Regionalization of Climate Change Simulations over the Eastern Mediterranean

BARIŞ ÖNOL

Aeronautics and Astronautics Faculty, Meteorological Engineering, Istanbul Technical University, Maslak, Istanbul, Turkey

FREDRICK H. M. SEMAZZI

Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina

(Manuscript received 8 December 2006, in final form 15 October 2008)

ABSTRACT

In this study, the potential role of global warming in modulating the future climate over the eastern Mediterranean (EM) region has been investigated. The primary vehicle of this investigation is the Abdus Salam International Centre for Theoretical Physics Regional Climate Model version 3 (ICTP-RegCM3), which was used to downscale the present and future climate scenario simulations generated by the NASA's finite-volume GCM (fvGCM). The present-day (1961–90; RF) simulations and the future climate change projections (2071–2100; A2) are based on the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas (GHG) emissions. During the Northern Hemispheric winter season, the general increase in precipitation over the northern sector of the EM region is present both in the fvGCM and RegCM3 model simulations. The regional model simulations reveal a significant increase (10%–50%) in winter precipitation over the Carpathian Mountains and along the east coast of the Black Sea, over the Kackar Mountains, and over the Caucasus Mountains. The large decrease in precipitation over the southeastern Turkey region that recharges the Euphrates and Tigris River basins could become a major source of concern for the countries downstream of this region. The model results also indicate that the autumn rains, which are primarily confined over Turkey for the current climate, will expand into Syria and Iraq in the future, which is consistent with the corresponding changes in the circulation pattern. The climate change over EM tends to manifest itself in terms of the modulation of North Atlantic Oscillation. During summer, temperature increase is as large as 7°C over the Balkan countries while changes for the rest of the region are in the range of 3°–4°C. Overall the temperature increase in summer is much greater than the corresponding changes during winter. Presentation of the climate change projections in terms of individual country averages is highly advantageous for the practical interpretation of the results. The consistence of the country averages for the RF RegCM3 projections with the corresponding averaged station data is compelling evidence of the added value of regional climate model downscaling.

1. Introduction

Regional climate change projections studies have been performed for many different regions of the world for agricultural, water resource management, health, and energy application sectors. General circulation models (GCMs) typically used to generate the Intergovernmental Panel on Climate Change (IPCC) climate projections do not have adequate resolution to resolve the steep regional gradients associated with the lower boundary conditions. During the past two decades major advances have been made in the use of high-resolution regional climate models to downscale global climate models predictions/projections of the climate. The projections generated by these models are used in the development of socioeconomic remedies for addressing the impacts of climate change. The eastern Mediterranean (EM) is one of the regions that could benefit from more detailed climate projections because of its economic and cultural diversity.

Climate change studies based on regional climate models have been carried out for several regions of the world: over North America (Giorgi et al. 1994, 1998; Chen et al. 2003; Leung et al. 2004; Diffenbaugh et al. 2005; Duffy et al. 2006), Europe (Giorgi et al. 2004a,b;

Corresponding author address: Bariş Önol, ITU Aeronautics and Astronautics Faculty, Meteorological Engineering, Maslak, 34469 Istanbul, Turkey.
E-mail: onolba@itu.edu.tr

DOI: 10.1175/2008JCLI1807.1

© 2009 American Meteorological Society

Räisänen et al. 2004; Gao et al. 2006), East Asia (Hirakuchi and Giorgi 1995), and Australia (McGregor and Walsh 1994).

