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Report of the Croatian Committee of Geodesy and Geophysics on activities carried out between 2015 and 2018

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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 four intervals: 1991–1994 (*Geofizika*, **11**, 1994), 1995–1998 (*Geodetski list*, **53**, 1999), 1999–2002 (*Geofizika*, **18/19**, 2001/2002) and 2011–2014 (*Geofizika*, **32**, 2015). 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 2015 and 2018 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 report confirms that Croatian geodesists and geophysicists represent a vibrant part of the scientific community: most often their findings are relevant for Croatia and sometimes their results and methodological improvements turn out to be useful to colleagues working in other countries. Moreover, the report reveals that the activities of Croatian scientists have expanded recently. Thus, for example, hydrological measurements and modelling have been extended so as to include the Plitvice Lakes – a world-famous system of sixteen cascading lakes that are subjected to a considerable anthropogenic pressure. Physical oceanographic investigations have been related more closely than before to meteorological studies, with the aim of addressing generation of meteotsunamis and storm surges in the Adriatic Sea and in some other basins. Finally, seismologists and geodesists have strengthened their cooperation, aiming at a combined use of *in situ* and remotely sensed data in the analysis of seismicity and tectonics of the region. The expansion was apparently stimulated by an improved access to international scientific projects, which supplement the relatively modest national funding of research activities. 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, 2015–2018

Report submitted to the International Association of Geodesy of the International Association of Geodesy and Geophisics

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This report presents a brief overview of research activities in the field of geodesy in Croatia in the period from 2015 to the end of 2018. The geodetic research has been carried out mainly at the Geodetic Faculty (GEOF), University of Zagreb and to a smaller extent at the Faculty of Civil Engineering, Architecture and Geodesy (FGAG), University of Split and at the State Geodetic Administration (SDA) and University North of Varaždin. Research activities resulted in about a dozen international peer-review (WoS) publications and a dozen of editor's books and book chapters.

FP7 and Horizon 2020 projects:

High-Resolution Solar Physics Network (SOLARNET), Duration: 1/4/2013–31/3/2017, Leader: Roman Brajša Ph.D.

European Solar Telescope Preparatory Phase (PRE-EST), Duration: 2017–2021, Principal Investigator: Davor Sudar Ph.D.

Croatian Science Foundation scientific projects:

Development of Multipurpose Land Administration System (DEMLAS), Duration: 1/9/2014–31/8/2018, Principal Investigator: Prof. Miodrag Roić.

Solar and Stellar Variability (SOLSTEL), Duration: 1/9/2014–31/8/2018, Principal Investigator: Bojan Vršnak Ph.D.

Geospatial Monitoring of Green Infrastructure by Means of Terrestrial, Airborne and Satellite Imagery (GEMINI), Duration: 1/3/2017–1/3/2021, Principal Investigator: Prof. Damir Medak.

Education of New Doctors of Science, Duration: 1/1–31/12/2015, Principal Investigator: Bojan Vršnak Ph.D.

Projects where the Faculty of Geodesy is a partner:

Advanced Forest Environmental Services Assessment (AFORENSA), Duration 1/7/2014–30/6/2018, Leader: Ivan Pilaš Ph.D., Leader at the Faculty of Geodesy: Prof. Damir Medak.

Other international scientific-research projects:

ESO Development Plan Study: Solar Research with ALMA, Duration: 1/11/2014–30/4/2017, Principal Investigator: Roman Brajša PhD.

Cosmic Ray Modulation by Solar Coronal Mass Ejections (CORAMOD), bilateral project Croatia–Germany, MZOS–DAAD, Duration: 1/1/2015–31/12/2016, Principal Investigator: Roman Brajša Ph.D.

European Social Fund (Operational Program "Human Resources Development" 2007–2013): Increasing Competitiveness by Developing Researchers in Physics of the Sun (PoKRet), Duration: 22/7/2015–22/10/2016, Principal Investigator: Mateja Dumbović Ph.D.D.

World Bank scientific project: Implementation of the Land Governance Assessment Framework (LGAF) in the Republic of Croatia, Duration: 2–10/2015, Principal Investigator: Prof. Miodrag Roić.

International Croatian-Montenegrin scientific project „GIS baza podataka zaštićenih područja na primjeru objekata geonasljeđa", Duration: 2015–2016, Principal Investigator: Prof. Miljenko Lapaine.

Erasmus+ KA2 Capacity Building in the Field of Higher Education project 574150: Western Balkans Academic Education Evolution and Professional's Sus-

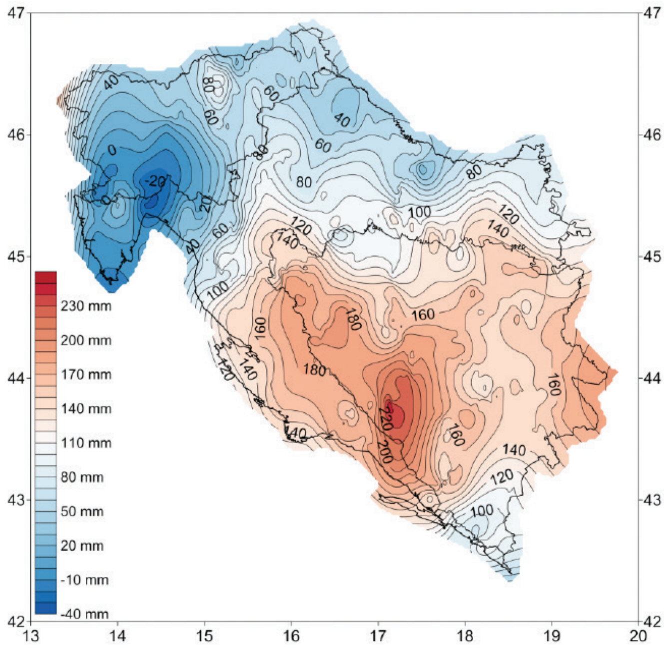

Figure 1. Grid model – parameter ΔH_0 (according to Rožić, 2017).

tainable Training for Spatial Dana Infrastructures (BESTSDI), Duration: 15/10/2016–14/10/2019, Principal Investigator: Prof. Željko Bačić.

Erasmus+ KA2 Sector Skills Aliances project 591991: Towards an Innovative Strategy for Skills Development and Capacity Building in the Space Geo-information Sector Supporting Copernicus User Uptake (EO4GEO), Duration: 1/1/2018–31/12/2021, Principal Investigator: Prof. Željko Bačić.

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Geomagnetism and aeronomy in Croatia, 2015–2018

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

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This report aims to provide an overview of the research, professional and education activities in the field of geomagnetism and aeronomy that have been carried out at the Department of Geophysics, Faculty of Science, University of Zagreb and some other institutions during the time span 2015–2018. The report is organized as follows. First, the research activity is outlined. Second, the professional work is described. The educational engagement follows. Finally the public outreach is reported.

The performed research studies in this period are very interdisciplinary embracing different parts of the geomagnetic field, aeronomy, changes on the Sun, in the interplanetary space and related responses of the Earth's magnetosphere and ionosphere. Accordingly, the research topics are also related to space weather and therefore are of broad interests and applications. Ground based data and data from satellites with orbits both within the magnetosphere and in the interplanetary space are generally employed in the analyses.

The temporal changes in the monthly magnetic observatory biases at 42 stations within the 2000–2009 interval are analysed by employing the model entirely based on geomagnetic observatory data and data provided by the CHAMP satellite. The bias evolution over several years to three decades (long-term trends) as well as its variation on a timescale of several months to one year is investigated. The comparison with biases based on two months of MAGSAT and Ørsted satellite data, related to the 1979.92 and 1992.92 epochs, is performed. The results indicate that the crustal magnetic field has probably not changed over the studied time span. This investigation and the obtained results are presented in the work by Verbanac et al. (2015).

