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
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 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 Önlö (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
| RCM     | GCM          | Reference                      | Institute Land surface | Rad. | Conv. | MP      | PBL               |
|---------|--------------|--------------------------------|-------------------------|------|-------|---------|-------------------|
| CCLM4   | CNRM-CM5,   | Buechignani et al. (2015)      |                          |      |       |         |                  |
|         | MPF-ESM-5L  |                                |                          |      |       |         |                  |
| ALADIN53| CNRM-CM5     | Colin et al. (2010)            |                          |      |       |         |                  |
|         |               | CLMcom Doms et al.             |                          |      |       |         |                  |
|         |               |                                |                          |      |       |         |                  |
| RCA4    | CNRM-CM5     | Colin et al. (2010)            |                          |      |       |         |                  |
|         |               | CLMcom Doms et al.             |                          |      |       |         |                  |
|         |               |                                |                          |      |       |         |                  |
| HIRHAM5 | CNRM-CM5     | Colin et al. (2010)            |                          |      |       |         |                  |
|         |               | CLMcom Doms et al.             |                          |      |       |         |                  |
|         |               |                                |                          |      |       |         |                  |
| REGCM4  | CNRM-CM5     | Colin et al. (2010)            |                          |      |       |         |                  |
|         |               | CLMcom Doms et al.             |                          |      |       |         |                  |
|         |               |                                |                          |      |       |         |                  |
| REMO2009| CNRM-CM5     | Colin et al. (2010)            |                          |      |       |         |                  |
|         |               | CLMcom Doms et al.             |                          |      |       |         |                  |
|         |               |                                |                          |      |       |         |                  |
| RCA4    | CNRM-CM5     | Colin et al. (2010)            |                          |      |       |         |                  |
|         |               | CLMcom Doms et al.             |                          |      |       |         |                  |
|         |               |                                |                          |      |       |         |                  |

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

*a* Only used in the evaluation mode.
the 1989–2008 period and (b) a historical mode (with vari-
ous GCM forcing) for the 1961–2005 period. The descrip-
tions 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 avail-
able 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
(a) evaluation mode vs. historical mode; (b) reanalyses
versus RCMs; and (c) point observation data vs. gridded

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

In the text, the expressions “evaluation” and “histori-
In the text, the expressions “evaluation” and “histori-
cal” periods are used. In the evaluation mode (1989–2008),
cal” periods are used. In the evaluation mode (1989–2008),
regional climate models were forced by initial and bound-
regional climate models were forced by initial and bound-
ary conditions from the ERA-Interim reanalysis data. ERA-
ary conditions from the ERA-Interim reanalysis data. ERA-
Interim is a global reanalysis dataset produced by the
Interim is a global reanalysis dataset produced by the
European Centre for Medium-Range Weather Forecasts. In
European Centre for Medium-Range Weather Forecasts. In
historical mode (1961–2005), regional climate models use
historical mode (1961–2005), regional climate models use
initial and boundary conditions from GCMs. Hereafter, the
initial and boundary conditions from GCMs. Hereafter, the
terms evaluation and historical mode periods indicate the
terms evaluation and historical mode periods indicate the
span of time and the type of initial and boundary condi-
span of time and the type of initial and boundary condi-
tions used for the regional climate models.
ions used for the regional climate models.

The skill metrics used in this study consist of the
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following:
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 \(N\)
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
values extracted from the atmospheric models and the
observations, respectively;
observations, respectively;

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

4 RESULTS

The model-to-observation RMSE of the annual T2 m
The model-to-observation RMSE of the annual T2 m
averages and trend difference analysis performed at the
averages and trend difference analysis performed at the
locations of the stations for the RCMs is presented in
locations of the stations for the RCMs is presented in
Figure 2 in the form of a series of RMSEs and differences
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trend between model results and observations. The
between model results and observations. The
RMSE results for the RCMs were very different between
RMSE results for the RCMs were very different between
the historical and evaluation periods (Figure 2). Gener-
the historical and evaluation periods (Figure 2). Gener-
ally, the RCMs in the evaluation period better represen-
ally, the RCMs in the evaluation period better represen-
ted the variability (RMSE of 0.5–1.5°C). This result was
oted the variability (RMSE of 0.5–1.5°C). This result was
because the RCMs were forced by the reanalysis, while in
because the RCMs were forced by the reanalysis, while in
the historical period, the variability was much higher
the historical period, the variability was much higher
(RMSE between 1.75 and 2.25°C) due to the effects of dif-
(RMSE between 1.75 and 2.25°C) due to the effects of dif-
f erent global models forcing the boundary conditions and
ferent global models forcing the boundary conditions and
the lack of included data assimilation. Only REMO2009
the lack of included data assimilation. Only REMO2009
showed higher RMSE values for all stations in the evalua-
showed higher RMSE values for all stations in the evalua-
tion period (>1.3°C); one possible reason for this result is
tion period (>1.3°C); one possible reason for this result is
the higher bias values over the Adriatic region than those
the higher bias values over the Adriatic region than those
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 (0.6–0.8°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 (0.6–0.8°C) in the evaluation than in the historical period (>1.25°C). The UERRA reanalyses showed similar RMSE values in both periods (0.25–0.8°C), where slightly smaller RMSEs were present at the southern stations of Hvar, Lastovo, and Dubrovnik.