Two major (European Union) EU-funded intercomparison regional climate modeling studies: Ensemble-Based Predictions of Climate Changes and their Impacts ENSEMBLES (Hewitt 2005) and the Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE; Christensen et al. 2002) have focused on Europe. In the PRUDENCE project, 4 atmospheric general circulation models (AGCMs) and 10 Regional Climate Models (RCMs) have been used to produce climate change projections and the corresponding model uncertainties over Europe (Christensen et al. 2007). These ensemble projections in the PRUDENCE project have recently been analyzed by Christensen and Christensen (2007) and Déqué et al. (2007). The overlapping numerical domains for these model simulations do not fully cover our EM domain except for Greece and western Turkey. The climate change obtained from the ensemble mean of the PRUDENCE projections is quite similar to ours based on the Regional Climate Model version 3 (RegCM3) model. Over southern and eastern Europe, the projected changes in winter precipitation and summer warming obtained by PRUDENCE by downscaling the ECHAM4/Ocean Isopycnal Model (OPYC) projections are more consistent with our projections than with any other results based on the other GCMs that they used. All the PRUDENCE simulations indicate a decrease in projected summer precipitation over southern Europe, which is consistent with our projections. However, Déqué et al.'s (2007) study showed that during summer over the Mediterranean region the uncertainty in precipitation projections associated with the choice of RCM is the largest. They found similar results for summer temperature over southern Europe. None of the domains adopted in ENSEMBLES and PRUDENCE projects corresponds to our model domain for direct comparison. Furthermore, none of the previous studies have focused on the use of regional climate models to study climate change over the EM region.

It is instructive to compare our projections [Abdus Salam International Centre for Theoretical Physics (ICTP) RegCM3, 30 km; 18 vertical levels], with those of Giorgi et al. (2004b; ICTP-RegCM3, 50 km; 14 sigma vertical levels), and Räisänen et al. [2004; Rossby Centre coupled regional climate model (RCAO), 49 km, 24 vertical levels]. Despite the differences in model physics and (horizontal/vertical) resolution among these three studies, comparison of the corresponding results is useful for ascertaining confidence in the projections (see section 3b). Other studies from PRUDENCE indicate that climatic conditions over Europe will be profoundly impacted by global warming including significant increases in the occurrence of extremes (Pal et al. 2004) and large changes in river flow (Graham 2004).

Recently, Krichak et al. (2007) employed the RegCM model (50-km horizontal resolution) forced by the National Aeronautics and Space Administration (NASA) finite-volume GCM (fvGCM) to downscale the present climate conditions (1961–90) over the EM region. Their winter temperature results exhibited bias of up to +4°C with annual precipitation twice the observed amounts along the coast of EM. We believe that the relatively coarse resolution of their model was partly responsible for the large biases in temperature. For this reason and other considerations we will adopt higher resolution of 30 km in our regional climate model simulations. Gao et al. (2006) have employed the ICTP-RegCM3 model for their climate change projections (A2 scenario) over the Mediterranean region with 20-km horizontal grid spacing. Their projections indicate that positive (negative) precipitation change will occur over the upslope (downslope) sides of mountain ranges over southeastern Europe and the Mediterranean region, which is consistent with our findings. Recently, Gao and Giorgi (2008) have shown widespread decrease in winter precipitation over most of the EM (10%–50% over Greece and southern Turkey) and warming during summer over the Balkans and western Turkey (5°–6°C). These results are in also close agreement with ours. We believe that the consistency of our results with previous studies is an important testimony of the robustness of RCM climate change projections over the EM region.

To compliment the regional climate modeling studies, several observational investigations have been carried out over the EM region. For example, Krichak et al. (2000), Eshel and Farrell 2000, Alpert et al. (2004), and Krichak and Alpert (2005) have investigated the relationship between rainfall variability over EM and the climate variability over the North Atlantic region. Evans et al. (2004) have used a regional climate model for investigating precipitation patterns over the Middle East covering the eastern part of our domain and validated the results using extensive observational station data analysis but their simulations only covered five recent years, which is relatively a short period to define the present climate.

The purpose of this study is to investigate the potential role of global warming on the future climate over the EM region by using the dynamical downscaling method. Our study employs higher resolution (30 km) than most of the previous studies to reduce computational bias. The computational domain is centered over the EM region. Our study goes beyond the scope of previous investigations by computing individual country climate change projection averages for each of the 21 EM countries to enhance its relevance to a broader spectrum of stakeholders. The rest of the paper is organized as follows. Section 2 describes the methodology of the investigation and the observational data used for the validation of our model present-day climate. The results are presented in section 3 and concluding remarks are given in section 4.