Brajša et al. (2015) investigated the possibility to predict and reconstruct the solar cycle 24 by applying the modified minimum–maximum method, which belongs to the precursor class of methods, to the smoothed monthly sunspot values. A comparison between the observed and predicted amplitude of the 24th solar cycle is performed. The obtained results indicate that the applied minimum–maximum method is a reliable one for the solar cycle prediction and moreover allow to predict the subsequent solar maximum amplitude already three years before the preceding minimum of solar activity.

Relationship between plasmapause, solar wind and geomagnetic activity between 2007 and 2011 is obtained using ACE and CLUSTER satellite data (Verbanac at al., 2015). The time delay of the plasmapause response to solar wind parameters and geomagnetic activity in different magnetic local times (MLT) is obtained by applying the cross-correlation analyses. In the study by Bandić at al. (2016) the MLT plasmapause dependence is further analysed for different phase of the solar cycle using CRRES satellite data. MLT propagation of the plasmapause is inferred from THEMIS satellite data by investigating the cross-corellation curves in each 1 hour MLT bin and the results are given in the study by Bandić at al. (2017).

Verbanac et al. (2018) compared the plasmapause characteristics obtained from THEMIS satellite data with the numerical simulations based on the interchange instability physical mechanism. The global plasmapause characteristics as the MLT sectors of the plasmapause erosion and azimuthal plasmapause motion are derived. This work has shown that the global plasmapause behaviour is indeed in agreement with interchange instability mechanism. The great importance of this study is that it contributes to resolve some of the long-lasting issues related to plasmapause formation and dynamics.

Observations from the European quasi-Meridional Magnetometer Array (EMMA) and their comparison with Dynamic Global Core Plasma Model (DGCPM) are considered by Jorgensen et al. (2017). The DGCPM model is modified in order to better fit the observations. The results suggest faster daytime refilling and nighttime loss.

In the study by Mandić and Korte (2017) the method for automatic estimation of the observatory baselines is presented. It is demonstrated that preparation of definitive geomagnetic data is possible within one year. The performed comparison with the baselines reported on INTERMAGNET DVDs for the period 2009–2011 has shown that the proposed method may be suitable for automatic data processing when automated absolute instruments are placed at remote sites.

Geomagnetic effects of corotating interaction regions from 2005 throughout 2008, the period belonging to the declining phase of Solar Cycle 23 which are characterized by a particularly low number of interplanetary coronal mass ejections, is presented by Vršnak (2017). The statistical relationship between solar wind flow speed, magnetic field and the convective electric field based on the southward magnetic field component is quantified.

Research results were presented at international conferences. Status report related to research activity in the fields was also presented at Europlanet NA1 Annual Meeting and Inclusiveness Forum in 2018 by G. Verbanac. There, the ongoing activities at Geophysical Department were especially emphasized.

The topics related to geomagnetism, aeronomy and space weather in general have been promoted within the Adriatic Aerospace Association since spring 2018 contributing to the professional activity in the fields. Further, the professional work was dedicated to geomagnetic observatory practice. Based on the quality of the data collected at geomagnetic observatory Lonjsko Polje during 2014 and 2015, the observatory took part in the INTERMAGNET network in February 2016. The official IAGA code LON was associated to the observatory. The verification of the quality of the first collected data is documented by Mandić et al. (2016). The observatory has been working almost permanently until today. In 2017 and 2018 the problems with the LEMI-03 magnetometar occurred. Fortunately, the problems were fixed at the end of 2018. Thereafter, the data have been continuously sent to European quasi-Meridional Magnetometer Array (EMMA) network reqularly in real time. Additional problems with running the observatory occurred in 2018 caused by natural disasters (flood). Since 2017 the observatory also serves for testing the instrumentation which has been used for reapeat station measurements in the framework of the project "Second Geomagnetic Information Renewal Cycle in the Republic of Croatia" that is led by the Faculty of Geodesy, University of Zagreb. Three workshops were attended (two IAGA and one MagNetE workshops) which contributed to new knowledge and enlarged experience related to observatory practice and instrumentation.

Except for the contacts that have been already put in place, the international collaboration in the fields of geomagnetism, aeronomy, solar physics and generally in planetary science is further extended in the period 2015–2018.

The education is actively performed at the Geophysical Department through the university undergraduate courses: Planetology, Geomagnetism, Aeronomy, Geophysical Practicum as well as university doctoral course: Planetary Magnetism. Important to note is that these courses for the first time in Croatia embrace fundamentals of plasma physics, magnetospheric physics, solar physics, geomagnetism in all aspects, high ionospheric levels (ionosphere and thermosphere) and planetary science in general. Through these courses the students gain diverse knowledge that allow them to easily fit in different international groups. The appropriate examples are the current visits of six months to one year of two students at the very well known international institutions (University of Graz, Austria and Max-Planck institute Goetingen, Germany) where they have so far demonstrated great capability to successfully face with all physical problems and tasks within the fields. Further, within the course Geophysical Practicum student visit to the geomagnetic observatory LON is organized, which helps them to better adopt the knowledge attained at other regular courses. Students acquire additional knowledge in the fields by preparing diploma theses and publications. In the reported period, one doctoral thesis that focused on quality and proposals for improvements in the baseline adaption at geomagnetic observatories was defended (Mandić, 2017).

Last, but not the least, it is important to note that geomagnetism, aeronomy and space science are regularly promoted to the wider audience through public talks, tribunes, festivals, talks at schools and popular scientific articles (e.g., Jerčić and Verbanac, 2018; Andrić and Verbanac, 2017; Majstorović and Verbanac, 2015; Belinić and Verbanac, 2015).

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Hydrology and physical limnology in Croatia, 2015–2018

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 the research activities in the field of hydrology in Croatia in the period from 2015 to the end of 2018. Several institutions were involved in the hydrological investigations during this period (Faculty of Civil Engineering, Zagreb; Faculty of Civil Engineering, Architecture and Geodesy, Split; Faculty of Civil Engineering, Rijeka; Faculty of Civil Engineering, Osijek; Faculty of Mining, Geology and Petroleum Engineering, Faculty of Science, Zagreb; Croatian Waters; Croatian Meteorological and Hydrological Service). The scientific interest of Croatian hydrologists ranged from local to world-wide hydrology. The scientific work of the scientists involved in the students education is mostly continuation of previous investigation in the field of karst hydrology and hydrogeology. The results of their scientific researches are published and presented through the international conferences and scientific papers in well recognized scientific journals covering hydrological topics (*Journal of Hydrology, Catena, Natural Hazards and Risk, Hydrological Processes, Hydrological Sciences Journal, Hydrology Research, Water, Geoscience, Environmental Earth Sciences, Journal of Hydroinformatics, Theoretical and Applied Climatology, Acta Carsologica …*).

The hydrological projects were mostly performed by the experts from the Croatian Meteorological and Hydrological Service. The projects are enumerated as follows:

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. Flood Risk Slovenia-Croatia Operations – Strategic Project 1 – Nonstructural Measures (FRISCO 1).

5. EUMETNET**:** Climate service is currently a rapidly growing area due to different initiatives and additional players (e.g. Copernicus Climate Change Service C3S). Therefore it is necessary that European NMHSs as a EUMETNET members follow up on the associated innovations and development. Moreover interaction between the NMHS and between the NMHS and European organisations and stakeholders, is necessary. This programme aims at supporting the members of EUMETNET in both tasks.
6. PannEx: Regional Hydroclimate Project (RHP) of the World Climate Research Programme (WCRP).
7. HyMeX is an international project which aims at: improving our understanding of the water cycle, with emphases on extreme events by means of monitoring and modelling the Mediterranean coupled system (atmosphere-land-ocean), its variability (from the event scale to the seasonal and interannual scales) and characteristics over one decade in the context of global change, evaluating societal and economical vulnerability and adaptation capacity to extreme meteorological and climate events.

