. (2020): Education on the effective application of measurement methods and services with the application of official geodetic datums. Zagreb, Republika Hrvatska, Državna geodetska uprava.

Pavasović, M., Đapo, A., Marjanović, M. and Pribičević, B. (2021): Present tectonic dynamics of the geological structural setting of the eastern part of the Adriatic region obtained from geodetic and geological data. *Applied Sciences-Basel*, 11 (12), 5735, 20, doi:10.3390/app11125735.

Pavasović, M., Đapo, A., Racetin, I., Banko, A. and Banković, T. (2021): Repeater of geometrical geodesy. Zagreb, Split. Sveučilište u Zagrebu – Geodetski fakultet, Sveučilište u Splitu - Fakultet građevinarstva, arhitekture i geodezije.

Peroš, J., Paar, R., Divić, V. and Kovačić, B. (2022): Fusion of laser scans and image data – RGB+D for structural health monitoring of engineering structures. *Applied Sciences (Basel)*, 12 (22), 11763, 23, doi:10.3390/app122211763.

Pilaš, I., Gašparović, M., Đodan, M., Balenović, I. and Dugački, I. (2019): Possibilities of the application of the medium Landsat 8 and the high-resolution RapidEye optical imagery in visualization and detection of forest cover changes by windthrows. *Geodetski list*, 73 (96) (3), 261-276 (https://www.bib.irb.hr/1014564).

Pilaš, I., Gašparović, M., Novkinić, A. and Klobučar, D. (2020): Mapping of the canopy openings in mixed beech–fir forest at Sentinel-2 subpixel level using UAV and machine learning approach. *Remote Sensing*, 12 (23), 3925, 29, doi:10.3390/rs12233925.

Pivac, D. and Roić, M. (2020): Systematic monitoring of cadastral resurveys. *Geodetski list*, 74 (97) (2), 221-238 (https://www.bib.irb.hr/1089472).

Pivac, D., Roić, M., Križanović, J. and Paar, R. (2021): Availability of historical cadastral data. *Land (Basel)*, 10 (9), 917, 20, doi:10.3390/land10090917.

Podladchikova, T., Jain, S., Veronig, A., Sutyrina, O., Dumbović, M., Clette, F. and Pötzi, W. (2022): Maximal growth rate of the ascending phase of a sunspot cycle for predicting its amplitude. *Astronomy & Astrophysics (Berlin)*, 663, A88, 11, doi:10.1051/0004-6361/202243509.

Poljančić Beljan, I., Jurdana-Šepić, R., Jurkić, T., Brajša, R., Skokić, I., Sudar, D., Ruždjak, D., Hržina, D., Pötzi, W., Hanslmeier, A. and Veronig, A. (2022): Variation of the solar differential rotation and activity in the period 1964–2016 determined by the Kanzelhöhe data set. *Astronomy & Astrophysics (Berlin)*, 663 (A24), 1-12, doi:10.1051/0004-6361/202140509.

Premužić, M., Đapo, A., Bačić, Ž. and Pribičević, B. (2020): Accuracy analysis of point velocities determined by different software packages and GNSS measurement processing methods. *Tehnički glasnik – Technical Journa*l, 14 (4), 446-457, doi:10.31803/tg-20200515225239.

Racetin, I. and Krtalić, A. (2021): Systematic review of anomaly detection in hyperspectral remote sensing applications. *Applied Sciences-Basel*, 11 (11), 4878, 35, doi:10.3390/app11114878.

Racetin, I., Kilić Pamuković, J. and Zrinjski, M. (2022): Role of marine spatial data infrastructure and marine cadastre in a sustainable world. *Journal of Marine Science and Engineering*, 10 (10), 1407, 19, doi:10.3390/jmse10101407.

Racetin, I., Kilić Pamuković, J., Zrinjski, M. and Peko, M. (2022): Blockchain-based land management for sustainable development. *Sustainability*, 14 (17), 10649, 15, doi:10.3390/su141710649.

Racetin, I., Krtalić, A., Srzić, V. and Zovko, M. (2020): Characterization of short-term salinity fluctuations in the Neretva River delta situated in the southern Adriatic Croatia using Landsat-5 TM. *Ecological Indicators*, 110, 1-14, doi:10.1016/j.ecolind.2019.105924.

Radočaj, D., Jug, I., Vukadinović, V., Jurišić, M. and Gašparović, M. (2021): The effect of soil sampling density and spatial autocorrelation on interpolation accuracy of chemical soil properties in arable cropland. *Agronomy*, 11 (12), 2430, 15, doi:10.3390/agronomy11122430.

Radočaj, D., Jurišić, M. and Gašparović, M. (2022): A wildfire growth prediction and evaluation approach using Landsat and MODIS data. *Journal of Environmental Management*, 304, 114351, 15, doi:10.1016/j.jenvman.2021.114351.

Radočaj, D., Jurišić, M. and Gašparović, M. (2022): The role of remote sensing data and methods in a modern approach to fertilization in precision agriculture. *Remote Sensing*, 14 (3), 778, 21, doi:10.3390/rs14030778.

Radočaj, D., Jurišić, M., Antonić, O., Šiljeg, A., Cukrov, N., Rapčan, I., Plaščak, I. and Gašparović, M. (2022): A multiscale cost–benefit analysis of digital soil mapping methods for sustainable land management. *Sustainability*, 14, 12170, 18, doi:10.3390/su141912170.

Radočaj, D., Jurišić, M., Gašparović, M. and Plaščak, I. (2020): Optimal soybean (Glycine max L.) land suitability using GIS-based multicriteria analysis and Sentinel-2 multitemporal images. *Remote Sensing*, 12 (9), 1463, 26, doi:10.3390/rs12091463.

Radočaj, D., Jurišić, M., Gašparović, M., Plaščak, I. and Antonić, O. (2021): Cropland suitability assessment using satellite-based biophysical vegetation properties and machine learning. *Agronomy*, 11 (8), 1620, 21, doi:10.3390/agronomy11081620.

Radočaj, D., Jurišić, M., Župan, R. and Antonić, O. (2020): Spatial prediction of heavy metal soil contents in continental Croatia comparing machine learning and spatial interpolation methods. *Geodetski list*, 4, 357-372, doi:https://hrcak.srce.hr/251228.

Radočaj, D., Obhođaš, J., Jurišić, M. and Gašparović, M. (2020): Global open data remote sensing satellite missions for land monitoring and conservation: A review. *Land*, 9 (11), 402, 24, doi:10.3390/land9110402.

Radočaj, D., Vinković, T., Jurišić, M. and Gašparović, M. (2022): The relationship of environmental factors and the cropland suitability levels for soybean cultivation determined by machine learning. *Poljoprivreda (Osijek)*, 28 (1), 53-59, doi:10.18047/poljo.28.1.8.

Razumović, I., Radanović, M. and Rožić, N. (2020): Impact of height datum parameters on height reference system realizations: case study in Croatia. *Journal of Surveying Engineering*, 146 (2), 05020001, 10, doi:10.1061/(asce)su.1943-5428.0000303.

Rodríguez-García, L., Gómez-Herrero, R., Zouganelis, I., Balmaceda, L., Nieves-Chinchilla, T., Dresing, N., Dumbovic, M., Nitta, N., Carcaboso, F., dos Santos, L., Jian, L., Mays, L., Williams, D. and Rodríguez-Pacheco, J. (2021): The unusual widespread solar energetic particle event on 2013 August 19. Solar origin and particle longitudinal distribution. *Astronomy & Astrophysics (Berlin)*, 202039960, 23, doi:10.1051/0004-6361/202039960.

Rodríguez-García, L., Nieves-Chinchilla, T., Gómez-Herrero, R., Zouganelis, I., Vourlidas, A., Balmaceda, L., Dumbović, M., Jian, L., Mays, L., Carcaboso, F., dos Santos, L. and Rodríguez-Pacheco, J. (2022): Evidence of a complex structure within the 2013 August 19 coronal mass ejection. Radial and longitudinal evolution in the inner heliosphere. *Astronomy & Astrophysics (Berlin)*, 662, A45, 19, doi:10.1051/0004-6361/202142966.

Rogulj, K. and Kilić Pamuković, J. (2021): Environmental adaptation of construction barriers under intuitionistic fuzzy theory. *Technical Journal*, 15, 1, 1-10, doi:10.31803/tg-20210215210742.

Rogulj, K., Kilić Pamuković, J. and Ivić, M. (2021): Hybrid MCDM based on VIKOR and cross entropy under rough neutrosophic set theory. *Mathematics*, 9, 12, 1334, 27, doi:10.3390/math9121334.

Rogulj, K., Kilić Pamuković, J. and Jajac, N. (2021): A decision concept to the historic pedestrian bridges recovery planning. *Applied Sciences*, 11, 3, 969, 23, doi:10.3390/app11030969.

Rogulj, K., Kilić Pamuković, J. and Jajac, N. (2021): Knowledge-based fuzzy expert system to the condition assessment of historic road bridges. *Applied Sciences*, 11, 3, 1021, 43, doi:10.3390/app11031021.

Rogulj, K., Kilić Pamuković, J., Antucheviciene, J. and Zavadskas, E. K. (2022): Intuitionistic fuzzy decision support based on EDAS and grey relational degree for historic bridges reconstruction priority. *Soft Computing*, 26, 18, 9419-9444, doi:10.1007/s00500-022-07259-6.

Roić, M., Križanović, J. and Pivac, D. (2021): An approach to resolve inconsistencies of data in the cadastre. *Land (Basel)*, 10 (1), 1, 20, doi:10.3390/land10010070.

Rožić, N. (2019): Croatian height reference system. Zagreb, Geodetski fakultet.

Rumora, L., Gašparović, M., Miler, M. and Medak, D. (2019): Quality assessment of fusing Sentinel-2 and WorldView-4 imagery on Sentinel-2 spectral band values: a case study of Zagreb, Croatia. *International Journal of Image and Data Fusion*, 1-20, doi:10.1080/19479832.2019.1683624.

Rumora, L., Majić, I., Miler, M. and Medak, D. (2020): Spatial video remote sensing for urban vegetation mapping using vegetation indices. *Urban Ecosystems*, 2020, 1-13, doi:10.1007/s11252-020-01002-5.

Rumora, L., Miler, M. and Medak, D. (2019): Contemporary comparative assessment of atmospheric correction influence on radiometric indices between Sentinel-2A and Landsat 8 imagery. *Geocarto International*, 1-15, doi:10.1080/10106049.2019.1590465.

Rumora, L., Miler, M. and Medak, D. (2020): Impact of various atmospheric corrections on Sentinel-2 land cover classification accuracy using machine learning classifiers. *ISPRS International Journal of Geo-Information*, 9 (4), 277, 23, doi:10.3390/ijgi9040277.

Scolini, C., Chané, E., Temmer, M., Kilpua, E., Dissauer, K., Veronig, A., Palmerio, E., Pomoell, J., Dumbović, M., Guo, J., Rodriguez, L. and Poedts, S. (2020): CME─CME interactions as sources of CME geoeffectiveness: The formation of the complex ejecta and intense geomagnetic storm in 2017 early September. *The Astrophysical Journal. Supplement Series*, 247 (1), 21, doi:10.3847/1538-4365/ab6216.

Selhorst, C., Simões, P., Brajša, R., Valio, A., de Castro, C., Costa, J., Menezes, F., Rozelot, J., Hales, A., Iwai, K. and White, S. (2019): Solar polar brightening and radius at 100 and 230 GHz observed by ALMA. *The Astrophysical Journal*, 871 (1), 45, 8, doi:10.3847/1538-4357/aaf4f2.

Seljan, S., Viličić, M., Nevistić, Z., Dedić, L., Grubišić, M., Cibilić, I., Kević, K., van Loenen, B., Welle Donker, F. and Alexopoulos, C. (2022): Open data as a condition for smart application development: assessing access to hospitals in Croatian cities. *Sustainability*, 14 (19), 12014-12060, doi:10.3390/su141912014.

Sertić, H., Rinaldo, P., Tomić, H. and Ravlić, F. (2022): Influence of flight height and image sensor on the quality of the UAS orthophotos for cadastral survey purposes. *Land*, 11 (8), 1250, 18, doi:10.3390/land11081250.

Skokić, I., Brajša, R., Sudar, D., Ruždjak, D. and Saar, S. (2019): Turbulent diffusion derived from the motions of SDO/AIA coronal bright points. *The Astrophysical Journal*, 877 (2), 142, 7, doi:10.3847/1538-4357/ab1d4f.

Srzić, V., Lovrinović, I., Racetin, I. and Pletikosić, F. (2020): Hydrogeological characterization of coastal aquifer on the basis of observed sea level and groundwater level fluctuations: Neretva valley aquifer, Croatia. *Water*, 12, 2, 348, 25, doi:10.3390/w12020348.

Stepinac, M. and Gašparović, M. (2020): A review of emerging technologies for an assessment of safety and seismic vulnerability and damage detection of existing masonry structures. *Applied Sciences-Basel*, 10, 5060, 16, doi:10.3390/app10155060.

Sudar, D., Brajša, R., Skokić, I. and H. Woehl (2019): Centre-to-limb brightness variations from the Atacama Large Millimeter-submillimeter Array (ALMA) full-disk solar images. *Solar Physics*, 294, 163, 14, doi:10.1007/s11207-019-1556-x.

Sudar, D., Vršnak, B., Dumbović, M., Temmer, M. and Čalogović, J. (2022): Influence of the drag force on the leading edge of a coronal mass ejection. *Astronomy & Astrophysics (Berlin)*, 665, A142, 5, doi:10.1051/0004-6361/202244114.

Suresh, K., Prasanna Subramanian, S., Shanmugaraju, A., Vršnak, B. and Umapathy, S. (2019): Study of interplanetary CMEs/shocks during solar cycle 24 using drag-based model: The role of solar wind. *Solar Physics*, 294, 47, 17, doi:10.1007/s11207-019-1432-8.

Šiljeg, A., Panđa, L., Domazetović, F., Marić, I., Gašparović, M., Borisov, M. and Milošević, R. (2022): Comparative assessment of pixel and object-based approaches for mapping of olive tree crowns based on UAV multispectral imagery. *Remote Sensing*, 14 (3), 757, 18, doi:10.3390/rs14030757.

Šugar, D., Bačić, Ž. and Dasović, I. (2021): Geodetic and seismological analysis of the CROPOSZAGR station kinematics during the Zagreb 2020 ML 5.5 earthquake. *Geofizika*, 38 (2), 191-214, doi:10.15233/gfz.2021.38.10.

Temmer, M., Holzknecht, L., Dumbović, M., Vršnak, B., Sachdeva, N., Heinemann, S., Dissauer, K., Scolini, C., Asvestari, E., Veronig, A. and Hofmeister, S. (2021): Deriving CME density from remote sensing data and comparison to in-situ measurements. *Journal of Geophysical Research, Space Physics*, 126 (1), e2020JA028380, 17, doi:10.1029/2020JA028380.

Tomić, H., Mastelić Ivić, S., Roić, M. and Šiško, J. (2021): Developing an efficient property valuation system using the LADM valuation information model: A Croatian case study. *Land Use Policy*, 104, 105368, 9, doi:10.1016/j.landusepol.2021.105368.

Topoljak, J., Mulahusić, A. and Kljajić, I. (2022): Analog cadastral maps in the function of interpretation of location of watermills of the settlements Kasapovići and Isakovići in Novi Travnik. *Geodetski glasnik*, 53, 62-84.

Varga, F., Hrustek, L., Kević, K., Welle Donker, F. and Šalamon, D. (2022): Urban dog spaces: The openness of dog-related government data in the City of Zagreb, Croatia. *Interdisciplinary Description of Complex Systems*, 20 (2), 125-135, doi:10.7906/indecs.20.2.5.

Vela, E., Miljković, V. and Babić, L. (2020): Spatiotemporal analysis of LANDSAT satellite imagery for change detection in Česma Forest ecosystem. *Tehnički vjesnik/Technical Gazette*, 27 (5), 1-6, doi:10.17559/TV-20190214121800.

Verbeke C., Leila Mays M., Kay C., Riley P., Palmerio E., Dumbovic M., Mierla M., Scolini C., Temmer M., Paouris E., Balmaceda L. A., Cremades H., and Hinterreiter J. (2022): Quantifying errors in 3D CME parameters derived from synthetic data using white-light reconstruction techniques. *Advances in Space Research*, doi:10.1016/j.asr.2022.08.056.

Verbeke, C., Mays, M., Temmer, M., Bingham, S., Steenburgh, R., Dumbović, M., Núñez, M., Jian, L., Hess, P., Wiegand, C., Taktakishvili, A. and Andries, J. (2019): Benchmarking CME arrival time and impact: Progress on metadata, metrics, and events. *Space Weather – The International Journal of Research and Applications*, 17 (1), 6-26, doi:10.1029/2018SW002046.

Vinković, A., Župan, R., Ivković, M. and Biljecki, Z. (2022): Creating a map of Switzerland using Swiss style relief shading. *Geodetski list*, 76 (99) (1), 53-70.

von Forstner, J., Dumbović, M., Möstl, C., Guo, J., Papaioannou, A., Elftmann, R., Xu, Z., Terasa, J., Kollhoff, A., Wimmer- Schweingruber, R., Rodríguez-Pacheco, J., Weiss, A., Hinterreiter, J., Amerstorfer, T., Bauer, M., Belov, A., Abunina, M., Horbury, T., Davies, E., O'Brien, Helen Allen, Robert C., Andrews, G., Berger, L., Boden, S., Cernuda Cangas, I., Eldrum, S., Espinosa Lara, F., Gómez Herrero, R., Hayes, J., Ho, G., Kulkarni, S., Lees, W., Martín, C., Mason, G., Pacheco, D., Prieto Mateo, M., Ravanbakhsh, A., Rodríguez Polo, O., Sánchez Prieto, S., Schlemm, C., Seifert, H., Tyagi, K. and Yedla, M. (2021): Radial evolution of the April 2020 stealth coronal mass ejection between 0.8 and 1 AU. Comparison of Forbush decreases at Solar Orbiter and near the Earth. *Astronomy & Astrophysics (Berlin), Solar Orbiter First Results Special Issue*, 202039848, 16, doi:10.1051/0004-6361/202039848.

Vranić, S., Matijević, H., Roić, M. and Vučić, N. (2021): Extending LADM to support workflows and process models. *Land Use Policy*, 104, 105358, 11, doi:10.1016/j.landusepol.2021.105358.

Vrdoljak, L. and Bašić, T. (2022): Bathymetry estimation from satellite altimeter-derived gravity data. In: Coleman, J. (Ed.) Altimetry – Theory, applications and recent advances [Working Title]. London, IntechOpen, 108511, 17, doi:10.5772/intechopen.108511.

Vršnak, B. (2019): Gradual pre-eruptive phase of solar coronal eruptions. *Frontiers in Astronomy and Space Sciences*, 6, 28, 8, doi:10.3389/fspas.2019.00028.

Vršnak, B. (2021) Analytical and empirical modelling of the origin and heliospheric propagation of coronal mass ejections, and space weather applications. *Journal of Space Weather and Space Climate*, 11, 11, 15, doi:10.1051/swsc/2021012.

Vršnak, B., Amerstorfer, T., Dumbović, M., Leitner, M., Veronig, A., Temmer, M., Möstl, C., Amerstorfer, U., Farrugia, C. and Galvin, A. (2019): Heliospheric evolution of magnetic clouds. *The Astrophysical Journal*, 877, 77, 16, doi:10.3847/1538-4357/ab190a.

Vršnak, B., Dumbović, M., Heber, B. and Kirin, A. (2022): Analytic modeling of recurrent Forbush decreases caused by corotating interaction regions. *Astronomy & Astrophysics (Berlin)*, 658, A186, 15, doi:10.1051/0004-6361/202140846.

Vučić, N. (2020): The role of 3D cadastre in the preservation of historical cultural heritage. In: Kopáčik, A., Kyrinovič, P., Erdélyi, J., Paar, R. and Marendić, A. (Eds) Contributions to international conferences on engineering surveying. Germany, Springer, Cham, pp. 309-316.

Vučić, N., Mađer, M., Vranić, S. and Roić, M. (2020): Initial 3D cadastre registration by cadastral resurvey in the Republic of Croatia. *Land Use Policy*, 98, 104335, 13, doi:10.1016/j.landusepol.2019.104335.

Wolf, M., Harmanec, P., Božić, H., Koubský, P., Yang, S., Ruždjak, D., Šlechta, M., Ak, H., Bakış, H., Bakış, V., Opluštilová, A. and Vitovský, K. (2021): Long-term, orbital, and rapid variations of the Be star V923 Aql = HD 183656. *Astronomy & Astrophysics*, 647, 97, 18, doi:10.1051/0004-6361/202039740.

Zhan, J., Zhang, D., Tan, L., Zhang, G. and Župan, R. (2022): Performance analysis of inverting optical properties based on quasi-analytical algorithms. *Multimedia Tools and Applications*, 81, 4693-4709, doi:10.1007/s11042-021-10748-9.

Zhang, D., Zhan, J., Qiao, Z. and Župan, R. (2020): Evaluation of the performance of the integration of remote sensing and Noah hydrologic model for soil moisture estimation in Hetao irrigation region of inner Mongolia. *Canadian Journal of Remote Sensing*, 46 (5), 552-566, doi:10.1080/07038992.2020.1810003.

Zhang, J., Temmer, M., Gopalswamy, N., Malandraki, O., Nitta, N., Patsourakos, S., Shen, F., Vršnak, B., Wang, Y., Webb, D., Desai, M., Dissauer, K., Dresing, N., Dumbović, M., Feng, X., Heinemann, S., Laurenza, M., Lugaz, N. and Zhuang, B. (2021): Earth-affecting solar transients: a review of progresses in solar cycle 24. *Progress in Earth and Planetary Science*, 8 (1), 56, 184, doi:10.1186/s40645-021-00426-7.

Zrinjski, M., Barković, Đ. and Baričević, S. (2019): Precise determination of calibration baseline distances. *Journal of Surveying Engineering*, 145 (4), 05019005, 9, doi:10.1061/(ASCE)SU.1943-5428.0000288.

Zrinjski, M., Barković, Đ. and Gudelj, M. (2019): Testing and analysis of the measurement quality of the rotating laser system. *Geodetski list*, 73 (96) (2), 109-128 (https://www.bib.irb.hr/1012513).

Zrinjski, M., Barković, Đ. and Matika, K. (2019): Development and modernization of GNSS. *Geodetski list*, 73 (96) (1), 45-65 (https://www.bib.irb.hr/994796).

Zrinjski, M., Barković, Đ. and Matika, K. (2020): 55 years of development of the Laboratory for Measurements and Measuring Technique at the Faculty of Geodesy, University of Zagreb. *Godišnjak 2019. Akademije tehničkih znanosti Hrvatske*, 14 (1), 501-515.

Zrinjski, M., Barković, Đ. and Matika, K. (2021): Precise measurement and analysis of the olympic-size swimming pool lanes distance. *Geodetski list*, 75 (98) (1), 45-58.

Zrinjski, M., Barković, Đ. and Špoljar, K. (2022): Review of precise calibration methods of geodetic calibration baselines. *Geodetski list*, 76 (99) (1), 25-52.

Zrinjski, M., Barković, Đ. and Tupek, A. (2021): Testing and analysis of precision of the optical level. *Godišnjak 2020. Akademije tehničkih znanosti Hrvatske*, 15 (1), 233-241.

Zrinjski, M., Barković, Đ., Tupek, A. and Polović, A. (2019): Testing and analysis of chimney verticality. *Geodetski list*, 73 (96) (3), 239-260.

Zrinjski, M., Matika, K. and Stojnović, M. (2021): Software support for geodetic measurement data processing. *Godišnjak 2020. Akademije tehničkih znanosti Hrvatske*, 15 (1), 242-248.

Zrinjski, M., Tupek, A., Barković, Đ. and Polović, A. (2021): Industrial masonry chimney geometry analysis: A total station based evaluation of the unmanned aerial system photogrammetry approach. *Sensors*, 21 (18), 6265, 25, doi:10.3390/s21186265.

Žic, B., Župan, R. and Frangeš, S. (2020): Optimization of 3D cartographic presentations on the example of the City of Krk. *Geodetski list*, 74 (97) (2), 199-220.

Župan, R., Frangeš, S. and Vinković, A. (2021): Geovisualization. Zagreb, Geodetski fakultet.

Župan, R., Frangeš, S., Šantek, D. and Baričević, V. (2019): Analysis and critical review of visualization of rocks and cliffs on maps. *Geodetski list*, 73 (96) (3), 277-298.

# 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. Chuliat 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 “2$^{nd}$ 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 MEDJimurje 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.

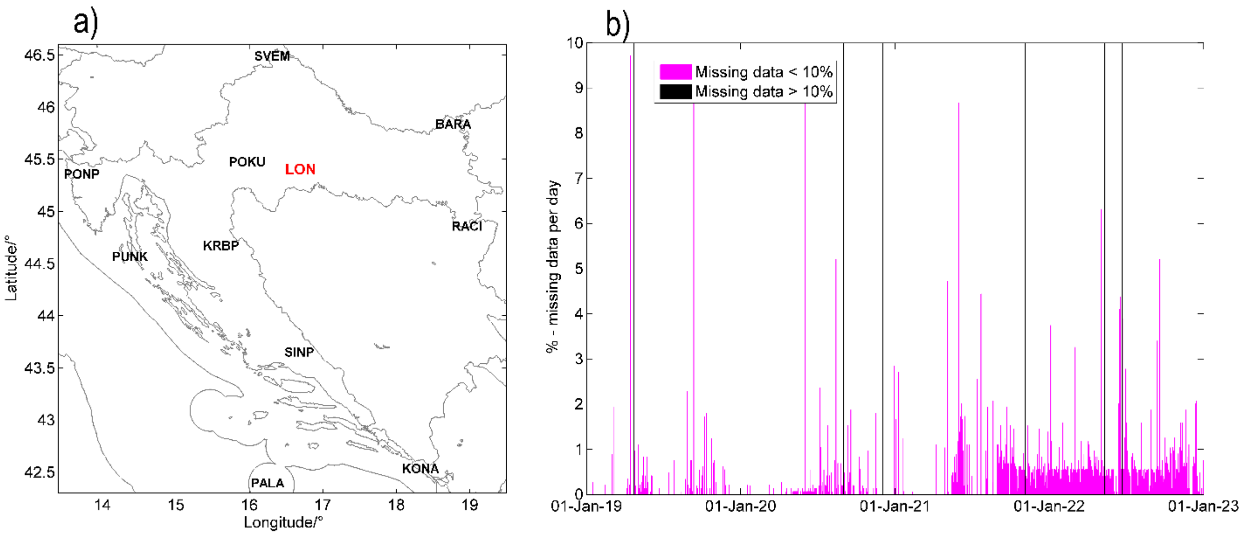


**Figure 1.** (a) Locations of CGRSN stations and LON observatory. (b) The percentage of missing data (upon removal of degradations) per day in the period 2019–2022. For only five days more than 10% of data is missing.

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 ≤ 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'/yr and 8.7'/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 ($\rho$) during the declining phase of solar cycle 23. The investigation of $\rho$ at the latitudinal bins (high, mid and low) in both hemispheres at dayside and nightside showed that $\rho$ values increase/decrease from high to low latitudes at dayside/nightside. Augmentation of $\rho$ 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 $\rho$ values are not the same prior and after the equinox. Quiet time $\rho$ differs among latitudinal bins; $\rho$ contains a clear imprint of solar and geomagnetic activity. The cross-correlation analysis reveals a high degree of correlation between $\rho$ and different $\rho$ indicators employed (based on solar wind parameters and geomagnetic activity measures). Time lags based on all $\rho$ indicators suggest that $\rho$ 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 $\rho$ variations during the periods in which the magnetospheric-thermospheric system is affected primarily by HSSs.