2. Methods and data

The primary vehicle of our investigation is the RegCM3 regional climate model. The NASA-fvGCM-archived model simulation data was used to construct the initial and lateral boundary conditions for two 30-yr RegCM3 model simulations: present climate (1961–90; RF) and the projected climate (2071–2100; A2). The A2 is the one of the extreme IPCC scenarios, and we adopted it because it provides the opportunity to understand the upper limits of human-induced global warming over the EM region.

a. Regional Climate Model, version 3

The Regional Climate Model, version 3 (RegCM3), that we used for both the RF and A2 simulations for downscaling is a three-dimensional hydrostatic atmospheric model and it uses a sigma-pressure-based vertical coordinate system. The radiation transfer package is based on the National Center for Atmospheric Research (NCAR) Coupled Climate Model, version 3 (CCM3), GCM scheme. The model code permits the user to specify concentrations for the CO_2, CH_4, N_2O, CFC_{11}, and CFC_{12} greenhouse gas emissions. Appropriate emission levels based on IPCC Special Report on Emissions Scenarios (SRES) were prescribed in our RF and A2 simulations. The atmospheric component of the model is coupled with the Biosphere–Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993). For large-scale precipitation the model uses the subgrid explicit moisture scheme SUBEX scheme (Pal et al. 2000) and has three options for the parameterization of convective precipitation. After systematic analysis of many test runs over the EM domain and comparing the model results with observations, we adopted the Grell (1993) convective scheme with the Arakawa and Schubert (1974) closure formulation. Further details regarding the RegCM3 model are given in Pal et al. (2005).

Since the model performance is sensitive to the choice of model domain the evolution of mesoscale features over the region has been considered in defining the model domain (28°–50°N, 10°–50°E). The vertical resolution of RegCM3 is 18 vertical levels. To resolve the complicated topographic gradients and large contrasts in vegetation over the model domain, we run RegCM3 at 30-km resolution.

b. NASA finite-volume GCM

NASA's fvGCM model output has been used to construct the lateral boundary and initial conditions for the RF and A2 RegCM3 simulations. This model employs the terrain-following Lagrangian control volume formulation for the vertical coordinate system (Lin 2004). The horizontal resolution of the model is 1° latitude × 1.25° longitude. This is considerably high resolution compared to the global model resolution used to generate lateral boundary conditions in most typical downscaling climate change studies. For the RF simulation, sea surface temperature (SST), sea ice distribution and greenhouse gas (GHG) concentrations were derived from observations. In case of the A2 simulation, monthly SST perturbations (A2 minus RF) calculated from the corresponding third climate configuration of the Met Office Unified Model (HadCM3) simulations were added to the RF SST values (Coppola and Giorgi 2005). This method was also adopted in the PRUDENCE project. The global and regional analysis of the precipitation and temperature for the NASA fvGCM simulations, which was used to drive RCM simulations in this study, have been discussed by Coppola and Giorgi (2005).

c. Observations

Three observed precipitation datasets have been used in this study to validate the RF climatology for the RegCM3 model: the Climate Research Unit TS 2.1 (CRU), Global Climate Normals (GCN) of the National Climatic Data Center (NCDC), and the Global Historical Climate Network Version 2-NCDC (GHCN2). The monthly mean gridded CRU data have resolutions of 0.5° × 0.5°. The GCN and GHCN monthly station datasets were used to compute the country area averages. Figure 1 displays the station locations for temperature and precipitation for the GCN and GHCN datasets over the region of interest. Altogether, there are 174 stations for temperature and 173 for precipitation.

3. Results

We adopted two complimentary methods to analyze the model results. The first approach is based on the analysis of the horizontal distribution of surface temperature and precipitation to investigate the spatial characteristics of the projected climate change over the EM region. In the second approach, we compute area averages for the 21 countries (listed in Tables 1 and 2) over the model domain (Fig. 1) for both the RF and A2 simulations and we compare the RegCM3 results with the observed station averages for each country.

