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Simulated and observed air temperature trends in the eastern Adriatic

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Abstract

Climate predictions of air temperature in coastal regions represent a great challenge due to the complex interactions among the atmosphere, sea, and land. With approximately 1,200 islands, the Adriatic is a region with a strong land-sea contrast, land-atmosphere feedback, and intense air-sea interaction. Because the Mediterranean has been regarded as a “hot spot” for climate change, regional climate models can be used to provide insight into a more realistic representation of small-scale weather and climate structure and variability. This advantage is due to the better representation of complex topography, developed coastlines, and land-sea contrasts, which are important for investigating air temperature trends. The use of regional climate models together with high-resolution reanalyses and observations in assessments of climate variability and climate change is highly valuable for understanding climate processes at regional scales. The present study focused on air temperature and its trends calculated from measurements and simulated by eight regional climate models from the EURO-CORDEX database; these data were represented by UERRA reanalyses and E-OBS gridded data. In the evaluation period (1989–2008), the models' RMSEs were fairly small, in the range 0.5–1.5°C, compared to the historical period (1961–2005), with RMSEs greater than 1.75°C. However, the models showed small absolute trend differences (up to 0.12°C-decade⁻¹ for the historical period). The ensemble means in both periods showed an accuracy improvement of 15–20% compared to the individual models. The models exhibited more success in terms of representing the main statistics and variability of the air temperature structure than in reproducing the temperature trends over 45 years, especially in the northern Adriatic, where there is complex coastal topography and significant seasonal variability in the wind regime. The reanalyses well represented temperature structure but showed less success in explaining the temperature trends than the results from the measured data.

KEYWORDS

Adriatic Sea, coastal climate trends, ensembles, E-OBS, EURO-CORDEX, UERRA

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1 | INTRODUCTION

In recent decades, public awareness of climate change and the scientific efforts coordinated by the Intergovernmental Panel on Climate Change (IPCC) have facilitated the rapid development and applications of global climate models (GCMs). However, GCMs, which have coarse spatial resolutions, have been proven insufficient for evaluating mesoscale processes (Christensen *et al.*, 2007; Branković *et al.*, 2013).

Improvements in dynamical downscaling techniques (Hewitson and Crane, 1996; Giorgi and Mearns, 1999; Giorgi, 2008; Wilby and Fowler, 2011; Branković *et al.*, 2012) have been pivotal to the development of regional climate models (RCMs) nested into GCM grids (McGregor, 1997; Wang *et al.*, 2004; Giorgi, 2006; Laprise, 2008). Based on model-to-observation comparisons (e.g., Moberg and Jones, 2004; Kjellström *et al.*, 2007; Kotroni *et al.*, 2008; Rivington *et al.*, 2008; Branković *et al.*, 2013), the use of high-resolution RCMs was found to largely improve the representation of small-scale weather and climate parameters and their variability, while better resolving complex topography, coastline, and land-sea contrasts (Kotlarski *et al.*, 2014).

Since 2009, the coordinated regional climate downscaling experiment initiative (CORDEX; Giorgi *et al.*, 2009) has been coordinating the production of climate change projections at regional scales. Furthermore, EURO-CORDEX (the European domain of CORDEX initiative) has been developing ensembles of climate simulations based on RCMs of approximately a 12 km (0.11°) resolution, where forcing is applied from the GCMs with resolutions between approximately 0.8° and 2°.

In addition, due to the growing need for higher quality reanalysis products, the uncertainties in ensemble of regional reanalysis (UERRA; coordinated by the European Centre for Medium-range Weather Forecasts) project has been creating ensembles of European regional meteorological reanalyses of essential climate variables for 50 years. To better represent variabilities and trends, as well as to be able to estimate the associated uncertainties in the reanalysis, the UERRA project strategy includes the use of consistent data (it includes observations from satellites and ground-based stations and results from models that comprise a consistent dataset describing the state and historical evolution of the climate) in time and an increased horizontal resolution (at least 12 km and down to 5.5 km) in regional models.

The Croatian coastal region, which is an orographically developed zone, is located in the eastern Adriatic, where weather and climate patterns are largely influenced by the complex topography and land-sea

