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Report of the Croatian Committee of Geodesy and Geophysics on activities carried out between 2011 and 2014

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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 three intervals: 1991–1994 (*Geofizika*, **11**, 1994), 1995–1998 (*Geodetski list*, **53**, 1999), and 1999–2002 (*Geofizika*, **18/19**, 2001/2002). After an eight-year break, the practice of reporting to the IUGG is reestablished with this report.

In the following pages, the work carried out between the years 2011 and 2014 by Croatian scientists, active in geodesy and in five geophysical disciplines (geomagnetism and aeronomy, hydrology, meteorology, physical oceanography, and seismology), is documented. The report shows 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. The four-year output is impressive, having in mind the recent decline in national funding of research activities. It appears that the problem was partially offset by an improved access to international research projects. Although the international projects could complement but could not replace the national projects, it is to be hoped that the international collaboration of Croatian scientists will expand in the future and that the IUGG-related activities will contribute to the expansion.

Mirko Orlić,
President,
Croatian Committee of Geodesy and Geophysics

Geodesy in Croatia, 2011–2014

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

Tea Duplančić Leder

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Split, Croatia

This report presents a brief overview of research activities in the field of geodesy in Croatia in the period from 2011 to the end of 2014. The geodesy 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). Research activities resulted in about dozen international peer-review (WoS) publications and a dozen of editor's books and book chapters.

The following research funded by the Ministry of Science, Education and Sports of the Republic of Croatia was performed by the Geodetic Faculty, University of Zagreb:

1. Height kinematics and dynamics of the Croatian continental crust;
2. Cartography of the Adriatic;
3. Geodetic management and monitoring of large objects;
4. Geopotential and geodynamics of the Adriatic (Geo++Adria);
5. Geoinformatics and geomatic engineering in the environmental protection;
6. Modern ultrasonic survey methods in the sustainable development of karst areas;
7. Scientific metrology laboratory for survey instruments development.

The projects were mosty continuation of previous scientific investigations in the field of geodesy, geodetic application in other disciplines, and interdisciplinary research topic (described in the previous report).

International scientific projects at the Geodetic Faculty, University of Zagreb, were:

1. Joint Croatian-Hungarian geomagnetic repeat station survey and joint geomagetic field model;
2. Toolbox implementation for removal of anti-personnel mines sub-munitions and UXO (TIRAMISU);
3. COST Acion TU0801: Semantic enrichment of 3D city models for sustainable urban development;
4. The impact of GNSS and the NSDI on spatial data use and their synergistic impact on management processes in Croatia and the region – SINERGIJA;

5. Geodetic-geological studies of loess edge plateau erosion in Croatian Danube;
6. Geodetic and geodynamic investigation of the recent movement of the lithosphere in sediments of Dinarides area.

Scientific research results have been mainly published in the ISI Web of Knowledge journals (*Survey Review*, *Technical Gazette*, *Annals of Geophysics*) and domestic journals (*Geodetski list*, *Kartografija i geoinformacije*, *Ekscentar*). Also, research results have been presenteed at numerous international and domestic scientific conferences covering geodesy and appliedd geodesy measurement topics.

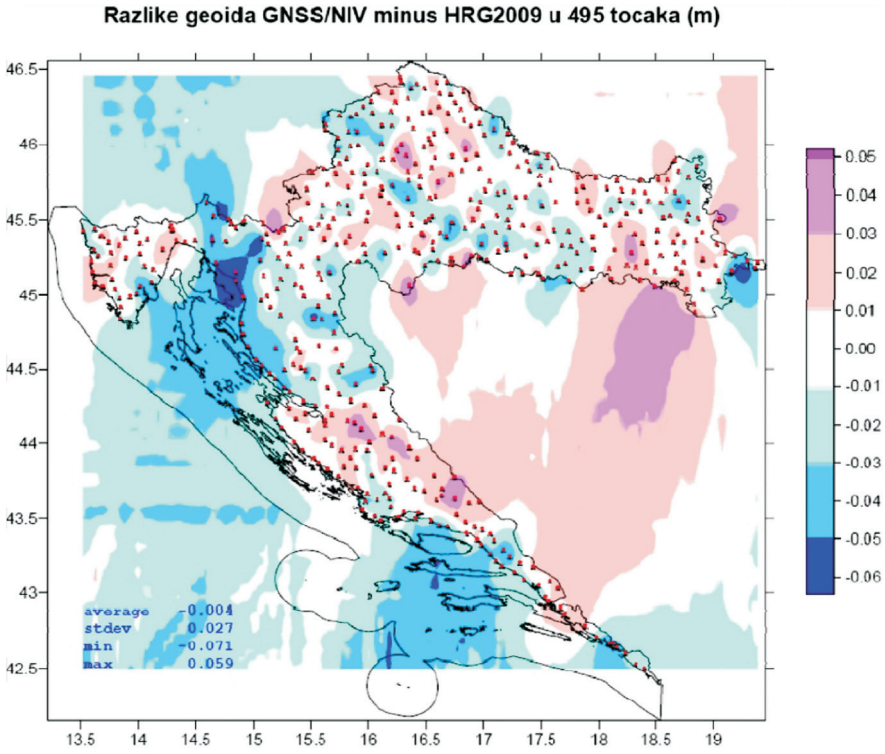

Figure 1. Comparison of geoid model HRG2009 with 495 GNSS leveling points (Grgić et al., 2014).

