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Doktorska disertacija – Sažetak
D.Sc. Thesis – Extended abstract

OPAŽANJA I MODELIRANJE KLIMATSKIH TRENDOVA TEMPERATURE ZRAKA I MORA ZA JADRANSKO PODRUČJE

Observations and modeling of air and sea temperature climate trends in the Adriatic region

SLAVKO RADILOVIĆ

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Sažetak: Klimatska predviđanja temperatura zraka i mora u obalnim područjima predstavljaju veliki izazov zbog kompleksnih međudjelovanja između atmosfere, mora i kopna. Pošto je Sredozemlje proglašeno jednim od mjesta na Zemlji gdje su klimatske promjene najizraženije, regionalni klimatski modeli (Regional Climate Models, RCMs) i reanalize su zbog toga najpoželjniji alati za istraživanje sastava lokalne klime i promjenjivosti iste. Prednost je u tome što RCM-i bolje prikazuju kompleksnu orografiju razvijene obale na području kakvo je Jadran. Sve je to važno za istraživanje temperaturnih trendova. Također, korištenje rezultata RCM-a, reanaliza visokih prostornih rezolucija te satelitskih mjerenja značajno pridonosi razumijevanju promjenjivosti klime te regionalnih klimatskih procesa. Jedni od takvih procesa su i morski toplinski valovi (Marine heatwaves, MHWs) koji u većini slučajeva nastaju kao posljedica klimatskih promjena (prijelaz velike količine topline iz atmosfere u more), odnosno rasta površinskih temperatura zraka i mora. Takvi ekstremni događaji imaju uvelike utjecaj na ekosustave i ljudske djelatnosti diljem svijeta, a posebice na ribarstvo.
Korišteni RCM-ovi uključuju modele iz CORDEX projekta s prostornim korakom od 0,11° s rezultatima povijesnih i evaluacijskih simulacija. Povijesne simulacije za rubne uvjete koriste rezultate simulacija globalnih klimatskih modela (Global Climate Models, GCMs) za razdoblje 1961. – 2005., dok evaluacijske simulacije koriste ERA-Interim reanalizu za razdoblje 1989. – 2008. Simulirane temperature zraka su uspoređene s temperaturama standardne mreže kopnenih meteoroloških postaja, podatcima reanaliza UERRA te mrežom interpoliranih E-OBS mjerenja za šire područje Jadrana. Također, pri evaluaciji trendova površinskih temperatura mora korišteni su satelitski podaci i podaci ERA5 reanalize. U analizi su se koristile statističke metode kao što su pristranost, korijen srednje kvadratne pogreške, razlike koeficijenata trendova i to uspoređujući: (a) rezultate evaluacijskih simulacija naspram rezultata povijesnih simulacija, (b) RCM-ovi naspram reanaliza i (c) točkasti podaci mjerenja na položajima postaja naspram mrežastih podataka (E-OBS). Ova analiza je rezultirala procjenom ograničenja u simuliranju temperaturnih trendova današnjom generacijom RCM-ova. Pokazano je da, bez obzira na ograničenja koja pojedini modeli imaju, ukoliko se više modela promatra kroz aritmetički srednjak ili težinske mjere njihovog ansambla, rezultati mogu biti bolji za 15 – 20 % u odnosu na pojedini RCM.
Pri analizi MHW-ova na Jadranu koristile su se još i klimatološke mape 99.-og percentila, temeljene na tridesetogodišnjem klimatološkom srednjaku u razdoblju od 1982. do 2012., koje su korištene kao pragovi za otkrivanje pojedinih epizoda MHW-ova tako što bi se računalo kada srednja dnevna površinska temperatura mora prelazi vrijednost 99.-og percentila. Uvidom u trenutni i prošli broj ponavljanja epizoda, pokazano je da se broj MHW-ova povećava, a ujedno i njihova jačina raste iz godine u godinu. Prosječno vremensko trajanje ljetnih epizoda MHW-ova na Jadranu za razdoblje 1982. – 2018. iznosi između 6 i 7 dana dok su se epizode u ljetnim sezonama 2003. i 2015. godine pokazale kao najjače u zadnjih nekoliko desetljeća.

Extended abstract:
1. Introduction

Investigating influence of climate change in last few decades led to conclusion that eliminating negative consequences of global warming needs scientific information on local and regional scales. Kotlarski et al. (2014) estimates that increased public interest has influenced the accelerated development of different climate scenarios. Part of this process is the development and improvement of techniques for adapting different techniques ("downscaling") with the aim of translating information from low-resolution domains used by global climate models (GCMs) to high-resolution domains used by regional climate models (RCMs; i.e., Hewitson and Crane, 1996; Wilby and Fowler, 2011). An important part in the development of climate models is the analysis and validation of model results in comparison with measurements. The procedure is to conduct an evaluation experiment with as best as possible boundary conditions, that is, the results of the reanalysis should be set as a boundary condition for the RCM.