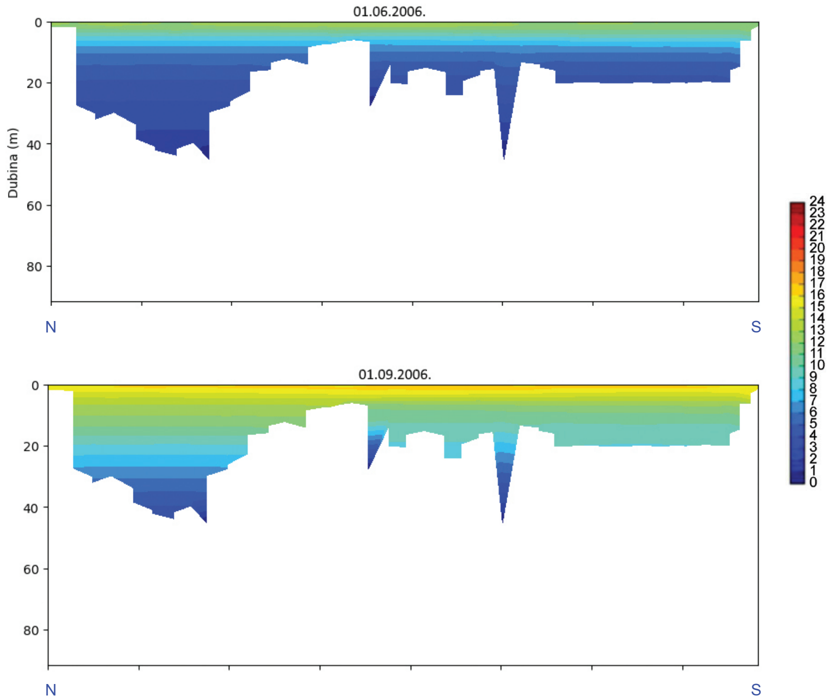

Figure 1. Modeled north-south vertical profile of Kozjak Lake temperature for 1 June 2006 and 1 September 2006 (*up* and *down*, respectively). Temperature values (°C) are indicated by a colorbar, while ordinate shows the depth (m).

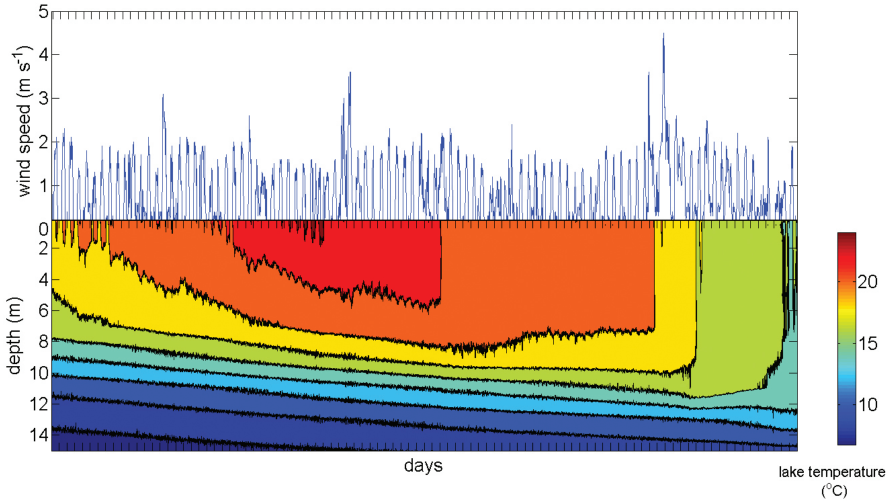

Figure 2. Observed wind speeds and concurrent Kozjak Lake temperatures for the period from 6 July to 10 October 2018. Wind and lake temperature data were recorded at resolution of 1 h and 2 min, respectively.

Considering physical limnology, during the reporting period one study of surface seiches was performed (Pasarić and Slaviček, 2016) and an ongoing research project (*Hydrodynamic modeling of Plitvice Lakes system*, funded by Plitvice Lakes National Park, Croatia) was initiated. The project is interdisciplinary and 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). It encompasses meteorology, hydrology, physical limnology and hydrogeochemistry. The main goal is to establish coupled atmosphere-lake numerical model for prediction of lake temperatures, currents and water levels, while the main challenge is the complex setup of sixteen karstic lakes, which are interconnected by cascades and waterfalls. This is the first-ever research project performed in Croatia which focuses on physical limnology (Klaić et al., 2018). So far, some preliminary modeling (Fig. 1) and experimental results (Fig. 2) are obtained.

Croatian scientists from other institutions have been included in activities of numerous international and national conferences and a number of scientific papers were published covering theoretical and practical topics in hydrology. Mostly, the papers are ralated to the numerical modelling, rainfall-runoff modeling in karst areas, water balance modelling, time series analysis, hydrometry of uninvestigated area in karst and the determination of hydrogeological properties of a complex Dinaric karst catchments. Also, the 6th Croatian Water Conference with international participation, named Croatian Waters on the Investment Waves, was organized in Opatija (2015).

The whole scientific work regarding hydrology in Croatia is documented in the publications the list of which is attached to this report. The list contains scientific papers published in Croatian and international journals.

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Meteorology in Croatia, 2015–2018

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

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Based on the published books, international peer-review scientific papers and Ph.D. theses, here we present a short overview of the topics of meteorological research in Croatia during the 2015–2018 period. In Croatia, the meteorological research is performed at several institutions: Department of Geophysics, Faculty of Science, University of Zagreb (hereafter, DG), Croatian Meteorological and Hydrological Service (MHS), the Physics Department, Faculty of Science, University of Split (PDS) and the Institute of Oceanography and Fisheries (IOF) in Split. During the reporting period, at these institutions in total forty-six projects (both, completed and still ongoing) were implemented. These were founded by European Union (17 projects), Croatian Science Foundation (12), other sources (9), funds of Cooperative Projects of European Meteorological and Hydrological Services (6) and Ministry of Science and Education of the Republic of Croatia (2). Research efforts resulted in over ninety international peer-review scientific papers, eight Ph.D. theses and several book chapters.

Researchers have addressed a wide span of relevant meteorological issues, such as present and anticipated future climate; turbulence characteristics over inhomogeneous surfaces and complex terrain under various atmospheric conditions; and mesoscale thermal circulations and their interplay with different multi-scale phenomena. Additionally, intensive research activity has been associated with efforts to improve numerical weather and climate prediction models. Severe weather and extreme events, such as, high winds, extraordinary droughts, heat waves, severe convective storms and consequent heavy rainfall, hail, lighting activity and waterspouts, as well as the ability of numerical weather forecast models to predict such episodes, have also been investigated.

Furthermore, a number of interdisciplinary studies dealt with meteorology and closely related disciplines, such as, the air quality, hydrology, oceanography, physical limnology, agronomy, forestry, energetics and engineering. Among others, impacts of weather and/or climate on the air and precipitation quality, agricultural and forest systems, ocean currents, sea-level variability and occurrence of the storm surges and meteotsunamis were investigated. Within the framework of meteotsunami research, new equipment (two weather stations and six microbarographs) was installed at several coastal locations and an operational one-way coupled numerical atmosphere-ocean model for forecast of the Adriatic meteotsunamis was developed. The observed data can be visualized at http://faust.izor.hr/autodatapub/postaje2 and downloaded from http://faust.izor.hr/autodatapub/mjesustdohvatpod?jezik=eng, while meteotsunami forecasts are available at http://faust.izor.hr/autodatapub/adrisc?jezik=eng.