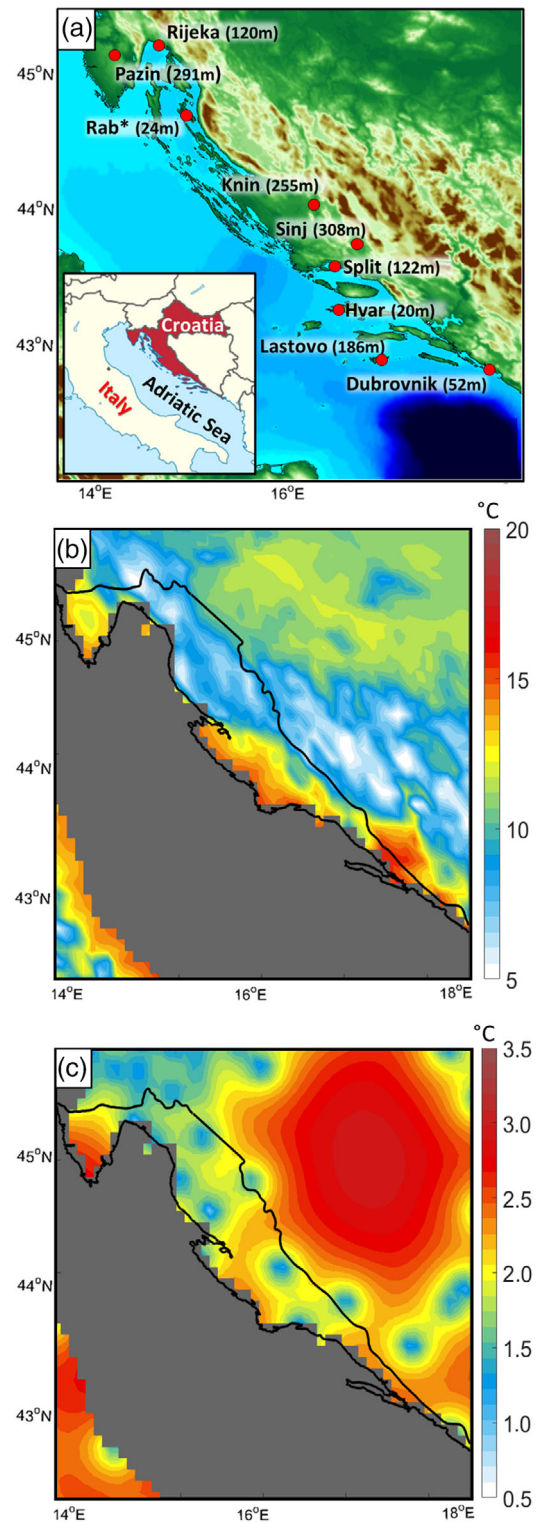


FIGURE 1 Selected stations located along the Croatian coastline (a); E-OBS mean surface air temperature averaged between 1961 and 2008 (b); and E-OBS surface air temperature range among ensemble members of the E-OBS results over the 1961–2008 period (c)

contrasts (Figure 1). High-resolution regional models show strong spatial coherence for air temperature (Branković *et al.*, 2013). Branković *et al.* (2012) found

that a 35-km resolution regional model could not reproduce the observed spatial variations in seasonally averaged temperature extremes for regions with complex orography, while Önoğlu (2012) showed that 10 km resolution results compared well with observations from a region with complex topography in Turkey. In addition, the maximum temperatures in the central and eastern Mediterranean region have been found to be overestimated by RCMs even if station data in coastal areas are compared with nearest-model grid points on land instead of grid boxes located on the coastline (Moberg and Jones, 2004).

Branković *et al.* (2013) investigated air temperature and total precipitation using regional model results with a 25 km spatial resolution from the previously conducted ENSEMBLES project. As a complementary effort, this study will uniquely investigate the skill of the latest available results from the regional climate models with the 12.5 km horizontal resolution to examine how well the models can reproduce temperature trends and the temporal and spatial variabilities of the air temperature over the eastern Adriatic region. Additionally, two types of ensembles of RCM simulations will be applied here: historical mode simulations with boundary conditions from various GCMs (1961–2005) and evaluation mode simulations forced by the ERA-Interim reanalysis data (1989–2008). The ERA-Interim reanalysis data have a higher spatial resolution and improved model physics than the previous ERA-40 reanalysis data used in the ENSEMBLES project (see, e.g., Branković *et al.*, 2013). The RCMs are compared with station measurements (divided into three different zones/belts [sea, coastline land, and hinterland] covering the eastern Adriatic region) to investigate the influence of coastal topography and land-sea contrasts on air temperature structure and trends.

As a complement to previous studies, regional climate models are spatially and temporally compared with gridded E-OBS data [European gridded observational datasets (Haylock *et al.*, 2008); coordinated by the Royal Netherlands Meteorological Institute]. It should be noted that the E-OBS results are gridded data over only land and use measurements to obtain spatial data fields. A new aspect of this study is the use of three new high-resolution UERRA reanalysis products in the evaluation of regional climate models from the EURO-CORDEX project archives. The three types of UERRA reanalyses (HARMONIE reanalysis [Van der Linden and Mitchell, 2009; Ridal *et al.*, 2017], MESCAN model [Bazile *et al.*, 2017], and unified model reanalysis [Renshaw *et al.*, 2013; Davis *et al.*, 2005]) use mesoscale models and data assimilation to provide gridded reanalysis results.

2 | DATA AND METHODS

2.1 | Observations and models

The in situ observations used in this study consist of daily mean air temperature at a height of 2 m (T2 m) measured by the Croatian Meteorological and Hydrological Service (DHMZ). Since Kotroni *et al.* (2008) argued that point measurements can be used in evaluation studies, nine stations were selected from the DHMZ network (Figure 1). The stations with a Köppen climate classification for each of these regions were chosen along the Croatian coastline to include (a) islands (Lastovo, Hvar, and Rab) and coastal areas (Rijeka, Split, and Dubrovnik) with a Mediterranean climate with mild winters and hot summers and (b) inland areas (Knin and Sinj) with a Mediterranean climate with continental influence (colder winters and hotter summers). In addition, a station located in the hinterland of the northern Adriatic coast (Pazin) plays an important role in the northern Adriatic climate because it is characterized by complex topography and proximity to the sea.

To estimate the skill assessment of eight regional models along the Croatian coastal area, E-OBS v18.0e (gridded dataset at 0.1° resolution) surface air temperature data were used in this study in addition to station data. As trends are crucial in climate studies, this evaluation focused on how both reanalyses and RCMs performed in reproducing the observed surface temperature trends along the Croatian coastline. Along the eastern Adriatic coast, the E-OBS dataset assimilates 11 in situ stations, including six (Rijeka, Knin, Split, Hvar, Lastovo, and Dubrovnik) presented in this study. The mean (“best-guess” field) and spread (difference between 5th and 95th percentiles) of the surface air temperature was extracted from the E-OBS ensembles and averaged over the 1961–2008 period, and the results are presented in Figure 1b,c.

The ability of regional models to reproduce the observed T2 m variations along the Croatian coast was assessed for three different reanalyses and eight different climate models. As part of the UERRA project, three high-resolution reanalyses are available in Europe and were used in this study: (a) the 11 km resolution HARMONIE reanalysis from the Swedish Meteorological and Hydrological Institute (SMHI); (b) the 5.5 km resolution MESCAN model reanalysis from Météo-France; and (c) the 12 km resolution unified model reanalysis (UM) from the UK Met Office.