Different plasmapause structures observed in nature are a sign of the complex processes that cause the formation and evolution of the plasmapause. Bandić et al. (2020) analysed the characteristics of the main plasmapause over a longer period and succeeded to simplify and systemize the global plasmapause 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 plasmapause 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, ***Bs*** fields are separated according to the IMF polarity – toward/away from the Sun. The obtained results showed that ***Bs*** 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 ***Bs*** and not because the field is pointing northward. The authors showed that patterns of the experimental ***Bs*** fields are not in agreement with the well-known Russell-McPherron model of ***Bs***. 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.

## *List of publications*


Bandić, M., Verbanac, G. and Pierrard, V. (2020): Relationship between global plasmapause characteristics and plasmapause structures in the frame of interchange instability mechanism. *Journal of Geophysical Research, Space Physics*, **125**, 2, 1-12, DOI: 10.1029/2019JA026768.

Brajša, R., Verbanac, G., Bandić, M. Hanslmeier, A., Skokić, I. and Sudar, D. (2022): A prediction for the 25$^{th}$ solar cycle maximum amplitude. *Astronomische Nachrichten*, **343**, 3, e2113960, 10, DOI: 10.1002/asna.202113960.

Brkić, M. (2019): Monitoring geomagnetic information on the territory of Croatia. *Geofizika*, 36, 1, 1-15, DOI: 10.15233/gfz.2019.36.3

Brkić, M., Varga, M., Grgić, M., Radović, N. and Bašić, T. (2020): Model radnog popravka kompasa za 2020. godinu. *Strategos*, **4**, 1, 7-29.

Brkić, M.,Grgić, M. and Radović, N. (2022): Zagreb earthquakes on 22$^{nd}$ March 2020 and geomagnetic information. *Tehnički vjesnik: znanstveno-stručni časopis tehničkih fakulteta Sveučilišta u Osijeku*, **29**, 653-658, DOI: 10.17559/TV-20201211131046.

Heinemann, S. G., Jerčić,V., Temmer, M., Hofmeister, S. J., Dumbović, M., Vennerstrom, S., Verbanac, G. and Veronig, A. M. (2020): A statistical study of long-term evolution of coronal hole properties as observed by SDO. *Astronomy & Astrophysics (Berlin)*, 638, A68, **11**, DOI: 10.1051/0004-6361/202037613.

Mandić, I. (2021): Note on the data processing in the Lonjsko Polje Observatory. Conrad Observatory Journal, Eds: Leonhardt, R., Arneitz, P., Zentralanstalt für Meteorologie und Geodynamik, Wien, 13.

Verbanac, G. and Bandić, M. (2021): Origin and characteristics of the southward component of the interplanetary magnetic field. *Solar Physics*, **269**, 183, 16, DOI: 10.1007/s11207-021-01930-1.

Verbanac, G., Bandić, M. and Krauss, S. (2022): Influence of the solar wind high-speed streams on the thermospheric neutral density during the declining phase of solar cycle 23. *Advances in Space Research*, **69**, 4335-4350, DOI: 10.1016/j.asr.2022.03.032.

# 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 Figures 1 and 2.

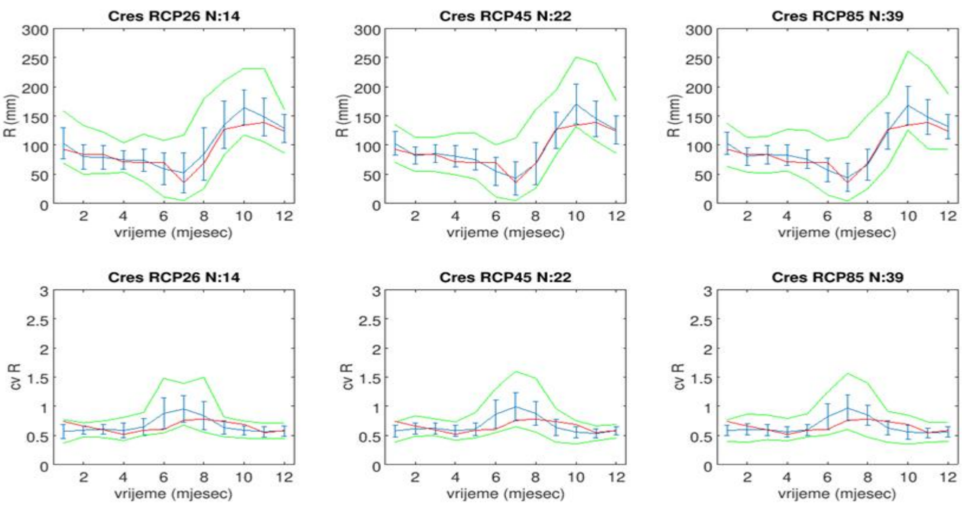


**Figure 1.** Annual cycle of the mean monthly precipitation (mm; first row) and annual cycle of the coefficient of variation of the monthly precipitation amount (dimensionless; second row). First column: models included in the RCP2.6 scenario; second column: models included in the RCP4.5 scenario; third 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.

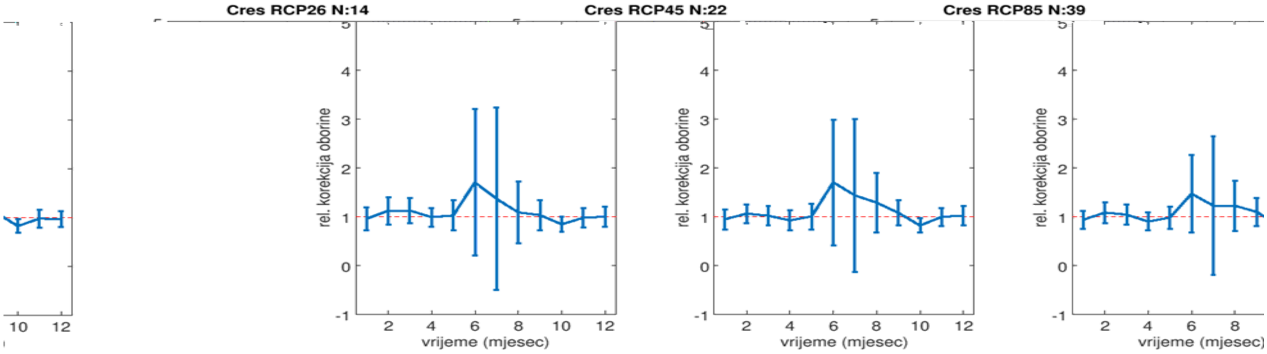


**Figure 2.** Annual cycle of relative correction of mean monthly precipitation (dimensionless). The mean and standard deviation of monthly corrections within the RCM ensemble are presented for models included in the scenarios RCP2.6 (first column), RCP4.5 (second column) and RCP8.5 (third column). Period: 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 (Figure 3, left) and fine-scale internal oscillations (Figure 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 (Figure 4, Šarović et al., 2022).

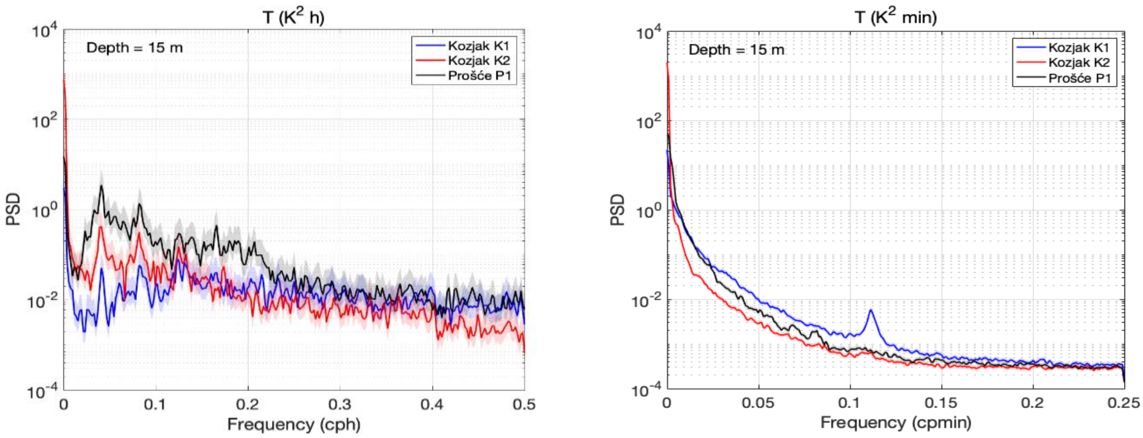


**Figure 3**. Power spectral densities (PSDs) computed from the 1 h and 2 min mean lake temperatures at the two points in Kozjak Lake (K1 and K2) and one point in Prošće Lake (P1) at the depth of 15 m for the period from 6 July 2019 to 4 November 2019 (Klaić et al., 2020a, 2020b). Full lines and shaded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

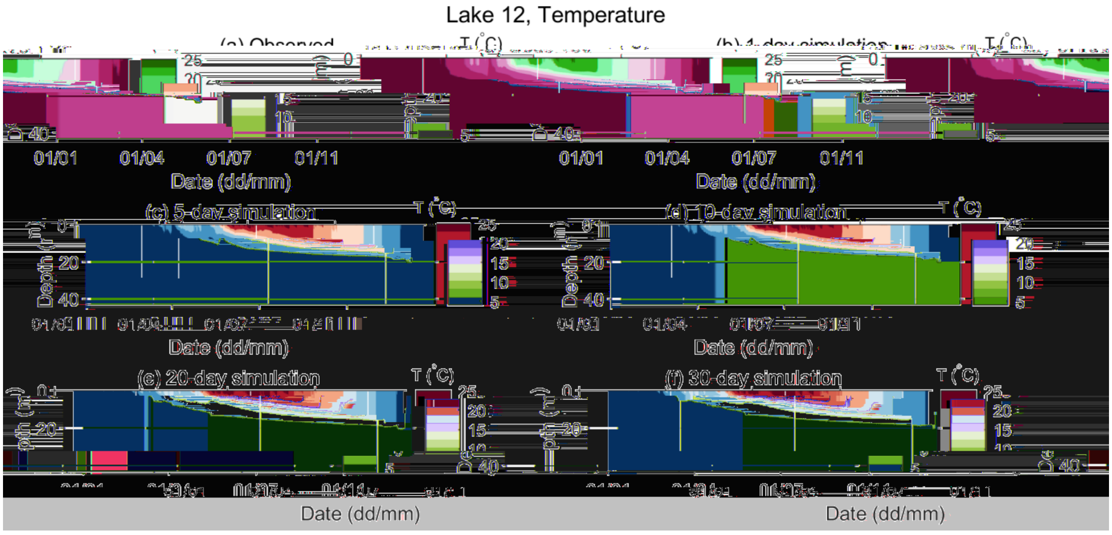


**Figure 4**. Observed and predicted water temperatures of Kozjak Lake for different simulation lengths for 2019. Periods with 425 missing data are seen as white vertical stripes (adopted from Šarović et al., 2022).

### *List of publications*

Barešić, J., Parlov, J., Kovač, Z. and Sironić, A. (2019): Use of nuclear power plant released tritium as a groundwater tracer. *Rudarsko-geološko-naftni zbornik*, *35*(1), https://doi.org/10.17794/rgn.2020.1.3.

Biondić, R., Meaški, H., Biondić, B. and Loborec, J. (2021): Karst Aquifer Vulnerability Assessment (KAVA) method – A novel GIS-based method for deep karst aquifers. *Sustainability*, *13*(6), https://doi.org/10.3390/su13063325.

Biondić, R., Ed. (2023): Governing coastal karst aquifers endangered by climate changes. Faculty of Geotechnical Engineering, University of Zagreb, Varaždin, 219 pp (in Croatian).

Bonacci, O. and Oskoruš, D. (2019): Human impacts on water regime. In: Lóczy, D. (Ed.): The Drava River environmental problems and solutions, Cham, Springer, pp. 125-137, doi:10.1007/978-3-319-92816-6_9.

Bonacci, O., Andrić, I., Roje-Bonacci, T., Oskoruš, D. and Vrsalović, A. (2020): Impact of large human constructions on a karst river hydrology: Case of the Cetina River (Dinaric karst). *Acta Hydrotechnica*, 33, 59, 155-174, doi:10.15292/acta.hydro.2020.10.

Bonacci, O., Đurin, B., Bonacci, T. R. and Bonacci, D. (2022): The influence of reservoirs on water temperature in the downstream part of an open watercourse: A case study at Botovo station on the Drava River. *Water*, *14*(21), https://doi.org/10.3390/w14213534.

Bonacci, O., Terzić, J., Roje-Bonacci, T. and Frangen, T. (2019): An intermittent karst river: The case of the Čikola River (Dinaric karst, Croatia). *Water*, *11*(11), https://doi.org/10.3390/w11112415.

Borković, D., Kovač, Z. and Krajcar Bronić, I. (2022): Time-series analysis of isotope composition of precipitation in Zagreb, Croatia. *Water*, *14*(13), https://doi.org/10.3390/w14132008.

Briški, M., Stroj, A., Kosović, I. and Borović, S. (2020): Characterization of aquifers in metamorphic rocks by combined use of electrical resistivity tomography and monitoring of spring hydrodynamics. *Geosciences*, *10*(4), https://doi.org/10.3390/geosciences10040137.

Brkić, Ž. and Kuhta, M. (2022): Lake level evolution of the largest freshwater lake on the Mediterranean islands through drought analysis and machine learning. *Sustainability*, *14*(16), https://doi.org/10.3390/su141610447.

Brkić, Ž., Kuhta, M., Hunjak, T. and Larva, O. (2020): Regional isotopic signatures of groundwater in Croatia. *Water*, *12*(7), https://doi.org/10.3390/w12071983.

Brkić, Ž., Larva, O. and Kuhta, M. (2021): Groundwater age as an indicator of nitrate concentration evolution in aquifers affected by agricultural activities. *Journal of Hydrology*, *602*, 126799, https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.126799.

Brleković, T. and Tadić, L. (2022): Hydrological drought assessment in a small lowland catchment in Croatia. *Hydrology*, *9*(5), https://doi.org/10.3390/hydrology9050079.

Buljan, R., Pavlić, K., Terzić, J. and Perković, D. (2019): A conceptual model of groundwater dynamics in the catchment area of the Zagorska Mrežnica Spring, the karst massif of Kapela Mountain. *Water*, *11*(10), 1983, https://doi.org/10.3390/w11101983.

Caren, M. and Pavlić, K. (2021). Autocorrelation and cross-correlation flow analysis along the confluence of the Kupa and Sava rivers. *Rudarsko-geološko-naftni zbornik*, *36*(5), 67–77, https://doi.org/10.17794/rgn.2021.5.7.

Ćosić-Flajsig, G., Karleuša, B. and Glavan, M. (2021): Integrated water quality management model for the rural transboundary river basin – A case study of the Sutla/Sotla River. *Water*, *13*(18), https://doi.org/10.3390/w13182569.

Dadar, S., Đurin, B., Alamatian, E. and Plantak, L. (2021): Impact of the pumping regime on electricity cost savings in urban water supply system. *Water*, *13*(9), https://doi.org/10.3390/w13091141.

Denić-Jukić, V., Lozić, A. and Jukić, D. (2020): An application of correlation and spectral analysis in hydrological study of neighboring karst springs. *Water*, *12*(12), https://doi.org/10.3390/w12123570.

Divić, V., Galešić, M., Di Dato, M., Tavra, M. and Andričević, R. (2020): Application of open source electronics for measurements of surface water properties in an estuary: A case study of River Jadro, Croatia. *Water*, *12*(1), https://doi.org/10.3390/w12010209.

Dogančić, D., Afrasiabian, A., Kranjčić, N. and Đurin, B. (2020): Using stable isotope analysis (δD and δ18O) and tracing tests to characterize the regional hydrogeological characteristics of Kazeroon County, Iran. *Water*, *12*(9), https://doi.org/10.3390/w12092487.

Dragičević, N., Karleuša, B. and Ožanić, N. (2019): Different approaches to estimation of drainage density and their effect on the erosion potential method. *Water*, *11*(3), https://doi.org/10.3390/w11030593.

Dragun, Z., Stipaničev, D., Fiket, Ž., Lučić, M., Udiković Kolić, N., Puljko, A., Repec, S., Šoštarić Vulić, Z., Ivanković, D., Barac, F., Kiralj, Z., Kralj, T. and Valić, D. (2022): Yesterday's contamination – A problem of today? The case study of discontinued historical contamination of the Mrežnica River (Croatia). *Science of the Total Environment*, *848*, 157775, https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.157775.

Dundović, I. and Tadić, L. (2022): A field experiment verification of theoretical exponent N1 for FAVAD method in defining the relationship of pressure and water losses. *Water*, *14*(13), https://doi.org/10.3390/w14132067.

Frančišković-Bilinski, S. and Sakan, S. (2021): Geochemistry of water and sediment. *Water*, *13*(5), https://doi.org/10.3390/w13050693.

Grbčić, L., Lučin, I., Kranjčević, L. and Družeta, S. (2020): Water supply network pollution source identification by random forest algorithm. *Journal of Hydroinformatics*, *22*(6), 1521–1535, https://doi.org/10.2166/hydro.2020.042.

Hasan, O., Miko, S., Brunović, D., Papatheodorou, G., Christodolou, D., Ilijanić, N. and Geraga, M. (2020): Geomorphology of canyon outlets in Zrmanja River estuary and its effect on the Holocene flooding of semi-enclosed basins (the Novigrad and Karin Seas, Eastern Adriatic). *Water*, *12*(10), https://doi.org/10.3390/w12102807.

Jajac, N., Marović, I., Rogulj, K. and Kilić, J. (2019): Decision support concept to selection of wastewater treatment plant location—the case study of Town of Kutina, Croatia. *Water*, *11*(4), https://doi.org/10.3390/w11040717.

Jozić, S., Baljak, V., Cenov, A., Lušić, D., Galić, D., Glad, M., Maestro, D., Maestro, N., Kapetanović, D., Kraus, R., Marinac-Pupavac, S. and Vukić Lušić, D. (2021): Inland and coastal bathing water quality in the last decade (2011–2020): Croatia vs. region vs. EU. *Water*, *13*(17), https://doi.org/10.3390/w13172440.

Jukić, D., Denić-Jukić, V. and Kadić, A. (2022): Temporal and spatial characterization of sediment transport through a karst aquifer by means of time series analysis. *Journal of Hydrology*, *609*, 127753, https://doi.org/https://doi.org/10.1016/j.jhydrol.2022.127753.

Jukić, D., Denić-Jukić, V. and Lozić, A. (2021): An alternative method for groundwater recharge estimation in karst. *Journal of Hydrology*, *600*, 126671, https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.126671.

Karleuša, B., Hajdinger, A. and Tadić, L. (2019): The application of multi-criteria analysis methods for the determination of priorities in the implementation of irrigation plans. *Water*, *11*(3), https://doi.org/10.3390/w11030501.

Karlović, I., Marković, T. and Vujnović, T. (2022): Groundwater recharge assessment using multi component analysis: Case study at the NW edge of the Varaždin alluvial aquifer, Croatia. *Water*, *14*(1), https://doi.org/10.3390/w14010042.

Karlović, I., Marković, T., Kanduč, T. and Vreča, P. (2022): Assessment of seasonal changes on the carbon cycle in the critical zone of a surface water (sw)-groundwater (gw) system. *Water*, *14*(21), https://doi.org/10.3390/w14213372.

Karlović, I., Marković, T., Smith, A. and Kanduč, T. (2022): Data on stable isotopic composition of d18 O and d15 N in nitrate in groundwater, and d15 N in solid matter in the Varaždin area, NW Croatia. *Data in Brief*, *45*, 1–6, https://doi.org/10.1016/j.dib.2022.108686.

Karlović, I., Marković, T., Šparica Miko, M. and Maldini, K. (2021): Geochemical characteristics of alluvial aquifer in the Varaždin region. *Water*, *13*(11), https://doi.org/10.3390/w13111508.

Karlović, I., Marković, T., Vujnović, T. and Larva, O. (2021): Development of a hydrogeological conceptual model of the Varaždin alluvial aquifer. *Hydrology*, *8*(1), https://doi.org/10.3390/hydrology8010019.

Karlović, I., Pavlić, K., Posavec, K. and Marković, T. (2021): Analysis of the hydraulic connection of the Plitvica Stream and the groundwater of the Varaždin alluvial aquifer. *Geofizika*, *38*(2), https://doi.org/10.15233/gfz.2021.38.3.

Kekez, T., Andričević, R., and Knezić, S. (2022): Flood risk modeling under uncertainties: The case study of Croatia. *Water, 14*(10), https://doi.org/10.3390/w14101585.

Kekez, T., Knezić, S., and Andričević, R. (2020). Incorporating uncertainty of the system behavior in flood risk assessment – Sava River case study. *Water*, *12*(10), https://doi.org/10.3390/w12102676.

Klaić, Z. B., Babić, K. and Mareković, T. (2020): Internal seiches in a karstic mesotrophic lake (Prošće, Plitvice Lakes, Croatia). *Geofizika*, *37*(2), 157–179, https://doi.org/10.15233/gfz.2020.37.11.

Klaić, Z. B., Babić, K. and Orlić, M. (2020): Evolution and dynamics of the vertical temperature profile in an oligotrophic lake. *Hydrology and Earth System Sciences*, *24*(7), 3399–3416, https://doi.org/10.5194/hess-24-3399-2020.

Kos, Ž., Đurin, B., Dogančić, D. and Kranjčić, N. (2021): Hydro-energy suitability of rivers regarding their hydrological and hydrogeological characteristics. *Water*, *13*(13), https://doi.org/10.3390/w13131777.

Kovač, Z., Barešić, J., Parlov, J. and Sironić, A. (2022): Impact of hydrological conditions on the isotopic composition of the Sava River in the area of the Zagreb aquifer. *Water*, *14*(14), https://doi.org/10.3390/w14142263.

Kovač, Z., Krevh, V., Filipović, L., Defterdarović, J., Buškulić, P., Han, L. and Filipović, V. (2022): Utilizing stable water isotopes (δ2H and δ18O) to study soil-water origin in sloped vineyard: first results. *Rudarsko-geološko-naftni zbornik*, *37*(3), 1–14, https://doi.org/10.17794/rgn.2022.3.1.

Krajcar Bronić, I. and Barešić, J. (2021): Application of stable isotopes and tritium in hydrology. *Water*, *13*(4), https://doi.org/10.3390/w13040430.

Krajcar Bronić, I., Barešić, J., Borković, D., Sironić, A., Mikelić, I. L. and Vreča, P. (2020): Long-term isotope records of precipitation in Zagreb, Croatia. *Water*, *12*(1), https://doi.org/10.3390/w12010226.

Krajcar Bronić, I., Barešić, J., Sironić, A., Lovrenčić Mikelić, I., Borković, D., Horvatinčić, N. and Kovač, Z. (2020): Isotope composition of precipitation, groundwater, and surface and lake waters from the Plitvice Lakes, Croatia. *Water, 12*(9), https://doi.org/10.3390/w12092414.

Krvavica, N. and Rubinić, J. (2020). Evaluation of design storms and critical rainfall durations for flood prediction in partially urbanized catchments. *Water*, *12*(7), https://doi.org/10.3390/w12072044.

Krvavica, N., Lončar, G., Oskoruš, D. and Ružić, I. (2021): Prilog unapređenju sustava hidroloških mjerenja prijelaznih voda: Hidraulička i spektralna analiza protoka na rijeci Neretvi. *Hrvatske vode*, 29 (2021), 118, 255-274.

Kulaš, A., Marković, T., Žutinić, P., Kajan, K., Karlović, I., Orlić, S., Keskin, E., Filipović, V. and Gligora Udovič, M. (2021): Succession of microbial community in a small water body within the alluvial aquifer of a large river. *Water*, *13*(2), https://doi.org/10.3390/w13020115.

Kvesić, M., Vojković, M., Kekez, T., Maravić, A. and Andričević, R. (2021): Spatial and temporal vertical distribution of chlorophyll in relation to submarine wastewater effluent discharges. *Water*, *13*(15), https://doi.org/10.3390/w13152016.

Lacko, M., Potočki, K., Škreb, K. A. and Bezak, N. (2022): Joint modelling of flood hydrograph peak, volume and duration using copulas case study of Sava and Drava River in Croatia, Europe. *Water*, *14*(16), https://doi.org/10.3390/w14162481.

Lajtner, J., Kozak, A., Špoljar, M., Kuczyńska-Kippen, N., Dražina, T., Sertić Perić, M., Tkalčec, I., Gottstein, S. and Zrinščak, I. (2022): Gastropod assemblages associated with habitat heterogeneity and hydrological shifts in two shallow waterbodies. *Water*, *14*(15), https://doi.org/10.3390/w14152290.

Larva, O., Brkić, Ž., Briški, M., Seidenfaden, I. K., Koch, J., Stisen, S. and Refsgaard, J. C. (2022): An ensemble approach for predicting future groundwater levels in the Zagreb aquifer impacted by both local recharge and upstream river flow. *Journal of Hydrology*, *613*, 128433, https://doi.org/https://doi.org/10.1016/j.jhydrol.2022.128433.

Lončar, G., Krvavica, N., Gotovac, H., Oskoruš, D. and Kulić, T. (2020): Numerička analiza djelovanja brane na sprječavanje prodora slane vode duž korita rijeke Neretve. *Hrvatske vode*, 28 (2020), 112, 113-124.

Lučić, M., Mikac, N., Bačić, N. and Vdović, N. (2021): Appraisal of geochemical composition and hydrodynamic sorting of the river suspended material: Application of time-integrated suspended sediment sampler in a medium-sized river (the Sava River catchment). *Journal of Hydrology*, *597*, 125768, https://doi.org/https://doi.org/10.1016/j.jhydrol.2020.125768.

Lukač Reberski, J., Terzić, J., Maurice, L. D. and Lapworth, D. J. (2022): Emerging organic contaminants in karst groundwater: A global level assessment. *Journal of Hydrology*, *604*, 127242, https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.127242.

Mance, D., Radišić, M., Lenac, D. and Rubinić, J. (2022): Hydrological behavior of karst systems identified by statistical analyses of stable isotope monitoring results. *Hydrology*, *9*(5), https://doi.org/10.3390/hydrology9050082.

Margeta, J. (2019): A review of sustainable septage management strategies on the islands in Croatia. *Water Science and Technology*, *79*(10), 1833–1843, https://doi.org/10.2166/wst.2019.184.

Margeta, J. and Marasović, K. (2020): The restoration of the Roman water supply system in 1880 for the water supply to Split. *Water Supply*, *20*(3), 1091–1102, https://doi.org/10.2166/ws.2020.038.

Marković, T., Karlović, I., Orlić, S., Kajan, K. and Smith, A. C. (2022): Tracking the nitrogen cycle in a vulnerable alluvial system using a multi proxy approach: Case study Varaždin alluvial aquifer, Croatia. *Science of the Total Environment*, *853*, 158632, https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.158632.

Marković, T., Karlović, I., Perčec Tadić, M. and Larva, O. (2020): Application of stable water isotopes to improve conceptual model of alluvial aquifer in the Varaždin area. *Water*, *12*(2), https://doi.org/10.3390/w12020379.

Marković, T., Sladović, Ž., Domitrović, D., Karlović, I. and Larva, O. (2022): Current utilization and hydrochemical characteristics of geothermal aquifers in the Bjelovar sub-depression. *Geologia Croatica*, *75*(2), 223–233, https://doi.org/10.4154/gc.2022.21.

Markovinović, D., Cetl, V., Šamanović, S. and Bjelotomić Oršulić, O. (2022): Availability and accessibility of hydrography and hydrogeology spatial data in Europe through INSPIRE. *Water*, *14*(9), https://doi.org/10.3390/w14091499.

Meaški, H., Biondić, R., Loborec, J. and Oskoruš, D. (2021): The possibility of Managed Aquifer Recharge (MAR) for normal functioning of the public water-supply of Zagreb, Croatia. *Water*, *13*(11), https://doi.org/10.3390/w13111562.

Nakić, D., Djurin, B., Hunt, J. and Dadar, S. (2022): A novel procedure for minimizing the volume of water tanks in water supply systems. *Water*, *14*(11), https://doi.org/10.3390/w14111731.