Scientific research topics dealt with geodetic, gravimetric, geomagnetic and geodinamic measurements and GNSS position measurements (Fig. 1).

Croatian geodetic scientist participated in numerous collaborative international scientific associations and committees, for instance in the International Association of Geodesy Reference Frame Sub-Commission for Europe (EUREF) activities related to the establishment and maintenance of the European Ter-

restrial Reference System and the Vertical Reference System. The majority of about fifty Croatian scientists dealt with geodetic measurements, their visualisation and application in other technical disciplines.

More information on the conducted research activities can be found on the web sites of GEOF (http://www.geof.unizg.hr), FGAG (http://gradst.unist.hr), and SDA (http://www.dgu.hr).

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Geomagnetism and aeronomy in Croatia, 2011–2014

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

Vladis Vujnović and Davorka Herak

University of Zagreb, Faculty of Science, Andrija Mohorovičić Geophysical Institute, Zagreb, Croatia

During the period 2011–2014, the research in the field of aeronomy carried out at the Department of Geophysics, Faculty of Science, University of Zagreb, was presented in eight publications. A scientific and historical commentary of young R. Bošković's treatise *De aurora boreali* from 1738 (Lisac et al., 2011) highlighted his mathematical skill and physical understanding. Written instructions of the text without a single mathematical formula helped to repeat his results. Aurorae observed in his time appeared during the first sunspot cycles coming after the Maunder minimum, and Bošković's study represents an example of the pra-aeronomic science. In the year 2011 – 300th anniversary of the birth of Ruđer Josip Bošković, one of the greatest and most famous Croatian philosophers and scientists – which was in Croatia proclaimed as The Year of the Ruđer Bošković, conference communications (Lisac et al., 2011, Vujnović, 2011, Vujnović and Lisac, 2011, Vujnović et al., 2011) were published, analysing Bošković's studies related to the atmospheric phenomena. Vujnović and Lisac (2011) presented the field of aeronomy focusing on the scopes that were treated by the staff of the Department of Geophysics.

Scientific geomagnetic research was organized within the framework of the project „Study of the geomagnetic field and heterogeneities of the lithosphere in Croatia", which was financed by the Ministry of Science, Education and Sports of the Republic of Croatia. Verbanac and Vujić (2012), Verbanac (2011) and Vujić et al. (2011) described geomagnetic investigations and procedures conducted to establish the location for the Croatian permanent geomagnetic observatory.

The total magnetic field and the horizontal and vertical gradients were measured in a selected area in the Nature Park Lonjsko Polje, about 65 kilometres from Zagreb, and measurements were compared with the Comprehensive Model prediction (Verbanac and Vujić, 2012).

Based on the ground survey of total field data at 53 sites (2003–2005), the core field and long wavelength lithospheric field over the northern central Croatia region was calculated (Vujić et al., 2011). The nearest observatory in Tihany was used as the reference one. Regarding the position selected for the observa-

tory, disturbances were observed by the leakage currents from the Zagreb's tramway and the Slovenian DC railways up to the distance of 35–40 km.

The core field behaviour from 1961 to 2002 over the entire Croatian territory was investigated by exploiting different global models. Using a regional European model, the secular variation over the country was calculated. The evolution of the core field at the potential location for installing the geomagnetic observatory was analysed in detail. The calculated field variations follow the general core field variations over Europe (Verbanac, 2011).

Different aspects of the Sun-Earth relation were studied by Verbanac et al. (2011a, 2011b, 2011c, 2013), such as the evolution of the solar and geomagnetic indices, and geoeffectiveness of the solar wind high-speed streams.

Cross-correlation analysis in Verbanac et al. (2011b, 2011c) of the fractional corona hole area (measured between central meridian distances ± 10°), solar wind parameters and geomagnetic indices Dst and Ap, gave the strongest influence of the solar wind parameter BV^2. For the declining phase of solar cycle 23, it was found that the combination of solar wind parameters BV^2 and BV plays the central role in the process of energy transfer from the solar wind to the magnetosphere.

Ten years after the beginning of the revival of research of Earth's magnetism in Croatia, the Department of Geophysics of Faculty of Science in Zagreb managed to build and equip the first and only geomagnetic observatory in Croatia. Observatory is located in the area of the Nature Park Lonjsko Polje (geographic coordinates of the absolute pillar are 45°24'29" N, 16°39'33" E, altitude of 95 m) – Figs. 1 and 2 (Markušić et al., 2012).

It belongs to the group of "remote" unmaintained observatories without permanent staff and observatory is visited only for the purpose of maintenance and absolute observations. Observatory is comprised of three small houses and the

Figure 1. Geomagnetic observatory in Lonjsko Polje.