For the climate models, the evaluation was performed for eight EURO-CORDEX RCMs (Giorgi *et al.*, 2009; Jacob *et al.*, 2014; Kotlarski *et al.*, 2014) using (a) an evaluation mode (with ERA-Interim reanalysis forcing) for

TABLE 1 Description of EURO-CORDEX climate models, including physics parameterization and GCM forcing in the historical mode

RCM	GCM	Reference	Institute	Land surface	Rad.	Conv.	MP	PBL
CCLM4	CNRM-CM5, MPI-ESM-LR	Bucchignani <i>et al.</i> (2015)	CLMcom	Doms <i>et al.</i> (2011)	Ritter and Geleyn (1992)	Tiedtke (1989)	Doms <i>et al.</i> (2011), Baldauf and Schulz (2004)	Louis (1979)
ALADIN53	CNRM-CM5	Colin <i>et al.</i> (2010)	CNRM	Colin <i>et al.</i> (2010)	Colin <i>et al.</i> (2010)	Colin <i>et al.</i> (2010)	Colin <i>et al.</i> (2010)	Colin <i>et al.</i> (2010)
RegCM4 ^a	/	Giorgi <i>et al.</i> (2012)	DHMZ	Gao <i>et al.</i> (2016)	Kiehl <i>et al.</i> (1996)	Grell (1993)	Pal <i>et al.</i> (2000)	Holtlag <i>et al.</i> (1990)
HIRHAM5	NCC-NorESM1-M	Lucas-Picher <i>et al.</i> (2012)	DMI	Roeckner <i>et al.</i> (1996)	Morcrette <i>et al.</i> (1986) Giorgetta and Wild (1995)	Tiedtke (1989)	Lohmann and Roeckner <i>et al.</i> (1996)	Louis (1979)
WRF331F	IPSL-CM5A-MR	Skamarock <i>et al.</i> (2008)	IPSL	Ek <i>et al.</i> (2003)	Iacono <i>et al.</i> (2008)	Grell and Dévényi (2002)	Hong <i>et al.</i> (2004)	Hong <i>et al.</i> (2006)
RACMO22E	ICHEC-EC-EARTH	Van Meijgaard <i>et al.</i> (2008)	KNMI	Van den Hurk <i>et al.</i> (2000)	Fouquart and Bonnel (1980), Mlawer <i>et al.</i> (1997)	Tiedtke (1989), Nordeng (1994), Neggers <i>et al.</i> (2009)	Tiedtke (1993), Neggers <i>et al.</i> (2009)	Lenderink and Holtlag (2004) Siebesma (2007)
REMO2009	MPI-ESM-LR	Jacob and Podzun (1997)	MPI-CSC	Dickinson <i>et al.</i> (1993)	Morcrette <i>et al.</i> (1986) Giorgetta and Wild (1995)	Tiedtke (1989), Nordeng (1994), Pfeifer (2006)	Lohmann and Roeckner (1996)	Louis (1979)
RCA4 ^a	/	Kjellström <i>et al.</i> (2016)	SMHI	Samuelsson <i>et al.</i> (2006)	Savijärvi (1990), Sass <i>et al.</i> (1994)	Kain and Fritsch, 1993	Rasch and Kristjánsson (1998)	Cuxart <i>et al.</i> (2000)

Note: Schemes from left to right: Land surface, radiation, convection, microphysics and planetary boundary layer.

^aOnly used in the evaluation mode.

the 1989–2008 period and (b) a historical mode (with various GCM forcing) for the 1961–2005 period. The descriptions of the RCMs used in this study, including their physics parameterizations, are presented in Table 1.

2.2 | Model skill metrics

With the aim of better understanding how well the available atmospheric regional models reproduced the T2 m along the Croatian coastal area, the analyses assessed their performances based on three major comparisons: (a) evaluation mode vs. historical mode; (b) reanalyses versus RCMs; and (c) point observation data vs. gridded product (i.e., E-OBS).

In practice, the monthly T2 m anomalies were calculated—for each model and reanalysis as well as for station measurements and E-OBS data—by removing an annual cycle of the time series for both the evaluation (1989–2008) and the historical (1961–2005) periods. All skill metrics calculated in this study were thus derived from 240 and 540 monthly T2 m anomalies for the evaluation and the historical periods, respectively. The EURO-CORDEX ensembles were derived by averaging the T2 m anomalies from the selected RCMs (eight for the evaluation period and seven for the historical period). To compare the model and ensemble results with the Croatian station measurements, the T2 m data were extracted from the grid cells that were nearest to the nine station locations, including island and coastal regions. The spatial resolutions of the high-resolution UERRA reanalyses and EOBS data were downgraded from the original resolutions (HARMONIE 11 km, MESCAN 5.5 km, and UM 12 km) to match the resolution of the EURO-CORDEX regional models, which is 12.5 km. Additionally, as the UM results do not cover the entire 1961–2005 period, they were excluded from the historical period analysis. Finally, a bias analysis against the E-OBS data (not shown) revealed that all RCMs were similarly bias-corrected for the evaluation period, except for the REMO2009 model, which showed higher bias values over the Adriatic region. Bias corrections are performed by the institutions who provided the model results. All analyses were performed for each model (RCM and reanalysis) as well as for the EURO-CORDEX ensembles during both the evaluation (1989–2008) and the historical (1961–2005) periods.

In the text, the expressions “evaluation” and “historical” periods are used. In the evaluation mode (1989–2008), regional climate models were forced by initial and boundary conditions from the ERA-Interim reanalysis data. ERA-Interim is a global reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts. In historical mode (1961–2005), regional climate models use

initial and boundary conditions from GCMs. Hereafter, the terms evaluation and historical mode periods indicate the span of time and the type of initial and boundary conditions used for the regional climate models.