**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).
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°C-decade⁻¹) were present; in contrast, ICHEC-EC-EARTH RACMO22E showed significant overestimations of the T2 m trends (>0.3°C-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 (1.5–2.1°C) and smaller absolute trend differences (0°C-decade⁻¹–0.12°C-decade⁻¹), while ICHEC-EC-EARTH RACMO22E is an outlier with an absolute trend difference of 0.17°C-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°C-decade⁻¹). Both
EURO-CORDEX ensembles show improved results compared to individual RCMs. As expected, the UERRA reanalyses show the smallest RMSE spread (0.4–0.7°C) in both periods but a large spread in absolute trend differences (0.05–0.38°C-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°C-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 (0.25–1°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 (1.25–1.9°C) and REMO2009 (1.5–2.25°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°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°C-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,
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.
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 ($-0.1 \text{--} 0.1^\circ \text{C-decade}^{-1}$). 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$^\circ$C). However, when they were forced by the GCMs in the historical period (1961–2005), their RMSEs were greater than 1.75$^\circ$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 $0.12^\circ$C-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 $0.37^\circ$C-decade$^{-1}$, while the range of the ensemble means is in the upper part of the measured trends (trend difference of $0.02^\circ$C-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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REFERENCES

Baldauf, M. and Schulz, J.P. (2004) Prognostic precipitation in the Local Model (LM) of DWD. COSMO Newsletter, 4, 177–180.
Bazile, E., Abida, R., Verrelle, A., Le Moigne, P. and Szczepa, C. (2017). Report for the 55 years MESCANSURFEX re-analysis. Report number: 607193 – UERRA, pp. 1–22.
Branković, Č., Güttler, I. and Gajić-Čapka, M. (2013) Evaluating climate change at the Croatian Adriatic from observations and regional climate models’ simulations. Climate Dynamics, 41, 2353–2373. https://doi.org/10.1007/s00382-012-1646-z.
Branković, Č., Patarčić, M., Güttler, I. and Srnec, L. (2012) Near-future climate change over Europe with focus on Croatia in an ensemble of regional climate model simulations. Climate Research, 52, 227–251.
Bucchiniani, E., Cattaneo, L., Panitz, H.J. and Mercogliano, P. (2015) Sensitivity analysis with the regional climate model COSMO-CLM over the CORDEX-MENA domain. Meteorology and Atmospheric Physics, 128(1), 73–95. https://doi.org/10.1007/s00703-015-0403-3.
Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.T., Laprise, R., Magana Rueda, V., Mearns, L., Menéndez, C.G., Raisanen, J., Rinke, A., Sarr, A. and Whetton, P. (2007) Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chan, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.) Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, NY: Cambridge University Press, pp. 847–940.
Colin, J., Déqué, M., Radu, R. and Somot, S. (2010) Sensitivity study of heavy precipitation in limited area model climate simulations: influence of the size of the domain and the use of the spectral nudging technique. Tellus A: Dynamic Meteorology and Oceanography, 62(5), 591–604.
Cuxart, J., Bougeault, P. and Redelsperger, J.-L. (2000) A turbulence scheme allowing for mesoscale and large-eddy simulations. Quarterly Journal of the Royal Meteorological Society, 126, 1–30. https://doi.org/10.1002/qj.49712656202.
Davis, T., Cullen, M.J., Malcom, A.J., Mawson, M.H., Staniforth, A., White, A.A. and Wood, N. (2005) A new dynamical core for the Met Office’s global and regional modelling of the atmosphere. Quarterly Journal of the Royal Meteorological Society, 131, 1759–1782.
Dickinson, R., Henderson-Sellers, A. and Kennedy, P.J. (1993). Biosphere-Atmosphere Transfer Scheme (BATS) version 1E as coupled to the NCAR Community Climate Model (No. NCAR/TN-387+STR). University Corporation for Atmospheric Research. http://dx.doi.org/10.5065/D67W6959.
Doms, G., Forstner, J., Heise, E., Herzog, H.-J., Mironov, D., Raschendorfer, M., Reinhardt, T., Ritter, B., Schrodin, R., Schulz, J.-P. and Vogel, G. (2011). A description of the non-hydrostatic regional COSMO model. Part II: physical parameterization. Technical report, Consortium for Small-Scale Modelling. Available at: www.cosmo-model.org/content/model/documentation/core/cosmoPhysParamr.pdf.
Ek, M.B., Mitchell, K.E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., Gayno, G. and Tarpley, J.D. (2003) Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. Journal of Geophysical Research: Atmospheres, 108(D22), 8851.
Fouquart, Y. and Bonnel, B. (1980) Computations of solar heating of the Earth’s atmosphere – a New parameterization. Contributions to Atmospheric Physics, 53, 35–62.
Gao, X.-J., Shi, J. and Giorgi, F. (2016) Comparison of convective parameterizations in RegCM4 experiments over China with CLM as the land surface model. Atmospheric and Oceanic Science Letters, 9(4), 246–254. https://doi.org/10.1080/16742834.2016.1172938.
Giorgetta, M.A. and Wild, M. (1995). The water vapour continuum and its representation in ECHAM4, Max Planck Institute for Meteorology. Rep 162, p. 47, Germany.
Giorgi, F. (2006) Regional climate modeling: status and perspectives. Journal de Physique IV, 139, 101–118. https://doi.org/10.1051/jp4:2006139008.
Gioiri, F. (2008) Regionalization of climate change information for impact assessment and adaptation. *World Meteorological Organization Bulletin*, 57, 86–92.