OP-hut, which are made from non-magnetic materials (mostly oak) and to allay temperature effects styrofoam coating is used for insulation of instruments. Huts foundations and pillars inside them are built from white cement. The observatory's power comes from the solar cells positioned on the roof of the control house.

The observatory runs two proton magnetometers for measurement of the total intensity, a geomagnetic theodolite for measurements of the absolute values of declination and inclination and the dIdD magnetometer which measures the relative changes in inclination, declination and the total intensity. With the establishment of the observatory, permanent monitoring of the geomagnetic activity in Croatia is renewed after 60 years of inactivity. This provides a good foundation for rapid development of geomagnetism, which has been neglected for a long time although being one of the first geophysical disciplines practised in Croatia.

From December 2012 we are hosting three-axial fluxgate magnetometer Lemi-035. It is a low-noise (< pT at 1 Hz) with 1 pT resolution at 1 Hz data rate with temperature drift < 0.5 nT/°C, installed under framework of the PLASMON Project (http://plasmon.elte.hu/home.htm) in cooperation with Tihany Observatory.

Figure 2. *Top left*: control house with solar cells on the roof; *Top right*: geomagnetic theodolite; *Bottom left*: dIdD magnetometer; *Bottom right*: proton magnetometer.

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Hydrology in Croatia, 2011–2014

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

Vesna Denić-Jukić

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Split, Croatia

This report presents the research activities in the field of hydrology in Croatia in the period from 2011 to the end of 2014.

The research projects were funded by the Croatian Ministry of Science, Education and Sports. The scientific research was performed by experts from the following institutions:

Faculty of Civil Engineering, Univesity of Zagreb (1 project):

1. Torrential erosion of soils on the flysch of Istria (082-1780692-2164);

Faculty of Civil Engineering, Architecture and Geodesy, University of Split (3 projects):

1. Research of extreme hydrological situation and water risks in karst (083-0831510-1511);
2. Surface water and groundwater monitoring in coastal karst areas (083-0822695-1526);
3. Water balance and modeling of flow in karst (083-0831510-1513);

Faculty of Civil Engineering, University of Rijeka (1 project):

1. Hydrology of sensitive water resources in karst (114-0982709-2549).

These projects are mostly the continuation of previous investigations in the field of karst hydrology and hydrogeology. The primary focus of those projects is evidently the karst hydrology. The hydrology of karst terraines was recognized as a distinct subdivision of groundwater hydrology. Aquifers are characterized by the distribution and anisotropy of hydraulic conductivity among various rock units that make up aquifer.

The flow of karst springs is often variable, rising and falling in response to storms. The water flowing from a spring represents a composite of all inputs and flow systems. Those projects are mostly based on the use of spring hydrographs to characterize the karst aquifers. The researchers also dealt with the construction of flow models for karst aquifer.

Scientists have been included in activities of numerous international and domestic conferences and a number of scientific papers were published covering theoretical and practical topics in hydrology. Also, the obtained results from the investigations were published in domestic and in international journals (*Journal of Hydrology*, *Hydrological Processes*, *Hydrological Sciences Journal*, *Water Resources Management*, *Environmental Earth Sciences, Journal of Hydroinformatics*, *Theoretical and Applied Climatology*, *Acta Carsologica*).

Mostly, the papers are ralated to the numerical modelling, rainfall-runoff modelling 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.

The Croatian-Japanese bilateral scientific project entitled Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia commenced on 27 March 2009 within the Science and Technology Research Partnership for Sustainable Development (SATREPS). The SATREPS programme enabled joint research to be carried out by Japanese and Croatian scientists, while the programme funded international research exchange as well as donations for equipment required for implementation of the project's activities. The project was evaluated at approximately 4 million USD, funded by the Japanese government, and co-funded by the Ministry of Science, Education and Sports of the Republic of Croatia. The Japanese partner institutions of the project were: the University of Niigata (The Research Center for Natural Hazards and Disaster Recovery), the University of Kyoto (Disaster Prevention Research Institute, DPRI) and the non-profit organization International Consortium on Landslides (the ICL). Croatian partner institutions in the project included three Croatian universities: the University of Rijeka (Faculty of Civil Enginering), the University of Zagreb (Faculty of Mining, Geology and Petroleum, and the Faculty of Agriculture) and the University of Split (Faculty of Civil Engineering, Architecture and Geodesy), as well as the Croatian Geological Survey. The project lasted 5 years, with over 20 participating researchers from Japan and some 30 from Croatia. One of the the main objectives of the project was geohazard analysis and development of guidelines for application of the project's results within a zoning system. The purpose of this project was contribution to sustainable development through application of suitable measures in planning documents. The project's activities have been carried out in pilot-areas near cities where the three Croatian partner-universities are located, i.e. Zagreb, Rijeka and Split.