Overall, meteorological community was very active during the reporting period. International and national inter-institutional cooperation was intense. Furthermore, research results were based on the state-of-the-art methodologies. Finally, some of the studies provided information on specific phenomena for Croatia for the first time (e.g., lighting activity and waterspouts events). Additional information on the conducted research is available at the web sites of individual institutions: http://www.pmf.unizg.hr/geof/en (DG), https://meteo.hr/index_en.php (MHS), https://www.pmfst.unist.hr/odjel-za-fiziku/ (PDS) and http://www.izor.hr/web/guest/home (IOF).

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Physical oceanography in Croatia, 2015–2018

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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Between 2015 and 2018 physical oceanographic research in Croatia has mainly been carried out in the following institutions: Institute of Oceanography and Fisheries, Split; Hydrographic Institute of the Republic of Croatia, Split; Center for Marine Research in Rovinj and Division for Marine and Environmental Research in Zagreb, both part of the Rudjer Bošković Institute; and Department of Geophysics, Faculty of Science, University of Zagreb.

Altogether 26 investigators (20 PhD's and 6 MSc's), supported by technical staff, were involved in the research. Field work was carried out by research vessels and boats owned by institutes in Split (*Bios dva, Navicula, Hidra, Palagruža*) and Rovinj (*Vila Velebita, Triton, Burin*). The oceanographic equipment used to study the hydrographic properties included several Seabird CTD probes and a Biospherical profiling radiometer. A towed undulating vehicle, equipped by a Seabird CTD probe, was used to perform hydrographic measurements of high temporal and spatial coverage. 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 (Nortek and RDI ADCP's) and high frequency radars (WERA), while tide gauges (analogue, digital and radar instruments, all manufactured by OTT GmbH) and directional wave riders (Datawell) were used to measure low- and high-frequency sea level oscillations. One buoy, designed and manufactured in Croatia, was deployed in the east Adriatic coastal area in front of the town of Rovinj in order to collect various meteorological and oceanographic data. The Division for Marine and Environmental Research at the Rudjer Bošković Institute possesses satellite antennas. Atmospheric conditions during oceanographic investigations were recorded using ultrasonic Vaisala anemometers, microbarographs and several automatic meteo-oceanographic stations placed in front of the Institute of Oceanography and Fisheries in Split and at Vela Luka (Korčula Island) and Stari Grad (Hvar Island). All institutions had a local computer network with a mainframe computer and a series of personal computers, connected to internet through Carnet (Croatian

Academic Research Network). Moreover, complex ocean model simulations with POM, ROMS, ADCIRC and SCHISM models were run on computer clusters and servers at the home institutions as well as at the University Computing Centre in Zagreb and the ECMWF Supercomputer Centre in Reading, UK.

During the four-year interval considered, some previously established measurement programs were maintained and new ones were started. Thus, basic oceanographic data were collected on a monthly or seasonal basis all along the east Adriatic coast, as well as along some cross-shore transects (Rovinj-Po, Split-Gargano, Šibenik-Ortona) within the framework of national projects and studies. Sea surface temperature was measured daily at a number of coastal stations by the Croatian Meteorological and Hydrological Service. Several campaigns of high-frequency CTD measurements with an undulating vehicle were performed in the northern and middle Adriatic. The water column profiling was done between the surface and a depth of 40 to 50 meters, at a horizontal resolution of approximately 200 meters and a vertical resolution of about 10 centimeters. The northern Adriatic cruises (March 2015, October 2016, February 2017, April 2017) were organized to document mesoscale variability and dense water formation in the area, whereas cruises in the middle Adriatic (May 2017, June 2018) were aimed at documenting upwelling in the area of the Jabuka Pit.

Continuous measurements of various physical parameters were established and carried out. Four directional wave riders for measuring wave parameters (height, direction and period) were deployed in the Ploče area and near the towns of Dubrovnik (CoRE project), Split and Rovinj in the period from December 2016 to May 2018 by the Hydrographic Institute staff. Two ultrasonic anemometers and a microbarograph were installed in the Ploče area and on the Hydrographic Institute building. A pair of high frequency radars installed in the middle Adriatic within the framework of the HAZADR project, at Cape Ražanj, Island of Brač and Cape Stončica, Island of Vis, in April 2014 is still collecting data on surface currents and waves. Tide-gauge measurements were continued at a previously established network of seven stations (Rovinj, Bakar, Zadar, Split-Marjan, Split-harbor, Ploče, Dubrovnik) using float-operated (analog and digital) and radar instruments. New OTT RLS (Radar Level Sensor) sea level measuring stations were installed at Vela Luka (Korčula Island), Stari Grad (Hvar Island) and Sobra (Mljet Island). High frequency air pressure measurements were carried out at previously established stations at Vis, Vela Luka and Vrboska and were started at six new microbarograph stations at Ražanj (Brač Island), Svetac Island, Palagruža Island, Ancona, Vieste and Ortona within the MESSI project. Vela Luka (Korčula Island) and Stari Grad (Hvar Island) were also equipped with GMX Gill weather stations measuring air pressure, temperature, relative humidity, wind speed and direction. Continuous ADCP measurements were carried out at three locations in the northern entrance of Kvarner Bay (Vela Vrata) and at two locations in the central entrance (close to Premuda/Skarda) within the NAdEx experiment, as well as in the Rovinj area (still measuring) and in the

Ploče region (2017). Occasional measurements were carried out near the towns of Umag and Biograd and the islands of Krk, Brač and Hvar.

Over the preceding four years Croatian institutions participated in national projects funded by the Croatian Science Foundation (HRZZ), Unity through Knowledge Fund (UKF) and Fund for Environment and Energetic Efficiency. HRZZ projects CARE, SCOOL, MARIPLAN and EcoRENA were dedicated to climate research, while interannual variability in the Adriatic was studied within the BIOTA and ADIOS projects. The scope of the ADAM-ADRIA project was to measure physical properties of the Adriatic Sea with advanced (e.g. ship towed CTD, ship-borne ADCP and gliders) and conventional instruments, all to identify fine scale features along sharp density fronts, particularly the Istrian Front (IF). Project MARRES is devoted to modelling Rogoznica Lake and other meromictic lakes. A new multidisciplinary project, MAUD, designed to investigate upwelling and downwelling in the area of the Jabuka Pit in the middle Adriatic, started in 2018. UKF funded projects were MESSI, dedicated to meteotsunamis and NEURAL, concentrating on interpreting and forecasting Adriatic surface currents. Project POZOR was dedicated to potentially dangerous sea level oscillations in the present and future climate. Research work was also done within numerous international projects. Projects BALMAS, HAZADR, JASPPer and ADRIATIC+ were funded by the IPA Adriatic Cross-border Cooperation Programme, while PERSEUS, EUROFLEETS 2, BLUEMED, SeaDataNet-II and SeaDATACloud projects were supported by the European Commission within the Seventh and H2020 framework programmes. Projects MEDCIS and QUIETMED were supported by the DG Environment Programme and project Emodnet Data Ingestion by the DG-mare. In addition to the research, physical oceanographers participated in a series of professional studies dealing with physical parameters relevant to ecosystem analysis and categorization of water within the European directives. Moreover, Croatian physical oceanographers joined international investigations of areas outside the Adriatic, such as the southwestern Australian coast (Mihanović et al., 2017; Hetzel et al., 2018), the north Atlantic (Perrie et al., 2018), the southwestern coast of Sicily (Šepić et al., 2018b), the Black Sea (Šepić et al., 2015c; 2018a), the Balearic Islands (Šepić et al., 2016b) and the German Bight (Fenoglio-Marc et al., 2015). Croatian physical oceanographers also took part in the IOC assemblies, MedGOOS and EuroGOOS meetings, as well as in a number of international conferences and workshops.

The work done is documented in the publications listed at the end of this report. The list contains scientific papers, books and theses. A short review of topics covered by Croatian physical oceanographers follows. Scientific research in the reporting period was carried out in several fields such as climate change studies, air-sea interaction related to extreme sea level events (meteotsunami, storm surge), mesoscale dynamics, dense water generation, surface circulation, surface waves, optics, pollution problems and different aspects of numerical modelling and forecasting systems. A number of papers resulted from collaboration of physical oceanographers with their colleagues from other closely related oceanographic disciplines: chemists, biologists, fishery scientists and geologists.