Gioiri, F. and Mearns, L.O. (1999) Introduction to special section: regional climate modelling revisited. *Journal of Geophysical Research*, 104, 6335–6352.

Gioiri, F., Coppola, E., Solmon, F., Mariotti, L., Sylla, M.B., Bi, X., Elguindii, N., Diro, G.T., Nair, V., Giuliani, G., Turuncoglu, U., Cozinni, S., Gütntler, I., O'Brien, T.A., Tawfik, A.B., Shalaby, A., Zakay, A.S., Steiner, A.L., Stordal, F., Sloan, L.C. and Brankovic, C. (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. *Climate Research*, 52, 7–29.

Gioiri, F., Jones, C. and Asrar, G.R. (2009) Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorological Organization Bulletin*, 58, 175–183.

Grell, G.A. (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. *Monthly Weather Review*, 121, 764–787.

Grell, G.A. and Dévényi, D. (2002) A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophysical Research Letters*, 29, 38–1–38–4. https://doi.org/10.1029/2002GL015311.

Haylock, M.R., Hofstra, N., Klein Tank, A.M., Jones, P.D. and New, M. (2008) A European daily high-resolution gridded dataset of surface temperature and precipitation. *Journal of Geophysical Research: Atmospheres*, 113, D20. https://doi.org/10.1029/2008JD012021.

Hewitson, B.C. and Crane, R.G. (1996) Climate downsampling: techniques and application. *Climate Research*, 85–95, V07–n2.

Holtslag, A., de Bruijn, E. and Pan, H. (1990) A high resolution air mass transformation model for short-range weather forecasting. *Monthly Weather Review*, 118, 1561–1575.

Hong, S.-Y., Noh, Y. and Dudhia, J. (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly Weather Review*, 134, 2318–2341. https://doi.org/10.1175/MWR3199.1.

Hong, Y., Hsu, K.-L., Sorooshian, S. and Gao, X. (2004) Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. *Journal of Applied Meteorology*, 43, 1834–1853. https://doi.org/10.1175/JAM2173.1.

Iacono, M.J., Delamere, J.S., Mlawer, E.J., Shephard, M.W., Clough, S.A. and Collins, W.D. (2008) Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models. *Journal of Geophysical Research*, 113, 1–8. https://doi.org/10.1029/2008JD009944.

Jacob, D. and Podzun, R. (1997) Sensitivity studies with the regional climate model REMO. *Meteorology and Atmospheric Physics*, 63, 119–129. https://doi.org/10.1007/BF01025368.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschem, S., Radermacher, C., Radtke, K., Rechid, D., Rousevill, M., Samueission, P., Somot, S., Soussana, J.F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. and Yiou, P. (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2.

Kain, J.S. and Fritsch, J.M. (1990) A one-dimensional entraining/detraining plume model and its application in convective parameterization. *Journal of the Atmospheric Sciences*, 47, 2784–2802.