The skill metrics used in this study consist of the following:

3 | T2 M ROOT MEAN SQUARE ERROR

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2};$$

where $\{M_i\}_{i=1}^N$ and $\{O_i\}_{i=1}^N$ are the ensembles of N values extracted from the atmospheric models and the observations, respectively;

1. T2 m trend differences (such as $\alpha_M - \alpha_O$ with the model and observation linear temperature trend defined at each observation point as $T_M(t) = \alpha_M t + \beta_M$ and $T_O(t) = \alpha_O t + \beta_O$, respectively; where α_M and α_O are trend coefficients from the models and observations);
2. Mean T2 m RMSE vs. mean absolute trend difference analysis with the mean calculated from the results extracted (a) at the nine stations and (b) from 161 cells of the model grids taken along the Croatian coast (Figure 1).

4 | RESULTS

The model-to-observation RMSE of the annual T2 m averages and trend difference analysis performed at the locations of the stations for the RCMs is presented in Figure 2 in the form of a series of RMSEs and differences in trend between model results and observations. The RMSE results for the RCMs were very different between the historical and evaluation periods (Figure 2). Generally, the RCMs in the evaluation period better represented the variability (RMSE of 0.5–1.5°C). This result was because the RCMs were forced by the reanalysis, while in the historical period, the variability was much higher (RMSE between 1.75 and 2.25°C) due to the effects of different global models forcing the boundary conditions and the lack of included data assimilation. Only REMO2009 showed higher RMSE values for all stations in the evaluation period (>1.3°C); one possible reason for this result is the higher bias values over the Adriatic region than those

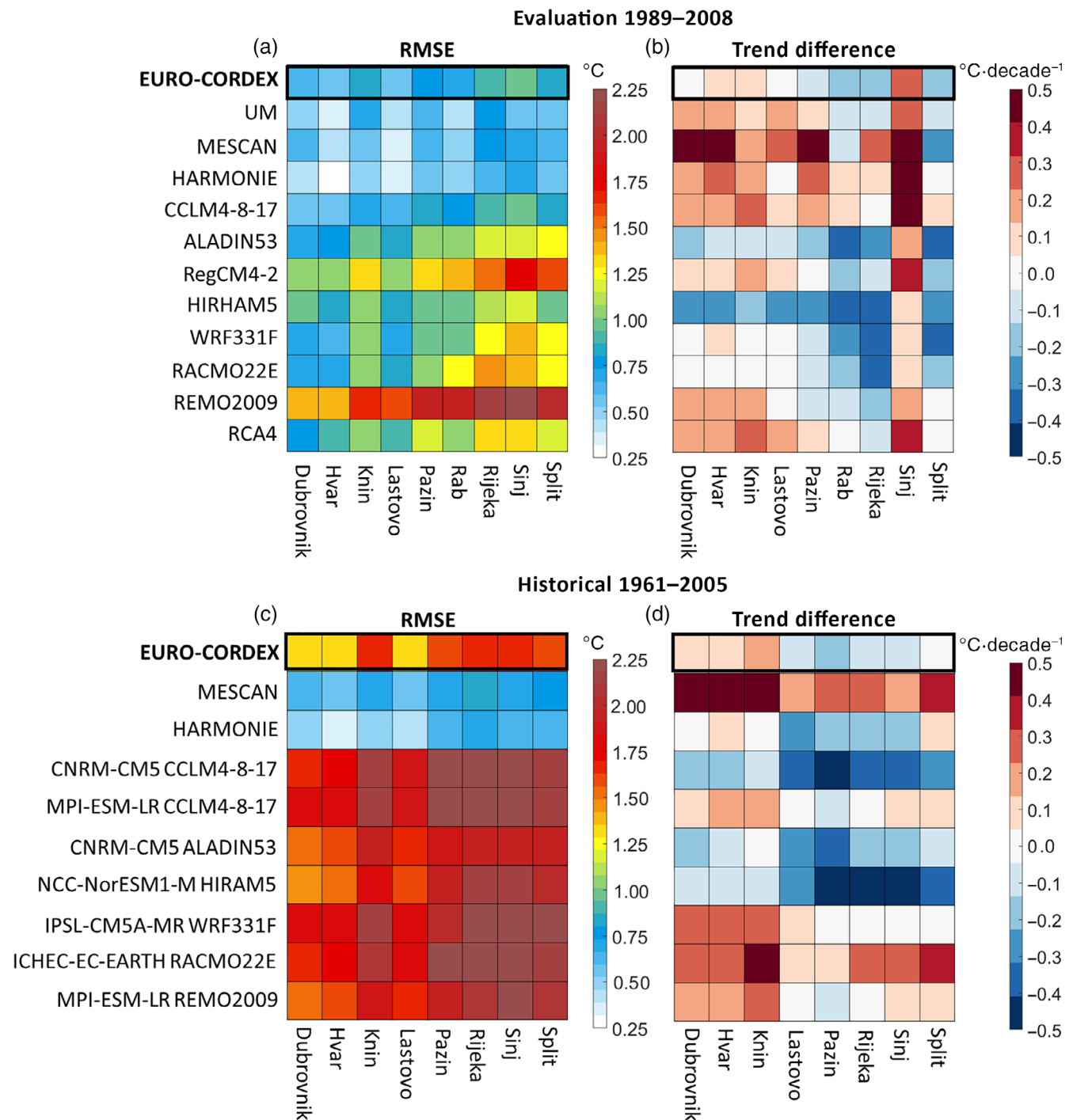


FIGURE 2 The T2 m (air temperature at a height of 2 m) model results for the RMSE [(a) and (c)] and trend difference [(b) and (d)] at each station for both the evaluation (1989–2008) (top row) and the historical (1961–2005) periods (bottom row)

in the other models. There was a small difference in the variability of the RCM results among stations. While the middle and southern stations of Hvar, Lastovo, and Dubrovnik showed small RMSEs ($0.6\text{--}0.8^{\circ}\text{C}$), the northern stations had RMSEs higher than 1°C , which may have been caused by the complex terrain in the northern and middle parts of the eastern Adriatic coast. According to the previous results and based on the

influence of using the ERA-Interim reanalysis data for the boundary conditions, the EURO-CORDEX ensembles showed smaller RMSE values ($0.6\text{--}0.8^{\circ}\text{C}$) in the evaluation than in the historical period ($>1.25^{\circ}\text{C}$). The UERRA reanalyses showed similar RMSE values in both periods ($0.25\text{--}0.8^{\circ}\text{C}$), where slightly smaller RMSEs were present at the southern stations of Hvar, Lastovo, and Dubrovnik.