The climate-related studies focused on formation and transport of dense water in the Adriatic Sea and on sea level changes, both global and Mediterranean. They were supported by long-term measurements of parameters collected at permanent oceanographic stations in the middle Adriatic (Mihanović et al., 2015; Vilibić et al., 2015a; 2015b; Matić et al., 2017) and of sea surface temperatures along the eastern Adriatic coast (Grbec et al., 2018). When considering formation of the Adriatic dense water, it is of special interest how the water is exchanged between two sites of formation – the open north Adriatic and the Croatian coastal sea. A simple two-box model was developed in order to interpret the exchange (Orlić, 2018). The model allows for surface heat loss from the two basins and for an advective exchange of heat between the basins. Explicit solutions were obtained for both the original, nonlinear problem and the simplified, linearized problem. The solutions point to a continuous temperature decrease in the two basins, with the sum of surface heat loss and advective heat gain in one basin tending to become equal to the sum of surface and advective heat losses in the other basin. The solutions also reveal which factors control the direction of dense-water transport.

High-resolution hydrographic measurements in the northern Adriatic, performed within the NAdEx 2015 experiment (Vilibić et al., 2018a), show that during a strong bora event a very sharp and strong thermohaline front, with fresher and colder water to the north and saltier and warmer water to the south, extending vertically throughout the entire water column, is formed in the region of the Istrian Front (IF). On some occasions, like in 2015, the front is not density compensated, but is also characterized by a strong density gradient. Under weaker wind conditions, the IF becomes much weaker, wider and inclined. Current measurements in the region and numerical model simulations demonstrated that during strong bora the outflow of cold water from the Kvarner Bay is deflected northward, closer to the Istrian coast (Kokkini et al., 2017).

The dense water formed on the Adriatic shelf is eventually transported across the Palagruža Sill whereupon it enters the south Adriatic. A recent study by Bonaldo et al. (2018) showed that the transport could be influenced by continental shelf waves developing at the Adriatic shelf break. Starting from the observations of high-intensity velocity pulses with a period of approximately 2 days, a sequence of operations was carried out on the results of a high-resolution, wave-ocean coupled numerical modelling experiment aiming to reproduce dense water formation and migration in the Adriatic Sea in winter-spring 2012. It was shown that the observations had been related to a perturbation system propagating southeastward along the Italian coast and amplified as a train of continental shelf waves along the shelf break and on the continental slope, thus providing the first evidence on the existence of such waves in the Adriatic Sea. Moreover, it was pointed out that the waves could influence the dense water dynamics and therefore also the benthic environments.

With the aim of analyzing and projecting global sea level, three variants of a semi-empirical method were considered (Orlić and Pasarić, 2015). They differ in assuming that the response of sea level to temperature forcing is equilibrium, inertial or a combination of the two. All variants produce a successful regression of the temperature and sea level data, albeit with controlling parameters that differ among the cases. The related response times vary considerably, with a realistic value (ca. 50 years) obtained only if both the equilibrium and the inertial dynamics are taken into account. A comparison of sea levels projected by using the three variants shows that the time series are similar through the middle of the 21st century but they radically diverge by the end of the 23rd century. This result is interpreted with the aid of the underlying transfer functions. It suggests that one should be cautious when using the semi-empirical method to project sea level beyond the 21st century.

Analysis of Mediterranean sea level in the second half of the 20th century was performed using long-term tide-gauge measurements, in order to identify long-term trends against decadal and multidecadal changes in each subbasin (Orlić et al., 2018). Linear trends in the 1950–1990 interval were analyzed using Bayesian statistics. Individual contributions, coming from direct atmospheric forcing and from thermosteric and halosteric changes, were determined and the sea level budget was examined within each region. In the Atlantic off Gibraltar and in the Black Sea regional sea level trends were close to the global values, in the Mediterranean they were close to zero. Throughout the Mediterranean and in the Black Sea, atmospheric forcing and steric effects induced lowering of sea level. In the Mediterranean and partly in the Black Sea, these regional effects compensated the effect of global mass increase. It is concluded that over the 1950–1990 interval the sea level budget is closed within the, rather wide, credible limits.

The study of short-term processes encompassed the phenomena of storm surges and meteotsunamis. The analysis of storm surges in the north Adriatic showed that during these episodes sea level can significantly slope not only in the along-basin but also in the cross-basin direction, which leads to stronger flooding of either the eastern or the western coastline. The eastern coastline, compared to the western side, is more exposed to flooding during the action of deeper Mediterranean cyclones that are shifted to the north. On these occasions the wind field over the Adriatic is characterized by a shear of along-basin wind and a strong cross-basin wind directed towards the eastern coast (Međugorac et al., 2015; Međugorac et al., 2016; Međugorac et al., 2018). Analysis of sirocco-like wind fields from climate simulations showed that their characteristics in future climate scenarios will remain similar to those in the present climate (Međugorac, 2018).

A study of Chrystal and Proudman resonances in a simple, rectangular closed basin of uniform depth was conducted to explore and compare how well the two resonant mechanisms are reproduced with different, nowadays widely used, numerical ocean models (Bubalo et al., 2018). The test case was based on air pressure disturbances of two commonly used shapes (a sinusoidal and a boxcar), having various wave lengths and propagating at different speeds. In total, 2250 simulations were performed for each of the three different numerical models: ADCIRC, SCHISM and ROMS. An inter-model comparison of the results showed that different models represent the two resonant phenomena in a slightly different way. For Chrystal resonance, all the models showed similar behavior; however, ADCIRC model is providing slightly higher values of the mean resonant period than the other two models. In the case of Proudman resonance, the most consistent results, closest to the analytical solution, were obtained using ROMS model whereas ADCIRC and SCHISM models showed small deviations from that value. The findings may seem small but could play an important role when resonance is a crucial process producing enhancing effects by two orders of magnitude (i.e., meteotsunamis).

Meteotsunamis were intensively studied during the reporting period. A potential for generation of meteotsunami waves via open ocean resonance has been investigated for the shallow northern Adriatic (Šepić et al., 2015a). Results based on a set of barotropic numerical modeling experiments were related to occurrence of the real events. The strong coherence between high-frequency sea level events and synoptic patterns introduced the possibility of a timely forecast of these events (Šepić, 2015; Šepić et al., 2015b). The MESSI project resulted in a number of papers aimed to build a reliable prototype of a meteotsunami warning system (Vilibić et al., 2016e). During the project both real-time measurements and modelling (Denamiel et al., 2018; Horvath et al., 2018; Vilibić et al., 2018b) were conducted. A catalogue of meteotsunamis was compiled for the Croatian part of the Adriatic Sea (Orlić, 2015). It included 21 flooding events, observed between the years 1931 and 2010. Vela Luka on the Island of Korčula and Stari Grad on the Island of Hvar were the most often affected locations. A majority of the events occurred in the warm part of the year. They tended to start either early in the morning or late in the afternoon, last between 1 and 6 hours and be dominated by sea level oscillations of the 10-40 min periods. The largest trough-to-crest height of 6 m was observed in Vela Luka on 21 June 1978.

In addition, Vilibić et al. (2017) provided a comprehensive review of all aspects of the Adriatic sea level research covered by the literature, while Vilibić and Šepić (2017) analyzed nonseismic sea level oscillations at tsunami timescales in the global data sets.