Model evaluation is an essential procedure for the development of RCMs. Within the European domain, evaluation of a large number of regional climate models was carried out within large projects (PRUDENCE, ENSEMBLES). Different parameters are studied, including mean climatological distributions of temperature and precipitation as the two main parameters for studying climate change (Bergant et al., 2007; Böhm et al., 2008; Holtanova et al., 2012; Branković et al., 2013; Jacob et al., 2014; Jaeger et al., 2008; Kotlarski et al., 2005, 2014), temperature trends (Lorenz and Jacob, 2010) and variability (Fischer et al., 2012; Vidale et al., 2007). The next generation of regional climate projections has been realized within the CORDEX initiative (Giorgi et al., 2009). The European part of the CORDEX initiative (EURO-CORDEX; Jacob et al., 2014) prepared regional climate projections for Europe with resolutions of 0.11° and 0.44° including ensembles of regional models forced by various projections of GCMs as well as historical and evaluation simulations.

The Mediterranean area is extremely sensitive to global warming, and due to the complex morphology and socio-economic conditions it is one of the so-called "hot spot" areas for climate change (Giorgi, 2008). Similarly, the Adriatic Sea is sensitive to climate change, and with its complex coastal topography channels regional winds such as the *bura* and *jugo*. With approximately 1,200 islands, the Adriatic is a region with a strong land-sea contrast, land-atmosphere feedback, and intense air-sea interaction. The inflow of 38 major rivers into the Adriatic is a significant component for dynamic and thermodynamic processes and represents one of the main dilution areas for the Mediterranean (Raicich, 1996). Significant differences in bathymetry of shallow northern and deep southern Adriatic, and the inflow of rivers, causes significant differences in seasonal characteristics of air and sea temperatures and has a strong impact on the Adriatic ecosystem (Zavatarelli et al., 2000; Spillman et al., 2007). Orlić et al. (1992) show that the main circulation has a seasonal dependence and consists of a large-scale cyclonic flow with smaller cells inside. Additionally, the connection between the southern Adriatic and the Ionian Sea is extremely complex (Manca et al., 2006; Civitarese et al., 2010) and shows significant seasonal differences (Zavatarelli and Pinardi, 2002). Shaltout and Omstedt (2014) show that sea surface temperature (SST) trends in the Mediterranean are mostly positive and have seasonal properties.

SST and air temperature trends are increasing in the Mediterranean and the Adriatic (Branković et al., 2013; Radilović et al., 2019). This increase results in occurrence increase of the warm temperature anomalies in the ocean which characterize the marine heat waves (MHW). MHW can occur on the sea surface as well as propagate deeper to the water column (Schaeffer and Roughan, 2017; Darmaraki et al., 2019a, 2019b, 2019c). Since, a stable stratification with a shallow mixing layer is present during the summer months, MHWs can be detected by the sea surface temperature. One of the strongest detected MHW occurred in the Mediterranean in the summer of 2003. This MHW episode registered SST anomalies of 2–3°C above climatological mean and lasted for more than 20 days. SST increase was influenced by sea properties, air-sea flux exchanges and wind stress reduction (Grazzini and Viterbo, 2003; Sparnocchia et al., 2006; Olita et al., 2007; Grbec et al., 2007).

Investigating MHWs has recently gained attention, where some studies analyzed past trends of extreme SST (e.g., MacKenzie and Schiedek, 2007; Scannell et al., 2016). Past MHWs have been investigated in coastal regions (Lima and Wethey, 2012; Schaeffer and Roughan, 2017) and global ocean (Oliver et al., 2018a, 2018b). Mediterranean MHWs are being studied for last two decades where Darmaraki et al. (2019b) found an increase in surface MHW intensity and frequency in the basin for current century relative to the past and, described future evolution of MHWs in the Mediterranean Sea (Darmaraki et al. 2019a).

The main goal of this research includes observations, modeling, and evaluation of climate trends of air and sea temperatures for the Adriatic area. Signals of temperature change are used to examine the impact of climate change as well as to assess performance of RCMs in temperature reproduction. Also, it is important to investigate changes in frequency, duration, intensity, and possible causes of past MHWs in the Adriatic as one of the extreme consequences of the global warming and SST increase. This is significant for the 2003 and 2015 MHWs which were investigated from the aspects of air-sea interactions, cloudiness, and wind stress. These MHWs are highlighted as most severe MHW events in the Adriatic Sea and Mediterranean in the last decades.