There was no significant distinction in trend differences among RCMs and observations at stations when both periods were compared (Figure 2). There was also consistency in the sign present in the trend difference at all stations for each RCM. In the historical period, this characteristic was especially pronounced for the NCC-NorESM1-M HIRHAM5 and CNRM-CM5 CCLM4-8-17 models, where pronounced trend underestimations ($>0.1^{\circ}\text{C}\cdot\text{decade}^{-1}$) were present; in contrast, ICHEC-EC-EARTH RACMO22E showed significant overestimations of the T2 m trends ($>0.3^{\circ}\text{C}\cdot\text{decade}^{-1}$). Station Sinj, which is located in a valley, showed a general overestimation of T2 m trends in all models and reanalyses, which could have been caused by specific microclimates. The EURO-CORDEX ensembles showed similar trend differences in both periods. Although there were no significant differences in the RMSEs among UERRA reanalyses, exist distinct trend differences. MESCAN showed the largest

trend differences with the observations relative to the results using other UERRA reanalyses. Because reanalyses have different horizontal resolutions and different surface models, this result calls for more research and additional comparisons of the reanalyses in the future.

Figure 3 shows the average RMSEs for each RCM versus trend difference using the data from the network stations (Figure 3a) and the E-OBS gridded data (Figure 3b). The results for the RCMs in each period are grouped into clusters and separated into two groups. The historical period cluster has higher RMSEs ($1.5\text{--}2.1^{\circ}\text{C}$) and smaller absolute trend differences ($0^{\circ}\text{C}\cdot\text{decade}^{-1}\text{--}0.12^{\circ}\text{C}\cdot\text{decade}^{-1}$), while ICHEC-EC-EARTH RACMO22E is an outlier with an absolute trend difference of $0.17^{\circ}\text{C}\cdot\text{decade}^{-1}$. For the evaluation period cluster, there are two outliers (REMO2009 with an RMSE of 1.81°C and HIRHAM5 with an absolute trend difference of $0.27^{\circ}\text{C}\cdot\text{decade}^{-1}$). Both