Nakić, Z., Kovač, Z., Parlov, J. and Perković, D. (2020): Ambient background values of selected chemical substances in four groundwater bodies in the Pannonian region of Croatia. *Water*, *12*(10), https://doi.org/10.3390/w12102671.

Oskoruš, D., Kapelj, S., Zavrtnik, S. and Leskovar, K. (2022): Suspended sediment metal and metalloid composition in the Danube River basin, Croatia. *Water*, *14*(21), https://doi.org/10.3390/w14213552.

Pandžić, K., Kobold, M., Oskoruš, D., Biondić, B., Biondić, R., Bonacci, O., Likso, T. and Curić, O. (2020): Standard normal homogeneity test as a tool to detect change points in climate-related river discharge variation: case study of the Kupa River basin. *Hydrological Sciences Journal*, *65*(2), 227–241, https://doi.org/10.1080/02626667.2019.1686507.

Pandžić, K., Likso, T., Trninić, D., Oskoruš, D., Macek, K. and Bonacci, O. (2022): Relationships between large-scale atmospheric circulation and monthly precipitation and discharge in the Danube River basin. *Theoretical and Applied Climatology*, 148 (2022), 1-2, 767-777, doi:10.1007/s00704-022-03977.

Parać, M., Cuculić, V., Cukrov, N., Geček, S., Lovrić, M. and Cukrov, N. (2022): Microplastic distribution through the salinity gradient in a stratified estuary. *Water*, *14*(20), https://doi.org/10.3390/w14203255.

Parlov, J., Kovač, Z., Nakić, Z. and Barešić, J. (2019): Using water stable isotopes for identifying groundwater recharge sources of the unconfined alluvial Zagreb aquifer (Croatia). *Water*, *11*(10), https://doi.org/10.3390/w11102177.

Pavlić, K. and Parlov, J. (2019): Cross-correlation and cross-spectral analysis of the hydrographs in the northern part of the Dinaric karst of Croatia. *Geosciences*, *9*(2), 86, https://doi.org/10.3390/geosciences9020086.

Pavlović, P., Marković, M., Kostić, O., Sakan, S., Đorđević, D., Perović, V., Pavlović, D., Pavlović, M., Čakmak, D., Jarić, S., Paunović, M. and Mitrović, M. (2019): Evaluation of potentially toxic element contamination in the riparian zone of the River Sava. *CATENA*, *174*, 399–412, https://doi.org/https://doi.org/10.1016/j.catena.2018.11.034.

Radišić, M., Rubinić, J., Ružić, I. and Brozinčević, A. (2021): Hydrological system of the Plitvice Lakes – Trends and changes in water levels, inflows, and losses. *Hydrology*, *8*(4), https://doi.org/10.3390/hydrology8040174.

Romić, D., Castrignanò, A., Romić, M., Buttafuoco, G., Bubalo Kovačić, M., Ondrašek, G. and Zovko, M. (2020): Modelling spatial and temporal variability of water quality from different monitoring stations using mixed effects model theory. *Science of the Total Environment*, *04*, 135875, https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.135875

Rossi, N., Bačić, M., Kovačević, M. S. and Librić, L. (2021): Development of fragility curves for piping and slope stability of river levees. *Water*, *13*(5), https://doi.org/10.3390/w13050738.

Sakan, S., Frančišković-Bilinski, S., Đorđević, D., Popović, A., Sakan, N., Škrivanj, S. and Bilinski, H. (2021): Evaluation of element mobility in river sediment using different single extraction procedures and assessment of probabilistic ecological risk. *Water*, *13*(10), https://doi.org/10.3390/w13101411.

Sakan, S., Frančišković-Bilinski, S., Đorđević, D., Popović, A., Škrivanj, S. and Bilinski, H. (2020): Geochemical fractionation and risk assessment of potentially toxic elements in sediments from Kupa River, Croatia. *Water*, *12*(7), https://doi.org/10.3390/w12072024.

Selak, A., Boljat, I., Lukač Reberski, J., Terzić, J. and Čenčur Curk, B. (2020): Impact of land use on karst water resources – A case study of the Kupa (Kolpa) transboundary river catchment. *Water*, *12*(11), https://doi.org/10.3390/w12113226.

Selak, A., Reberski, J. L., Klobučar, G. and Grčić, I. (2022): Ecotoxicological aspects related to the occurrence of emerging contaminants in the Dinaric karst aquifer of Jadro and Žrnovnica springs. *Science of the Total Environment*, *825*, 153827, https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.153827.

Selak, L., Marković, T., Pjevac, P. and Orlić, S. (2022): Microbial marker for seawater intrusion in a coastal Mediterranean shallow Lake, Lake Vrana, Croatia. *Science of the Total Environment, 849*, 157859, https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.157859.

Stroj, A., Briški, M. and Oštrić, M. (2020). Study of groundwater flow properties in a karst system by coupled analysis of diverse environmental tracers and discharge dynamics. *Water*, *12*(9), https://doi.org/10.3390/w12092442.

Sudar, V., Malvić, T., Vujnović, T. and Ivšinović, J. (2021): Modeling of the geological probability procedure for the prediction of high flows in small streams, Case study of Medvednica Mt., Croatia. *Hydrology*, *8*(2), https://doi.org/10.3390/hydrology8020083.

Surić, M., Czuppon, G., Lončarić, R., Bočić, N., Lončar, N., Bajo, P. and Drysdale, R. N. (2020): Stable isotope hydrology of cave groundwater and its relevance for speleothem-based paleoenvironmental reconstruction in Croatia. *Water*, *12*(9), https://doi.org/10.3390/w12092386.

Susmel, S., Girolametti, F., Fonti, V., Figueredo, F., Scognamiglio, V., Antonacci, A., Manna, V., Bilić, J., Soljan, V., De Bortoli, N., Martin, T., Mion, M., Kekez, T., Andricevic, R., Ben Aissa, S., Celussi, M. and Annibaldi, A. (2022): The Interreg project AdSWiM: Managed use of treated wastewater for the quality of the Adriatic Sea. *Water*, *14*(16), https://doi.org/10.3390/w14162460.

Šarović, K., Burić, M. and Klaić, Z. B. (2022): SIMO v1.0: simplified model of the vertical temperature profile in a small, warm, monomictic lake. *Geoscientific Model Development*, *15*(22), 8349–8375, https://doi.org/10.5194/gmd-15-8349-2022.

Šiljeg, A., Marić, I., Cukrov, N., Domazetović, F. and Roland, V. (2020): A multiscale framework for sustainable management of tufa-forming watercourses: A case study of National Park "Krka", Croatia. *Water*, *12*(11), https://doi.org/10.3390/w12113096.

Šperac, M. and Zima, J. (2022): Assessment of the impact of climate extremes on the groundwater of eastern Croatia. *Water*, *14*(2), https://doi.org/10.3390/w14020254.

Šrajbek, M., Kranjčević, L., Kovač, I. and Biondić, R. (2022): Groundwater nitrate pollution sources assessment for contaminated wellfield. *Water*, *14*(2), https://doi.org/10.3390/w14020255.

Šreng, Ž., Lončar, G. and Grubišić, M. (2019): Methodology for determining the die-off coefficient of Enterococci in the conditions of transport through the karst aquifer – Case study: Bokanjac–Poličnik catchment. *Water*, *11*(4), https://doi.org/10.3390/w11040820.

Švob, M., Domínguez-Villar, D. and Krklec, K. (2022): Characterization of soil drainage dynamics on karst terrains by developing a site-specific reservoir cascade scheme hydrological model with preferential flows. *Journal of Hydrology*, *612*, 128147, https://doi.org/https://doi.org/10.1016/j.jhydrol.2022.128147.

Tadić, L., Brleković, T., Hajdinger, A. and Španja, S. (2019): Analysis of the inhomogeneous effect of different meteorological trends on drought: An example from continental Croatia. *Water*, *11*(12), https://doi.org/10.3390/w11122625.

Telak, L. J., Pereira, P., Ferreira, C. S. S., Filipović, V., Filipović, L. and Bogunović, I. (2020): Short-term impact of tillage on soil and the hydrological response within a fig (Ficus Carica) orchard in Croatia. *Water*, *12*(11), https://doi.org/10.3390/w12113295.

Terzić, J., Frangen, T., Borović, S., Reberski, J. L. and Patekar, M. (2022): Hydrogeological assessment and modified conceptual model of a Dinaric karst island aquifer. *Water*, *14*(3), https://doi.org/10.3390/w14030404.

Terzić, J., Grgec, D., Lukač Reberski, J., Selak, A., Boljat, I. and Filipović, M. (2021): Hydrogeological estimation of brackish groundwater lens on a small Dinaric karst island: Case study of Ilovik, Croatia. *CATENA*, *204*, 105379, https://doi.org/https://doi.org/10.1016/j.catena.2021.105379.

Vilenica, M. and Mihaljević, Z. (2022): Odonata assemblages in anthropogenically impacted habitats in the Drava River – A long-term study. *Water*, *14*(19), https://doi.org/10.3390/w14193119.

Vlaičević, B., Gulin, V., Matoničkin Kepčija, R. and Turković Čakalić, I. (2022): Periphytic ciliate communities in lake ecosystem of temperate riverine floodplain: Variability in taxonomic and functional composition and diversity with seasons and hydrological changes. *Water*, *14*(4), https://doi.org/10.3390/w14040551.

Vrsalović, A., Andrić, I., Buzjak, N. and Bonacci, O. (2022): Karst lake's dynamics analysis as a tool for aquifer characterisation at field scale, Example of cryptodepression – Red Lake in Croatia. *Water*, *14*(5), https://doi.org/10.3390/w14050830.

Zhu, S., Bonacci, O. and Oskoruš, D. (2019): Assessing sediment regime alteration of the lower Drava river. *E-GFOS: elektronički časopis građevinskog fakulteta Osijek*, 10 (2019), 19, 1-12 doi:10.13167/2019.19.1.

Zhu, S., Bonacci, O., Oskoruš, D., Hadzima-Nyarko, M. and Wu, S. (2019): Long term variations of river temperature and the influence of air temperature and river discharge: case study of Kupa River watershed in Croatia. *Journal of Hydrology and Hydromechanics*, 67, 4, 305-313, doi:10.2478/johh-2019-0019.

# 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 (Figure 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.

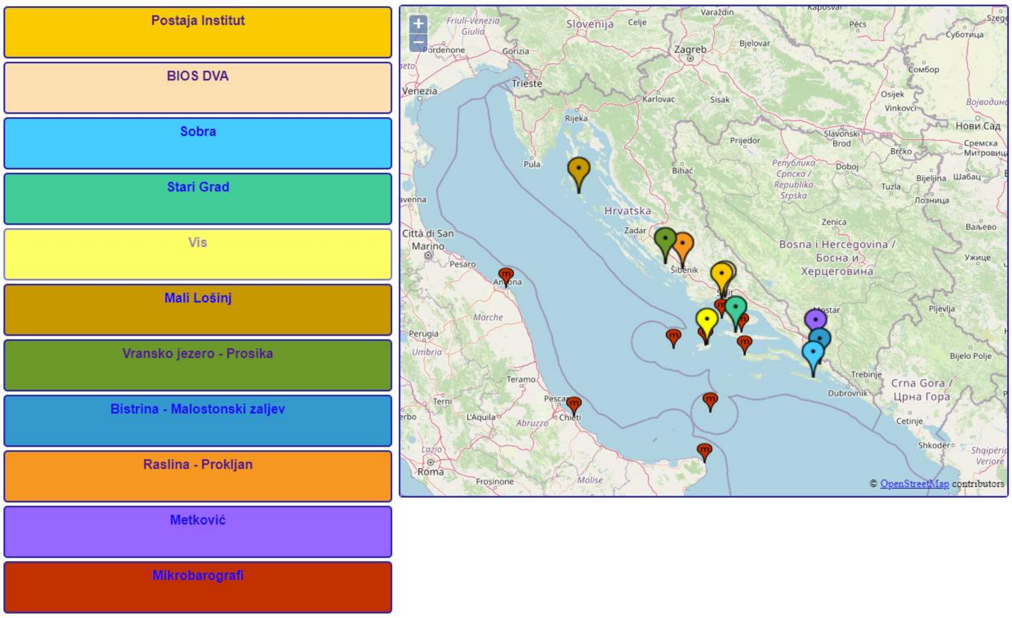


**Figure 1.** Automatic meteo-ocean stations of the Institute of Oceanography and Fisheries (IOF).

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 (Figure 2); studies of bora events based on high-resolution wind observations and high-resolution meteorological model simulations (Figure 3); investigation of lake-land breezes produced by a small, elongated lake (Figure 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 (Figure 5); identification of diverse air pollution sources in urban environment based on positive matrix factorization and conditional bivariate polar plots (Figure 6); and studies of the observed, wind-forced internal seiches in lakes (Figure 7).

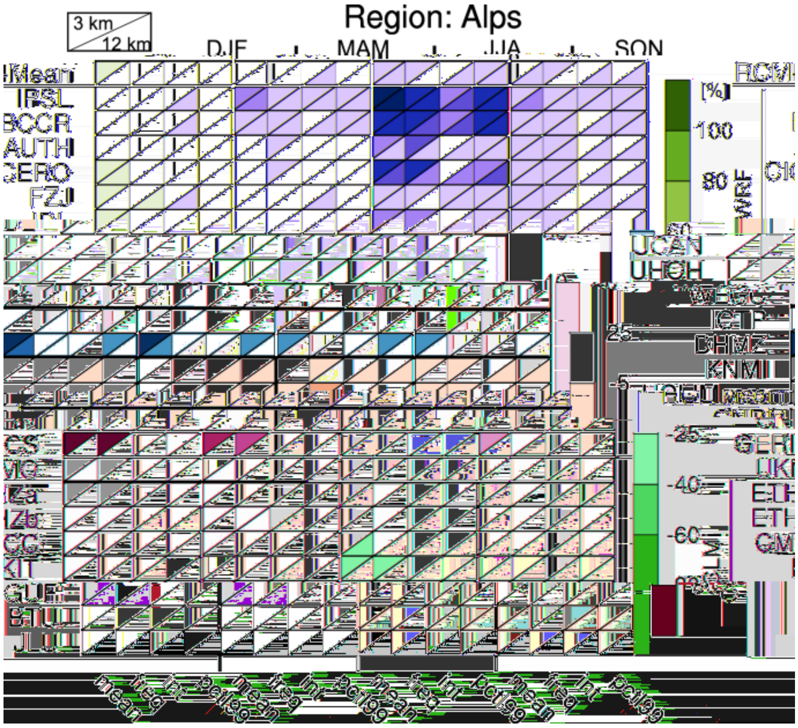


**Figure 2.** Relative bias of a daily precipitation in winter, spring, summer, and fall. White colour indicates an acceptable bias range which accounts for the uncertainties in the observations due to the systematic rain gauge under-catch (~20%) (Ban et al., 2021).

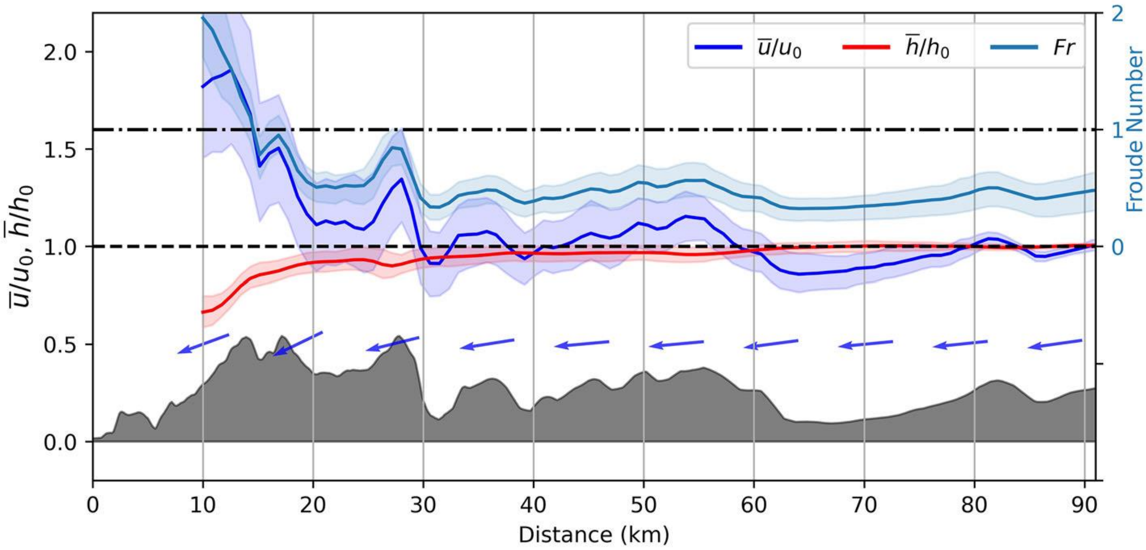


**Figure 3.** Median normalized layer-mean wind speed *u/u*0, median normalized inversion-top height *h/h*0, and barotropic Froude number *Fr* (solid lines) for several cross-sections along the very long lasting bora flow over Kvarner region. Shaded areas represent the 10–90% quantile span. The dot–dashed 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).

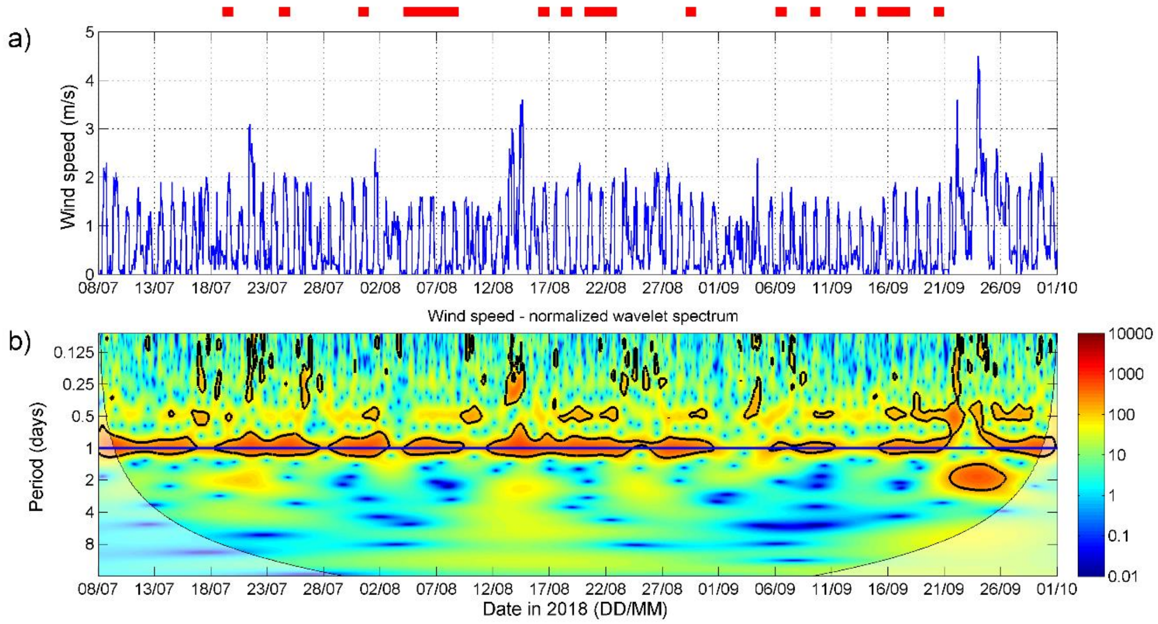


**Figure 4.** Observed wind speed (a) and the corresponding normalized wavelet spectrum (b) in the vicinity of Kozjak (Plitvice Lakes, Croatia) for summer 2018. Time intervals with lake-land breezes are indicated in red above panel a. The horizontal blue line in panel b corresponds to a period of 24 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).

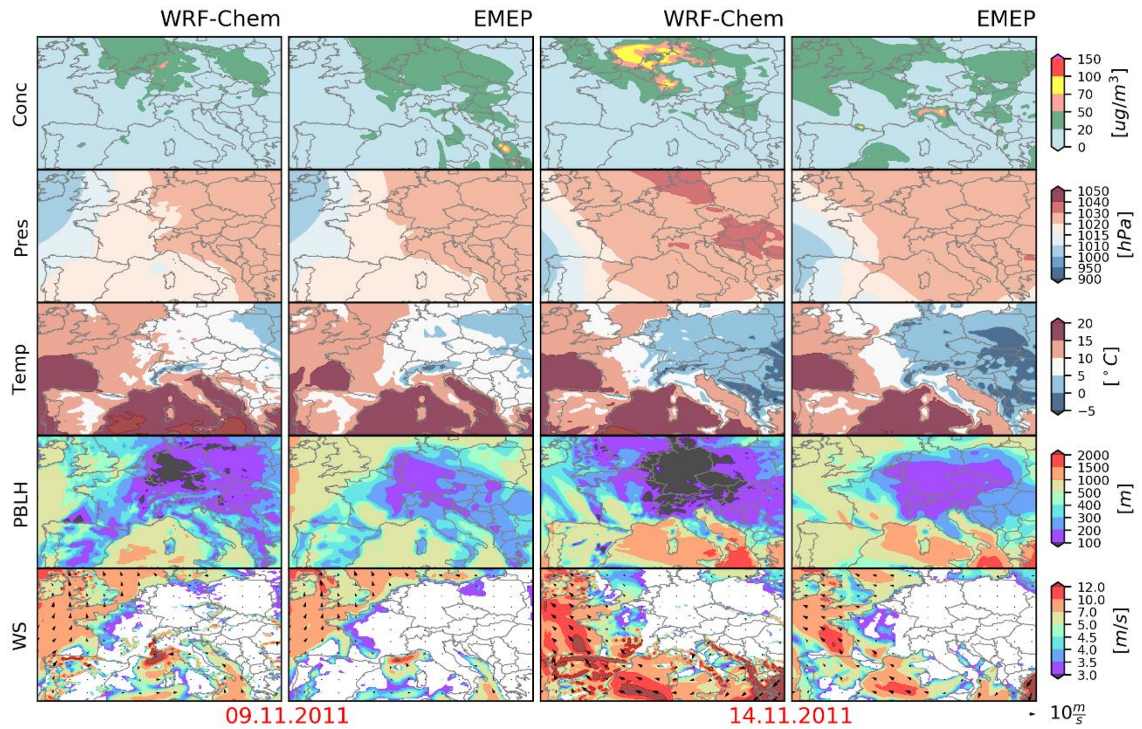


**Figure 5.** Daily mean values of $PM_{10}$ concentrations (Conc), sea level pressure (Pres), temperature at 2 m (Temp), planetary boundary layer height (PBLH), and wind speed and direction (WS) for two days in November 2011, obtained by the WRF-Chem and EMEP models (Gašparac et al., 2020).

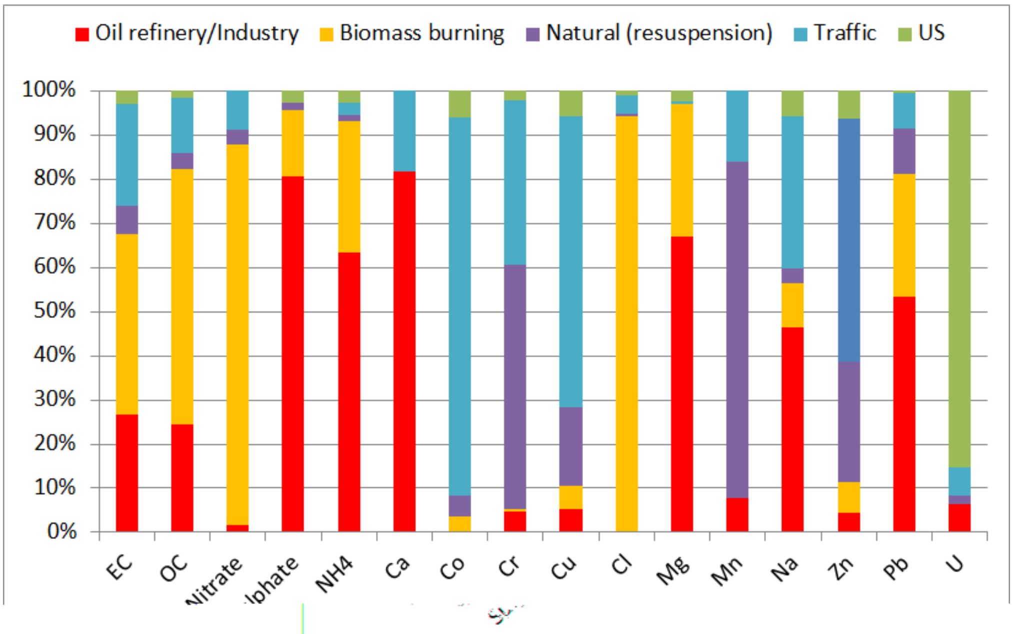


**Figure 6.** Contribution of five different emission sources and unidentified sources (US) to species concentrations in PM2.5 (%) determined from positive matrix factorization analysis for Slavonski Brod, Croatia, during 2015 (Jeričević et al., 2019).

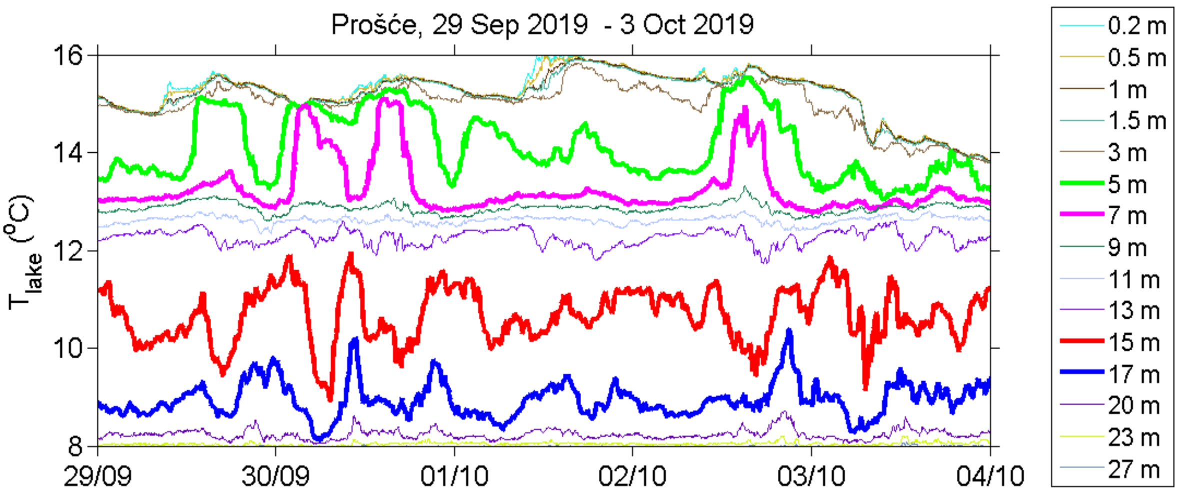


**Figure 7.** Prominent lake temperature oscillations observed in Prošće (Plitvice Lakes, Croatia) at depths of 5, 7, 15 and 17 m. These oscillations point to the second vertical, first horizontal (V2H1) seiche mode. They are produced by along-basin stronger southern winds, which are associated with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


Altobelli, F., Monteleone, A., Cimino, O., Dalla Marta, A., Orlandini, S., Trestini, S., Toulios, L., Nejedlik, P., Vučetić, V., Cicia, G., Panico, T., et al. (2019): Farmers' willingness to pay for an environmental certification scheme: Promising evidence for water saving, *Outlook Agric.*, **48**, 136–142, DOI:10.1177/0030727019841059.

Anić, M. (2019): Inter-annual variability of CO2 exchange between pedunculate oak forest (Quercus robur L.) and the atmosphere, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 106 pp.