2. Data and methods

For the purpose of this study, evaluation of eight EURO-CORDEX RCMs were performed using results from the evaluation mode (with ERA-Interim reanalysis forcing) for the 1989–2008 time period and results from the historical mode (with various GCM forcing) for the 1961–2005 period. Also, multi-model ensemble composed of eight EURO-CORDEX RCMs (seven for the historical mode) simulations at a 0.11° evaluation were evaluated. In addition, three high-resolution reanalyses, from the UERRA project, were used in this study: HARMONIE reanalysis from the Swedish Meteorological and Hydrological Institute (SMHI) with the spatial resolution of 11 km; MESCAN-SURFEX model reanalysis from Météo-France with 5.5 km resolution; and the unified model reanalysis (UM) from the UK Met Office with a 12 km resolution. All skill metrics were thus derived from monthly air temperature anomalies for the evaluation and the historical periods, respectively. The UERRA reanalyses were upscaled from the original resolutions to match the resolution of the EURO-CORDEX regional models, which is 12.5 km (0.11°). Since, the UM results do not cover the entire 1961–2005 period it was excluded from the historical period analysis.

Skill assessment of eight RCMs and three different reanalyses in the Adriatic are estimated using the E-OBS surface air temperature data in addition to in-situ station observations measured by Croatian Meteorological and Hydrological Service (DHMZ). Observations consists of daily mean air temperature at 2 meters (T2m) to cover three regions of the Adriatic: islands (Lastovo, Hvar, and Rab), coastline (Dubrovnik, Split, and Rijeka), and inland areas (Sinj, Knin and Pazin). The E-OBS dataset (version v18.0e) interpolates 11 in-situ observations from stations along the eastern Adriatic coast, including six presented in this study (Rijeka, Knin, Split, Hvar, Lastovo, and Dubrovnik). The analyses assessed EURO-CORDEX RCMs performances based on three major comparisons. First, evaluation mode versus historical mode, then, reanalyses versus individual RCM (multi-model ensemble included), and, finally, point observation data versus gridded data (E-OBS). Statistical measures such as bias, root mean square error (RMSE) and differences in trend coefficients were used in the analysis.

To investigate trends in regional SST and detect extreme events such as MHWs, satellite SST data provided by Earth-orbiting satellites are complementary to the in-situ network, providing finer and more complete spatio-temporal sampling. Since, during the summer, the mixed layer is thin and MHW are usually confined close to the surface, SST data of the first layer depth represent surface temperatures relevant for analysis and detection of the MHWs. Analysis and evaluation include satellite data provided by the Copernicus Climate Change Service (C3S) for the period 1982–2018, and ERA5 reanalysis data provided by European Centre for Medium-Range Weather

Forecasts (ECMWF). C3S include L4 data of daily reprocessed SSTs on a 0.05° grid. This data is derived from satellite measurements collected by two series of sensors from the Earth-orbiting satellites: 11 Advanced Very High-Resolution Radiometers (AVHRRs) and three Along-Track Scanning Radiometers (ATSRs). ERA5 provides hourly worldwide estimates by using the 4D-Var assimilation method. Spatial resolution of ERA5 is 0.28°. Data used for analysis are hourly 2-meter air temperature, surface latent heat flux, surface sensible heat flux, total cloud cover, and U and V wind components at 10 m. All these parameters are averaged to construct daily means. For a uniform temperature diagnostic and for every grid point, the 99th quantile of daily SST was computed. Then a 2D threshold map was constructed from 30-year climatological means of these extreme values. An MHW episode at every grid point is assumed at any given day when the local SST 99th quantile threshold is exceeded with minimum duration of 5 days, following Hobday et al. (2016). The analysis includes the frequency, duration and intensity of each MHW event, especially, most prominent episodes of 2003 and 2015. Intensity is characterized by a mean difference of the temperature anomaly relative to the 99th quantile climatological threshold over the event duration. Also, episodes of 2003 and 2015 are additionally analyzed to examine air-sea interactions to potentially see causes of MHWs in the Adriatic Sea. This investigation includes correlation of the SST with parameters like surface latent heat flux, surface sensible heat flux, cloud cover, and wind stress.

3. Results and concluding remarks

The model-to-observation RMSE of the annual T2m averages and trend difference analysis show different behavior of the evaluation and historical results. In the evaluation period, RCMs, better represent variability with RMSE between 0.5 and 1.5°C than in the historical period where variability is much higher (1.75–2.25°C). This is due forcing and boundary condition issues where simulations in the evaluation mode are forced by ERA-Interim reanalysis and historical ones with GCMs. This, also, includes lack of data assimilation in historical simulations. One model, REMO2009, shows high RMSE (>1.3°C) for all stations in the evaluation period. Higher REMO2009 model bias values, compared to the other RCMs, over Adriatic region, suggest possible reason why REMO2009 shows higher RMSE values.