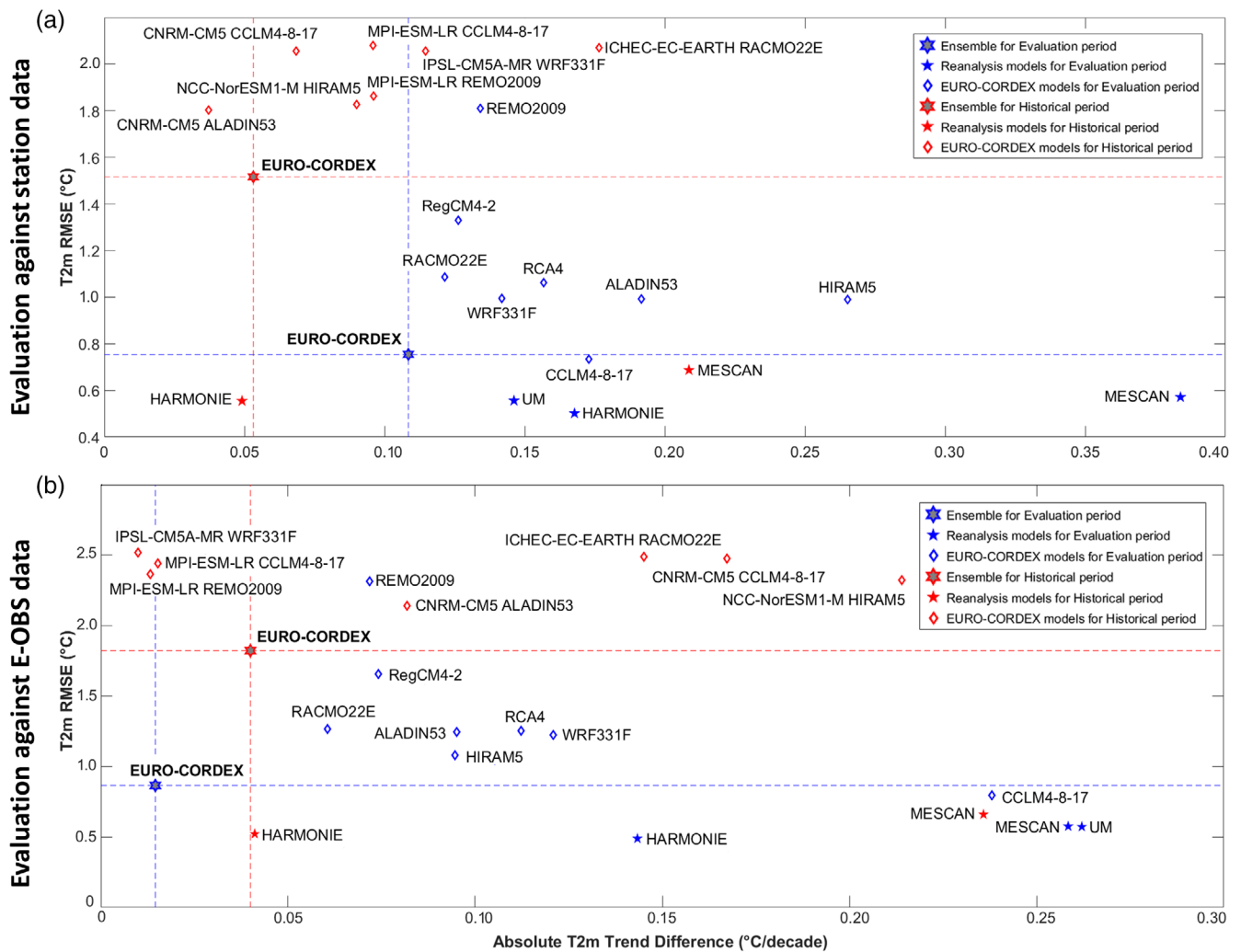


FIGURE 3 Ranking of the T2 m (air temperature at a height of 2 m) model results in terms of the RMSE and the absolute trend difference against station data (a) and E-OBS data (b) along the Croatian coastal area for both the evaluation (1989–2008) and the historical (1961–2005) periods

EURO-CORDEX ensembles show improved results compared to individual RCMs. As expected, the UERRA reanalyses show the smallest RMSE spread ($0.4\text{--}0.7^\circ\text{C}$) in both periods but a large spread in absolute trend differences ($0.05\text{--}0.38^\circ\text{C}\cdot\text{decade}^{-1}$), although a longer (historical) period results in smaller absolute trend differences. This result is due to the data assimilation process, where reanalyses results are closer to the observations based on the station locations; thus, the variability is small. However, because (in the evaluation period) there is a small number of values for comparison (only 20), the trend difference is larger. In Figure 3b, the coastal points of all 161 models are considered, forming a “coastal belt.” A comparison of models with the E-OBS data for the whole coastal belt showed similar results, but both EURO-CORDEX ensembles and UERRA reanalyses had smaller RMSEs and similar trend differences as those of the RCMs. In the evaluation cluster, REMO2009 is an outlier with an RMSE of 2.3°C , while CCLM4-8-17 is an outlier with an absolute trend difference of $0.24^\circ\text{C}\cdot\text{decade}^{-1}$.

A spatial distribution of the RMSEs for the Adriatic (Figures 4 and 5) shows the same behaviour as the RMSEs from station comparison analysis (Figure 2). All UERRA reanalyses exhibit small RMSEs over the eastern Adriatic coast ($0.25\text{--}1^\circ\text{C}$). The results are similar for both periods, which provides definite evidence that variability does not differ with the length of the observed period. The majority of RCMs had RMSEs between 1 and 1.75°C for the evaluation period, except for the high variability observed for two RCMs, RegCM4-2 ($1.25\text{--}1.9^\circ\text{C}$) and REMO2009 ($1.5\text{--}2.25^\circ\text{C}$). These models are the same two RCMs, which also show high variability with the station

comparison (Figure 2a). For the historical period, the situation was different. All RCMs under the influence of global models (even RCMs driven by the same global model) had high RMSE values ($>1.75^\circ\text{C}$). Boundary conditions can create differences in the RMSEs at the station locations (Figure 2) and spatially in the eastern Adriatic (Figures 4 and 5). These differences in the RMSEs between periods are shown for the ensembles. The evaluation period ensemble had a smaller RMSE (0.75°C in the coastal area of the eastern Adriatic to 1°C in the inland) than that of the historical period ensemble (RMSE is 1.5°C in the coastal area of the eastern Adriatic to 2°C in the inland). This result signifies a general improvement in the model results for T2 m by switching from GCM forcing in the historical period to reanalysis forcing (by assimilation of observational data) in the evaluation period. This improvement is between 15–20%. Higher RMSE values were found in the central part of the eastern Adriatic coast, where the majority of mountain ranges are located and the orography is very steep; thus, differences in the temperature values between models and observations were higher.

A comparison of the RCM T2 m trend differences with the E-OBS gridded data shows that all models have differences between -0.5 and $0.5^\circ\text{C}\cdot\text{decade}^{-1}$ over the eastern part of the Adriatic coast, while there are larger differences over the western part and Italy (Figures 6 and 7). There is no connection between the models' land sea fractions and orography with patterns of T2 m differences in both the historical and the evaluation periods. For example, there was a consistent pattern of trend overestimation by the RCMs over the middle Adriatic coast,

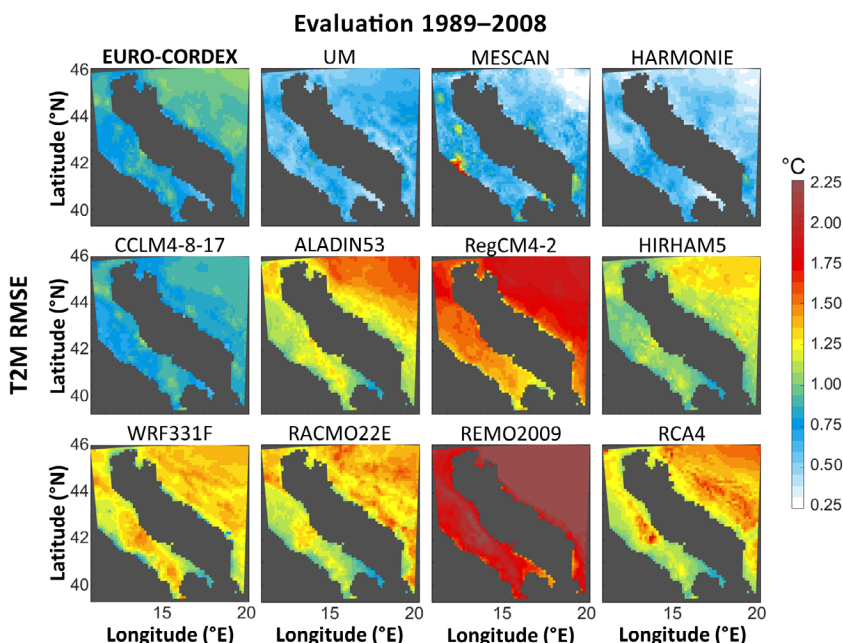


FIGURE 4 The T2 m (air temperature at a height of 2 m) model results for the spatial RMSE for the Adriatic region for the evaluation (1989–2008) period