Kain, J.S. and Fritsch, J.M. (1993) Convective parameterization for mesoscale models: the Kain-Fritsch scheme. In: Emanuel, K.A. and Raymond, D.J. (Eds.) The Representation of Cumulus Convection in Numerical Models. *Meteorological Monographs*. Boston, MA: American Meteorological Society. https://doi.org/10.1007/978-1-935704-13-3_16.

Kiehl, J.T., Hack, J.J., Bonan, G.B., Boville, B.A., Briegleb, B.P., Williamson, D.L. and Rasch, P.J. (1996). Description of the NCAR Community Climate Model (CCM3). *NCAR Technical Note*.

Kjellström, E., Bärring, A., Nikulin, G., Nilsson, C., Persson, G. and Strandberg, G. (2016) Production and use of regional climate model projections – a Swedish perspective on building climate services. *Climate Services*, 2–3, 15–29. https://doi.org/10.1016/j.climser.2016.06.004.

Kjellström, E., Bärring, L., Jacob, D., Lenderink, G. and Schär, C. (2007) Modelling daily temperature extremes: recent climate and future changes over Europe. *Climate Change*, 81 (Supplement 1), 249. https://doi.org/10.1007/s10584-006-9220-5.

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A. and Wulffmeyer, V. (2014) Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geoscientific Model Development*, 7, 1297–1333.

Kotriono, V., Lykoudis, S., Lagouvardos, K. and Lallas, D. (2008) A fine resolution regional climate change experiment for the Eastern Mediterranean: analysis of the present climate simulations. *Global and Planetary Change*, 64, 93–104.

Laprise, R. (2008) Regional climate modeling. *Journal of Computational Physics*, 227, 3641–3666.

Lenderink, G. and Holtslag, A.A. (2004) An updated length-scale formulation for turbulent mixing in clear and cloudy boundary layers. *Quarterly Journal of the Royal Meteorological Society*, 130 (604), 3405–3427. https://doi.org/10.1256/qj.03.117.

Lohmann, U. and Roeckner, E. (1996) Design and performance of a new cloud microphysics scheme developed for the ECHAM general circulation model. *Climate Dynamics*, 12, 557–572. https://doi.org/10.1007/BF00207939.

Louis, J.-F. (1979) A parametric model of vertical eddy fluxes in the atmosphere. *Boundary-Layer Meteorology*, 17, 187–202. https://doi.org/10.1007/BF00117978.

Lucas-Picher, P., Wulf-Nielsen, M., Christensen, J.H., Aðalgeirsdóttir, G., Mottram, R. and Simonsen, S.B. (2012) Very high resolution regional climate model simulations over Greenland: identifying added value. *Journal of Geophysical Research*, 117, 1–16. https://doi.org/10.1029/2011JD016267.

McGergor, J.L. (1997) Regional Climate Modelling. *Meteorology and Atmospheric Physics*, 63, 105–117.

Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J. and Clough, S.A. (1997) Radiative transfer for inhomogeneous
atmospheres: RRTM, a validated correlated-k model for the longwave. *Journal of Geophysical Research*, 102, 16663–16682. https://doi.org/10.1029/97JD00237.

Moberg, A. and Jones, P.D. (2004) Regional climate model simulations of daily maximum and minimum near-surface temperatures across Europe compared with observed station data 1961–1990. *Climate Dynamics*, 23, 695–715.

Morcrette, J.-J., Smith, L.D. and Fouquart, Y. (1986) Pressure and temperature dependence of the absorption in longwave radiation parameterizations. *Contributions to Atmospheric Physics*, 59, 455–469.

Neggers, R.A., Köhler, M. and Beljaars, A.C. (2009) A dual mass flux framework for boundary layer convection. Part I: transport. *Journal of the Atmospheric Sciences*, 66, 1465–1487. https://doi.org/10.1175/2008JAS2635.1.

Nordeng, T.E. (1994). Extended versions of the convection parametrization scheme at ECMWF and their impact upon the mean climate and transient activity of the model in the tropics, *ECMWF Research Department*. Technical Memorandum No. 206, ECMWF, Reading, UK.

Önol, B. (2012) Effects of coastal topography on climate: high resolution simulation with a regional climate model. *Climate Research*, 52, 159–174.

Orlić, M., Gačić, M. and Laviolette, P.E. (1992) The currents and circulation of the Adriatic Sea. *Oceanologica Acta*, 15(2), 109–124.

Pal, J.S., Small, E.E. and Eltahir, E.A. (2000) Simulation of regional scale water and energy budgets: influence of a new moist physics scheme within RegCM. *Journal of Geophysical Research*, 105, 29579–29594.