A number of publications dealt with high-frequency (HF) radar measurements in the northern and middle Adriatic. Sensitivity experiments of high-frequency (HF) radar-derived surface current Self-Organizing Maps (SOM) to various processing procedures and mesoscale wind forcing were conducted by Vilibić et al. (2016b) within the NEURAL project. Moreover, an ocean surface currents forecasting system, based on a SOM neural network algorithm, HF ocean radar measurements and numerical weather prediction products, has been developed for a coastal area of the northern Adriatic and compared with operational ROMS-derived surface currents (Vilibić et al., 2016d). The SOM-based forecasting system has a slightly better forecasting skill, especially during strong wind conditions, with potential for further improvement when data sets of higher quality and longer duration will be used for training. As the HF radars and high-resolution weather prediction models are strongly expanding in coastal oceans, providing reliable and long-term data sets, the applicability of the proposed SOM-based forecasting system is expected to be high (Kalinić et al., 2017). Sensitivity and performance of the SOM method were analyzed by Kalinić et al. (2015) using HF radar data set, while Matić et al. (2018) used temperature and salinity data collected in the middle Adriatic to obtain quality measures for the method.

Morović et al. (2015) and Kraus et al. (2018a) studied pollution problems caused by oil spills and ballast waters, respectively. Kraus et al. (2018b) aimed at developing a strategy of ballast water management within BALMAS project.

Results of the numerical model simulations were used in a variety of research and application studies. POM model was used to study the influence of synoptic conditions on the north Adriatic circulation (Beg Paklar et al., 2015), while ROMS model was applied in studies of meteotsunamis (Bubalo et al., 2018; Denamiel et al., 2018), dense water formation (Vilibić et al., 2016c; Mihanović et al., 2018) and mesoscale dynamics in the northern and middle Adriatic. A majority of the data collected during 2015 within the NAdEx experiment were used in ROMS 4DVar data assimilation experiment to obtain optimal analysis of the Adriatic dynamics. On the other hand, a two-dimensional model was setup in order to simulate copper concentration dynamics in the Punat Bay waters (Lončar et al., 2015). A modelling study conducted by MIKE 3fm revealed the impact of winds, tidal oscillations and density distribution on the water mass exchange and wave field in marinas (Lončar et al., 2016; 2017). In addition, two operational systems were established in the reporting period: a surface wave forecast described by Dutour Sikirić et al. (2018) and a one-way coupled numerical atmosphere-ocean model for meteotsunami forecast (Denamiel et al., 2018). Perrie et al. (2017) assessed the impact of source term parametrizations on wave forecasts for the NorEaster tempests. This is important as Cycle III parameterizations are commonly used despite their shortcomings. Fenoglio et al. (2015) investigated the impact of using SAR vs altimeter in the quality of determined wave height. Bio-physical interactions in phyto- (Kovač, 2016) and ichthyoplankton dynamics (Džoić, 2018) were also investigated by analytical and numerical models. An inverse modelling procedure was developed in order to recover photosynthesis parameters from measured profiles of primary production and tested on data collected off Hawaii (Kovač et al., 2016a; 2016b; 2017a) and Bermuda Islands (2017b) and in the Adriatic Sea (Kovač et al., 2018b). Moreover, a coupled modelling system consisting of ROMS and individual based model

ICHTHYOP was developed to study the early stage dynamics of two commercially important species: Atlantic bluefin tuna (Džoić et al., 2017) and gilthead seabream (Džoić, 2018). Useful results were obtained from rigorous model skill assessments in study of dense water formation (Dunić et al., 2018) and atmospheric forcing for ocean models (Dutour Sikirić et al., 2015).

Collaboration with chemists, biologists, fishery scientists and geologists was intensified and resulted in a number of interdisciplinary papers dealing with climate and circulation impact on the ecosystem variability (Babić et al., 2017; 2018; Batistić et al., 2016; Brautović et al., 2018; Bušelić et al., 2015; Bužančić et al., 2016; Ciglenečki et al., 2015; Džoić et al., 2017; Grbec et al., 2015; Grbin et al., 2017; Hure et al., 2018; Lučić et al., 2017; Ninčević-Gladan et al., 2015; Peharda et al., 2016; Peharda et al., 2018a; 2018b; Skejić et al., 2015; 2018; Šegvić-Bubić et al., 2018; Šilović et al., 2018; Šolić et al., 2018; Šupraha et al., 2016; Vidjak et al., 2016; Vilibić et al., 2016a; Živković et al., 2018; Žuljević et al., 2016). Based on data collected in the northern Adriatic, several investigations relating physical influence to biogeochemical conditions were performed. The role of geostrophic currents in distribution of bottom oxygen concentration (Djakovac et al., 2015) and macroaggregates spreading (Kraus and Supić, 2015) was found to be important. Changes in winter oceanographic conditions reflected on zooplankton abundance in the region with implications on the Adriatic anchovy stock prognosis (Kraus et al., 2015). Factors favoring phytoplankton blooms in the northern Adriatic were analyzed showing that in winter and early spring the phytoplankton abundances depend on existing circulation fields, whereas in summer and autumn they are related to the Po River discharge rates recorded 1–15 days earlier and to the concomitant circulation fields; in late spring they increase 1–3 days after high Po River discharge rates regardless of the circulation fields (Kraus et al., 2016).

The Laboratory of Physical Oceanography at the Institute of Oceanography and Fisheries, Split in cooperation with the Croatian Meteorological and Hydrological Service maintained a Virtual Laboratory (http://www.izor.hr/web/guest/virtual-laboratory) and continued to study interactions between climate change and marine ecosystem through monitoring variability of physical parameters in the atmosphere, the sea and at the air-sea interface. Through the interactive interface, the measured oceanographic data have been made available in near real time, as was the weather forecast over the Adriatic Sea.

Finally, it may be concluded that in the period from 2015 to 2018 many new research topics were opened and many problems and questions in the Croatian physical oceanography were resolved. Improvement and modernization of the equipment used were important for new achievements. The list of publications as well as the number of realized and ongoing national and international projects for the Adriatic and other ocean and coastal areas were significantly enlarged in comparison to the previous periods.

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Seismology in Croatia, 2015–2018

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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During the period 2015–2018, most of the research in seismology was done in the frameworks of the VELEBIT project (funded by the Croatian Science Foundation), as well as AlpArray and AlpArray-CASE projects that were executed in cooperation with ETH, Switzerland (Hetenyi et al., 2018; Molinari et al., 2018). The seismic network density has been considerably increased, as 18

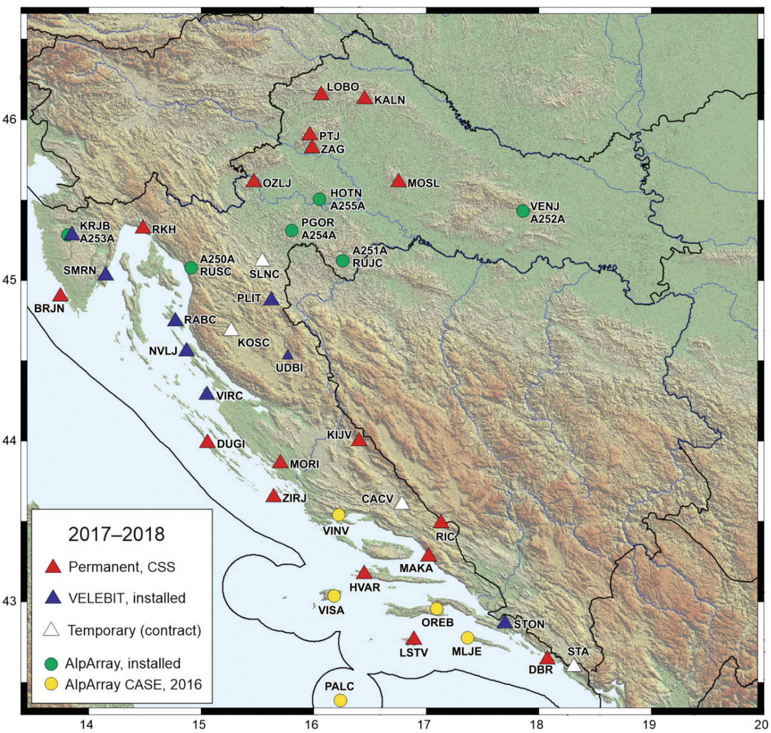

Figure 1. Seismic network in Croatia in the period 2017–2018.

temporary BB-stations were deployed and maintained from project funds (see Fig. 1).