FIGURE 5 The T2 m (air temperature at a height of 2 m) model results for the spatial RMSE for the Adriatic region for the historical (1961–2005) period

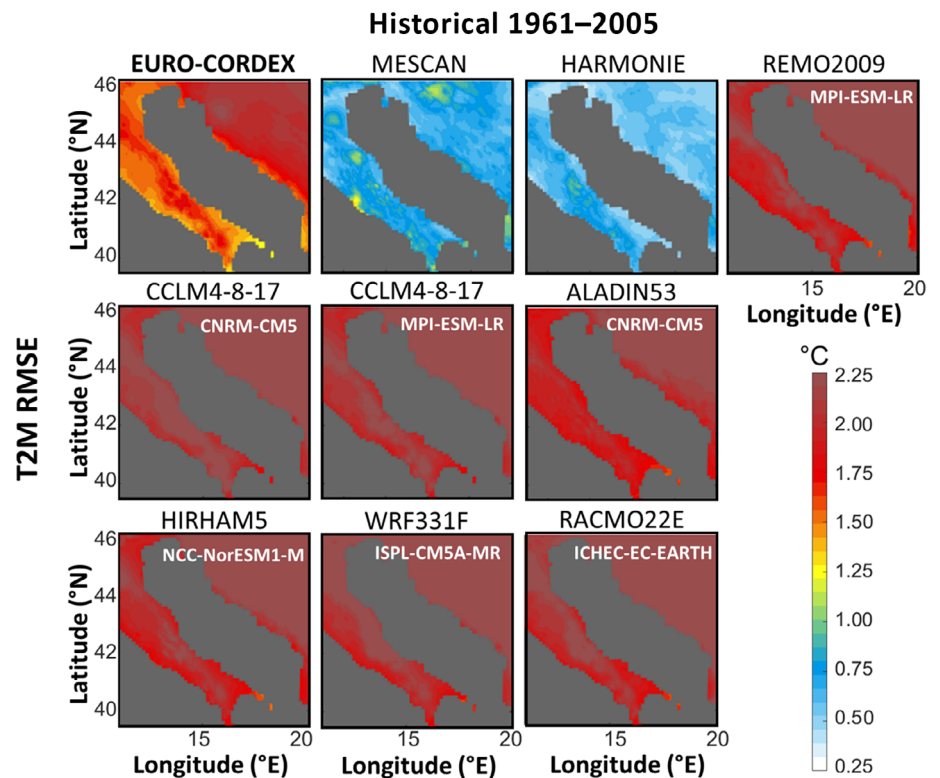
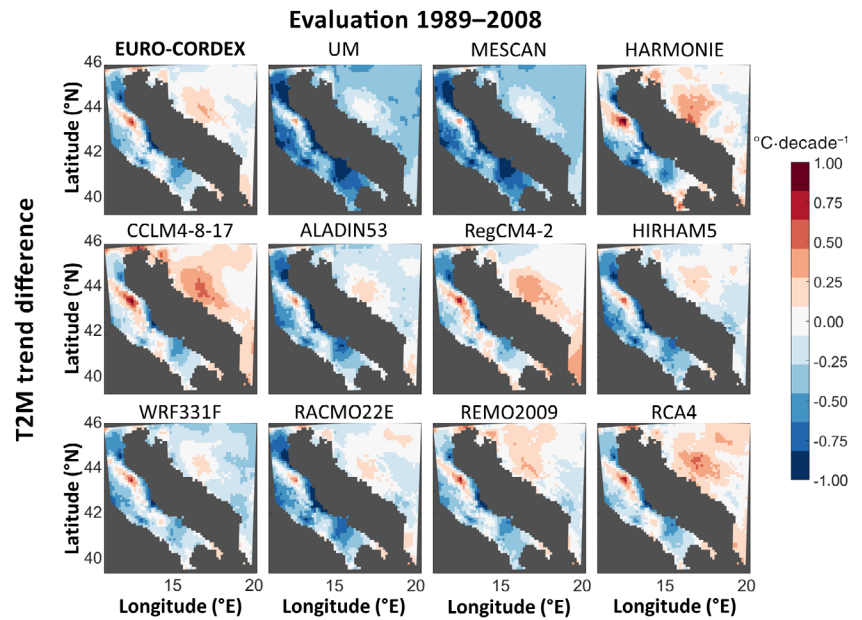


FIGURE 6 The T2 m (air temperature at a height of 2 m) model results for the spatial trend difference for the Adriatic region for the evaluation (1989–2008) period

but the land sea fraction and orography difference did not differ drastically from the E-OBS settings (not shown). The simulated temperature uncertainty is ultimately determined by the density of stations, and the large amount of station data for the whole eastern Adriatic coast hinders easy model comparisons. Two of the UERRA reanalyses, MESCAN and UM, show general spatial underestimations of the E-OBS temperature trends in the evaluation period, while the RCMs and

EURO-CORDEX ensemble agree more with the HARMONIE, with no significant trend differences in the northern and southern parts of the eastern Adriatic coast. It is interesting to note that although RegCM4-2 and REMO2009 show significantly different behaviour in terms of RMSEs than those of other RCMs for the evaluation period, they behave similarly to other models in terms of trend differences. For the historical period, all RCMs and reanalyses show even smaller differences.