Pfeifer, S. (2006) Modeling cold cloud processes with the regional climate model REMO. PhD thesis, Reports on Earth System Science, Max Planck Institute for Meteorology, Hamburg.

Rasch, P.J. and Kristjánsson, J.E. (1998) A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations. *Journal of Climate*, 11, 1587–1614. https://doi.org/10.1175/1520-0442(1998)011<1587:ACMFSF>2.0.CO;2.

Renshaw, R., Jermey, P., Barker, D., Maycock, A. and Oxley, S. (2013). EUROM4 regional reanalysis system. Forecasting Research Technical Report No 583, Met Office.

Ridal, M., Olsson, E., Unden, P., Zimmermann, K. and Ohlsson, A. (2017). Uncertainties in Ensembles of Regional Re-Analyses: HARMONIE reanalysis report of results and dataset. Project: 607193 – UERRA_D2.7.

Ritter, B. and Geleyn, J.-F. (1992) A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. *Monthly Weather Review*, 120, 303–325. https://doi.org/10.1175/1520-0493(1992)120<0303:ACRFSN>2.0.CO;2.

Rivington, M., Miller, D., Matthews, K.B., Russell, G., Bellocchi, G. and Buchanan, K. (2008) Evaluating regional climate model estimates against site-specific observed data in the UK. *Climate Change*, 88, 157–185.

Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Clausen, M., Dümenil, L. and Schulzweida, U. (1996). *The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate*. Max-Planck-Institut für Meteorologie Report Series. 218. Technical Report.

Samuelsson, P., Gollvik, S. and Ullerstig, A. (2006). The land-surface scheme of the Rossby Centre regional atmospheric climate model (RCA3). Rep. Meteorology 122, SMHI, Norrköping, Sweden.

Sass B. H., Rontu L., Savijärvi H. and Raisanen P. (1994) HIRLAM-2 radiation scheme: documentation and tests. Hirlam Technical Report Number: 16.

Savijärvi, H. (1990) Fast radiation parameterization schemes for mesoscale and short-range forecast models. *Journal of Applied Meteorology and Climatology*, 29, 437–447. https://doi.org/10.1175/1520-0450(1990)029<0437:FRPSFM>2.0.CO;2.

Siebesma, A.P. (2007) A combined eddy-diffusivity mass-flux approach for the convective boundary layer. *Journal of the Atmospheric Sciences*, 64, 1230–1248. https://doi.org/10.1175/JAS3888.1.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D., Duda, M.G., Huang, X.-Y., Wang, W. and Powers, J.G. (2008) A Description of the Advanced Research WRF Version 3. Boulder, CO: National Center for Atmospheric Research, pp. 3–27.

Thorne, P.W. and Vose, R.S. (2010) Reanalyses suitable for characterizing long-term trends. *Bulletin of the American Meteorological Society*, 91, 353–361. https://doi.org/10.1175/2009bams2858.1.

Tiedtke, M. (1989) A comprehensive mass flux scheme for cumulus parametrization in large-scale models. *Monthly Weather Review*, 117, 1779–1800. https://doi.org/10.1175/1520-0493(1989)117<1779:ACMFSF>2.0.CO;2.

Tiedtke, M. (1993) Representation of clouds in large-scale models. *Monthly Weather Review*, 121, 3040–3061. https://doi.org/10.1175/1520-0493(1993)121<3040:ROCILS>2.0.CO;2.

Van den Hurk, B.J., Viterbo, P., Beljaars, A.C., and Betts, A.K. (2000). Offline validation of the ERA40 surface scheme. ECMWF Technical Memorandum 295.

van der Linden, P., and Mitchell, J. F. (Eds.) (2009). *ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project*. Met Office Hadley Centre, Exeter, 160.

van Meijgaard, E., van Uldt, L.H., van de Berg, W.J., Bosveld, F.C., van den Hurk, B., Lenderink, G. and Siebesma, A.P. (2008). *The KNMI regional atmospheric model RACMO version 2.1*. Technical Report 302, KNMI.

Wang, Y., Leung, L.R., McGregor, J.L., Lee, D.K., Wang, W.-C., Ding, Y. and Kimura, F. (2004) Regional climate modeling: progress, challenges, and prospects. *Journal of the Meteorological Society of Japan*, 82, 1599–1628. https://doi.org/10.2151/jmsj.82.1599.

Wilby, R.L. and Fowler, H.J. (2011) Regional climate downscaling. In: Fung, F., Lopez, A. and New, M. (Eds.) *Modelling the Impact of Climate Change on Water Resources*. West Sussex: Wiley-Blackwell Publishing, pp. 34–85. https://doi.org/10.1002/9781444324921.ch1.

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