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, 2011–2014

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

Kristian Horvath[1] *and Branka Grbec*[2]

[1]Meteorological and Hydrological Service, Zagreb, Croatia

[2]Institute of Oceanography and Fisheries, Split, Croatia

This report presents a brief overview of meteorological research in Croatia during the 2011–2014 interval, as evidenced by published editor's books, book chapters, international peer-review (CC) publications and PhD theses. Over two dozens of nationally and internationally funded projects in this period were implemented at the Geophysics Department, Faculty of Science, University of Zagreb (GFZ), the Meteorological and Hydrological Service (DHMZ), the Physics Department, Faculty of Science, University of Split (PMFST), and the Institute of Oceanography and Fisheries (IOF) in Split. The research activity resulted in about eighty international peer-review (CC) publications and over a dozen of editor's books and book chapters.

The research conducted by Croatian scientists covered a wide range of state-of-the-art topics in meteorology. Dynamical and synoptic meteorology focused on the analysis of mesoscale and synoptic systems, with a special emphasis on orographic flows and mesoscale cyclones in the area. Climatologists investigated past climate, climate variability and climate change, and evaluated and advanced the skill of regional climate models. Turbulence research predominantly dealt with turbulence in planetary boundary layer, especially during bora events, as well as turbulence in sub-urban areas. Intensive research has been performed on natural hazards related to hydrological cycle, especially convection, heavy precipitation and flash floods in Mediterranean but also in the tropics, especially through satellite, radar and lightening data, process-based studies and climatologies and numerical modelling. Methods for advancing numerical weather prediction focused on numerical instabilities, stiffness and phenomenology of parametrization schemes, the area of data assimilation, and verification of numerical weather predictions.

Furthermore, meteorological research intensively diffused to interdisciplinary research topics. Air-pollution studies addressed air-quality issues over complex topography and long-range transmission of air pollutants in our region as well as the related effects of climate change on air pollution. Air-sea-interaction studies dealt with land-sea breezes, effects of extreme weather events and climate on the dynamical sea processes near the coasts as well as monitoring of

physical properties in the boundary layers of the atmosphere and the sea. Agrometeorologists investigated the effects of climate and adverse weather relevant for the field, especially yield of crops. Collaboration between meteorology and energy sectors was stimulated through collaborative research in renewables, microgrids and energy efficiency in buildings. Other research topics considered were climate tourism, heat-waves effects on mortality, wildfires, refraction of radio-waves, estimates of wind extremes and loads on structures, statistical properties of hail, and homogenization of meteorological data.

More information on the conducted projects can be found on the web sites of GFZ (http://www.pmf.unizg.hr/geof), DHMZ (http://meteo.hr), PMFST (http://www.pmfst.unist.hr) and IOF (http://www.izor.hr).

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Physical oceanography in Croatia, 2011–2014

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Gordana Beg Paklar

Institute of Oceanography and Fisheries, Split, Croatia

Between 2011 and 2014 physical oceanographic research in Croatia has been carried out mainly in the following institutions: Institute of Oceanography and Fisheries (IOF), Split; Hydrographic Institute of the Republic of Croatia (HI), Split; Center for Marine Research (CMR), Rudjer Bošković Institute, Rovinj and Zagreb; Andrija Mohorovičić Geophysical Institute (AMGI), Faculty of Science, University of Zagreb; and Department of Electrical Engineering and Computing (DEEC), University of Dubrovnik.

Altogether 27 investigators (20 PhD's and 7 MSc's), supported by technical staff, were involved in the research. Research vessels owned by institutes in Split (*Bios dva*, *Navicula*, *Hidra*, *Palagruža*) and Rovinj (*Vila Velebita*, *Posejdon*) were used in the field work. The oceanographic equipment used to study the hydrographic properties included several Seabird CTD probes, thermistor chains, XBTs and Biospherical profiling radiometer. A towed undulating vehicle, equipped by a Seabird CTD probe, has been acquired to perform hydrographic measurement of high temporal and spatial coverage. Currents were measured with a number of current meters (Aanderaa RCM's and RDI ADCP's) and high-frequency radars, while tide gauges (Ott analog instruments and Aanderaa, Ott and Parascientific digital instruments, radar Ott instrument) and wave gauges (Datawell, Seabird) were used to measure low- and high-frequency sea-level oscillations, respectively. Three buoys, designed and manufactured in Croatia, were deployed in the east Adriatic coastal areas in order to collect various meteorological and oceanographic data. Atmospheric conditions during oceanographic investigations were also recorded using microbarographs and an automatic meteo-oceanographic station in front of the Institute of Oceanography and Fisheries in Split. 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 and MIKE models were run on computer clusters and servers.