Anić, M., Osrečak, M., Andabaka, Ž., Tomaz, I., Večenaj, Ž., Jelić, D., Kozina, B., Karoglan Kontić, J. and Karoglan, M. (2021): The effect of leaf removal on canopy microclimate, vine performance and grape phenolic composition of Merlot (Vitis vinifera L.) grapes in the continental part of Croatia, *Sci. Hortic.*, **285**, 110161, 8, DOI:10.1016/j.scienta.2021.110161.

Babić, N., Stiperski, I., Marinović, I., Večenaj, Ž. and De Wekker, S.F.J. (2021): Examining relationships between entrainment- driven scalar dissimilarity and surface energy balance underclosure in a semiarid valley, *Agric. For. Meteorol.*, **288-289**, DOI:10.1016/j.agrformet.2020.108272.

Bajić, A., Cvitan, L., Gajić-Čapka, M., Perčec Tadić, M., Sokol Jurković, R., Zaninović, K. (2019): Prostorno planiranje, urbanizam i graditeljstvo, Primijenjena znanstvena istraživanja u Državnom hidrometeorološkom zavodu: u povodu 50 godina istraživanja i 70 godina osnivanja DHMZ-a, Ivančan-Picek, B. (ur.), Zagreb, Državni hidrometeorološki zavod, 75-86.

Ban, N., Caillaud, C., Coppola, E., Pichelli, E., Sobolowski, S., Adinolfi, M., Ahrens, B., Alias, A., Anders, I., Bastin, S., Belušić, D., Berthou, S., Brisson, E., Cardoso, R. M., Chan, S. C., Christensen, O. B., Fernández, J., Fita, L., Frisius, T., Gašparac, G., Giorgi, F., et al. (2021): The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, Part I: evaluation of precipitation, *Clim. Dyn.*, **57**, 275–302, https://doi.org/10.1007/s00382-021-05708-w.

Barčić, D., Dubravac, T. and Vučetić, M. (2020): Potential hazard of open space fire in black pine stands, Pinus nigra J.F. Arnold, in regard to fire severity, *South-East Eur. For.*, **11,** 161–168, DOI: org/10.15177/seefor.20-16.

Beg Paklar, G., Vilibić, I., Grbec, B., Matić, F., Mihanović, H., Džoić, T., Šantić, D., Šestanović, S., Šolić, M., Ivatek-Šahdan, S. and Kušpilić, G. (2020): Record-breaking salinities in the middle Adriatic during summer 2017 and concurrent changes in the microbial food web, *Prog. Oceanogr.*, **185**, 102345, 17, DOI: 10.1016/j.pocean.2020.102345.

Belušić Vozila, A., Güttler, I., Ahrens, B., Obermann-Hellhund, A. and Telišman Prtenjak, M. (2019): Wind over the Adriatic region in CORDEX climate change scenarios, *J. Geophys. Res.-Atmos.*, **124**, 110–130, doi:10.1029/2018JD028552.

Belušić Vozila, A., Telišman Prtenjak, M. and Güttler, I. (2021): A weather type classification and its application to near-surface wind climate change projections over the Adriatic region, *Atmosphere*, **12**, 948, https://www.mdpi.com/2073-4433/12/8/948.

Berthou, S., Roberts, M. J., Vanniere, B., Ban, N., Belušić, D., et al. (2022): Convection in future winter storms over Northern Europe, *Environ. Res. Lett.*, **17**, 114055, DOI: 10.1088/1748-9326/aca03a.

Blauhut, V., Stoelzle, M., Ahopelto, L., Brunner, M., I., Teutschbein, C., Wendt, D., E., Akstinas, V., Bakke, S., J., B., Lucy J., Bartošová, L., et al. (2022): Lessons from the 2018–2019 European droughts, a collective need for unifying drought risk management, *Nat. Hazards Earth Syst. Sci.*, **22**, 2201–2217, DOI:10.5194/nhess-22-2201-2022.

Bonacci, O., Andrić, I., Roje-Bonacci, T., Oskoruš, D. and Vrsalović, A. (2020): Impact of large human constructions on a karst river hydrology: Case of the Cetina River, Dinaric karst, *Acta Hydrotech.*, **33**, 155–174, DOI: 10.15292/acta.hydro.2020.10.

Boras, M., Herceg-Bulić, I., Žgela, M. and Nimac, I. (2022): Temperature characteristics and heat load in the city of Dubrovnik, *Geofizika*, **39**, 259–279, https://doi.org/10.15233/gfz.2022.39.16.

Cesarec, K., Oskoruš, D., Pandžić, K. (2019): Vodno gospodarstvo – Hidrološki dio, Primijenjena znanstvena istraživanja u Državnom hidrometeorološkom zavodu: u povodu 50 godina istraživanja i 70 godina osnivanja DHMZ-a, Ivančan-Picek, B. (ur.), Zagreb, Državni hidrometeorološki zavod, 199-223.

Cindrić Kalin, K. (2020): Methods for analysis of dry spell durations based on the theory of extremes, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 126 pp (in Croatian).

Cindrić Kalin, K. and Pasarić, Z. (2022): Regional patterns of dry spell durations in Croatia, *Int. J. Climatol.*, DOI:10.1002/joc.7545.

Cindrić Kalin, K., Cvitan, L., Gajić-Čapka, M., Güttler, I., Perčec Tadić, M., Srnec, L., Zaninović, K. (2019): Klima i klimatske promjene, Primijenjena znanstvena istraživanja u Državnom hidrometeorološkom zavodu u povodu 50 godina istraživanja i 70 godina osnivanja DHMZ-a, Ivančan-Picek, B., (ur.), Zagreb, Državni hidrometeorološki zavod, 49-74.

Cindrić, K., Gajić-Čapka, M. (2019): Vodno gospodarstvo – Meteorološki dio, Primijenjena znanstvena istraživanja u Državnom hidrometeorološkom zavodu: u povodu 50 godina istraživanja i 70 godina osnivanja DHMZ-a, Ivančan-Picek, B. (ur.), Zagreb, Državni hidrometeorološki zavod, 184-198.

Cuxart, J., Telišman Prtenjak, M. and Matjačić, B. (2021): Pannonian basin nocturnal boundary layer and fog formation: Role of topography, *Atmosphere*, **12**, 712, https://doi.org/10.3390/atmos12060712 .

Čavlek, N., Cooper, C., Krajinović, V., Srnec, L. and Zaninović, K. (2019): Destination climate adaptation, *J. Hosp. Tour. Res.*, **43**, 314–322, DOI:10.1177/1096348018793507.

Čavlina Tomašević, I. (2022): Analysis of extreme fire weather during catastrophic wildfires in Croatia and Australia, PhD thesis, Cotutelle, Faculty of Science, University of Zagreb, Zagreb, 202 pp.

Čavlina Tomašević, I., Cheung K., Vučetić, V., Fox-Hughes, P., Horvath, K., Telišman Prtenjak, M., Beggs, P. J., Malečić, B. and Milić, V. (2022): The 2017 Split wildfire in Croatia: Evolution and the role of meteorological conditions, *Nat. Hazards Earth Syst. Sci.*, **22**, 3143–3165, doi:10.5194/nhess-2022-116.

Čavlina Tomašević, I., Cheung, K., K., W., Vučetić, V. and Fox-Hughes, P. (2022): Comparison of wildfire meteorology and climate at the Adriatic coast and southeast Australia, *Atmosphere*, **13**, 755, 27, DOI:10.3390/atmos13050755.

Ferina, J., Vučetić, V., Bašić T. and Anić, M. (2021): Spatial distribution and long-term changes in water balance components in Croatia, *Theor. Appl. Climatol*., **144**, 1311–1333, DOI:10.1007/s00704-021-03593-1.

Freistetter, NC., Médus, E., Hippi, M., Kangas, M., Dobler, A., Belušić, D., Käyhkö, J. and Partanen, A-I. (2022): Climate change impacts on future driving and walking conditions in Finland, Norway and Sweden, *Reg. Environ. Change*, **22**, 58, DOI: 10.1007/s10113-022-01920-4.

Gašparac, G. (2020): Development and application of the coupled atmospheric-chemistry modelling system over the Republic of Croatia, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 105 pp.

Gašparac, G., Jeričević, A., Kumar, P. and Grisogono, B. (2020): Regional-scale modelling for the assessment of atmospheric particulate matter concentrations at rural background locations in Europe, *Atmos. Chem. Phys*., **20**, 6395–6415, https://doi.org/10.5194/acp-20-6395-2020.

Golem, P., Večenaj, Ž., Kozmar, H. and Grisogono, B. (2022a): The effect of orography on Bora wind turbulence, *Bound.-Layer Meteorol*, DOI: 10.1007/s10546-022-00767-w.

Golem, P., Toman, I., Večenaj, Ž., Kozmar, H. and Grisogono, B. (2022b): Unique windward measurements and WRF simulation of an extremely long-lasting severe Bora event, *Bound.-Layer Meteorol*., **183**, 495–504.

Grisogono, B., Sun, J. and Belušić, D., (2020): A note on MOST and HOST for turbulence parameterization, *Quart. J. Roy. Meteorol. Soc*., **146**, 1991–1997, https://doi.org/10.1002/qj.3770.

Güttler, I., Stilinović, T., Srnec, L., Branković, Č., Coppola, E. and Giorgi, F. (2020): Performance of RegCM4 simulations over Croatia and adjacent climate regions, *Int. J. Climatol*., **40**, 5843–5862, DOI: 10.1002/joc.6552.

Ha, M. T., Bastin, S., Drobinski, P., Fita, L., Polcher, J., Bock, O., Chiriaco, M., Belušić, D., et al. (2022): Precipitation frequency in Med-CORDEX and EURO-CORDEX ensembles from 0.44° to convection-permitting resolution: impact of model resolution and convection representation, *Clim. Dyn.*, DOI: 10.1007/s00382-022-06594-6.

Herjavić, G., Matasović, B., Arh, G. and Kovač-Andrić, E. (2020): Investigation of non-methane hydrocarbons at a central Adriatic marine site Mali Lošinj, Croatia, *Atmosphere*, **11**, 651, 14, DOI: 10.3390/atmos11060651.

Horvath, K., Šepić, J. and Telišman Prtenjak, M. (2019): Atmospheric forcing conducive for the Adriatic 25 June 2014 meteotsunami event, Meteorology and Climatology of the Mediterranean and Black Seas, Vilibić, I., Horvath, K., Palau, J.,L., (Eds), Basel, Switzerland, Birkhäuser, Springer Nature Switzerland AG, 97-117.

Ivasić, S. (2022): The effects of teleconnections in climate variability of north Atlantic European region, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 107 pp.

Ivasić, S. and Herceg-Bulić, I. (2022): A modelling study of the impact of tropical SSTs on the variability and predictable components of seasonal atmospheric circulation in the North Atlantic–European region, *Clim. Dyn*., https://doi.org/10.1007/s00382-022-06357-3.

Ivasić, S. Herceg-Bulić, I. and King, M. P. (2021): Recent weakening in the winter ENSO teleconnection over the North Atlantic European region, *Clim. Dyn*., **57**, 1953–1972, https://doi.org/10.1007/s00382-021-05783-z.

Ivušić, S., Güttler, I., Somot, S., Guérémy, J., F., Horvath, K. and Alias, A. (2021): Modelling extreme precipitation over the Dinaric Alps: An evaluation of the CNRM-ALADIN regional climate model, *Q. J. R. Meteorol. Soc*., **1**, 1–29, DOI:10.1002/qj.4187.

Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Belda, M., Benestad, R., Boberg, F., Buonomo, E., Cardoso, R., M., et al. (2020): Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community, *Reg. Environ. Change*, **20**, DOI:10.1007/s10113-020-01606-9.

Janeković, I., Mihanović, H.,Vilibić, I., Grčić, B.,; Ivatek-Šahdan, S., Tudor, M. and Đakovac, T. (2019): Using multi-platform 4D-Var data assimilation to improve modelling of Adriatic Sea dynamics, *Ocean Model*., **146**, 101538, DOI: 10.1016/j.ocemod.2019.101538.

Jelić, D. (2022): Hail characteristics in present and future climate over Croatia, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 116 pp (in Croatian).

Jelić, D., Megyeri, O. A., Malečić, B., Belušić Vozila, A., Strelec Mahović, N., and Telišman Prtenjak, M. (2020): Hail climatology along the northeastern Adriatic, *J. Geophys. Res*., **125**, e2020JD032749, https://doi.org/10.1029/2020JD032749.

Jelić, D., Telišman Prtenjak, M., Malečić, B., Belušić Vozila, A., Megyeri, O. A. and Renko, T. (2021): A new approach for the analysis of deep convective events: Thunderstorm Intensity Index, *Atmosphere*, **12**, 908, https://www.mdpi.com/2073-4433/12/7/908.

Jeričević, A., Gašparac, G., Maslać Mikulec, M., Kumar, P. and Telišman Prtenjak, M. (2019): Identification of diverse air pollution sources in a complex urban area of Croatia, *J. Environ. Manage*., **243**, 67–77, https://doi.org/10.1016/j.jenvman.2019.04.024.

Kehler-Poljak, G. (2020): The relationship between deep convection and sea/land breeze circulation along the eastern Adriatic coast, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 128 pp (in Croatian).

Keresturi, E. (2021): Initial condition perturbations in a convective scale ensemble prediction system, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 108 pp.

Keresturi, E., Wang, Y., Meier, F., Weidle, F., Wittmann, C. and Atencia, A. (2019): Improving initial condition perturbations in a convection-permitting ensemble prediction system, *Q. J. R. Meteorol. Soc*., **145**, 993–1012, DOI:10.1002/qj.3473.

Kjellström, E., Hansen, F. and Belušić, D. (2022): Contributions from changing large-scale atmospheric conditions to changes in Scandinavian temperature and precipitation between two climate normals, *TellusA*, **74**, 204–221, DOI: 10.16993/tellusa.49.

Klaić, Z. B., Babić, K. and Orlić, M. (2020a): Evolution and dynamics of the vertical temperature profile in an oligotrophic lake, *Hydrol. Earth Syst. Sci.*, **24**, 3399–3416, https://doi.org/10.5194/hess-24-3399-2020.

Klaić, Z. B., Babić, K. and Mareković, T. (2020b): Internal seiches in a karstic mesotrophic lake (Prošće, Plitvice Lakes, Croatia), *Geofizika*, **37**, 157–179, https://doi.org/10.15233/gfz.2020.37.11.

Klaić, Z. B., Leiva-Guzmán, M. A. and Brozinčević, A. (2022): Influence of number of visitors and weather conditions on airborne particulate matter mass concentrations at the Plitvice Lakes National Park, Croatia during summer and autumn, *Arh. Hig. Rada Toksikol*., **73**, 1–14, https://doi.org/10.2478/aiht-2022-73-3610.

Kozmar, H. and Grisogono, B. (2021): Characteristics of downslope wind storms in the view of the typical atmospheric boundary layer. Chapter 5 in: *The Oxford Handbook of Non-Synoptic Wind Storms*, edited by H. Hangan and A. Kareem. Oxford Univ. Press, 85-114, DOI: https://doi.org/10.1093/oxfordhb/9780190670252.013.15.

Lakatos, M., Szentes, O., Cindrić Kalin, K., Nimac, I., Kozjek, K., Cheval, S., Dumitrescu, A., Irașoc, A., Stepanek, P., Farda, A., et al. (2021): Analysis of sub-daily precipitation for the PannEx region, *Atmosphere*, **12**, 1–18, DOI: 10.3390/atmos12070838.

Lind, P., Belušić, D., Médus, E., et al. (2022): Climate change information over Fenno-Scandinavia produced with a convection-permitting climate model, *Clim. Dyn.*, DOI: 10.1007/s00382-022-06589-3.

Lipzig, N.P.M.v., Walle, J.V.d., Belušić, D. et al. (2022): Representation of precipitation and top-of-atmosphere radiation in a multi-model convection-permitting ensemble for the Lake Victoria Basin (East-Africa), *Clim. Dyn*., DOI: 10.1007/s00382-022-06541-5.

Lűkő, G., Torma, P., Krámer, T., Weidinger, T., Večenaj, Ž. and Grisogono, B. (2020): Observation of wave-driven air–water turbulent momentum exchange in a large but fetch-limited shallow lake, *Adv. Sci. Res*., **17**, 175–182, https://asr.copernicus.org/articles/17/175/2020/.

Malečić, B., Telišman Prtenjak, M., Horvath, K., Jelić, D., Mikuš Jurković, P., Ćorko, K. and Strelec Mahović, N. (2022): Performance of the HAILCAST and Lightning Potential Index in simulating hail events over the Croatian area in the mesoscale model – Sensitivity to the PBL and microphysics parameterization schemes, *Atmos. Res*., **272**, 106143, doi:10.1016/j.atmosres.2022.106143.

Marinović, I., Cindrić Kalin, K., Guttler, I. and Pasarić, Z. (2021): Dry spells in Croatia: Observed climate change and climate projections, *Atmosphere*, **12**, DOI:10.3390/atmos12050652.

Marković, T., Karlović, I., Perčec Tadić, M. and Larva, O. (2020): Application of stable water isotopes to improve conceptual model of alluvial aquifer in the Varaždin area, *Water*, **12**, 1–13, DOI: 10.3390/w12020379.

Matić, F., Džoić, T., Kalinić, H., Ćatipović, L., Udovičić, D., Juretić, T., Rakuljić, L., Sršen, D. and Tičina, V. (2022): Observation of abrupt changes in the sea surface layer of the Adriatic Sea, *J. Mar. Sci. Eng*., **10**, 848, doi:10.3390/jmse10070848.

Matić, F., Kalinić, H., Vilibić, I., Grbec, B. and Morožin, K. (2019): Adriatic-Ionian air temperature and precipitation patterns derived from self-organizing maps: relation to hemispheric indices, *Clim. Res*., **78**, 149–163, doi:10.3354/cr01565.

Médus, E. (2022): Regional climate over Northern Europe: from observations to high-resolution modeling, PhD thesis, Faculty of Science, University of Helsinki, Helsinki, Finland, 58 pp.

Médus, E., Thomassen, E. D., Belušić, D., Lind, P., Berg, P., Christensen, J. H., Christensen, O. B., Dobler, A., Kjellström, E., Olsson, J. and Yang, W. (2022): Characteristics of precipitation extremes over the Nordic region: added value of convection-permitting modeling, *Nat. Hazards Earth Syst. Sci*., **22**, 693–711, DOI: 10.5194/nhess-22-693-2022.

Međugorac, I., Pasarić, M. and Güttler, I. (2020): Will the wind associated with the Adriatic storm surges change in future climate? *Theor. Appl. Climatol*., **143**, 1–18, DOI:10.1007/s00704-020-03379-x.

Mifka, B., Telišman Prtenjak, M., Kuzmić, J., Čanković, M., Mateša, S. and Ciglenečki, I. (2022): Climatology of dust deposition in the Adriatic Sea; a possible impact on marine production, *J. Geophys. Res.-Atmos.*, https://doi.org/10.1029/2021JD035783.

Milinković, A., Gregorič, A., Džaja Grgičin, V., Vidič, S., Penezić, A., Cvitešić Kušan, A., Bakija Alempijević, S., Kasper- Giebl, A. and Frka, S. (2021): Variability of black carbon aerosol concentrations and sources at a Mediterranean coastal region, *Atmos. Pollut. Res.*, **12**, 101221, DOI: 10.1016/j.apr.2021.101221.

Montanari, A., Bice, D., M., Jull, A., J., T., Kudryavtsev, A., B., Macalady, J., L., Schaperdoth, I., Sharp, W. D., Shimabukuro, D. ; Schopf, W., J. and Vučetić, V. (2019): Pelagosite revisited, The origin and significance of a laminated aragonitic encrustation of Mediterranean supralittoral rocks, 250 Million Years of Earth History in Central Italy, Celebrating 25 Years of the Geological Observatory of Coldigioc, Koeberl, C., Bice, D., M., (eds.), Boulder, Geological Society of America, 501-532.

Nimac, I. (2022): Characteristics and modelling of the urban heat island, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 120 pp (in Croatian).

Nimac, I., Cindrić Kalin, K., Renko, T., Vujnović, T. and Horvath, K. (2022): The analysis of summer 2020 urban flood in Zagreb (Croatia) from hydro-meteorological point of view, *Nat. Haz.*, **112**, 873–897, DOI:10.1007/s11069-022-05210-4.

Nimac, I., Herceg-Bulić, I. and Žuvela-Aloise, M. (2022): The contribution of urbanisation and climate conditions to increased urban heat load in Zagreb (Croatia) since the 1960s, *Urban Clim.*, **46**, DOI:10.1016/j.uclim.2022.101343.

Nimac, I., Herceg-Bulić, I., Cindrić Kalin, K. and Perčec Tadić M. (2021): Changes in extreme air temperatures in the mid-sized European city situated on southern base of a mountain (Zagreb, Croatia), *Theor. Appl. Climatol*. **146**, 429–441, https://doi.org/10.1007/s00704-021-03689-8.

Nimac, I., Herceg-Bulić, I., Žuvela-Aloise, M. and Žgela, M. (2022): Impact of North Atlantic Oscillation and drought conditions on summer urban heat load – a case study for Zagreb, *Int. J. Climatol*., **42**, 4850–4867, https://doi.org/10.1002/joc.7507.

Odak Plenković, I. (2020): Wind speed prediction using the analog method over complex topography, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 119 pp.

Odak Plenković, I., Schicker, I., Dabernig, M., Horvath, K. and Keresturi, E. (2020): Analog-based post-processing of the ALADIN-LAEF ensemble predictions in complex terrain, *Q. J. R. Meteorol. Soc*., **146**, 1842–1860, DOI:10.1002/qj.3769.

Ognjenović, M., Seletković, I., Potočić, N., Marušić, M., Perčec Tadić, M., Jonard, M., Rautio, P., Timmermann, V., Lovreškov, L. and Ugarković, D. (2022): Defoliation change of European beech, (Fagus sylvatica L.), depends on previous year drought, *Plants*, **11**, 1–13, DOI:10.3390/plants11060730.

Omazić, B., Telišman Prtenjak, M., Prša, I., Belušić Vozila, A., Vučetić, V., Karoglan, M., Karoglan Kontić, J., Prša, Ž., Anić, M., Šimon, S. and Güttler, I. (2020): Climate change impacts on viticulture in Croatia; viticultural zoning and future potential, *Int. J. Climatol*., **40**, 5634–5655, doi:10.1002/joc.6541.

Pandžić, K., Likso, T. and Bonacci, O. (2022): A review of extreme air temperature analysis in Croatia, *Atmosphere*, **13**, 1893, DOI:10.3390/atmos13111893.

Pandžić, K., Likso, T., Pejić, I., Šarčević, H., Pećina, M., Šestak, I., Tomšić, D. and Strelec Mahović, N., (2022): Application of the self-calibrated Palmer drought severity index and standardized precipitation index for estimation of drought impact on maize grain yield in Pannonian part of Croatia, *Nat. Haz*., **113**, 1237–1262, DOI:10.1007/s11069-022-05345-4.

Pandžić, K., Kobold, M., Oskoruš, D., Biondić, B., Biondić, R., Bonacci, O., Likso, T. and Curić, O., (2020): Standard normal homogeneity test as a tool to detect change points in climate-related river discharge variation: case study of the Kupa River Basin, *Hydrol. Sci. J.*, **65**, 227–241, DOI: 10.1080/02626667.2019.1686507.

Pandžić, K., Likso, T., Curić, O., Mesić, M., Pejić, I. and Pasarić, Z. (2020): Drought indices for the Zagreb-Grič Observatory with an overview of drought damage in agriculture in Croatia, *Theor. Appl. Climatol*., **142**, 555–567, DOI:10.1007/s00704-020-03330-0.

Pandžić, K., Likso, T., Trninić, D., Oskoruš, D., Macek, K. and Bonacci, O. (2022): Relationships between large-scale atmospheric circulationand monthly precipitation and discharge in the Danube River basin, *Theor. Appl. Climatol*., **148**, 767–777, DOI:10.1007/s00704-022-03977-x.

Perčec Tadić, M., Pasarić, Z. and Guijarro, J., A. (2022): Croatian high-resolution monthly gridded dataset of homogenised surface air temperature, *Theor. Appl. Climatol*., **1**, 1–23, DOI:10.1007/s00704-022-04241-y.

Prein, A.F., Ban, N., Ou, T., ..., Belušić, D., et al. (2022): Towards ensemble-based kilometer-scale climate simulations over the Third Pole region, *Clim. Dyn*., DOI: 10.1007/s00382-022-06543-3.

Prka, M., Habek, D., Kruezi, D., Plačko-Vršnak, D., Srnec, L. and Medved, K. (2022): Association of weather conditions and the day with extreme number of deliveries with spontaneous onset in a tertiary referral perinatal center, *Period. Biol*., **124**, 63–65, DOI:10.18054/pb.v124i1-2.20829.

Rabinovich, A., Šepić, J. and Thomson, R. E. (2021): The meteorological tsunami of 1 November 2010 in the southern Strait of Georgia: a case study, *Nat. Hazards*, **106**, 1503–1544, doi:10.1007/s11069-020-04203-5.

Radilović, S., Koračin, D., Denamiel, C., Belušić, D., Güttler, I. and Vilibić, I. (2020): Simulated and observed air temperature trends in the eastern Adriatic, *Atmos. Sci. Lett*., **21**, e951, DOI:10.1002/asl.951.

Renko, T., Ivušić, S., Telišman Prtenjak, M., Šoljan, V. and Horvat, I. (2019): Waterspout forecasting method over the eastern Adriatic using a high-resolution numerical weather model, meteorology and climatology of the Mediterranean and Black Seas, Vilibić, I., Horvath, K., Palau, J.,L., (Eds), Springer Nature Switzerland AG: Birkhäuser Basel, 39-58, DOI: 978-3-030-11958-4/4.

Sekulić, A., Kilibarda, M., Protić, D., Perčec Tadić, M. and Bajat, B. (2020): Spatio-temporal regression kriging model of mean daily temperature for Croatia, *Theor. Appl. Climatol.*, **140**, 101–114, DOI: 10.1007/s00704-019-03077-3.

Soares, P.M.M., Careto, J.A.M., Cardoso, R.M., Goergen K., Katragkou E., Sobolowski S., Coppola E., Ban N., Belušić D., et al. (2022): The added value of km-scale simulations to describe temperature over complex orography: the CORDEX FPS-Convection multi-model ensemble runs over the Alps, *Clim. Dyn*., DOI: 10.1007/s00382-022-06593-7.

Srnec, L. and Magjarević, V. (2022): Heat wave warning system in health protection, Climate changes and arterial hypertension – global risk, Environmental Hypertensiology, Jelaković, B. (Ed.), Zagreb, Medicinska naklada, 11-17.

Srnec, L., Magjarević, V. (2022): Sustav upozorenja na toplinske valove u zaštiti zdravlja, Klimatske promjene i arterijski tlak – ukupni rizik, Hipertenziologija okoliša, Jelaković, B., (ur.), Zagreb, Medicinska naklada, 11-17.

Srnec, L., Zaninović, K. (2019): Zdravlje, rekreacija i turizam, Primijenjena znanstvena istraživanja u Državnom hidrometeorološkom zavodu: u povodu 50 godina istraživanja i 70 godina osnivanja DHMZ-a, Ivančan-Picek, B. (ur.), Zagreb, Državni hidrometeorološki zavod, 154-167.

Stanešić, A. (2020): Mesoscale data assimilation in regional numerical weather prediction model, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 93 pp (in Croatian).

Stanešić, A., Horvath, K. and Keresturi, E. (2019): Comparison of NMC and ensemble-based climatological background-error covariances in an operational limited-area data assimilation system, *Atmosphere*, **10**, 570, DOI: 10.3390/atmos10100570.

Staver, D., Mihanović, H. and Klaić, Z. B. (2022): Lake-land breezes over a small elongated lake (Kozjak, Plitvice Lakes, Croatia), *Geofizika*, **39**, 51–70, https://doi.org/10.15233/gfz.2022.39.11.

Šarović, K., Burić, M. and Klaić, Z. B. (2022): SIMO v1.0: simplified model of the vertical temperature profile in a small, warm, monomictic lake, *Geosci. Model Dev*., **15**, 8349–8375, https://doi.org/10.5194/gmd-15-8349-2022.