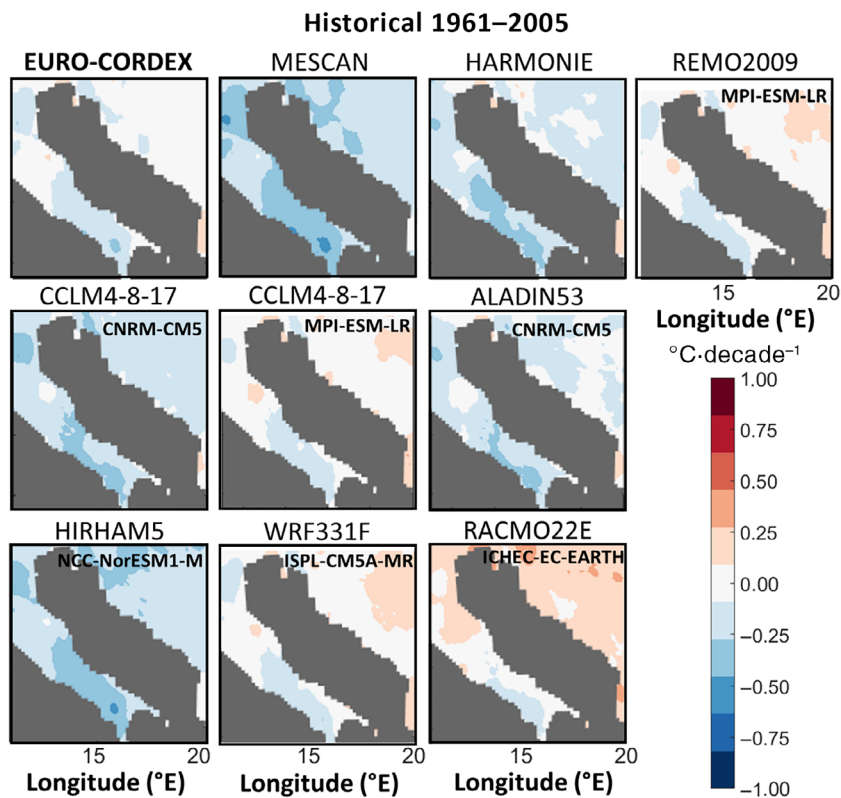


FIGURE 7 The T2 m (air temperature at a height of 2 m) model results for the spatial trend difference for the Adriatic region for the historical (1961–2005) period

Models forced with the same global model are strongly influenced by the same boundary conditions and show similar patterns (e.g., CCLM4-8-17 and REMO2009 with the MPI-ESM-LR global model; CCLM4-8-17 and ALADIN53 with the CNRM-CM5 global model). The EURO-CORDEX ensemble in the historical period shows small trend differences (-0.1 – $0.1^{\circ}\text{C}\cdot\text{decade}^{-1}$). There is no significant distinction in the trend differences for the RCMs and UERRA reanalyses between the historical and evaluation periods, although there is significant difference in the variability in the historical period for RCMs due to forcing by different global models (Figures 2c and 5).

5 | CONCLUSIONS

Air temperature variability and trends in the eastern Adriatic were investigated using Croatian national observation data, E-OBS gridded data, ERA-Interim reanalysis, three UERRA reanalyses, and a set of eight EURO-CORDEX regional climate models. When forced by the reanalysis in the evaluation period (1989–2008), the RCMs were able to reproduce air temperature patterns with sufficient accuracy (the RMSEs were from 0.8 to 1.5°C). However, when they were forced by the GCMs in the historical period (1961–2005), their RMSEs were greater than 1.75°C . The GCM forcing appears to have a

dominant impact because the different RCMs with the same GCM forcing show similar patterns and accuracy. In spite of some outliers (REMO2009, CCLM4-8-17), the ensemble means in both periods exhibit 15–20% improvement over individual models. The UERRA reanalyses follow closely observed patterns of air temperature in the evaluation and historical periods.

Identifying air temperature trends was much more difficult than representing air temperature structure using the models and reanalyses. For the historical period, the measured air temperature trend differences for eight stations were in the range of $0.12^{\circ}\text{C}\cdot\text{decade}^{-1}$. The trend differences for the HARMONIE reanalysis provide the best results and cover almost the same range. All RCM results are in a wider range of $0.37^{\circ}\text{C}\cdot\text{decade}^{-1}$, while the range of the ensemble means is in the upper part of the measured trends (trend difference of $0.02^{\circ}\text{C}\cdot\text{decade}^{-1}$). The model exhibits worse accuracy for the northern stations due to the strong seasonal variability in the wind regime and the shallower waters than those in the southern part (Orlić *et al.*, 1992). This result is due to shallow bathymetry, which causes faster heating and cooling of the sea surface and thus produces higher differences in the air temperature. The significant overestimation of trends by MESCAN requires further evaluation studies.

Scatterplots (Figure 3) of the trend differences versus RMSEs for station data and gridded E-OBS data show separate clusters of RCMs for the historical and

evaluation periods. The UERRA reanalyses show the smallest variability but have similar trend differences as the RCMs (both compared to the station data and E-OBS results in Figure 3). A spatial comparison of the trends between the reanalyses and E-OBS gridded data shows occasionally wider areas of increased or decreased differences (Figures 6 and 7). The differences can be caused by a lack of measurement locations in the eastern Adriatic and the Balkans in general as well as by differences in basic models and data assimilation Schemes. A successful comparison between measurements and reanalyses can also be hindered by measurement errors and micro-location specifics. In conclusion, there is a strong case for creating two classes of reanalyses: one that retains long-term fidelity and one that gives the best instantaneous field estimate because one type of reanalysis generally cannot satisfy different purposes. This conclusion was also previously argued by Thorne and Vose (2010).

Future work will include further evaluations of various aspects of reanalyses with respect to spatial and temporal characteristics and will examine reasons for the differences among the reanalyses (differences in resolution and driving surface models). Possible topics of future work include assessing how regional climate model parametrizations, including land surface processes, soil hydrology, and land-sea fraction specifics, impact variability in coastal regions.

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