During the four-year interval considered some previously established measurement programs were maintained and some new 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) within the framework of national projects and studies. Analyses of dynamic depths distribution and geostrophic currents became part of standard reports of a large national project developing an ecological model of the Adriatic Sea. In September 2012 the oceanographers from the AMGI carried out the first high-resolution CTD measurements with the undulating vehicle, in the vicinity of the Cetina River mouth, on the eastern coast of the middle Adriatic. The profiling covered an 11 by 2.5 km radiator area, from near surface to some 35 m depth; the horizontal resolution was about 200 m along the track and the vertical resolution was better than 0.1 m. Another campaign of the towed CTD measurements was undertaken in July 2014 in the northern Adriatic, between Rovinj and Po and in front of the Po River mouth. Current measurements were performed within the second phase of the Adriatic Sea Monitoring Project and in the framework of various hydrotechnical projects (Drage, Smrka and Grška Bay in Brač Island). High-frequency radars were used for mapping surface currents and waves in the northern and middle Adriatic Sea within HAZADR project. Tide-gauge measurements were continued at a previously established network of seven stations (Rovinj, Bakar, Zadar, Split-Marjan, Split-harbour, Sućuraj, Dubrovnik), with some new stations being established temporarily (e.g. Ist). Sea-surface temperature was measured daily at a number of coastal stations. And finally, three microbarographs were installed at Vis, Vela Luka and Vrboska to provide high-frequency air-pressure data with the main goal to study and forecast meteotsunamis and sea surges.

Over the preceding four years Croatian institutions participated in national projects founded by the Ministry of Science, Education and Sports of the Republic of Croatia, the Croatian Science Foundation and the Unity through Knowledge (UKF) fund. In addition to the research, physical oceanographers participated in series of professional studies dealing with physical parameters relevant to ecosystem and the categorizations of water within the European directives. Projects BALMAS, HAZADR and JASPPer were funded by IPA Adriatic Cross-border Cooperation Programme program, while SESAM, PERSEUS and SeaDataNet-II projects were supported by the European Community. Moreover, Croatian physical oceanographers participated in several international projects investigating areas outside the Adriatic, like the U.S. East coast (Horvath and Vilibić, 2014; Šepić and Rabinovich, 2014; Vilibić et al., 2014a, Vilibić et al., 2014b) and the Pacific Ocean (Powel et al., 2012; Matthews et al., 2012; Janeković and Powel, 2012; Janeković et al., 2013). Croatian physical oceanographers also took part in the IOC assemblies, GOOS and GODAR meetings, as well as in a number of international conferences and workshops.

The work done is documented in the publications the list of which is attached to this report. The list contains scientific papers, books and theses. The 2011–2014 interval followed after the period of intense field measurements, done within the Croatian-American project ITHACA, when a large set of temperature, current and CTD data were gathered in the area of the Palarguža Sill. The analysis of the data revealed that large diurnal thermocline oscillations, observed at the Lastovo Island, were related to resonantly driven upwelling imposed by sea breeze circulation (Orlić et al., 2011). The response of the coastal sea to periodic along-shore and cross-shore wind forcing along a straight coast was studied by a simple analytical model. The wind at subinertial frequencies leads to coastally-trapped variability while at superinertial frequencies it leads to baroclinic inertia–gravity waves propagating away from the coast (Orlić and Pasarić, 2011). Under favourable stratification conditions internal coastally-trapped Kelvin-like waves that revolve in a clockwise direction around the island are also induced by periodic currents; depending on the perimeter of the island and the periodicity of the forcing, the resonance is achieved (Mihanović et al., 2014).

A number of publications dealt with open Adriatic hydrography and current field variability. In some of them long-term changes in physical conditions were related to the ecosystem variability. Interaction between air-sea heat fluxes and geostrophic currents in the northern Adriatic was analysed and it has been found that winter circulation patterns are stable for longer time period and form in autumn, depending on meteorological conditions (Supić et al., 2012). Year-to-year changes in phytoplankton abundances and in other oceanographic parameters relevant for the intensity of bioproduction in the northern Adriatic were found to be related to year-to-year changes in geostrophic circulation patterns in the region (Kraus and Supić, 2011; Marić et al., 2012; Djakovac et al., 2012). The presence of two isolated circulation cells in the northern Adriatic during a spring cruise was detected on the basis of oceanographic data, including dynamic depths distribution, and confirmed by spatial variations in the structure of microbial community (Orlić et al., 2013). An intense winter convection event in the South Adriatic Pit resulting in increased bioproduction was documented as well (Najdek et al., 2014). Long-term time series of physical and chemical parameters collected between 1960 and 2010 along the Palagruža Sill transect were investigated as well. Vilibić et al. (2013a) studied temperature, salinity and dissolved oxygen data from the transect. Their analysis revealed that the northwestern part of the Adriatic-Ionian thermohaline circulation cell, one of the three cells that drive the deep Mediterranean thermohaline circulation, weakens in time (Vilibić et al., 2013a). In addition, Vilibić et al. (2012) studied chemical parameters (nutrients, pH values) collected over the transect. Higher-than-usual nutrient levels peaking in the mid 1990s, coupled with lower-than-usual temperature, salinity, dissolved oxygen and pH values, were related to the inflow of the nutrient richer Western Mediterranean waters to the Adriatic during the anticyclonic phase of the Bimodal Adriatic-Ionian Oscillation (BiOS). Mihanović et al.