Šimunić, I., Likso, T., Husnjak, S. and Bubalo Kovačić, M. (2021): Analysis of climate elements in central and western Istria for the purpose of determining irrigation requirements of agricultural crops, *Agric. Conspec. Sci*., **86**, 225–233.

Šimunić, I., Likso, T., Husnjak, S., Orlović-Leko, P. and Bubalo Kovačić, M. (2021): Analysis of climate elements in the northeastern region of Croatia for the purpose of determining irrigation requirements of maize and soybean on drained soil, *Agric. For.*, **67**, 7–20, DOI:10.17707/AgricultForest.67.2.01.

Šimunić, I., Likso, T., Orlović-Leko, P., Ciglenečki, I., Bubalo Kovačić, M., Gilja, G. and Mustać, I. (2022): The influence of combined drainage on the stability of agricultural production in condition of climate change, *Reliab. Theory Appl*., **17**, 82–87, DOI:10.24412/1932-2022-366-82-87.

Škurić Kuraži, D., Nižetić Kosović, I. and Herceg-Bulić, I. (2022): A review of forest fire research directions: Different approaches for one goal, *Geofizika*, **39**, 85–104, https://doi.org/10.15233/gfz.2022.39.7.

Tomasović, S., Sremec, J., Koščak Lukač, J., Sičaja, G., Bačić Baronica, K., Ostojić, V., Raifi, Z., Tomić Sremec, N., Plačko-Vršnak, D., Srnec, L. and Mikec, K. (2022): Weather patterns and occurrence of epileptic seizures, *BMC Neurol*., **22, 33**, 1–11, DOI:10.1186/s12883-021-02535-8.

Toro A. R., Kvakić, M., Klaić, Z. B., Koračin, D., Morales, R. G. E. and Leiva, G. M. A. (2019): Exploring atmospheric stagnation during a severe particulate matter air pollution episode over complex terrain in Santiago, Chile, *Environ. Pollut*., 244, 705–714, https://doi.org/10.1016/j.envpol.2018.10.067.

Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S., M., Volairee, F., Boone, A., Page, M., Llasat, M., c., Albergel, C., Burak, S., et al. (2020): Challenges for drought assessment in the Mediterranean region under future climate scenarios, *Earth Sci. Rev*., **210**, 103348-103348, DOI:10.1016/j.earscirev.2020.103348.

Trošić Lesar, T. and Filipčić, A. (2021): The hourly simulation of PM2.5 particle concentrations using the Multiple Linear Regression, MLR, model for sea breeze in Split, Croatia, *Water Air Soil Pollut*., **232**, 261, DOI:10.1007/s11270-021-05209-w.

Trošić Lesar, T. and Filipčić, A. (2022): Lagrangian particle dispersion (HYSPLIT) model analysis of the sea breeze case with extreme mean daily PM10 concentration in Split, Croatia, *Environ. Sci. Pollut. Res*., **29**, 73071–73084, DOI:10.1007/s11356-022-20918-3.

Večenaj, Ž., Malečić, B. and Grisogono, B. (2021): Estimation of turbulent triplet covariances for Bora flows, *Fluids*, **6**, 452. https://doi.org/10.3390/fluids6120452.

Vilibić, I., Horvath, K. and Palau, J.L. (Eds) (2019): Meteorology and Climatology of the Mediterranean and Black Seas, Pageoph Topical Volumes, Springer Nature Switzerland AG, VI, 410 pp, 978-3-030-11957-7.

Vučetić, M. (2020): Biljke koje kazuju vrijeme, Zagreb, Hrvatsko agrometeorološko društvo (monografija).

Vučetić, V. (2019): Poljoprivreda i šumarstvo, Primijenjena znanstvena istraživanja u Državnom hidrometeorološkom zavodu u povodu 50 godina istraživanja i 70 godina osnivanja DHMZ-a, Ivančan-Picek, B. (ur.), Zagreb, Državni hidrometeorološki zavod, 168-183.

Vučetić, V., Anić, M. (2021): Agroklimatski atlas Hrvatske u razdoblju 1991.-2020. povodom 70 godina osnutka agrometeorološke službe u DMHZ, Zagreb, Državni hidrometeorološki zavod (atlas).

Vujec, I. and Odak Plenković, I. (2022): Kalman filter sensitivity tests for the NWP and analog-based forecasts post-processing, *Meteorol. Atmos. Phys*., **135**, 1–19, DOI:10.1007/s00703-022-00939-w.

Wang, Y., Belluš, M., Weidle, F., Wittmann, C., Tang, J., Meier, F., Xia, F. and Keresturi, E. (2019): Impact of land surface stochastic physics in ALADIN-LAEF, *Q. J. R. Meteorol. Soc*., **146**, 1–18, DOI:10.1002/qj.3623.

Wastl, C., Wang, Y., Atencia, A., Weidle, F., Wittmann, C., Zingerle, C. and Keresturi, E. (2021): C-LAEF Convection-permitting Limited-Area Ensemble Forecasting system, *Q. J. R. Meteorol. Soc*., **147**, 1431–1451, DOI:10.1002/qj.3986.

Zemunik, P., Bonanno, A., Mazzola, S., Giacalone, G., Fontana, I., Genovese, S., Basilone, G., Candela, J., Šepić, J., Vilibić, I. and Aronica, S., (2021): Observing meteotsunamis (“Marrobbio”) on the southwestern coast of Sicily, *Nat. Hazards*, **106**, 1337–1363, doi:10.1007/s11069-020-04303-2.

Žužul, I., Šegvić-Bubić, T., Talijančić, I., Džoić, T., Lepen-Pleić, I., Beg Paklar, G., Ivatek-Šahdan, S., Katavić, I. and Grubišić, L. (2019): Spatial connectivity pattern of expanding gilthead seabream populations and its interactions with aquaculture sites: a combined population genetic and physical modelling approach, *Sci. Rep*., **9**, 14718, DOI:10.1038/s41598-019-51256-z.

## *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 dana (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).

Impoving 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 mouned 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; Figure 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 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.

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

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.

**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).

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 (Figure 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.

**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.

Mayority 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 SCOOL, 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 our 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 (Heiderzadeh 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; Figure 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 (Ciglenečki 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.

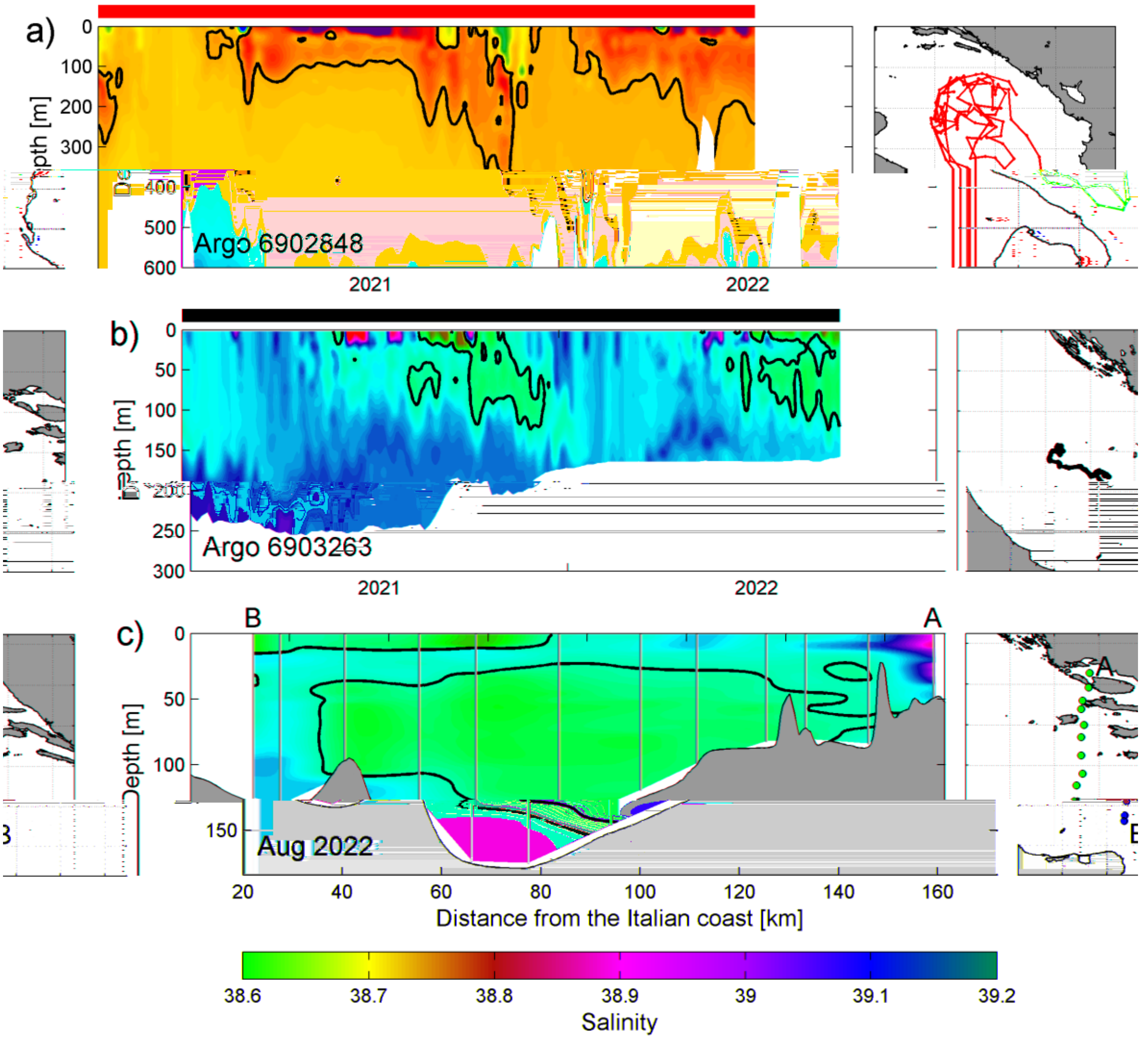


**Figure 3.** a) Hovmöller diagram of salinity data for the Argo float 6902848 in the first 600 m in the period 2021–2022 (left panel) with corresponding float trajectory (right panel). (b) As in panel (a) except for the Argo float 6903263 between the surface and the bottom. Note that the vertical scale 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.

**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). 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 Paficic 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.

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

**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 el al., 2020; Šolić el al., 2020; Paliaga et al., 2021; Šantić el al., 2021; Džoić et al., 2022; Šolić el 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 Ichtyhop, 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 el al., 2020; Šolić el al., 2020; Paliaga et al., 2021; Šantić el al., 2021; Šolić el 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 spreding of plankton species and large organic production of the region was analyzed by Budiša et al. (2021), Ciglenečki et al. (2021) and Malej et al. (2022). A dispersive model was developed by Paliaga et al. (2021) for tracing the paths of alochtonious potentialy harmful zooplankton species *Mnemiopsis leidyi.* Further, the connectivity between bivalve growth, its chemical properties and 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 (Figure 4) in different regions of the Adriatic was assessed by Biolchi et al. (2019a, b) and Korbar et al. (2022).

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## *List of publications*

Abdolali, A., Roland, A., van der Westhuysen, A., Meixner, J., Chawla, A., Hesser, T.J., Smith, J.M. and Dutour Sikirić, M. (2020): Large-scale hurricane modeling using domain decomposition parallelization and implicit scheme implemented in WAVEWATCH III wave model, *Coast. Eng.*, **157**, 103656, DOI: /10.1016/j.coastaleng.2020.103656.

Abdolali, A., Hesser, T.J., Anderson Bryant, M., Roland, A., Khalid, A., Smith, J., Ferreira, C., Mehra, A. and Dutour Sikirić, M. (2022): Wave attenuation by vegetation: model implementation and validation Study, *Front. Built. Environ.*, **8**, 891612, DOI: 10.3389/fbuil.2022.891612.

Babeyko, B., Lorito, S., Hernandez, F., Lauterjung, J., Løvholt, F., Rudloff, A., Sørensen, M., Androsov, A., Aniel-Quiroga, I., Armigliato, A. et al. (2022): Towards the new Thematic Core Service Tsunami within the EPOS Research Infrastructure, *Ann. Geophys.*, **65**, DM215, DOI: 10.4401/ag-8762.

Bajo, M., Međugorac, I., Umgiesser, G. and Orlić, M. (2019): Storm surge and seiche modelling in the Adriatic Sea and the impact of data assimilation. *Q. J. Roy. Meteorol. Soc.*, **145**, 2070-2084, https://doi.org/10.1002/qj.3544.

Beg Paklar, G., Vilibić, I., Grbec, B., Matić, F., Mihanović, H., Džoić, T., Šantić, D., Šestanović, S., Šolić, M., Ivatek-Šahdan, S. and Kušpilić, G. (2020): Record-breaking salinities in the middle Adriatic during summer 2017 and concurrent changes in the microbial food web, *Prog. Oceanogr.*, **185**, 102345, DOI: 10.1016/j.pocean.2020.102345.

Biolchi, S., Denamiel, C., Devoto, S., Korbar, T., Macovaz, V., Scicchitano, G., Vilibić, I. and Furlani, S. (2019a): Impact of the October 2018 storm Vaia on coastal boulders in the northern Adriatic Sea, *Water*, **11**, 2229, DOI: 10.3390/w11112229.

Biolchi, S., Furlani, S., Devoto, S., Scicchitano, G., Korbar, T., Vilibić, I. and Šepić, J. (2019b): Origin and dynamics of coastal boulders in a semi-enclosed shallow basin: a Northern Adriatic case study, *Mar. Geol.*, **411**, 62-77.

Bubalo, M. (2019): Atmosphere-sea interaction, formation of wave packets in the open sea and flooding of the coastal area, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 76 pp, available at https://repozitorij.pmf.unizg.hr/islandora/object/pmf%3A5555 (in Croatian).

Bubalo, M., Janeković, I. and Orlić, M. (2019): Simulation of flooding and drying as an essential element of meteotsunami modelling, *Cont. Shelf Res.*, **184**, 81-90, https://doi.org/10.1016/j.csr.2019.07.003.

Bubalo, M., Janeković, I. and Orlić, M. (2021): Meteotsunami-related flooding and drying: numerical modeling of four Adriatic events, *Nat Hazards,* **106**, 1365-1382, https://doi.org/10.1007/s11069-020-04444-4.

Budiša, A., Paliaga, P., Juretić, T., Lučić, D., Supić, N., Pasarić, Z., Djakovac, T., Mladinić, M., Dadić, V. and Tičina, V. (2021): Distribution, diet and relationships of the invasive ctenophore Mnemiopsis leidyi with anchovies and zooplankton, in the northeastern Adriatic Sea, *Mediterr. Mar. Sci.*, **22**, 4, DOI: 10.12681/mms.23305.

Ciglenečki, I., Vilibić, I., Dautović, J., Vojvodić, V., Ćosović, B., Zemunik, P., Dunić, N. and Mihanović, H. (2020): Dissolved organic carbon and surface active substances in the northern Adriatic Sea: Long-term trends, variability and drivers, *Sci. Tot. Environ.*, **730**, 139104, DOI: 10.1016/j.scitotenv.2020.139104.

Ciglenečki, I., Paliaga, P., Budiša, A., Čanković, M., Dautović, J., Djakovac, T., Dutour-Sikirić, M., Kraus, R., Kužat, N., Lučić, D., Marić Pfannkuchen, D., Njire, J., Pasarić, Z. and Supić, N. (2021): Dissolved organic carbon accumulation during a bloom of invasive gelatinous zooplankton Mnemiopsis leidyi in the northern Adriatic Sea; case of the anomalous summer in 2017, *J. Marine Syst.*, **222**, 1-19.

Čanković, M., Dutour-Sikirić, M., Radić, I.D. and Ciglenečki, I. (2022): Bacterioneuston and bacterioplankton structure and abundance in two trophically distinct marine environments – a marine lake and the adjacent coastal site on the Adriatic Sea, *Microb. Ecol.*, **84**, 996–1010, https://doi.org/10.1007/s00248-021-01934-1.

Denamiel, C., Šepić, J., Ivanković, D. and Vilibić, I. (2019a): The Adriatic Sea and coast modelling suite: Evaluation of the meteotsunami forecast component, *Ocean Model.*, **135**, 71-93.

Denamiel, C., Šepić, J., Huan, X., Bolzer, C. and Vilibić, I. (2019b): Stochastic surrogate model for meteotsunami early warning system in the eastern Adriatic Sea, *J. Geophys. Res. Oceans*, **124**, 8485-8499, DOI: 10.1029/2019JC015574.

Denamiel, C., Pranić, P., Quentin, F., Mihanović, H. and Vilibić, I. (2020a): Pseudo-global warming projections of extreme wave storms in complex coastal regions: the case of the Adriatic Sea, *Clim. Dyn.*, **55**, 2483-2509, DOI: 10.1007/s00382-020-05397-x.

Denamiel, C., Tojčić, I. and Vilibić, I. (2020b): Far future climate (2060–2100) of the northern Adriatic air-sea heat transfers associated with extreme bora events, *Clim. Dyn.*, **55**, 3043-3066, DOI: 10.1007/s00382-020-05435-8.

Denamiel, C., Šepić, J., Huan, X. and Vilibić, I. (2020c): Uncertainty propagation using polynomial chaos expansions for extreme sea level hazard assessment: the case of the eastern Adriatic meteotsunamis, *J Phys. Oceanogr.*, **50**, 1005-2021.

Denamiel, C., Pranić, P., Ivanković, D., Tojčić, I. and Vilibić, I. (2021a): Performance of the Adriatic Sea and Coast (AdriSC) climate component – a COAWST V3.3-based coupled atmosphere–ocean modelling suite: atmospheric dataset, *Geosci. Model Dev.*, **14**, 3995–4017, DOI: 10.5194/gmd-14-3995-2021.

Denamiel, C, Tojčić, I. and Vilibić, I. (2021b): Balancing accuracy and efficiency of atmospheric models in the northern Adriatic during severe bora events, *J. Geophys. Res. Atmos*., **126**, e2020JD033516.

Denamiel, C., Huan, X. and Vilibić, I. (2021c): Conceptual design of extreme sea-level early warning systems based on uncertainty quantification and engineering optimization methods, *Front. Mar. Sci.*, **8**, 650279, DOI: 10.3389/fmars.2021.650279.

Denamiel, C., Tojčić, I., and Vilibić, I. (2022a): Meteotsunamis in orography-free, flat bathymetry and warming climate conditions. *J. Geophys. Res. Oceans*, **127**, e2021JC017386, DOI: 10.1029/2021JC017386.

Denamiel, C., Tojčić, I., Pranić, P. and Vilibić, I. (2022b): Modes of the BiOS-driven Adriatic Sea thermohaline variability, *Clim. Dyn.*, **59**, 1097–1113, DOI: 10.1007/s00382-022-06178-4.

Dorman, C. E., Mejia, J., Koračin, D. and McEvoy, D. (2019): World marine fog analysis based on 58-years of ship observations, *Int. J. Climatol*, **40**, 145-168, https://doi.org/10.1002/joc.6200.

Dunić, N. (2019): Thermohaline properties and dynamical processes in the Adriatic sea simulated with regional climate models, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 141 pp, availbale at https://repozitorij.pmf.unizg.hr/islandora/object/pmf%3A7217 (in Croatian).

Dunić, N., Vilibić, I., Šepić, J., Mihanović, H., Sevault, F., Somot, S., Waldman, R., Nabat, P., Arsouze, T., Pennel, R., Jordà, J. and Precali, R. (2019): Performance of multi-decadal ocean simulations in the Adriatic Sea, *Ocean Model.*, **134**, 84-109.

Dunić, N., Supić, N., Sevault, F. and Vilibić, I. (2022): The northern Adriatic circulation regimes in the future winter climate, *Clim. Dyn.*, https://doi.org/10.1007/s00382-022-06516-6.

Džoić, T., Zorica, B., Matić, F., Šestanović, M. and Čikeš Keč, V. (2022): Cataloguing environmental influences on the spatiotemporal variability of Adriatic anchovy early life stages in the eastern Adriatic Sea using an artificial neural network, *Front. Mar. Sci.*, **9**, 997937, https://doi:10.3389/fmars.2022.997937.

Ezgeta-Balić, D., Peharda, M., Schöne, B.R., Uvanović, H., Vrgoč, N., Markulin, K., Radonić, I., Denamiel, C. and Kovač, Ž. (2022): Different life strategies of the three commercially exploited scallop species living under the same environmental conditions, *Front. Mar. Sci.*, **9**, 992042, DOI: 10.3389/fmars.2022.992042.

Ferrarin, C., Bajo, M., Benetazzo, A., Cavaleri, L., Chiggiato, J., Davison, S., Davolio, S., Lionello, P., Orlić, M. and Umgiesser, G. (2021): Local and large-scale controls of the exceptional Venice floods of November 2019, *Prog. Oceanogr.*, **197**, 102628, https://doi.org/10.1016/j.pocean.2021.102628.

Ferrarin, C., Lionello, P., Orlić, M., Raicich, F. and Salvadori, G. (2022): Venice as a paradigm of coastal flooding under multiple compound drivers, *Sci. Rep.*, **12**, 5754, https://doi.org/10.1038/s41598-022-09652-5.

Gačić, M., Ursella, L., Kovačević, V., Menna, M., Malačič, V., Bensi, M. et al. (2021): Impact of dense-water flow over a sloping bottom on open-sea circulation: laboratory experiments and an Ionian Sea (Mediterranean) example, *Ocean Sci.*, **17**, 975-996, https://doi.org/10.5194/os-17-975-2021.

Gianni, F., Manea, E., Cataletto, B., Pugnetti, A., Bergami, C., Bongiorni, L., Pleslić, G., Vilibić, I. and Bandelj, V. (2022): Are we overlooking Natura 2000 sites? Lessons learned from a transnational project in the Adriatic Sea, *Front. Mar. Sci.*, https://doi.org/10.3389/fmars.2022.1070373.

Heidarzadeh, M., Šepić, J., Rabinovich, A., Allahyar, M., Soltanpour, A. and Tavakoli, F. (2020): Meteorological tsunami of 19 March 2017 in the Persian Gulf: observations and analyses, *Pure Appl. Geophys.*, **177**, 1231–1259, DOI: 10.1007/s00024-019-02263-8.

Heidarzadeh, M., Riadi Gusman, A., Ishibe, T., Sabeti, R. and Šepić, J. (2022): Estimating the eruption-induced water displacement source of the 15 January 2022 Tonga volcanic tsunami from tsunami spectra and numerical modelling, *Ocean Eng.*, **261**, 112165, https://doi.org/10.1016/j.oceaneng.2022.112165.

Janeković, I., Mihanović, H., Vilibić, I., Grčić, B., Ivatek-Šahdan, S., Tudor, M. and Djakovac, T. (2020): Multi-platform 4D-Var data assimilation for improving the Adriatic Sea dynamics, *Ocean Model.*, **146**, 101538, DOI: 10.1016/j.ocemod.2019.101538.

Jelaković, A., Srnec, L., Orlić, M., Premužic, V., Domislović, M., Begić, Z., Barišić, K., Radunović, D., Prelević, V., Dika, Z., Stevanović, R. and Jelaković, B. (2022): Seasonal variations in meteorological parameters and blood pressure in Croatian adult population, *J. Hypertens.*, **40**, e116-e116, https://doi.org/10.1097/01.hjh.0000836436.68413.10.

Kalinić, H., Bilokapić, Z. and Matić, F. (2021): Can local geographically restricted measurements be used to recover missing geo-spatial data? *Sensors*, **21**, 3507, https://doi.org/10.3390/s21103507.

Kalinić, H., Ćatipović, L. and Matić, F. (2022): Optimal sensor placement using learning models – A Mediterranean case study, *Remote Sens.*, **14**, 2989, https://doi.org/doi:10.3390/rs14132989.

Kazeminezhad, M.H., Vilibić, I., Denamiel, C., Ghafarian, P. and Negah, S. (2021): Weather radar and ancillary observations of the convective system causing the northern Persian Gulf meteotsunami on 19 March 2017, *Nat. Hazards*, **106**, 1747–1769, DOI: 10.1007/s11069-020-04208-0.

Korbar, T., Navratil, D., Denamiel, C., Kordić, B., Biolchi, S., Vilibić, I. and Furlani, S. (2022): Coarse-clast storm deposit and solitary boulders on the Island of Mana (NP Kornati, Central Adriatic, Croatia), *Geosciences*, **12**, 355, DOI: 10.3390/geosciences12100355.

Kovač, Ž., Platt, T. and Sathyendranath, S. (2020): Stability and resilience in a nutrient-phytoplankton marine ecosystem model, *ICES J. Mar. Sci.*, **77**(4), 1556-1572, https://doi.org/10.1093/icesjms/fsaa067.

Kovač, Ž., Platt, T. and Sathyendranath, S. (2021): Sverdrup meets Lambert: Analytical solution for Sverdrup's critical depth, *ICES J. Mar. Sci.*, **78**(4),1398-1408, https://doi.org/10.1093/icesjms/fsab013.

Kovač, Ž. and Sathyendranath, S. (2022): Fragility of marine photosynthesis, *Front. Mar. Sci.*, **9**, 963395, https://doi.org/10.3389/fmars.2022.963395.

Kraus, R., Grilli, F., Supić, N., Janeković, I., Brailo, M., Cara, M., Bratoš Cetinić, A., Campanelli, A., Cozzi, S., D'Adamo, R., Djakovac, T., Dutour-Sikirić, M. et al. (2019): Oceanographic characteristics of the Adriatic Sea – Support to secondary HAOP spread through natural dispersal, *Mar. Pollut. Bull.*, **147**, 59-85.

Kulichkov, S. N., Chunchuzov, I. P., Popov, O. E., Gorchakov, G. I., Mishenin, A. A., Perepelkin, V. G., Bush, G. A., Skorokhod, A. I., Vinogradov, Yu. A., Semutnikova, E. G., Šepić, J., Medvedev, I. et al. (2022): Acoustic-gravity Lamb waves from the eruption of the Hunga-Tonga-Hunga-Hapai volcano, Its energy release and impact on aerosol concentrations and tsunami, *Pure Appl. Geophys.,* **179**, 1533-1548, https://doi.org/10.1007/s00024-022-03046-4.

Kulk, G., Platt, T., Dingle, J., Jackson, T., Jönsson, B., Heather A. Bouman, Babin, M., Brewin, R. J. W., Doblin, M., Estrada, M., Figueiras, F. G. et al. (2020): Primary production, an index of climate change in the ocean: Satellite-based estimates over two decades, *Remote Sens.*, **12**, 826, https://doi.org/10.3390/rs12050826.

Lazar, M., Bubalo, M. and Begić, J. (2022): Analytical model of thermohaline circulation in land-locked basins: analyzing the impact of friction on circulation reversal, *J. Phys. Oceanogr.*, **52**, 2343-2359, https://doi.org/10.1175/JPO-D-21-0251.1.

Li, X., Zhang, S., Koračin, D., Yi, L. and Zhang, X. (2022): Atmospheric conditions conducive to marine fog over the northeast Pacific in winters of 1979–2019., *Front. Earth Sci.*, **10**, https://doi.org/10.3389/feart.2022.942846.

Lionello, P., Barriopedro, D., Ferrarin, C., Nicholls, R.J., Orlić, M., Raicich, F., Reale, M., Umgiesser, G., Vousdoukas, M. and Zanchettin, D. (2021): Extreme floods of Venice: characteristics, dynamics, past and future evolution (review article), *Nat. Hazard Earth Sys.*, **21**, 2705–2731, https://doi.org/10.5194/nhess-21-2705-2021.

Lorente, P., Aguiar, E., Bendoni, M., Berta, M., Brandini, C., Cáceres-Euse, A., Capodici, F., Cianelli, D., Ciraolo, G., Corgnati, L., Dadić, V., Doronzo, B. et al. (2022): Coastal HF radars in the Mediterranean: status of operations and a framework for future development, *Ocean Sci.*, **18**, 761–795, DOI: 10.5194/os-18-761-2022.