The VELEBIT project was focused around the greater region of Mt. Velebit, dealing with multidisciplinary research of its seismicity (including historical seismicity), earthquake relocation, tectonics, etc. In particular, four important historical events in the Bakar and Rijeka areas were studied together with the Slovenian colleagues, thus adding valuable information on historical seismicity of the area (Fig. 2; Herak et al., 2017; 2018). Macroseismology was also the topic of papers by Sović and Šariri (2016), Markušić et al. (2017) and Tertulliani et al. (2018).

The work on attenuation was primarily concentrated on the area of Central External Dinarides (CED). Dasović et al. (2015) analysed the coda, P-wave and S-wave attenuation there, concluding that the body-wave attenuation is strongly frequency-dependent and comparatively strong. Majstorović et al. (2017) attempted to separate the contribution of scattering and intrinsic attenuation to observed total attenuation in the CED (Fig. 3). A study of κ-parameter controlling the high-frequency strong-motion attenuation was done by Stanko et al. (2017) for a set of Croatian stations.

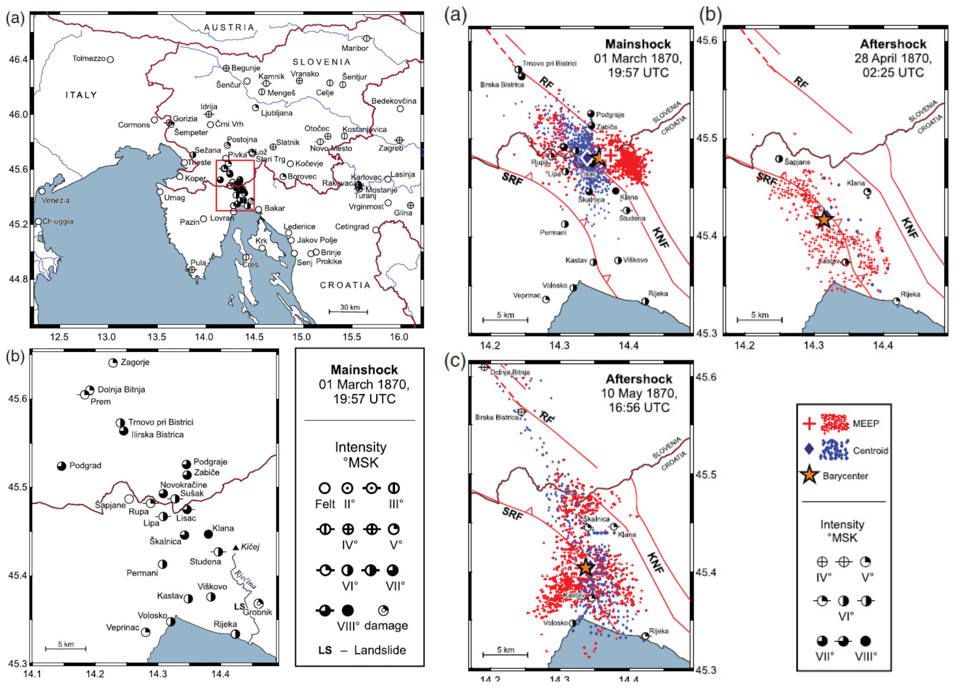

Figure 2. Macroseismic analyses of the Klana eartqhuake of 1870. *Left:* assigned intensities. *Right:* determination of the macroseismic epicentre (from Herak et al., 2018).

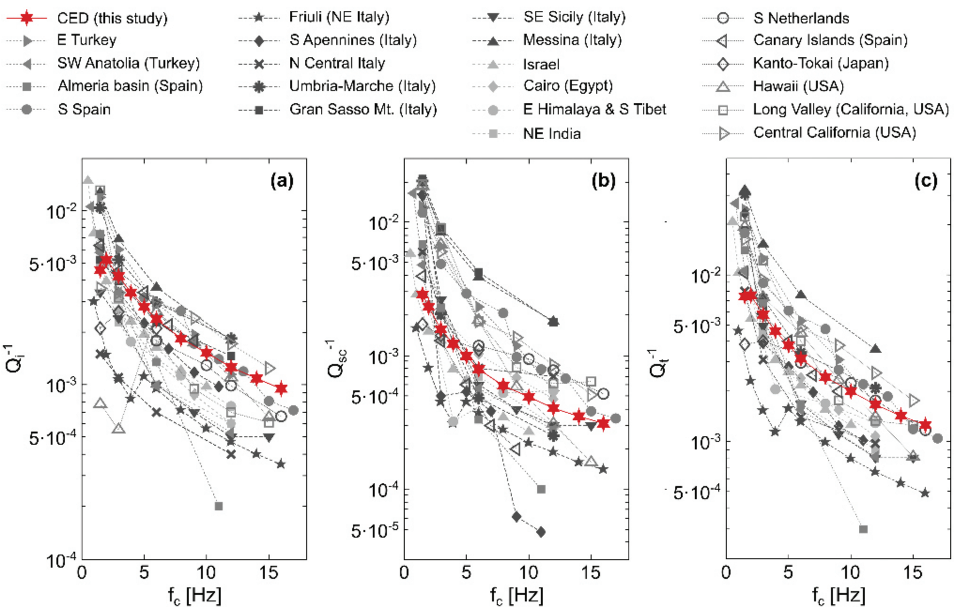

Figure 3. Intrinsic (*a*), scattering (*b*) and total (*c*) attenuation in the Central External Dinarides (CED), compared to a number of regions worldwide (from Majstorović et al., 2017).

The series of papers on seismicity of Croatia was continued by the review of seismicity in the period 2006–2015 by Ivančić et al. (2018). In the framework of the BSHAP-2 project, Markušić et al. (2016) described the updated and unified earthquake catalogue for the Western Balkan Region (WBR). Šalić et al. (2017) presented the BSHAP project Ground Motion Database, whereas Mihaljević et al. (2017) proposed the seismic source model for the WBR.

SKS-splitting measurements and their interpretation was the topic of the paper by Subašić et al. (2017) (Fig. 4, left), who analysed seismograms from stations in the Central External Dinarides concluding that the fast axis is oriented perpendicularly to the strike of the Dinarides. Dettmer et al. (2015) presented direct-seismogram inversion technique to map receiver-side structure by treating source signal as a vector of unknown parameters in a Bayesian framework. Belinić and Markušić (2017) wrote about empirical criteria for earthquake location accuracy. Belinić et al. (2018) used S-receiver functions to infer the lithospheric thickness under the Dinarides area, detecting three distinct domains (see Fig. 4, right). Several other seismological investigations were conducted during this period focusing on the transition zone between Dinarides and Pannonian basin. Šumanovac and Dudjak (2016) employed inversion of the teleseismic P-wave travel times to map deep reaching high velocity anomaly in the NW Dinarides. Šumanovac et al. (2017) extended this investigation to the central-southern portion of the Dinarides and found similar deep reaching high velocity

