Physical oceanography in Croatia, 2015–2018

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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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