Similar variability of the RCM results prevails among stations. Middle and southern Adriatic stations of Dubrovnik, Lastovo and Hvar exhibits RMSE between 0.6 and 0.8°C. The northern Adriatic stations have higher RMSEs (>1°C) because of complex terrain in the northern part of the Adriatic coast. This agrees with smaller RMSE values (0.6–0.8°C) of the EURO-CORDEX ensemble in the evaluation period. All UERRA reanalyses showed similar RMSE values in both periods (0.25–0.8°C), where slightly smaller RMSEs were present at the southern Adriatic stations (Dubrovnik, Lastovo and Hvar).

Trend differences among RCMs and observations at station locations of the stations are very similar when we compare both time periods. Also, there is a consistency in the sign present in the trend difference at all stations for each RCM. In the historical period, significant underestimation (>0.1°C decade^{-1}) was especially pronounced for the NCCNorESM1-M HIRHAM5 and CNRM-CM5 CCLM4-8-17 RCMs. A general overestimation of T2m trends in all RCMs and reanalyses, is present at station Sinj, which could have been caused by specific microclimates of the valley in which it is located. Although there were no significant differences in the RMSEs among UERRA reanalyses, distinct trend differences exist because different horizontal resolutions and surface models. It is significant to say that historical and evaluation EURO-CORDEX ensembles show improved results by 15–20% compared to individual RCMs for trend difference results.

Spatial comparison of the T2m trend differences between RCMs and E-OBS gridded data show small differences (-0.5–0.5°C decade^{-1}) for all models over the eastern Adriatic coast, while there are larger differences over the western coast and Italy. It can be emphasized that there is no connection between the land sea fractions and orography in RCMs with patterns of T2m differences in both periods. It is important that uncertainty, of simulated T2m, is determined by the density of stations, and the large amount of station data for the whole eastern Adriatic coast hinders easy model comparisons. All RCMs forced with the same global model, in the historical period, are strongly influenced by the same boundary conditions and show similar patterns.

Investigating summer SST of the Adriatic, during 1982–2018 period, western part is warmer than the eastern part by 2°C on average. In the Adriatic Sea, a NE-SW pattern of cold-warm temperatures is present during summer season (range from 22–25°C). This western-eastern difference in summer SST is around 3°C, where highest SST is observed in the shallow northern Adriatic. There is a warming tendency of mean annual SST and extremes (99^{th} quantile). Both, reanalysis (ERA5) and satellite data (C3S-L4) show that the extreme trends of SST99Q are higher than trends of mean annual values by about 0.02°C $year^{-1}$ and are most pronounced in the south Adriatic. Comparing the Ionian and Adriatic Seas, it is shown that Ionian Sea is warmer than Adriatic by 0.5°C although they have similar trends. There is a significant effect of T2m on the SST in the Adriatic by analyzing air-sea interaction. This is highly correlated with the Ionian Sea SST (correlation coefficient $R = 0.92$). High correlation suggests that local variability of SST is controlled by air-sea fluxes and local ocean processes.

Analysis of the MHW events in the Adriatic shows that average duration of the episodes is about 6–7 days in the 1982–2018 period. Result is obtained from both the reanalysis and satellite data. Also, 2003 and 2015 are detected as years with most pronounced MHWs in the last few decades. The 2015 episode is concentrated in the middle and southern Adriatic and connected with the Ionian Sea where average duration is higher than 20 days. In contrast, the 2003 episode was localized in the northern and middle Adriatic and appears to be decoupled from the Ionian Sea. The mean intensity of the MHW episodes for this 36-year period is 0.04°C above SST99Q threshold. This is lower in comparison with the 2003 and 2015 events where mean intensities are 0.3°C and 0.4°C, on average.

Closely investigating causes and the effects of 2003 and 2015 episodes it appears that 2003 episode is more related by the surface sensible heat flux (correlation coefficient 0.2–0.5) which can signify that colder air advection increases surface sensible heat flux while the 2015 episode is more related to surface latent heat flux which is positively correlated with SST (0.2–0.5) and can indicate possible existence of drier air advection over the Adriatic that summer. In 2003, negative correlation (between -0.4 and -0.1) in the Adriatic implicates that weaker winds over the warm water regions can reduce the latent heat flux and increase the SST preventing formation of deep convective clouds (correlation -0.3 and -0.5). Generally, analyzing occurrence frequency of MHW episodes of different duration (5-days, 10-days, 15-days, and 20-days), only 5 and 10-day episodes have noticeable increase of 0.1 event per decade. Statistical significance (95%) of all frequency occurrences is confirmed by Mann-Kendal test.

Increasing climate change requires investigation of capabilities of regional climate models to predict MHW events in terminal seas such as the Adriatic. Additionally, assessing of how regional climate model parametrizations, including land surface processes, soil hydrology, and land-sea fraction specifics, impact variability in coastal regions. This is, also, important for the identification of regions with high physical predisposition for these extreme events because of MHW influence on the various ecosystems.

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