(2013) and Janeković et al. (2014) studied an event of exceptional dense water formation on the Adriatic shelf in the winter of 2012. Vilibić and Mihanović (2013) used data from Argo profiling float to study the same event. This float was advected to the Jabuka Pit and neighbouring shallow area, where it was drifting near the bottom during the 2012 dense water formation episode. The profiler measured strong spatial-temporal changes in the bottom density current (BDC) thickness (from a few metres to 50 m) and the bottom density (between 1029.46 and 1029.88 kg/m^3). It was shown that Argo floats have a capability to observe BDC and that it could be possible to systematically use such floats to investigate dense water formation and BDC over coastal shelves.

Another line of research was the study of the response of global sea level to temperature forcing. The semi-empirical method, which uses various physically motivated relationships between temperature and sea level to project future sea level, was improved by including both the inertial and the equilibrium response. Thus obtained value of sea-level rise was substantially smaller than previously published semi-empirical projections and was brought closer to the corresponding process-based values (Orlić and Pasarić, 2013). Šepić et al. (2012) and Vilibić et al. (2013b) studied long-term sea-level variability over the Mediterranean and the world ocean. Investigated data included both long-term tide-gauge measurements (Vilibić et al., 2013b), and outputs (present climate and climate projections) from a Mediterranean numerical ocean model (Šepić et al., 2012). The most coherent result obtained in these studies involved a significant decrease in sea-level variability over the tropical and subtropical Pacific, particularly at the synoptic scale frequencies (Vilibić et al., 2013b).

Croatian scientists within an international group managed a NOAA/NWS project "Towards a meteotsunami warning system along the U.S. coastline (TMEWS)". Overall objective of the project was to build procedures and protocols for rising meteotsunami warning alerts along the U.S. coastline. As a result of this project a special *Natural Hazards* issues and a corresponding *Springer* book on meteorological tsunamis were issued (Vilibić et al., 2014). Several papers by Croatian oceanographers dealing mostly with meteotsunamis observed along the eastern U.S. coastline were published in this special issue (Horvath and Vilibić, 2014; Šepić and Rabinovich, 2014; Vilibić et al., 2014a, Vilibić et al., 2014b). In addition, Pasquet and Vilibić (2013) noticed that strongest meteotsunami waves hit the eastern U.S. 2–3 hours after atmospheric pressure disturbances cross the coastline. It was shown that offshore propagating atmospheric pressure disturbances resonantly generate long-ocean waves as they travel over the shallow shelf. Upon reaching the shelf edge, long-ocean waves are reflected back towards the coast where they can generate dangerous sea-level oscillations.

As a first step in assessing tsunami hazard in the Adriatic, a detailed study of historic tsunamis from contemporary and original documents was carried out. The result of the study is a new catalog of Adriatic tsunamis (Pasarić et al., 2012).

New methods for measurements and analysis of the physical parameters were introduced in the considered four-year period. A towed undulating vehicle, equipped by a Seabird CTD probe, has been used to perform quasi-synoptic 3D measurements of hydrographic properties near the Cetina River mouth. Results revealed a shallow fresh-water plume slightly warmer than the surrounding sea, with anticyclonic, cyclostrophic gyre formed in front of the mouth and a narrow coastal current extending downstream. A detailed study of the observed phenomena is still in progress. HF radars were used to map the surface currents in the northern and middle Adriatic. Mihanović et al. (2011) studied current measurements in the northern Adriatic from February to August 2009. Current patterns and temporal evolutions of different physical processes were extracted by using Self-Organizing Maps (SOM) analysis based on neural networks approach. A strong resemblance has been found between SOM patterns extracted from HF radar data only and from combined HF radar and wind data sets, revealing the predominant wind influence on the surface circulation structures and their temporal changes in the northern Adriatic. Results of this research served as a baseline idea for the UKF project "Interpreting and forecasting Adriatic surface currents by an artificial brain (NEURAL)". The aim of this ongoing project (2013–2015) is to investigate and develop a hybrid ocean forecasting system for the eastern coastal regions of the Adriatic Sea, based on the neural network approach. The SOM method was used not only in the study of high-frequency radar data but also to analyse long term changes in deep Adriatic water patterns (Vilibić et al., 2011) and underwater sound noise (Rako et al., 2013). Significant improvements in the algorithms for calculations of the satellite-derived sea surface temperatures in the Adriatic and Mediterranean were achieved by Tomažić et al. (2011, 2014).

Results of the numerical model simulations were used in a variety of research (Klaić et al., 2011; Orlić et al., 2011; Janeković et al., 2014; Mihanović et al., 2014) and application studies (Lončar et al. 2011; 2012). POM model was used to study the influence of the atmospheric forcing resolution on the simulation of coastal circulation, wind induced diurnal upwelling and internal tides, while ROMS model results revealed details in the exceptional dense water formation in the winter of 2012. Application studies on oil spills (Lončar et al., 2012) and effluent plume dynamics (Lončar et al., 2011) were performed with MIKE model. Coupled modelling system with ROMS and Wind Wave Model II was used in the analytical test case and to hindcast near-surface dynamics in the Adriatic (Dutour Sikirić et al., 2012; 2013).