Malej, A., Lučić, D., Bojanić, N., Vodopivec, M., Paliaga, P., Prestorić, B., Violić, I. and Supić, N. (2022): The occurrence of the jellyfish Aequorea cf. forskalea in the Adriatic Sea: comparison of historical and recent data, *Acta Adriat*., **63**, 2.

Markulin, K., Peharda, M., Mertz- Kraus, R., Schoene, B. R., Uvanović, H., Kovač, Ž. and Janeković, I. (2019): Trace and minor element records in aragonitic bivalve shells as environmental proxies, *Chem. Geol.*, **507**, 120-133, https://doi.org/10.1016/j.chemgeo.2019.01.008.

Matić F., Kalinić H., Vilibić I., Grbec B. and Morožin, K. (2019): Adriatic-Ionian air temperature and precipitation patterns derived from self-organizing maps: relation to hemispheric indices, *Clim. Res.,* **78**, 149-163, https://doi.org/10.3354/cr01565.

Matić, F., Džoić, T., Kalinić, H., Ćatipović, L., Udovičić, D.; Juretić, T., Rakuljić, L., Sršen, D. and Tičina, V. (2022): Observation of abrupt changes in the sea surface layer of the Adriatic Sea, *J. Mar. Sci. Eng.*, **10**, 848, https://doi.org/10.3390/jmse10070848.

Matić-Skoko, S., Pavičić, M., Šepić, J., Janeković, I., Vrdoljak, D., Vilibić, I., Stagličić, N., Šegvić Bubić, T. and Vujević, A. (2022): Impacts of sea bottom temperature on CPUE of European lobster Homarus gammarus (Linnaeus, 1758; Decapoda, Nephropidae) in the Eastern Adriatic Sea, *Front. Mar. Sci.*, **9**, 891197, DOI: 10.3389/fmars.2022.891197.

Međugorac, I., Pasarić, M. and Güttler, I. (2021): Will the wind associated with the Adriatic storm surges change in future climate? *Theor. Appl. Climatol.*, **143 (1)**, 1-18, https://doi.org/10.1007/s00704-020-03379-x.

Međugorac, I., Pasarić, M. and Orlić, M. (2022a): Long-term measurements at Bakar tide-gauge station (east Adriatic), *Geofizika*, **39**, 149-162, https://doi.org/10.15233/gfz.2022.39.8.

Međugorac, I., Pasarić, M. and Orlić, M. (2022b): Historical sea-level measurements at Bakar (east Adriatic) [Dataset], *SEANOE*, https://doi.org/10.17882/85171.

Medvedev, I., Vilibić, I. and Rabinovich, A.B. (2020): Tidal resonance in the Adriatic Sea: Observational evidence, *J. Geophys. Res. Oceans*, **125**, e2020JC016168.

Medvedev, I. P., Rabinovich, A. B. and Šepić, J. (2022): Destructive coastal sea level oscillations generated by Typhoon Maysak in the Sea of Japan in September 2020, *Sci. Rep.*, **12**, 8463, https://doi.org/10.1038/s41598-022-12189-2.

Mihanović, H., Vilibić, I., Šepić, J., Matić, F., Ljubešić, Z., Mauri, E., Gerin, R., Notarstefano, G. and Poulain, P.-M. (2021): Observation, preconditioning and recurrence of exceptionally high salinities in the Adriatic Sea, *Front. Mar. Sci.*, **8**, 672210, DOI: 10.3389/fmars.2021.672210.

Ninčević Gladan, Ž., Matić, F., Arapov, J., Skejić, S., Bužančić, M., Bakrač, A., Straka, M., Dekneudt, Q., Grbec, B., Garber, R. and Nazlić, N. (2020): The relationship between toxic phytoplankton species occurrence and environmental and meteorological factors along the Eastern Adriatic coast, *Harmful Algae*, **92**, 101745, https://doi:10.1016/j.hal.2020.101745.

Orlić, M. (2022): Introduction to physical oceanography, Element d.o.o., Zagreb, 335 pp (in Croatian).

Paliaga, P., Budiša, A., Dautović, J., Djakovac, T., Dutour-Sikirić, M.A., Mihanović, H., Supić, N., Čelić, I., Iveša, N., Bursić, M., Balković, I., Jurković, L. and Ciglenečki, I. (2021): Microbial response to the presence of invasive ctenophore Mnemiopsis leidyi in the coastal waters of the Northeastern Adriatic, *Estuar. Coast. Shelf Sci.*, **259**, 10745, DOI: 10.1016/j.ecss.2021.107459.

Peharda, M., Vilibić, I., Black, B., Uvanović, H., Markulin, K. and Mihanović, H. (2019a): A network of bivalve chronologies from semienclosed seas, *PLoS ONE*, **14**, e0220520, https://doi.org/10.1371/journal.pone.0220520.

Peharda, M., Walliser, E.O., Markulin, K., Purroy, A., Uvanović, H., Janeković, I., Župan, I., Vilibić, I. and Schöne, B.R. (2019b): Glycymeris pilosa (Bivalvia) – A high-potential geochemical archive of the environmental variability in the Adriatic Sea, *Mar. Environ. Res.*, **150**, 104759, DOI:10.1016/j.marenvres.2019.104759.

Peharda, M., Gillikin, D.P., Schoene, B.R., Verheyden, A., Uvanović, H., Markulin, K., Šarić, T., Janeković, I. and Župan, I. (2022): Nitrogen isotope sclerochronology-insights into coastal environmental conditions and Pinna nobilis ecology, *Front. Mar. Sci.*, **8**, 816879, DOI: 10.3389/fmars.2021.816879.

Pellikka, H., Šepić, J., Lehtonen, I. and Vilibić, I. (2022): Meteotsunamis in the northern Baltic Sea and their relation to synoptic patterns, *Weather Clim. Extrem.*, **38**, 100527, DOI: 10.1016/j.wace.2022.100527.

Pérez Gómez, B., Vilibić, I., Šepić, J., Međugorac, I., Ličer, M., Testut, L., Fraboul, C., Marcos, M., Abdellaoui, H., Álvarez Fanjul, E., Barbalić, D., Casas, B. et al. (2022): Coastal sea level monitoring in the Mediterranean and Black Seas, *Ocean Sci.*, **18**, 997–1053, https://doi.org/10.5194/os-2021-125.

Picciulin, M., Armelloni, E., Falkner, R., Rako-Gospić, N., Radulović, M., Pleslić, G., Muslim, S., Mihanović, H. and Gaggero, T. (2022): Characterization of the underwater noise produced by recreational and small fishing boats (<14 m) in the shallow-water of the Cres-Lošinj Natura 2000 SCI, *Mar. Pollut. Bull.*, **183**, 114050, https://doi:10.1016/j.marpolbul.2022.114050.

Pranić, P., Denamiel, C. and Vilibić, I. (2021): Performance of the Adriatic Sea and Coast (AdriSC) climate component – a COAWST V3.3-based one-way coupled atmosphere-ocean modelling suite: ocean results, *Geosci. Model Dev.*, **14**, 5927–5955, DOI: 10.5194/gmd-14-5927-2021.

Rabinovich, A. B., Šepić, J. and Thomson, R. E., (2021): The meteorological tsunami of 1 November 2010 in the southern Strait of Georgia: a case study, *Nat. Hazards*, **106**, 1503-1544, https://doi.org/10.1007/s11069-020-04203-5.

Radilović, S., Koračin, D., Denamiel, C., Belušić, D., Güttler, I. and Vilibić, I. (2020): Simulated and observed air temperature trends in the eastern Adriatic, *Atmos. Sci. Lett.*, **21**, https://doi.org/doi/10.1002/asl.951.

Reyes, E., Aguiar, E., Bendoni, M., Berta, M., Brandini, C., Cáceres-Euse, A., Capodici, F., Cardin, V., Cianelli, D., Ciraolo, G., Corgnati, L., Dadić, V. et al. (2022): Coastal HF radars in the Mediterranean: Applications in support of science priorities and societal needs, *Ocean Sci.*, **18**, 797–837, DOI: 10.5194/os-18-797-2022.

Rubino, A., Gačić, M., Bensi, M., Kovačević, V., Malačič, V., Menna, M. N., Negretti, E. M., Sommeria, J., Zanchettin, D., Barreto, V. R., Ursella, L., Cardin, V. et al. (2020): Experimental evidence of long-term oceanic circulation reversals without wind influence in the North Ionian Sea, *Sci. Rep.*, **10**, 1905, https://doi.org/10.1038/s41598-020-57862-6.

Šantić, D., Kovačević, V., Bensi, M., Giani, M., Vrdoljak T., Šestanović, S., Ordulj, M., Santinelli, C., Šolić, M. and Grbec, B. (2020): Picoplankton distribution and activity in the deep waters of the southern Adriatic Sea, *Ocean Exchange and Circulation*, Gačić, M. and Bensi, M. (Eds), Basel, Switzerland: MDPI, 153-173.

Šantić, D., Piwosz, K., Matić, F., Vrdoljak Tomaš, A., Arapov, J., Dean, J.L., Šolić, M., Koblížek, M., Kušpilić, G. and Šestanović, S. (2021): Artificial neural network analysis of microbial diversity in the Central and Southern Adriatic Sea, *Sci. Rep.*, **11**, 1-15, https://doi:10.1038/s41598-021-90863-7.

Sathyendranath, S., Platt, T., Kovač, Ž., Dingle, J., Jackson, T., Brewin, J. W., Franks, P., Maranon, E., Kulk, G. and Bouman, H. (2020): Reconciling models of primary production and photoacclimation, *Appl. Opt.*, **59,** https://doi.org/10.1364/AO.386252.

Šepić, J., Pasarić, M., Međugorac, I., Vilibić, I., Karlović, M. and Mlinar, M. (2022): Climatology and process-oriented analysis of the Adriatic sea level extremes, *Prog. Oceanogr.*, **209**, 102908, DOI: 10.1016/j.pocean.2022.102908.

Šolić, M., Šantić, D., Šestanović, S., Bojanić, N., Grbec, B., Jozić, S., Vrdoljak, A., Ordulj, M., Matić, F., Kušpilić, G. and Ninčević Gladan, Ž. (2020): Impact of water column stability dynamics on the succession of planktonfood web types in the offshore area of the Adriatic Sea, *J. Sea Res.*, **158**, 101860, https://doi:10.1016/j.seares.2020.101860.

Šolić, M., Šantić, D., Šestanović, S., Kušpilić, G., Matić, F., Vrdoljak Tomaš, A., Jozić, S., Bojanić, N. and Ninčević Gladan, Ž. (2022): Changing ecological conditions in the marine environment generate different microbial food web structures in a repeatable manner, *Front. Mar. Sci.*, **8**, 1-16, https://doi:10.3389/fmars.2021.811155.

Talijančić, I., Šegvić-Bubić, T., Žužul, I., Džoić, T., Maršić-Lučić, J. and Grubišić, L. (2019): Morphological and ecophysiological adaptations of wild gilthead seabream Sparus aurata associated with tuna farms, *Aquacult. Environ. Interact.*, **11**, 97-110, https://doi:10.3354/aei00294.

Tintoré, J., Pinardi, N., Álvarez-Fanjul, E., Aguiar, E., Álvarez-Berastegui, D., Bajo, M., Balbin, R., Bozzano, R., Buongiorno Nardelli, B., Cardin, V., Casas, B., Charcos-Llorens, M. et al. (2019): Challenges for sustained observing and forecasting systems in the Mediterranean Sea, *Front. Mar. Sci.*, **6**, 568, DOI: 10.3389/fmars.2019.00568.

Tojčić, I., Denamiel, C. and Vilibić, I. (2021): Performance of the Adriatic early warning system during the multi-meteotsunami event of 11-19 May 2020: an assessment using energy banners, *Nat. Hazards Earth Syst. Sci.*, **21**, 2427-2446, DOI: 10.5194/nhess-21-2427-2021.

Umgiesser, G., Bajo, M., Ferrarin, C., Cucco, A., Lionello, P., Zanchettin, D., Papa, A., Tosoni, A., Ferla, M., Coraci, E., Morucci, S., Crosato, F. et al. (2021): The prediction of floods in Venice: methods, models and uncertainty (review article), *Nat. Hazard Earth Sys.*, **21**, 2679-2704, https://doi.org/10.5194/nhess-21-2679-2021.

Vilibić, I., Zemunik, P., Šepić, J., Dunić, N., Marzouk, O., Mihanović, H., Denamiel, C., Precali, R. and Djakovac, T. (2019): Present-climate trends and variability in thermohaline properties of the northern Adriatic shelf, *Ocean Sci.*, **15**, 1351–1362.

Vilibić, I., Zemunik, P., Dunić, N. and Mihanović, H. (2020): Local and remote drivers of the observed thermohaline variability on the northern Adriatic shelf (Mediterranean Sea), *Cont. Shelf Res.*, **199**, 104110, DOI: 10.1016/j.csr.2020.104110.

Vilibić, I., Rabinovich, A.B. and Anderson, E.J. (2021a): Special issue on the global perspective on meteotsunami science: editorial, *Nat. Hazards*, **106**, 1087-1104, DOI: 10.1007/s11069-021-04679-9.

Vilibić, I., Denamiel, C., Zemunik, P. and Denamiel, C. (2021b): The Mediterranean and Black Sea meteotsunamis: An overview, *Nat. Hazards*, **106**, 1223-1267, DOI: 10.1007/s11069-020-04306-z.

Vilibić, I., Dunić, N. and Peharda, M. (2022): Near-surface ocean temperature variations across temporal scales in the coastal eastern Adriatic, *Cont. Shelf Res.*, **245**, 104786, DOI: 10.1016/j.csr.2022.104786.

Vrdoljak Tomaš, A., Šantić, D., Šolić, M., Ordulj, M., Jozić, S., Šestanović, S., Matić, F., Kušpilić, G. and Ninčević Gladan, Ž. (2019): Dynamics of aerobic anoxygenic phototrophs along the trophic gradient in the central Adriatic Sea, *Deep Sea Res. PT II,* **164**, 112-121, https://doi:10.1016/j.dsr2.2019.06.001.

Zemunik, P., Bonanno, A., Mazzola, S., Giacalone, G., Fontana, I., Genovese, S., Basilone, G., Candela, J., Šepić, J., Vilibić, I. and Aronica, S. (2021a): Observing meteotsunamis („Marrobbio“) in the southwestern coast of Sicily, *Nat. Hazards*, **106**, 1337-1363, DOI: 10.1007/s11069-020-04303-2.

Zemunik, P., Šepić, J., Pellikka, H., Ćatipović, L. and Vilibić, I. (2021b): Minute Sea-Level Analysis (MISELA): a high-frequency sea-level analysis global dataset, *Earth Syst. Sci. Data*, **13**, 4121–4132, DOI: 10.5194/essd-13-4121-2021.

Zemunik, P. (2022): Climatology of high-frequency sea-level oscillations in the world ocean, PhD thesis, Faculty of Science, University of Zagreb, Zagreb, 127 pp, availbale at https://repozitorij.pmf.unizg.hr/islandora/object/pmf%3A11478 (in Croatian).

Zemunik, P., Denamiel, C., Šepić, J. and Vilibić, I. (2022a): High-frequency sea-level analysis: Global distributions, *Global Planet. Change*, **210**, 103775, DOI: 10.1016/j.gloplacha.2022.103775.

Zemunik, P., Denamiel, C., Williams, J. and Vilibić, I. (2022b): High-frequency sea-level extremes: Global correlations to synoptic atmospheric patterns, *Weather Clim. Extrem.*, **38**, 100516, DOI: 10.1016/j.wace.2022.100516.

Živković, I., Fajon, V., Kotnik, J., Shlyapnikov, Y., Obu Vazner, K., Begu, E., Šestanović, S., Šantić, D., Vrdoljak, A., Jozić, S., Šolić, M., Lušić, J. et al. (2019): Relations between mercury fractions and microbial community components in seawater under the presence and absence of probable phosphorus limitation conditions, *J. Environ. Sci-China*, **75**, 145-162, https://doi:10.1016/j.jes.2018.03.012.

Žužul, I., Šegvić-Bubić, T., Talijančić, I., Džoić, T., Lepen-Pleić, I., Beg Paklar, G., Ivatek-Šahdan, S., Katavić, I. and Grubišić, L. (2019): Spatial connectivity pattern of expanding gilthead seabream populations and its interactions with aquaculture sites: a combined population genetic and physical modelling approach, *Sci. Rep.*, **9**, 14718, https://doi.org/10.1038/s41598-019-51256-z.

# 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. (Figure 1). The main earthquake was followed by a large number of aftershocks.

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

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 (Figure 2).

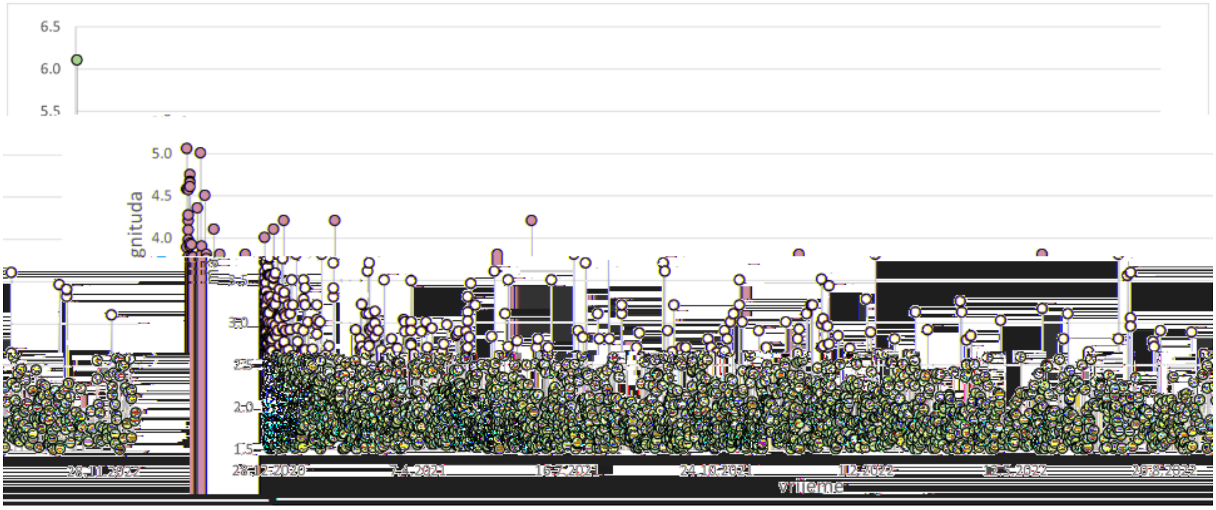

**Figure 2.** Temporal distribution of the magnitudes of the Petrinja series of earthquakes – magnitudes greater than 1.5 (URL 1).

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 curent locations of seismological stations of the mobile network is displayed in Figure 3.

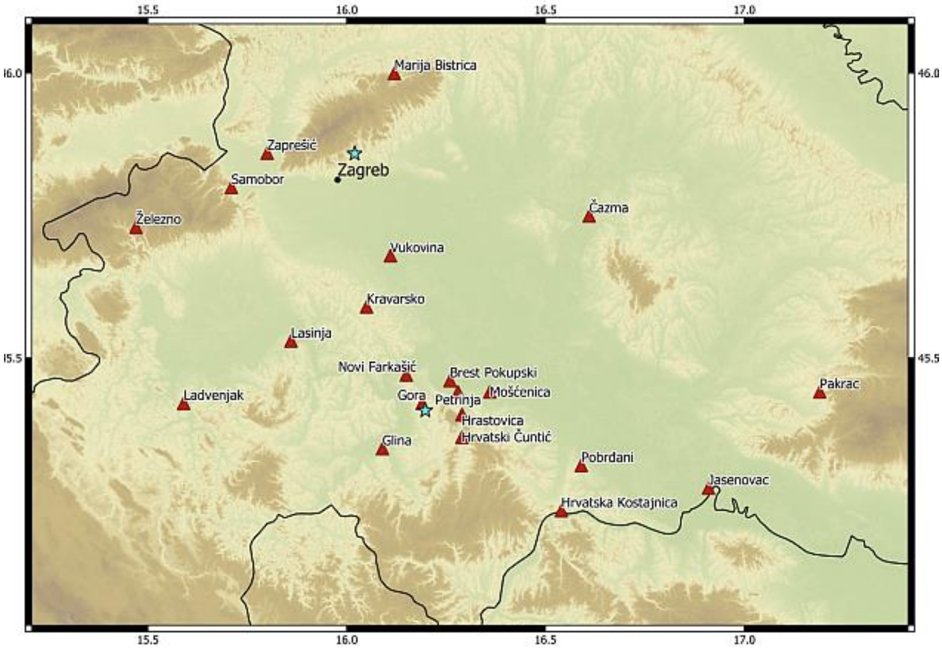


**Figure 3.** Map of currently active seismological stations of the mobile network (red triangles) and the locations of the epicenters of the main Zagreb and Petrinja earthquakes (blue stars) (URL 4).

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.

***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 (Figure 4). 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.

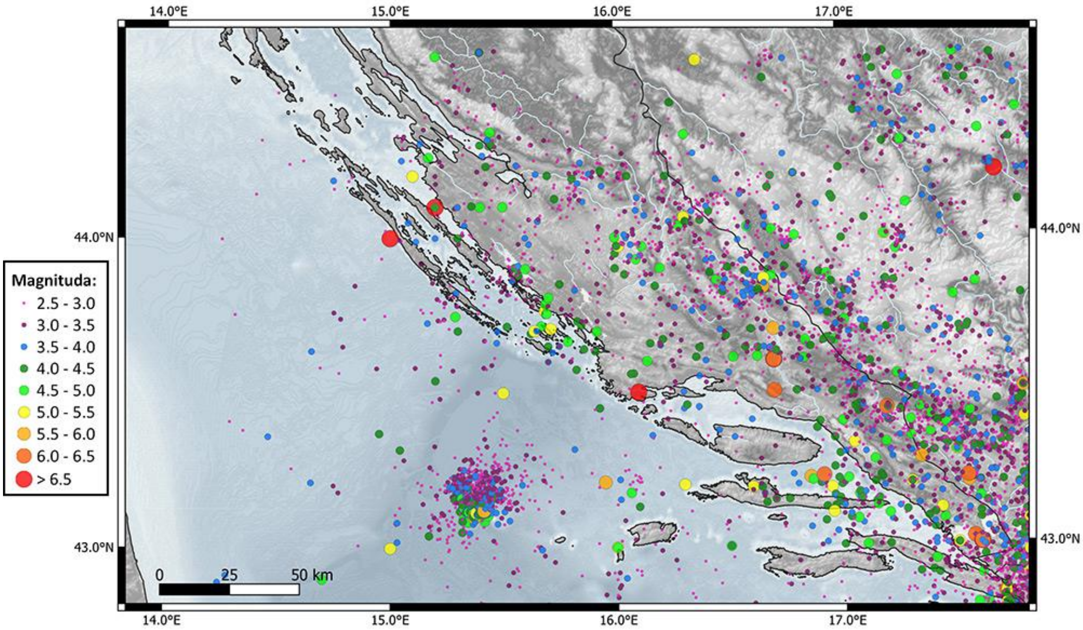


**Figure 4.** The research area of the CRONOS project (URL 6).

***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 (Figure 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.

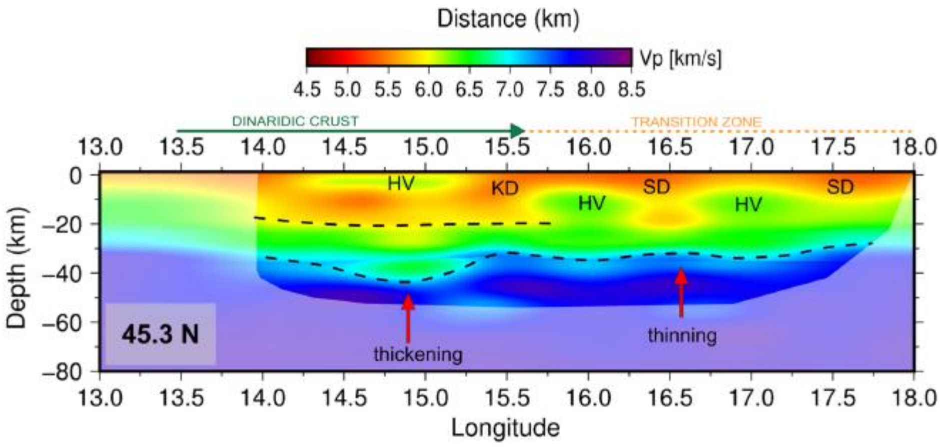


**Figure 5.** Section along 45.3 N across the P-wave inversion model (from Kapuralić et al., 2019). HV – high-velocity anomalies, KD – Karlovac depression, SD – Sava depression. Black dashed lines represent an intra-crustal discontinuity and the Moho discontinuity.

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, encompasing wider Dinarides region (Figure 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.

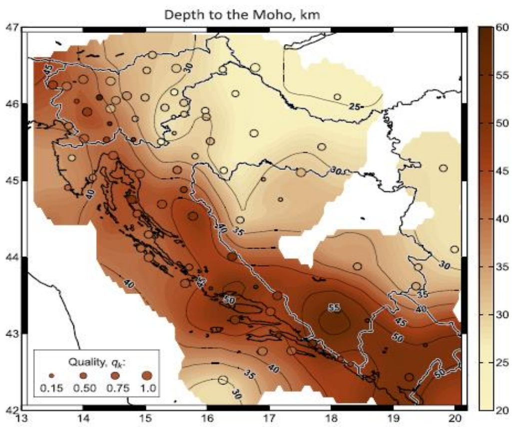


**Figure 6.** Depth to the Mohorovičić discontinuity below each of the stations is shown by the colored circles according to the color scale on the right (from Stipčević et al., 2020). The interpolated Moho surface was spatially smoothed with a smoothing kernel of the radius of 41.5 km.

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 (Figure 7).

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 (Figure 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.

***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 (nothwestern 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 (Figure 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).