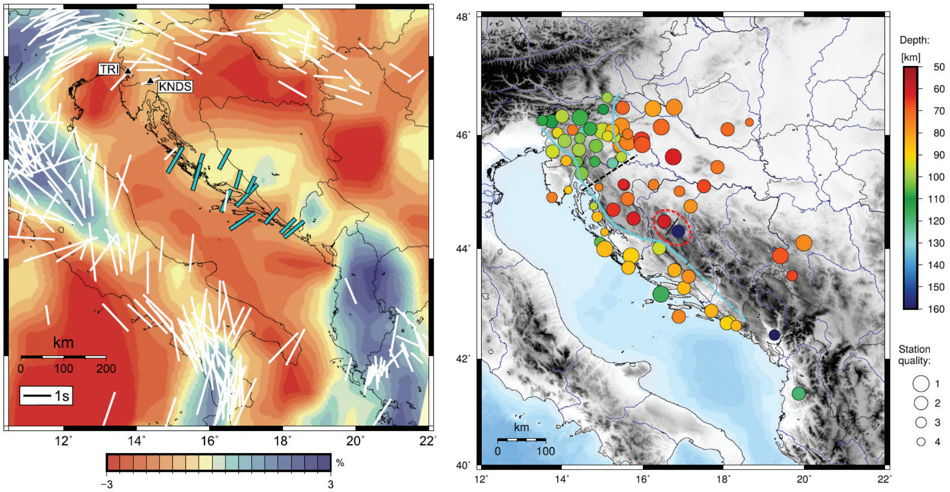

Figure 4. *Left*: Directions of fast axes from SKS-splitting (Subašić et al., 2017). *Right*: Lithospheric thickness estimated by S-receiver function analyses (Belinić et al., 2018).

body under this region too (Fig. 5). In contrast to these deep investigations Šumanovac et al. (2016) used various seismic methods to map crustal structure in the northern Dinarides-southwestern Pannonian basin transition zone.

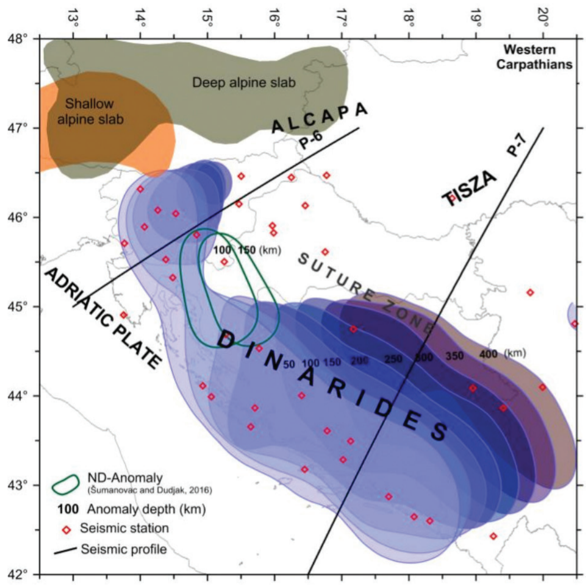

Figure 5. Overview display of the fast anomaly in the Dinarides area from Šumanovac et al. (2017).

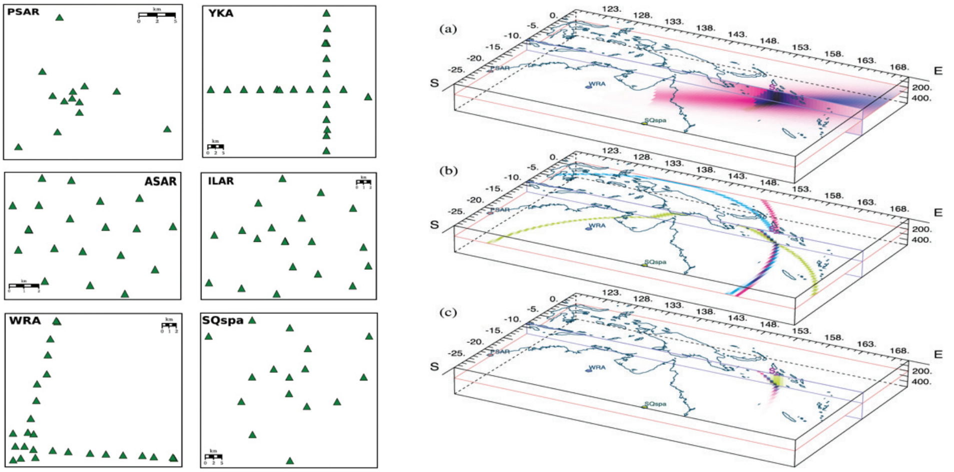

Figure 6. *Left*: Configuration of the six arrays used for multiple array analysis (Kennett et al., 2015; Stipčević et al., 2017). *Right*: Illustration of the interaction of spatial constraints for multiple arrays target (Stipčević et al., 2017).

Kennett et al. (2015) used spiral shaped seismic arrays to enhance the resolution in comparison with more traditionally shaped seismic array (Fig. 6, left). Stipčević et al. (2017) published a paper on the simultaneous use of multiple seismic arrays (Fig. 6, right).

A series of papers (Lee et al., 2015; Lee et al., 2017a-c) were devoted to seismic hazard assessment in the Balkan countries. Local soil amplification for a site in northern Croatia was analysed by Stanko et al. (2017a,b).

The Seismological Survey of Croatia is in charge of maintaining the permanent network, archiving of seismograms, regular compilation of the Croatian Earthquake Catalogue (CEC), data exchange and interaction with Civil Protection authorities. Their duties were duly executed during the reporting period. In particular, the CEC is now finalized up to the end of 2017 and contains about 120,000 records (Fig. 7). Current rate of event inclusion into the catalogue exceeds 10,000 earthquakes/year.

Fault-plane solutions (FPS) using first-motion polarity data are computed for all events in the Croatian neighbourhood, roughly for magnitudes exceeding 3.5. The corresponding data-base of FPS now contains 278 solutions as shown in Fig. 7.

Current research includes efforts to map the mantle transition zone and to reassess the Moho depth beneath the Dinarides using newly collected data and P-receiver functions. Study of anisotropy of attenuation properties is also under way, as well as a continuation of SKS-splitting analyses using data from other stations. It is also planned to perform a thorough relocation of the instrumental

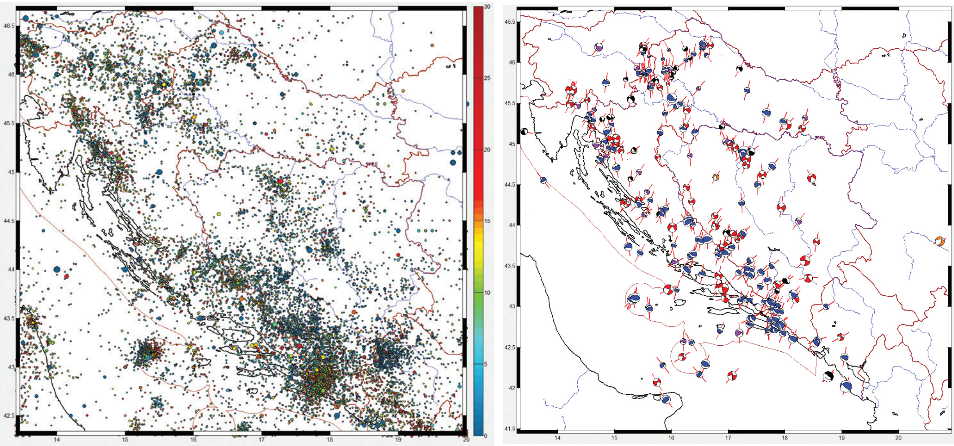

Figure 7. *Left*: Epicentres from the Croatian Earthquake Catalogue (BCE–2017, $M \geq 2.2$). Focal depth is indicated by the colour scale and symbols scale with magnitude. *Right:* First-motion polarity fault-plane solutions (FPS; blue – reverse, red – strike slip). Short red lines are oriented in the direction of the P-axes.

part of the catalogue using improved models and source-specific station corrections. Historical seismicity of the Međimurje region (northern Croatia) is currently also being studied. The Ston-Slano earthquake sequence of 1996 is being revisited using DInSAR data to resolve complex faulting of the mainshock.

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