Collaboration with chemists, biologists, fishery scientists and geologists was established, resulting in number of interdisciplinary papers dealing with climate and circulation impact on the ecosystem variability (Skejić et al., 2014; Sikora et al., 2014; Gašparović et al., 2013; Gordijan et al., 2013; Marić et al., 2013; Rako et al., 2013; Viličić et al., 2013; Zorica et al., 2013; Carić et al., 2012; Vilibić et al., 2012; Kršinić and Grbec, 2012; Morović et al., 2012; Vidjak et al., 2012; Viličić

et al., 2011). The Laboratory of Physical Oceanography at the Institute of Oceanography and Fisheries, Split, in cooperation with the State Hydrometeorology Institute of Croatia, has established a virtual laboratory (http://www.izor.hr/web/guest/virtual-laboratory) in order to study interactions between climate change and the marine ecosystem through monitoring of a variety 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 a near real time, as were the weather forecasts at a 2×2 km grid over the Adriatic Sea.

Overall, increased number of scientists active in the Croatian physical oceanography community and their intensified collaboration with colleagues abroad considerably improved scientific activity from 2011 to 2014 in comparison to the activities described in the previous reports to the International Association for the Physical Sciences of the Oceans. Improvement and modernization of the used equipment enabled new research topics to be addressed and important findings to be obtained. The list of publications as well as the number of realized and ongoing national and international projects for the Adriatic and the other ocean and coastal areas were significantly enlarged in comparison to the previous reporting intervals.

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Seismology in Croatia, 2011–2014

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

Davorka Herak and Marijan Herak

University of Zagreb, Faculty of Science, Andrija Mohorovičić Geophysical Institute, Zagreb, Croatia

Seismological research in Croatia is carried almost exclusively within the Department of Geophysics, Faculty of Science, University of Zagreb. Scientific investigations were largely supported in the framework of two national projects, „Seismicity of Croatia" and „Study of the geomagnetic field and heterogeneities of the lithosphere in Croatia", which were financed by the Ministry of Science, Education and Sports of the Republic of Croatia. The staff of Croatian Seismological Survey (a part of the department) maintains and develops the networks of seismographs and of strong-motion instruments, compiles the earthquake catalogue and analyses and exchanges the seismological data. In the period 2011–2014 the number of seismological stations increased, as six new stations were opened (near Dubrovnik, in Makarska, Morići, Ozalj, Moslavačka gora and on Lastovo island). All of the existing stations have been set-up with digital broad-band instruments, and they transmit the data to the central observatory in Zagreb in real time. In total there are now 19 permanent seismological stations in Croatia.

Thirteen Croatian researchers (4PhD, 5 MSc and 4BSc) took part in seismological investigations. Two employees have retired after long service in the Croatian Seismological Survey (Vlado Kuk and Krešimir Marić) in October of 2013. In the period 2011–2014 a total of 13 research papers and the Croatian earthquake hazard map has been published. Researchers participated in 10 conferences with 12 conference communications. One doctoral thesis and six graduate theses were defended. Croatian seismologists were active in national and international scientific projects. For instance, the objective of the NATO SfP Project 984374 (Improvements in the Harmonized Seismic Hazard Maps for the Western Balkan Countries) is to improve the seismic hazard maps of the region using the project end products (seismotectonic and acceleometric database) and state-of-the art seismic hazard assessment methods. Croatian earthquake catalogue has been regularly updated and currently lists over 78,000 earthquake records (BC–2014), whereas the database on fault-plane solutions lists 224 events (Fig. 1).

The research topics included investigations of crustal and uppermost mantle structure by receiver functions (Stipčević et al., 2011). This study revealed that

Moho beneath the southern Dinarides could lie at depth well over 55 km. Herak M. et al. (2011) compiled the seismic hazard map for the region of Croatia, which was adopted as a part of the national annex for the Eurocode-8 set of norms. Herak M. (2011) gave on overview of ambient noise measurements and interpretation in Croatia in free-field and in buildings. The research on attenuation of seismic waves and coda waves in the area of Croatia has been renewed (Dasović et al., 2012; 2013). Furthermore, some elements of seismic hazard in the Kraljevo region (Serbia) (Herak D. et al., 2011; Lee et al., 2011a, 2011b) as well as in the region of the western Balkan Peninsula (Lee et al., 2013) have been estimated. A detailed study of the seismotectonic and seismological properties of the greater Banja Luka region was presented by Ustaszewski et al. (2014), identifying main seismogenic structures, and suggesting that most strain in the area is most likely released along active segments of internal thrusts of the Dinarides (Fig. 2). The study also indicates that the entire Adria–Europe plate convergence