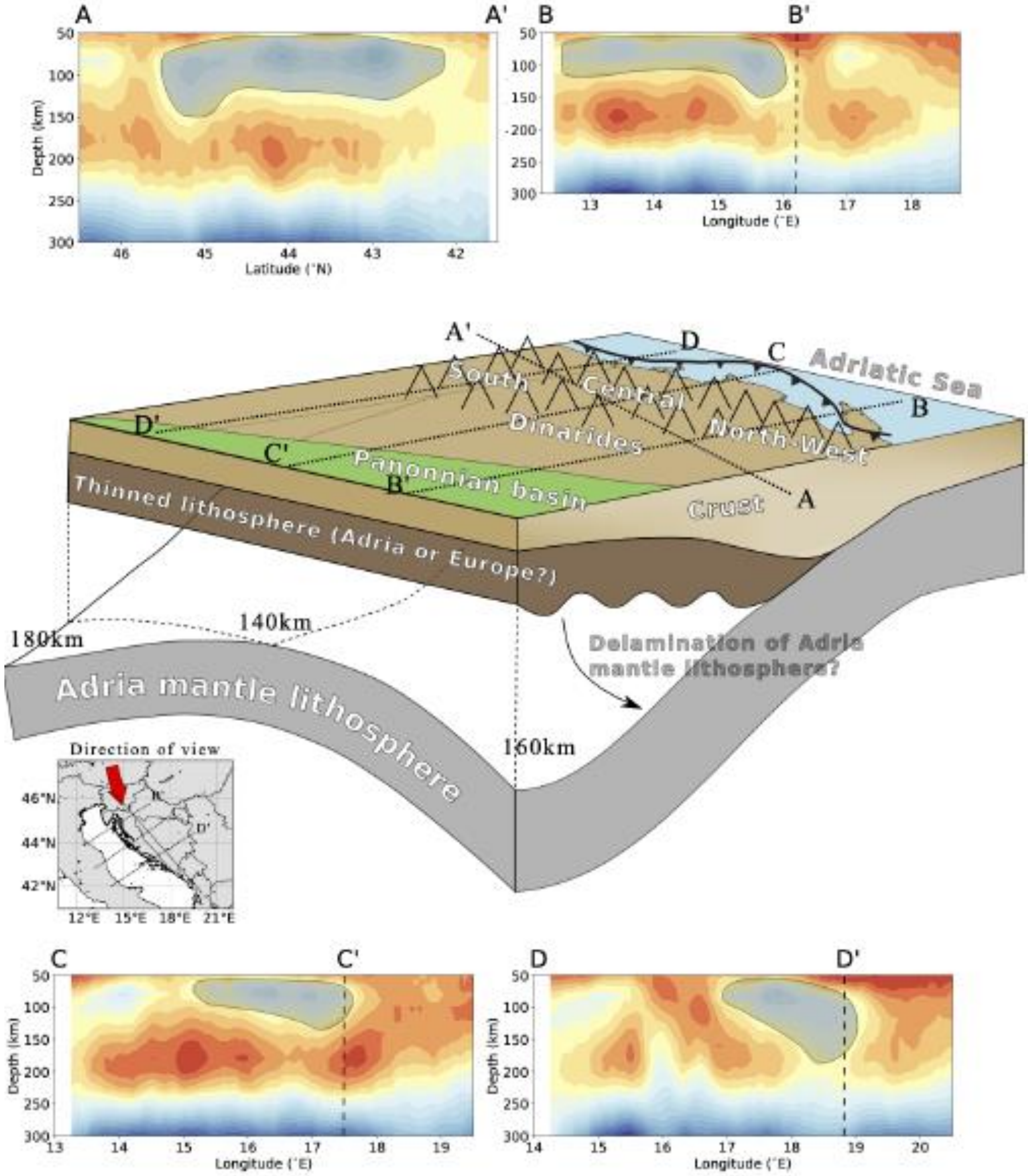


**Figure 7.** Schematic interpretation of the Dinarides lithospheric structure (not to scale) from the new 3-D shear-wave velocity model (from Belinić et al., 2021). Subimages a) to d) are the cross-sections through the new shear-wave velocity model with shaded areas marking the location and shape of 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.

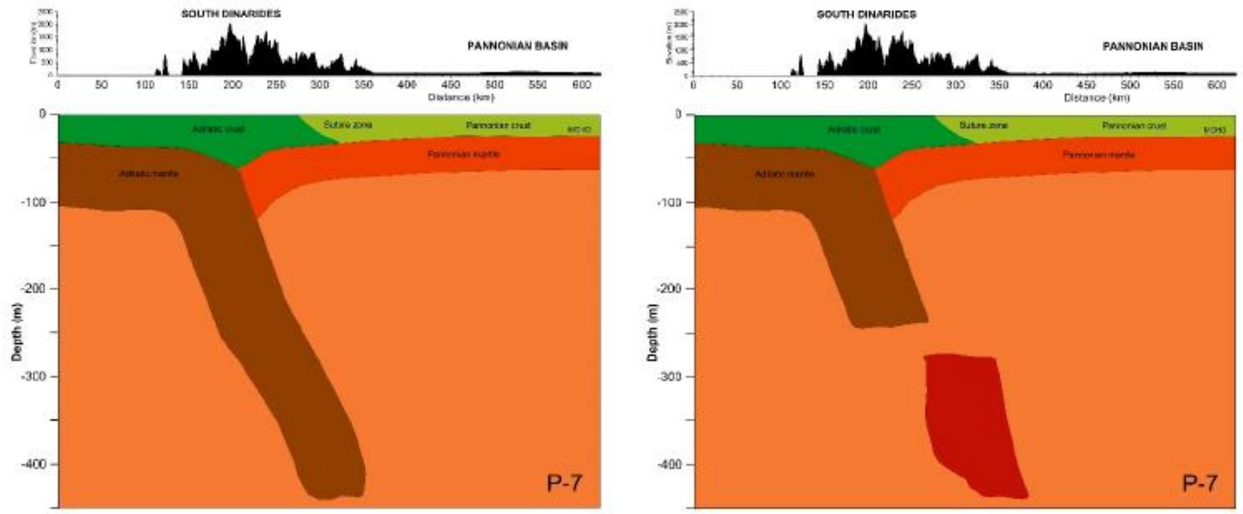


**Figure 8.** Two possible structural models of the lithosphere in the Southern Dinarides (from Šumanovac, 2022). The first model (on the left) assumes a steeply dipping continuous Adriatic lithospheric slab. The second model (on the right) presumes that the Adriatic slab consists of two separate blocks,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

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 (Figure 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.

A semi-empirical estimation of the Zagreb $M_L$5.5 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_L$5.5 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 (Figure 12).

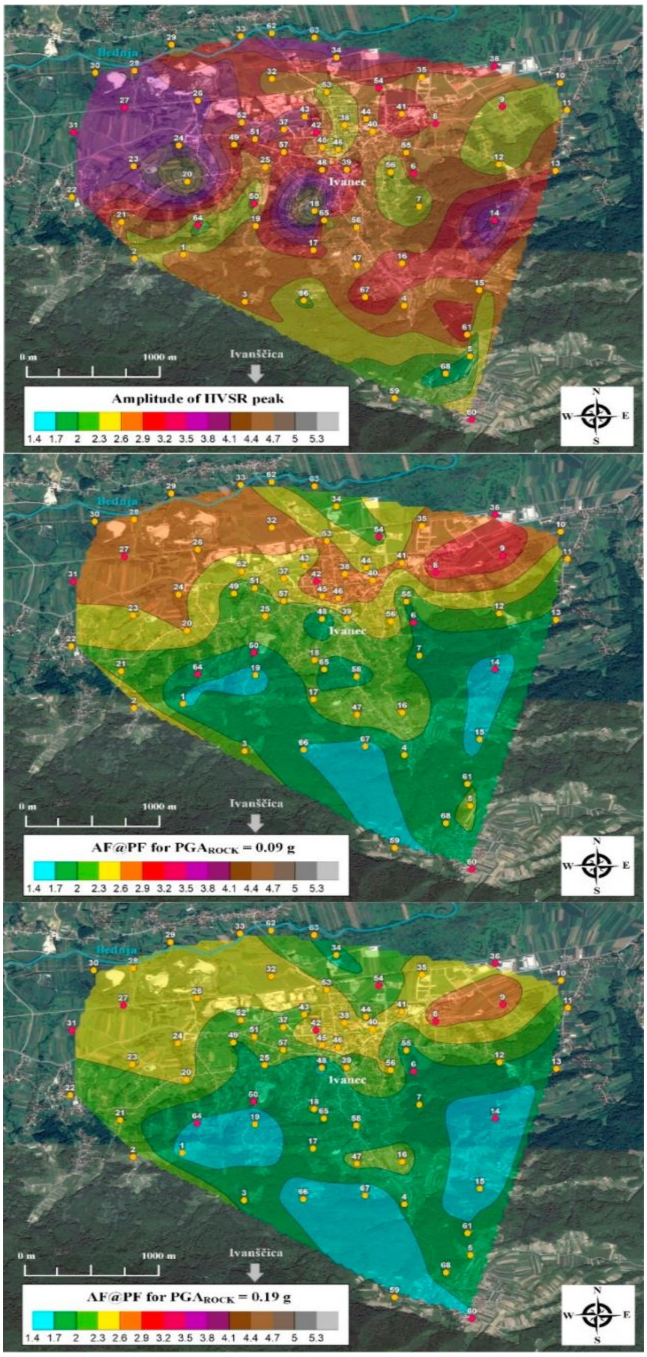


**Figure 9.** *Up:* Map of the amplitude of HVSR peak at fundamental HVSR frequency. *Middle:* Map of site response amplification factor at predominant frequency for input $PGA_{ROCK}$ = 0.09 g (95yrp). *Bottom:* Map of site response amplification factor at predominant frequency for input $PGA_{ROCK}$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

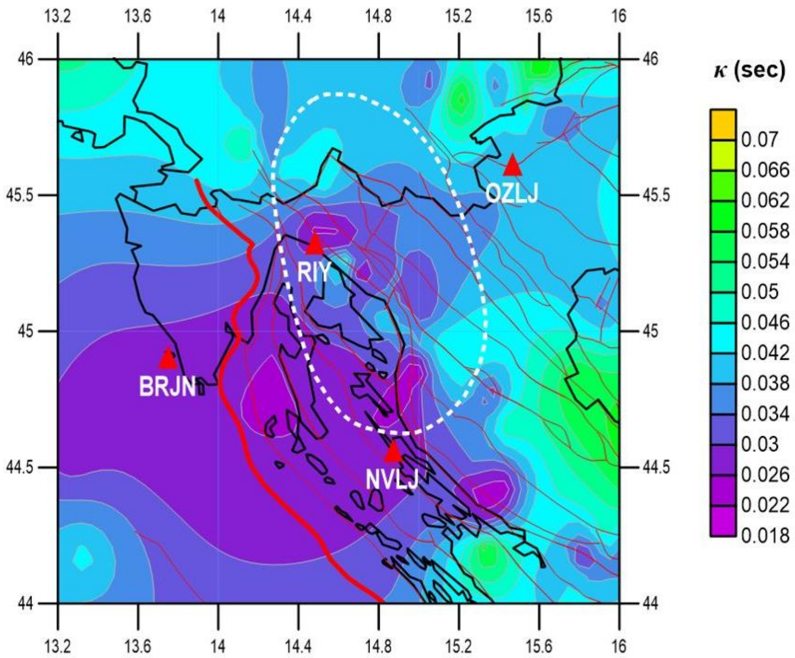


**Figure 10.** Spatial distribution of kappa parameter – high-frequency attenuation parameter (from Markušić et al., 2019). Red lines represent the possible seismogenic surface faults, red triangles mark the locations of seismic stations, thick white dashed line marks the contours of the northern Dinaric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

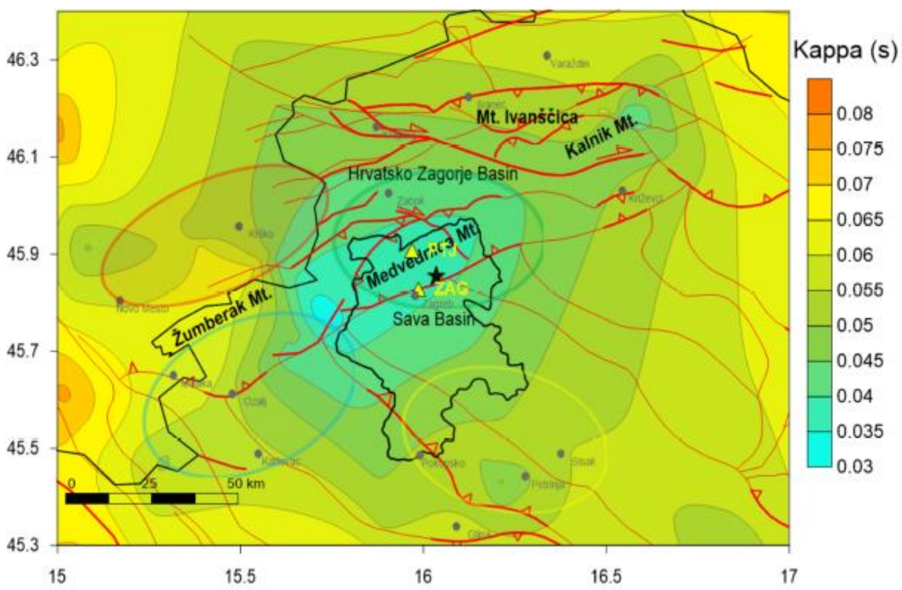


**Figure 11.** Regional kappa dependence around the PTJ and ZAG seismological stations shown as a spatial distribution of individual kappa values (from Stanko et al., 2020). Red lines represent the possible seismogenic surface faults in Croatia and possible active faults are marked with thick lines. 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.

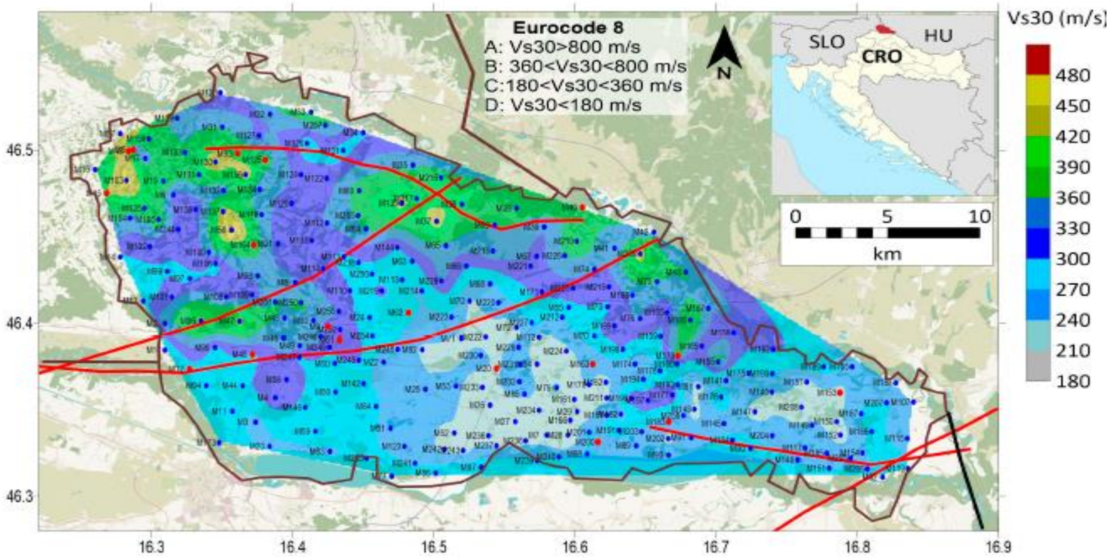


**Figure 12.** Map of estimated $V_{S30}$ values of the Međimurje region (from Stanko et al., 2022). The most important seismogenic faults are shown with red lines.

***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 (Figure 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 geoacoustical 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 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 $km^2$. 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 (Figure 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.

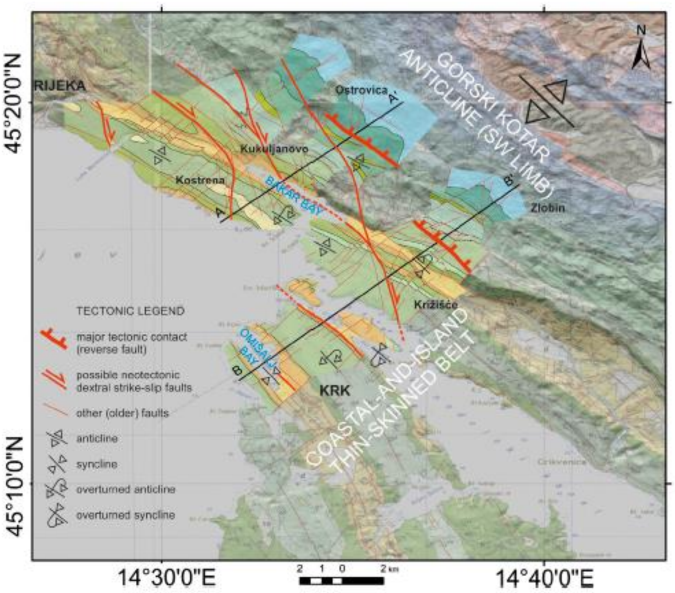


**Figure 13.** Simplified new geological map of the area of focused fieldwork (from Korbar et al., 2020). The major fault (the thickest red lines) delineates the Gorski Kotar anticline and the coastal-and-island thin-skinned belt. Possible neotectonic dextral strike-slip faults on the surface are marked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

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

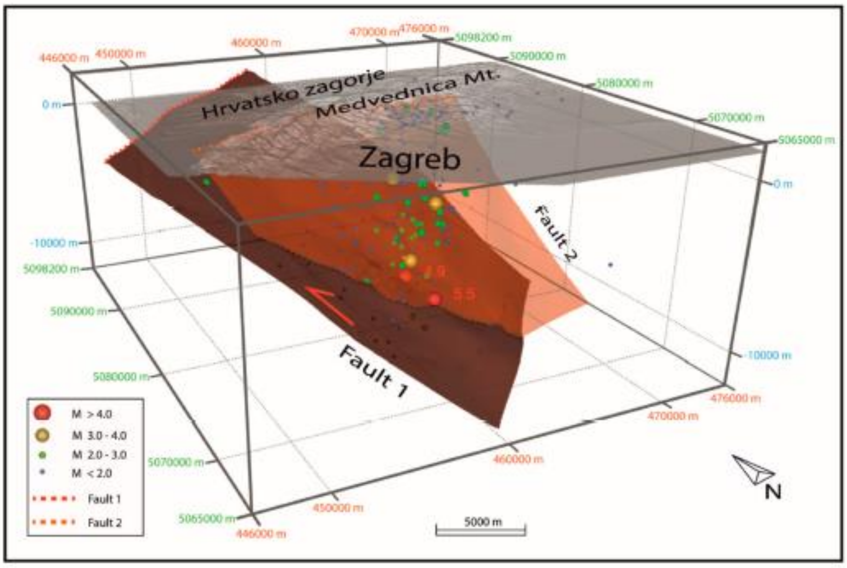


**Figure 14.** Preliminary structural 3D model of the Zagreb 2020 earthquake sequence (from Markušić et al., 2020). Coordinates are shown in HTRS96/TM coordinate system, and the elevation is in meters (no vertical exaggeration). Fault 1 is interpreted as a primary thrust fault, and Fault 2 is interpreted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

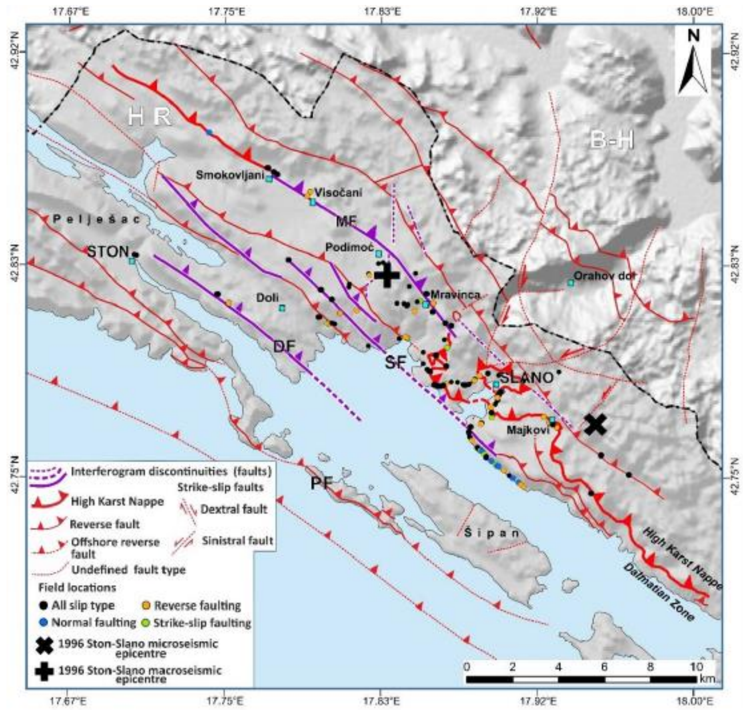


**Figure 15.** Simplified structural map of the Ston–Slano area with faults mapped onshore and offshore (from Govorčin et al., 2020). Fault measurements conducted at the 127 locations are indicated with multicolour dots in accordance to the measured fault's kinematic properties. Locations of microseismic 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 (PGAsite) values were likely between 0.4 and 0.6 g depending on the local site characteristics and the distance from the epicentre.

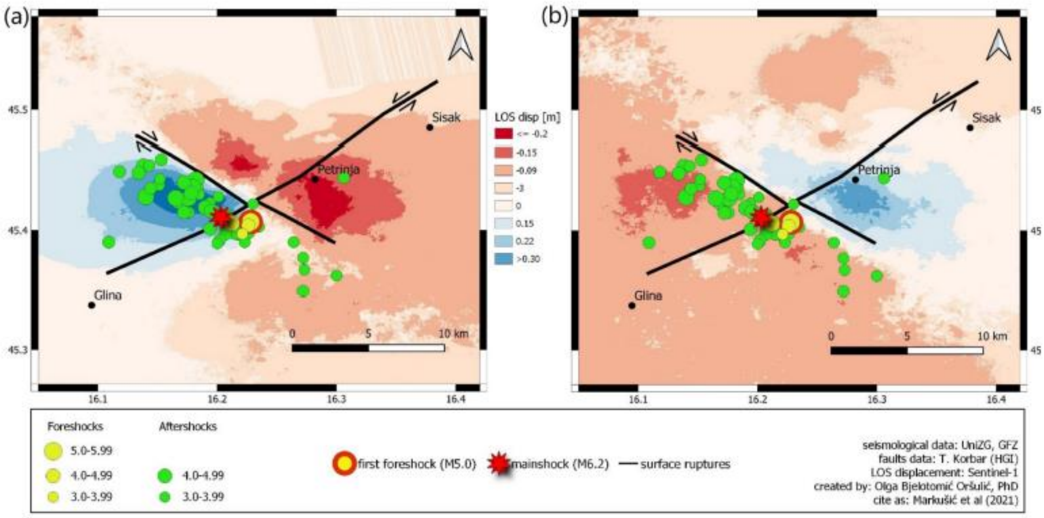


**Figure 16.** Line of sight (LOS) displacements for (a) Sentinel-1A ascending orbit T146, which has an amplitude of 74 cm and (b) Sentinel-1B descending orbit T124, which has an amplitude of 53 cm (from Markušić et al., 2021).

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 $km^2$ 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.

**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.

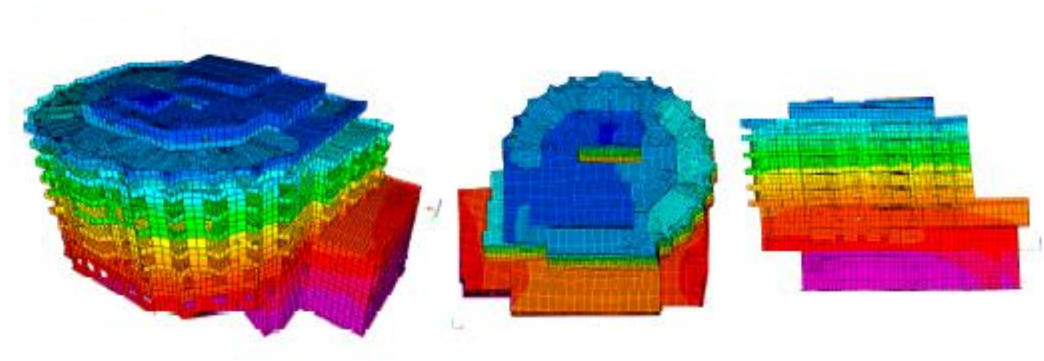

**Figure 19.** Three-dimensional view of mode shapes of the initial numerical model of the General Hospital Dubrovnik – first mode (from Uroš et al., 2020).

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_L$6.2 scenario (chosen as case study). Model is applicable for magnitudes up to $M_w$6.5 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_L$5.3) and the Zagreb 2020 ($M_L$5.5) 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.

# *List of publications*


Abrahamczyk, L., Penava, D., Markušić, S., Stanko, D., Hasan Luqman, P., Haweyou, M. and Schwarz, J. (2022): Die Magnitude 6.4 Albanien und Kroatien Erdbeben Ingenieuranalyse der Erdbebenschäden und Erfahrungswerte für die Baunormung. *Mauerwerk*, **126/3,** 109-121. DOI:10.1002/dama.202210022.

(AlpArray – CASE) Salimbeni, S., Prevolnik, S., Silvia, P., Molinari, I., Stipčević, J., Dasović, I., Šipka, V., Herak, M., Kissling, E., ALPARRAY-CASE working group (2019): Seismic anisotropy distribution in Southern Italy and Dinaric region: new results from ”Central Adriatic Seismic Experiment” (CASE) project. *EGU General Assembly 2019, Vienna, Austria, 7-12th April 2019*, Geophysical Research Abstracts, Vol. 21, EGU2019-15176.

(AlpArray - CASE) Stipčević, J., Herak, M., Molinari, I. and Dasović. I. (2019): New Moho depth map for the wider Dinarides region. *EGU General Assembly 2019, Vienna, Austria, 7-12th April 2019*, Geophysical Research Abstracts, Vol. 21, EGU2019-13536.

Atalić, J., Šavor Novak, M., Uroš, M., Prevolnik, S., Lazarević, D., Hak, S. (2019): Izazovi pri procjenama rizika od potresa u Hrvatskoj. *Dani ovlaštenih inženjera građevinarstva, Opatija, Hrvatska, 13. – 15. lipnja 2019.*

Atalić, J., Uroš, M., Šavor Novak, M., Demšić, M., Baniček, M., Herak, M., Dasović, I., Prevolnik, S. (2021): A. Uvodno o potresu i njegovim učincima – A.3. Potres u Zagrebu u ožujku 2020. godine. Potresno inženjerstvo – Obnova zidanih zgrada (urednici: Uroš, M., Todorić, M., Crnogorac, M., Atalić, J., Šavor Novak, M., Lakušić, S.), Zagreb, Građevinski fakultet Sveučilišta u Zagrebu, 46-68.

Baize, S., Amoroso, S., Belić, N., Benedetti, L., Boncio, P., Budić, M., Cinti, F.R., Henriquet, M., Jamšek Rupnik, P., Kordić, B., Markušić, S. et al. (2022): Environmental effects and seismogenic source characterization of the December 2020 earthquake sequence near Petrinja, Croatia. *Geophysical Journal International*, **230(2)**, 1394-1418. DOI:10.1093/gji/ggac123.

Belinić, T., Kolínský, P. and Stipčević, J. (2019): Shear-wave velocity structure beneath the Dinarides from the inversion of Rayleigh-wave dispersion. *EGU General Assembly 2019, Vienna, Austria, 7-12th April 2019*, Geophysical Research Abstracts, Vol. 21, EGU2019-13775.

Belinić, T., Kolínský, P. and Stipčević, J. (2021): Shear-wave velocity structure beneath the Dinarides from the inversion of Rayleigh-wave dispersion. *Earth and Planetary Science Letters*, **555**, 116686. DOI:10.1016/j.epsl.2020.116686.

Brcković, A. and Orešković, J. (2022): Employing machine learning algorithm for cross validating porosity-velocity model. *International Congress on Geomathematics in Earth and Environmental Sciences, and the 22nd Hungarian Geomathematical Congress (GEOMATES), Pécs, Hungary, 19-21st May 2022*, edited by Gábor Hatvani, I., Erdélyi, D. and Fedor, F., Abstract book, 77.

Dasović, I., Herak, D., Herak, M., Latečki, H., Mustać, M., Tomljenović, B. (2020): O potresima u Hrvatskoj. *Vijesti Hrvatskoga geološkog društva*, **57/1**, 4-27.

Dasović, I., Herak, D., Herak, M., Stipčević, J. (2021): Niz potresa na Baniji. *Vijesti Hrvatskoga geološkog društva*, **57/2**, 4-7.

Donner, S., Mustać, M., Hejrani, B., Tkalčić, H. and Igel, H. (2020): Seismic moment tensors from synthetic rotational and translational ground motion: Green's functions in 1-D versus 3-D. *Geophysical Journal International*, **223/1**, 161-179. DOI:10.1093/gji/ggaa305.

Faivre, S., Bakran-Petricioli, T., Herak, M., Barešić, J. and Borković, D. (2021): Late Holocene interplay between coseismic uplift events and interseismic subsidence at Koločep island and Grebeni islets in the Dubrovnik archipelago (southern Adriatic, Croatia). *Quaternary Science Reviews*, **274**, 1-16. DOI:10.1016/j.quascirev.2021.107284.