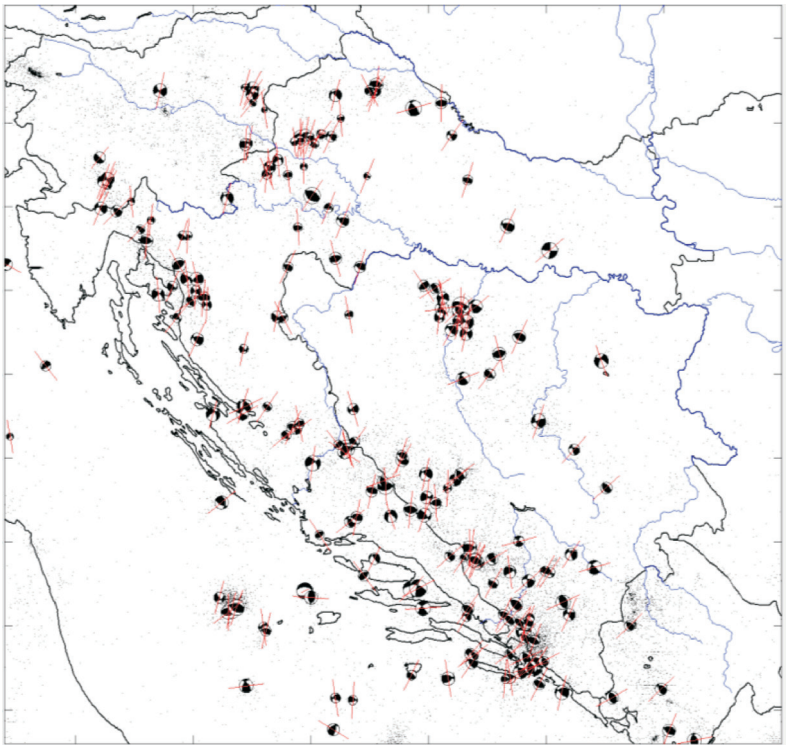

Figure 1. Earthquake fault-plane solutions (FPS) depicted as the lower-hemisphere equal-area projection. Red lines show the orientation of the maximal tectonic compression (the P-axes) indicated by particular solutions. Data are from the Croatian FPS database.

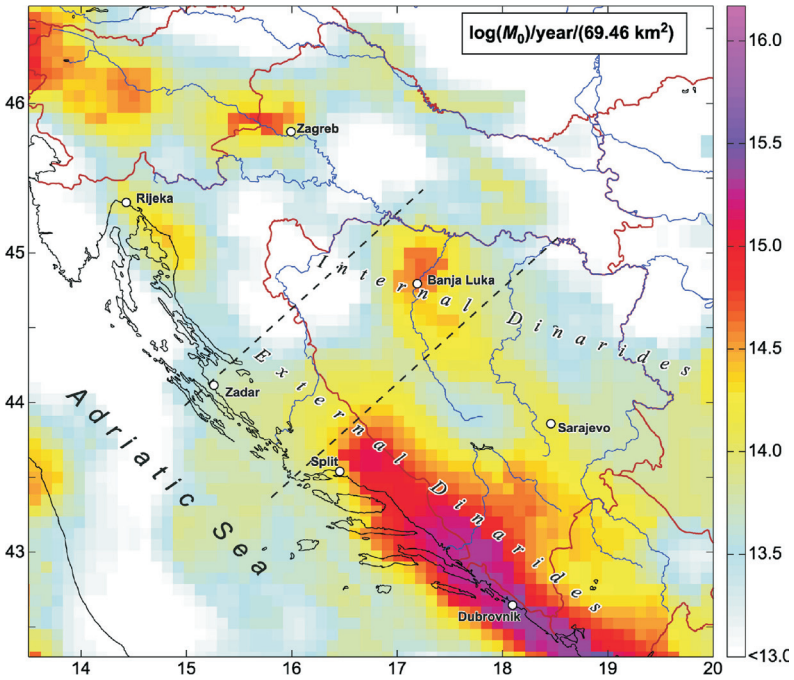

Figure 2. Scalar seismic moment (in Nm, log scale) release rate based on the seismicity model of Lee et al. (2011, 2013). The two dashed lines mark the area where current Adria–Europe convergence is apparently being primarily accommodated in the internal Dinarides (from Ustaszewski et al., 2014).

is currently distributed across the entire Dinarides fold-and-thrust belt, over a width of about 300 km.

Two seismologists took part in the expedition onboard the Meteor vessel in the southern part of the Adriatic Sea to collect data which would help determine the structure of the lithosphere in that region (Kopp et al., 2013).

Croatian seismologists have also entered the AlpArray project, which is an initiative to study the greater Alpine area with a large-scale broadband seismological network. The interested parties from 17 countries plan to combine their existing and new infrastructures into an all-out transnational effort that includes data acquisition, processing, imaging and interpretation. The experiment will encompass the greater Alpine area from the Black Forest and the Bohemian Massif in the north to the Northern Apennines in the south and from the Pannonian Basin in the east to the French Massif Central in the west. Also, at the end of 2014 the Croatian seismological network joined the Central and Eastern European Earthquake Research Network (CE^{3}RN), thus joining the networks from Italy, Slovenia and Austria which freely share their recordings in real time.

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