Faivre, S., Bakran-Petricioli, T., Herak, M., Barešić, J., Horvatić, D. and Borković, D. (2022): Lithophyllum rims as markers of palaeoseismic events and relative sea-level change in the Dubrovnik archipelago, Southern Adriatic, Croatia. *The 10th International Conference on Geomorphology, Geomorphology and Global Change, International Association of Geomorphologists (IAG). Coimbra, Portugal, 12-16th September 2022*, Book of Abstracts, 1-2. DOI:10.5194/icg2022-36.

Govorčin, M., Herak, M., Matoš, B., Pribičević, B. and Vlahović, I. (2020): Constraints on complex faulting during the 1996 Ston-Slano (Croatia) earthquake inferred from the DInSAR, seismological, and geological observations. *Remote Sensing*, **12/7**, 1157. DOI:10.3390/rs12071157.

Grabar, K., Strelec, S., Jug, J. and Stanko, D. (2019): Workflow for the geotechnical landslide model – case study from north Croatia. *19th International Multidisciplinary Scientific GeoConference SGEM 2019, Albena, Bulgaria, 28 June – 7 July 2019*, Conference Proceedings, Volume 19: Science and Technologies in Geology, Exploration an Mining, Issue: 1.2 Hydrogeology, Engineering Geology and Geotechnics, Oil and Gas Exploration, 587-594. DOI:10.5593/sgem2019/1.2.

Herak, M. (2019): Mohorovičićev seizmološki opus. *Kroz koru do plašta, nove spoznaje o Andriji Mohorovičiću (1857.-1936.)*, Paušek-Baždar, S., Ilakovac, K., Orlić, M. (ur.), Zagreb: Hrvatska akademija znanosti i umjetnosti, Razred za matematičke, fizičke i kemijske znanosti, 77-90. DOI:10.21857/9xn31crkqy.

Herak, M., Herak, D. and Stipčević, J. (2019): Seismology in Croatia, 2015-2018. *Geofizika*, **36/2**, 217-224.

Herak, M., Živčić, M., Vrkić, I. and Herak, D. (2019): The Međimurje earthquake of 1738 – from historical data to macroseismic parameters. *The 7th International Colloquium on Historical Earthquakes & Paleoseismology Studies, Barcelona, Spain, 4-6th November 2019,* Book of Abstracts, 50.

Herak, M. (2020): Conversion between the local magnitude (ML) and the moment magnitude (Mw) for earthquakes in the Croatian Earthquake Catalogue. *Geofizika*, **37/2**, 197-211. DOI:0.15233/gfz.2020.37.10.

Herak, M., Herak, D. and Živčić, M. (2021): Which one of the three latest large earthquakes in Zagreb was the strongest – the 1905, 1906 or 2020 one? *1st Croatian Conference on Earthquake Engineering, 1CroCEE, Zagreb, Croatia, 22-24th March 2021*, edited by Lakušić, S. and Atalić, J., Proceedings, 225-227.

Herak, M., Herak, D., Živčić, M. and Vrkić, I. (2021). Earthquakes of 1838 and 1839 in the Slovene Hills (Slovenia) – Međimurje (Croatia) area. *Geofizika*, **38/1**, 37-59. DOI:0.15233/gfz.2021.38.2.

Herak, M., Herak, D., Stipčević, J. and Dasović, I. (2022): In search of activated faults in the Petrinja (Croatia) earthquake sequence of 2020–2021. *The 3rd European Conference on Earthquake Engineering & Seismology, Bucharest, Romania, 4-9th September 2022*, edited by Arion, C., Scupin, A. and Ţigănescu, A., Conference Proceedings, 4654-4658.

Jug, J., Stanko, D., Grabar, K. and Hrženjak, P. (2020): New approach in the application of seismic methods for assessing surface excavatability of sedimentary rocks. *Bulletin of Engineering Geology and the Environment*, **79**, 01802, 17. DOI:10.1007/s10064-020-01802-1.

Kapuralić, J. and Šumanovac F. (2019): 3D velocity model of the crust and uppermost mantle in the area of the Dinarides and southwestern Pannonian basin. *6th Croatian Geological Congress, Zagreb, Croatia, 9-12th October 2019*, edited by Horvat, M. Matoš, B. and Wacha, L., Abstracts Book, 98-99.

Kapuralić, J., Šumanovac, F. and Markušić, S. (2019): Crustal structure of the northern Dinarides and southwestern part of the Pannonian basin inferred from local earthquake tomography. *Swiss Journal of Geosciences*, **112**, 181-198. DOI:10.1007/s00015-018-0335-2.

Kapuralić, J., Šumanovac, F. and Medved, I. (2022): Characterization of the contact between Adriatic and Pannonian lithosphere based on the 3D velocity model from local earthquake tomography. *XXII International Congress of the Carpathian-Balkan Geological Association (CBGA), Plovdiv, Bulgaria, 7-11th September 2022*, edited by Peytcheva, I., Lazarova, A., Granchovski, G., Lakova, I., Ivanova, R. and Metodiev, L., Abstract Book, 173.

Kastelic, V., Atzori, S. Carafa, M.M.C., Govorčin, M., Herak, M., Herak, D., Matoš, B., Stipčević, J. and Tomljenović, B. (2021): Petrinja seismogenic source and its 2020-2021 earthquake sequence (central Croatia). *EGU General Assembly 2021, online, Vienna, Austria, 19-23 April 2021*, EGU21-16579.

Korbar, T., Markušić, S., Hasan, O., Fuček, L., Brunović, D., Belić, N., Palenik, D. and Kastelic, V. (2020): Active tectonics in the Kvarner region (External Dinarides, Croatia) – an alternative approach based on focused geological mapping, 3D seismological and shallow seismic imaging data. *Frontiers in Earth Science*, **8**, 582797. DOI:10.3389/feart.2020.582797.

Korbar, T., Markušić, S., Stanko, D. and Penava, D. (2021): Petrinja M6.2 earthquake in 2020 damaged also solid linear infrastructure: Are there similar active faults in Croatia? *1st Croatian Conference on Earthquake Engineering, 1CroCEE, Zagreb, Croatia, 22-24th March 2021*, edited by Lakušić, S. and Atalić, J., Proceedings, 353-362. DOI:10.5592/CO/1CroCEE.2021.253.

Kuveždić Divjak, A., Govorčin, M., Matoš, B., Đapo, A., Stipčević, J. and Pribičević, B. (2019): Geoinformation for research of ongoing geodynamic processes in the Republic of Croatia. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Prague, Czech Republik, 3-6th September 2019,* edited by Tanzi, T., Altan, O., Chandra, M. and Sunar, F., Volume XLII-3/W8, 233-240. DOI:10.5194/isprs-archives-xlii-3-w8-233-2019.

Latečki, H., Molinari, I. and Stipčević, J. (2021): 3D physics-based seismic shaking scenarios for city of Zagreb, Capital of Croatia. *Bulletin of Earthquake Engineering*, **20**, 167-192. DOI:10.1007/s10518-021-01227-5.

Latečki, H., Stipčević, J. and Molinari, I. (2021): Seismic shaking scenarios for city of Zagreb, Croatia. *1st Croatian Conference on Earthquake Engineering, 1CroCEE, Zagreb, Croatia, 22-24th March 2021*, edited by Lakušić, S. and Atalić, J., Proceedings, 1625. DOI:10.5592/co/1crocee.2021.138.

Latečki, H., Stipčević, J. and Molinari, I. (2021): Seismic shaking scenarios for city of Zagreb, Croatia. *EGU General Assembly 2021, online, Vienna, Austria, 19-23 April 2021*, EGU21-8781. DOI:10.5194/egusphere-egu21-8781.

Latečki, H., Sečanj, M., Dasović, I. and Stipčević, J. (2022): Seismic shaking scenarios for city of Dubrovnik, Croatia. *EGU General Assembly 2022, Vienna, Austria, 23-27 May 2022*, EGU22-8291. DOI:10.5194/egusphere-egu22-8291.

Lončar, I., Markušić, S., Stanko, D., Gazdek, M., Ivančić, I. and Uglešić, J.S. (2022): SeisRICHerCRO project: seismicity of earthquake prone regions (Trakošćan, Šibenik, and Dubrovnik) in Croatia. *7th World Multidisciplinary Civil Engineering – Architecture – Urban Planning Symposium – WMCAUS 2022, Prague, Czech Republic, 5-9th September 2022*, edited by Yilmaz, A., Marschalko, M. and Drusa, M., Abstract book, 304.

Marković Vukadin, I., Mustać, M., Nujić, L., Fio Firi, K., Martinjak, J., Marušić, Z. and Baniček, M. (2021): Importance of scientifically based facts in crisis communication: Evidence from earthquakes in Zagreb and Petrinja. *Sociologija i prostor*, **59/3**, 535-555. DOI:10.5673/sip.59.3.10.

Markušić, S., Stanko, D., Korbar, T. and Sović, I. (2019): Estimation of near-surface attenuation in the tectonically complex contact area of the northwestern External Dinarides and the Adriatic foreland. *Natural Hazards and Earth System Sciences*, **19/12**, 2701-2714. DOI:10.5194/nhess-19-2701-2019.

Markušić, S., Stanko, D., Korbar, T., Belić, N., Penava, D. and Kordić, B. (2020): The Zagreb (Croatia) M5.5 earthquake on 22 March 2020. *Geosciences*, **10/7**, 252, 21. DOI:10.3390/geosciences10070252.

Markušić, S., Stanko, D., Penava, D. and Trajber, D. (2021): Use of ambient vibration measurements in earthquake protection of historical buildings – Case study: Castle Trakošćan, Croatia. *37th General Assembly (GA) of the European Seismological Commission – ESC 2021, Athens, Greece, 19-24th September (virtual)*, edited by Voulgaris, N., Book of abstracts, 53.

Markušić, S., Frolova, N., Gabsatarova, I., Suchshev, S. and Malaeva, N. (2021): Calibration of shaking intensity models of the “Extremum” system to simulate loss due to the 2020 Croatia earthquakes. *Geofizika*, **38(2)**, 175-189. DOI:10.15233/gfz.2021.38.8.

Markušić, S., Stanko, D., Penava, D., Trajber, D. and Šalić, R. (2021): Preliminary observations on historical castle Trakošćan (Croatia) performance under recent ML ≥ 5.5 earthquakes. *Geosciences*, **11**, 461, 17. DOI:10.3390/geosciences11110461.

Markušić, S., Stanko, D., Penava, D., Ivančić, I., Bjelotomić Oršulić, O., Korbar, T. and Sarhosis, V. (2021): Destructive M6.2 Petrinja earthquake (Croatia) in 2020 – Preliminary multidisciplinary research. *Remote Sensing*, **13/6**, 1095, 29. DOI:10.3390/rs13061095.

Mustać, M., Hejrani, B., Tkalčić, H., Kim, S., Lee, S. and Cho, Ch. (2020): Large isotropic component in the source mechanism of the 2013 Democratic People’s Republic of Korea nuclear test revealed via a hierarchical Bayesian inversion. *Bulletin of the Seismological Society of America*, **110/1**, 166-177. DOI:10.1785/0120190062.

Mustać, M., Cecić, I., Latečki, H. and Dasović, I. (2021): Social media as a tool for providing information following a hazardous event: „Zagrebački potres 2020 – vaše info za seizmologe“ Facebook group. *1st Croatian Conference on Earthquake Engineering, 1CroCEE, Zagreb, Croatia, 22-24th March 2021*, edited by Lakušić, S. and Atalić, J., Proceedings, 675. DOI:10.5592/co/1crocee.2021.249.

Mustać, M., Dasović, I., Latečki, H. and Cecić, I. (2021): The public response and educational outreach through social media after the Zagreb earthquake of 22 March 2020. *Geofizika*, **38/2**, 215-234. DOI:10.15233/gfz.2021.38.7.

Orešković, J. and Šimičević, F. (2019): Use of Ant-tracking attribute and combined seismic volumes for fault identification: A case study from Sava depression. *6th Croatian Geological Congress, Zagreb, Croatia, 9-12th October 2019*, edited by Horvat, M. Matoš, B. and Wacha, L., Abstracts Book, 152.

Palenik, D. Matičec, D., Fuček, L., Matoš, B., Herak, M. and Vlahović, I. (2019): Tectonic evolution and identification of potential seismogenic sources of the Vinodol Valley (NW Adriatic, Croatia) based on geological mapping and structural investigations. *The 6th Croatian Geological Congress with International participation, Zagreb, Croatia, 9-12th October 2019*, edited by Horvat, M., Matoš, B. and Wacha, L., Abstract Book, 154-155.

Palenik, D., Matičec, D., Fuček, L., Matoš, B., Herak, M. and Vlahović, I. (2019): Geological and structural setting of the Vinodol valley (NW Adriatic, Croatia): insights into tectonic evolution based on structural investigations. *Geologia Croatica: Journal of the Croatian Geological Survey and the Croatian Geological Society*, **72/3**, 179-193. DOI:10.4154/gc.2019.13.

Pavičić, I., Matoš, B., Vlahović, I., Govorčin, M., Pavelić, D., Matešić, D., Parlov, J., Stipčević, J., Terzić, J., Kosović, I. et al. (2021): The 29th December 2020, Mw 6.4 Petrinja earthquake (Croatia): Geological framework and observed coseismic deformation features. *18th Meeting of the Central European Tectonic Studies Groups & 25th Meeting of the Czech Tectonic Studies Group, Terchova, Slovakia, 22-25th September 2021*, edited by Gregáňová, M., Molčan-Matejová, M. and Šimonová, V., Book of Abstracts, 106-107.

Penava, D., Anić, F., Stober, D., Markušić, S., Stanko, D. (2020): Ocjenjivanje potresne otpornosti zidanih lukova dviju baroknih građevina: primjer nastave na daljinu. *10. susret Hrvatskog društva za mehaniku, Slavonski Brod, Hrvatska, 1 i 2. listopada 2020. (online)*, urednici Damjanović, D., Kozak, D., Konjatić, P. i Katinić, M., Zbornik radova, 191-200.

Penava, D., Trajber, D., Markušić, S., Stanko, D., Kesedžić, M. (2021): Oštećenja Dvora Trakošćan tijekom potresa M≥5.5 u Zagrebu i Petrinji u 2020. godini. *11. susret Hrvatskog društva za mehaniku, Rijeka, Hrvatska, 16. i 17. rujna 2021.*, urednici Brčić, M., Skoblar, A. i Ribarić, D., Zbornik radova, 201-209.

Penava, D., Vrban, A., Uglešić, J.S., Stanko, D. and Markušić, S. (2022): Episcopal seminary building and classical gymnasium (Jesuit college) in Dubrovnik construction 1662-1765 in terms of contemporary earthquake resistant design supported by measurements. *10th International Congress of Croatian Society of Mechanics, Pula, Croatia, 28-30 September 2022*, edited by Skozrit, I., Tonković, Z. and Sorić, J., Proceedings, 39-40.

Penava, D., Trajber, D., Markušić, S., Glibo, F., Grgić, F., Valičnić, M. and Zovkić, J. (2022): Preliminary assessment of the earthquake performance of cultural heritage assets: The case of Castle Trakošćan (Croatia). *Bauhaus Summer School Forecast Engineering, Weimar, Germany, 20th August – 2nd September 2022*, edited by Abrahamczyk, L., Course book, 1-10.

Pollak, D., Gulam, V., Novosel, T., Avanić, R., Tomljenović, B., Hećej, N., Terzić, J., Stipčević, J., Bačić, M., Kurečić, T. et al. (2021): The preliminary inventory of coseismic ground failures related to December 2020 – January 2021 Petrinja earthquake series. *Geologia Croatica: Journal of the Croatian Geological Survey and the Croatian Geological Society*, **74/2**, 189-208. DOI:10.4154/gc.2021.08.

Prevolnik, S., Markušić, S. and Ivančić, I. (2021): Strong ground motion records of the Zagreb earthquake of 22 March 2020. *1st Croatian Conference on Earthquake Engineering, 1CroCEE, Zagreb, Croatia, 22-24th March 2021*, edited by Lakušić, S. and Atalić, J., Proceedings, 671-673.

Rajh, G., Stipčević, J., Živčić, M., Herak, M. and Gosar, A. (2021): Crustal velocity structure beneath the NW Dinarides from 1-D hypocenter-velocity inversion. *EGU General Assembly 2021, online, Vienna, Austria, 19-23 April 2021*, EGU21-8226. DOI:10.5194/egusphere-egu21-8226.

Šavor Novak, M., Atalić, J., Uroš, M., Prevolnik, S. and Nastev, M. (2019): Seismic risk reduction in Croatia: mitigating the challenges and grasping the opportunities. *Future Trends in Civil Engineering*, edited by Mandić Ivanković, A. and Lakušić, S. Zagreb, University of Zagreb, Faculty of Civil Engineering, 71-109. DOI:10.5592/CO/FTCE.2019.04.

Šavor Novak, M., Uroš, M., Atalić, J., Herak, M., Demšić, M., Baniček, M., Lazarević, D., Bijelić, N., Crnogorac, M. i Todorić, M. (2020): Potres u Zagrebu od 22. ožujka 2020. – preliminarni izvještaj o seizmološkim istraživanjima i oštećenjima zgrada. *Građevinar: časopis Hrvatskog saveza građevinskih inženjera*, **72/10**, 843-867. DOI:10.14256/JCE.2966.2020.

Sinadinovski, C., Markušić, S., Stanko, D., McCue, K.F. and Pekevski, L. (2022): Seismic analysis of moderate size earthquakes recorded on stations at close epicentral distances. *Applied Sciences-Basel*, **12/1**, 470, 14. DOI:10.3390/app12010470.

Stanko, D. and Markušić, S. (2019): Application of Horizontal-to-Vertical Spectral Ratio (HVSR) method for estimation of local site effects in Varaždin County (NW Croatia). *50th Meeting of Young Geoscientists 2019 (Association of Hungarian Geophysicists and the Youth Foundation of the Hungarian Geological Society), Rackeve, Hungary, 29-30th March 2019*, edited by Egyed, L., Abstract book, 34.

Stanko, D., Gulerce, Z., Markušić, S. and Šalić, R. (2019a): Evaluation of the site amplification factors estimated by equivalent linear site response analysis using time series and random vibration theory based approaches. *Soil Dynamics and Earthquake Engineering*, **117**, 16-29. DOI:10.1016/j.soildyn.2018.11.007.

Stanko, D., Markušić, S., Gazdek, M., Slukan, I. Sanković, V. and Ivančić, I. (2019b): Assessment of the seismic site amplification in the city of Ivanec (NW part of Croatia) using the microtremor HVSR method and equivalent-linear site response analysis. *Geosciences*, **9/7**, 312, 27. DOI:10.3390/geosciences9070312.

Stanko, D. and Markušić, S. (2020): An empirical relationship between resonance frequency, bedrock depth and Vs30 for Croatia based on HVSR forward modelling. *Natural Hazards*, **103**, 3715-3743. DOI:10.1007/s11069-020-04152-z.

Stanko, D., Markušić, S. and Penava, D. (2020): Back to the future – Andrija Mohorovičić lecture (1909) & Zagreb (2020) M5.5 earthquake. *Environmental Engineering = Inženjerstvo okoliša*, **7/1**, 1-10. DOI:10.37023/ee.7.1.1.

Stanko, D., Markušić, S., Korbar, T. and Ivančić, J. (2020): Estimation of the high-frequency attenuation parameter kappa for the Zagreb (Croatia) seismic stations. *Applied Sciences-Basel*, **10/24**; 8974, 17. DOI:10.3390/app10248974.

Stanko, D., Markušić, S. and Gazdek, M. (2021): Analysis of the local site effects of the Međimurje region (North Croatia) and its consequences following the 1738 M5.1 Međimurje, 2020 M5.5 Zagreb and M6.2 Petrinja 2020 earthquakes. *37th General Assembly (GA) of the European Seismological Commission – ESC 2021, Athens, Greece, 19-24th September (virtual)*, edited by Voulgaris, N., Book of Abstracts, 42.

Stanko, D., Sović, I., Belić, N. and Markušić, S. (2022): Analysis of local site effects in the Medjimurje region (North Croatia) and its consequences related to historical and recent earthquakes. *Remote Sensing*, **14**, 4831, 23. DOI:10.3390/rs14194831.

Stanko, D., Markušić, S., Uglešić, J.S., Gazdek, M. and Lončar, I. (2022): SeisRICHerCRO: Mapping the local site effects from the analysis of ambient noise measurements in earthquake-prone (with significant cultural heritage buildings) areas in Croatia. *7th World Multidisciplinary Civil Engineering – Architecture – Urban Planning Symposium – WMCAUS 2022, Prague, Czech Republic, 5-9th September 2022*, edited by Yilmaz, A., Marschalko, M. and Drusa, M., Abstract book, 305.

Stipčević, J., Herak, M., Molinari, I., Dasović, I., Tkalčić, H. and Gosar, A. (2020): Crustal thickness beneath the Dinarides and surrounding areas from receiver functions. *Tectonics*, **37**, 1-15. DOI:10.1029/2019TC005872.

Stipčević, J., Belinić Topić, T., Kolínský, P., Herak, M., Molinari, I. and Dasović, I. (2021): Adria microplate fragmentation: geophysical perspective. *EGU General Assembly 2021, online, Vienna, Austria, 19-23 April 2021*, EGU21-14133. DOI:10.5194/egusphere-egu21-14133.

Stipčević, J., Poggi, V., Herak, M., Parolai, S., Herak, D., Dasović, I., Bertoni, M., Barnaba, C. and Pesaresi, D. (2021): First results from temporary deployment of small seismic network following the Mw=6.4 Petrinja earthquake. *EGU General Assembly 2021, online, Vienna, Austria, 19-23 April 2021*, EGU21-16479. DOI:10.5194/egusphere-egu21-16579.

Šugar, D., Bačić, Ž. and Dasović, I. (2021): Geodetic and seismological analysis of the CROPOS ZAGR station kinematics during the Zagreb 2020 ML 5.5 earthquake. *Geofizika*, **38/2**, 191-214. DOI:10.15233/gfz.2021.38.10.

Šumanovac, F. (2019): New litosphere model of the Dinarides based on the forward teleseismic modelling. *6th Croatian Geological Congress, Zagreb, Croatia, 9-12th October 2019*, edited by Horvat, M. Matoš, B. and Wacha, L., Abstracts Book, 197-198.

Šumanovac, F. (2022): Lithosphere structure of the Southern Dinarides and continuity of the Adriatic lithosphere slab beneath the Northern Dinarides unravelled by seismic modelling. *Geosciences*, **12**, 1-21. DOI:10.3390/geosciences12120439.

Šumanovac, F., Medved, I. and Kapuralić, J. (2022): Three-dimensional crustal model of the Dinarides and marginal areas based on gravity and seismic models. *XXII International Congress of the Carpathian-Balkan Geological Association (CBGA), Plovdiv, Bulgaria, 7-11th September 2022*, edited by Peytcheva, I., Lazarova, A., Granchovski, G., Lakova, I., Ivanova, R. and Metodiev, L., Abstract Book, 179.

Tomac, I., Kovačević Zelić, B., Perić, D., Domitrović, D., Štambuk Cvitanović, N., Vučenović, H., Parlov, J., Stipčević, J., Matešić, D., Matoš, B. and Vlahović, I. (2022): Geotechnical reconnaissance of an extensive cover-collapse sinkhole phenomena of 2020–2021 Petrinja earthquake sequence (Central Croatia). *Earthquake Spectra*, Online first, 1-34. DOI:10.1177/87552930221115759.

Uglešić, J.S., Markušić, S., Padovan, B. and Stanko, D. (2021): Semi-empirical estimation of the Zagreb ML5.5 earthquake (2020) ground motion amplification by 1-D equivalent linear site response analysis. *Geofizika*, **38/2**, 147-173. DOI:10.15233/gfz.2021.38.9.

Uglešić, J. S., Markušić, S., Stanko, D., Gazdek, M. and Lončar, I. (2022): SeisRICHerCRO: Estimation of local site frequencies using microtremor measurements in earthquake prone (with significant cultural heritage buildings) areas in Croatia. *7th World Multidisciplinary Civil Engineering – Architecture – Urban Planning Symposium – WMCAUS 2022, Prague, Czech Republic, 5-9th September 2022*, edited by Yilmaz, A., Marschalko, M. and Drusa, M., Abstract book, 30.

Uglešić, J. S., Skendrović, F., Lončar, I., Markušić, S. and Stanko, D. (2022): Regionally adjusted ground motion model: Case study of the ML6.2 (Mw6.4) Petrinja (Croatia) 2020 earthquake. *Studia Geophysica et Geodaetica*, **66 (3-4)**, 162-186. DOI:10.1007/s11200-022-0914-6.

Uroš, M., Šavor Novak, M., Lazarević, D., Herak, M., Prevolnik, S., Atalić, J. (2019): Numerička analiza postojećih zgrada pri djelovanju potresa. *14. Dani Hrvatske komore inženjera građevinarstva, Opatija, Hrvatska, 13. – 15. lipnja 2019.*, Knjiga sažetaka, 42.

Uroš, M., Atalić, J., Šavor Novak, M. and Kuk, K. (2020): Seismic performance assessment of existing stone masonry school building in Croatia using nonlinear static procedure. *17th International Conference IB2MaC'2020 (International Brick and Block Masonry Conference), Krakow, Poland, 5-8th July 2020*, edited by Kubica, J. Kwiecień, A. and Bednarz, Ł., Brick and Block Masonry, From Historical to Sustainable Masonry, 517-523.

Uroš, M., Prevolnik, S., Šavor Novak, M. and Atalić, J. (2020): Seismic performance assessment of an existing RC wall building with irregular geometry: A case- study of a hospital in Croatia. *Applied Sciences-Basel*, **10(16)**, 5578. DOI:10.3390/app10165578.

Uroš, M., Demšić, M., Šavor Novak, M., Atalić, J., Prevolnik, S. (2021): H. Procjena ponašanja tipične zidane zgrade u Zagrebu pri potresnom djelovanju – H.2 Procjena ponašanja zgrade pri potresnom djelovanju. Potresno inženjerstvo – Obnova zidanih zgrada (urednici: Uroš, M., Todorić, M., Crnogorac, M., Atalić, J., Šavor Novak, M., Lakušić, S.), Zagreb, Građevinski fakultet Sveučilišta u Zagrebu, 456-519.

Varga, M. and Stipčević, J. (2021): Gravity anomaly models with geophysical interpretation of the Republic of Croatia, including Adriatic and Dinarides regions. *Geophysical Journal International*, **226/3**, 2189-2199. DOI:10.1093/gji/ggab180.

Vukadin, D., Orešković, J. and Kutasi, C. (2021): Elastic properties of Pannonian basin limestone under different saturation conditions. *Energies*, **14(21)**, 7291. DOI:10.3390/en14217291.

## *Appendix: List of internet pages*

URL 1: Dvije godine od petrinjskog potresa.
https://www.pmf.unizg.hr/geof/seizmoloska_sluzba/potresi_kod_petrinje?@=1na56#news_118053
(accessed on 31 January 2023).

URL 2: CROATIA EARTHQUAKE Rapid Damage and Needs Assessment 2020.
https://mpgi.gov.hr/UserDocsImages/dokumenti/Potres/RDNA_web_04082020.pdf
(accessed on 5 February 2023).

URL 3: CROATIA DECEMBER 2020 EARTHQUAKE, Rapid Damage and Needs Assessment.
https://mpgi.gov.hr/UserDocsImages/dokumenti/Potres/RDNA_2021_07_01_web_ENG.pdf
(accessed on 5 February 2023).

URL 4: Mobilna mreža seizmoloških postaja.
http://www.pmf.unizg.hr/geof/seizmoloska_sluzba/mobilna_mreza
(accessed on 28 January 2023).

URL 5: CROSSNET project.
https://crossnet.potres.hr
(accessed on 15 January 2023).

URL 6: CRONOS project.
https://projekt-cronos.hr
(accessed on 17 January 2023).

URL 7: SeisRICHerCRO project.
https://seisrichercro.wordpress.com/project
(accessed on 10 January 2023).

URL 8: DuFAULT project.
https://projectdufault.geof.pmf.unizg.hr/hr
(accessed on 25 January 2023).