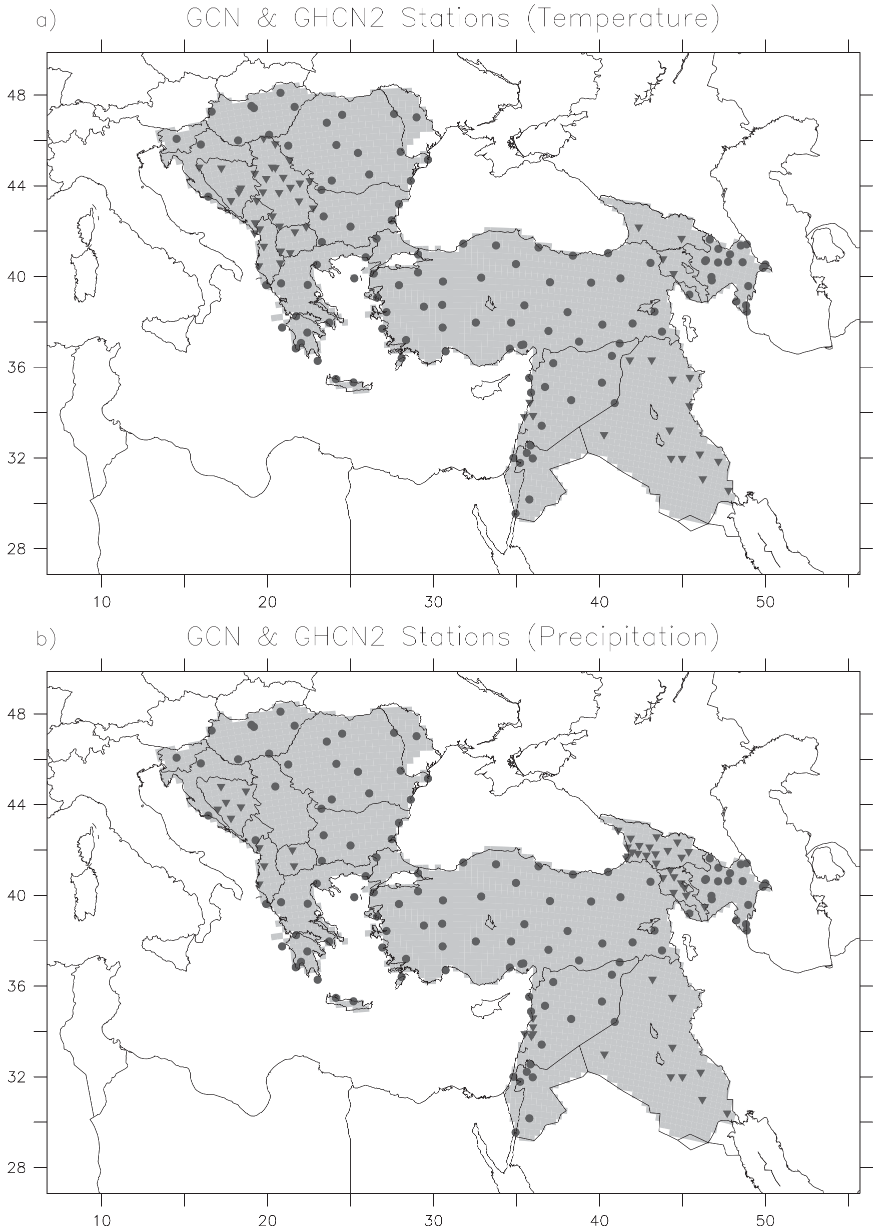

FIG. 1. Location of GCN (circle) and GHCN (delta) stations. A total of 21 interested countries are shaded: (a) 174 stations for temperature and (b) 173 stations for precipitation.

a. Present-day simulation: RF

In this section, we perform a three-way systematic comparison among the model simulation results, CRU 0.5° resolution gridded observational data and station data, to investigate the performance of the model, and examine the potential deficiencies in the observations.

1) SURFACE TEMPERATURE

The climatological surface temperature distribution produced by RegCM3 for the 1961–90 (RF) period is in good agreement with the observed climatology for all the seasons (Fig. 2). However, there is a 2°–4°C warm bias over the Caucasus Mountains, over the northern sector of the model domain during winter (Fig. 2a), and over the southern region of the model domain in summer (Fig. 2c). The observed seasonal autumn and spring temperature averages are also in agreement with the RF simulation (Figs. 2b,d). The annual mean for the RF run is about 2°C warmer than the corresponding CRU temperatures (not shown). It is noteworthy that the fvGCM simulation generally has a warm bias of about

TABLE 1. Seasonal temperature area averages (°C) of station observations, RF and A2, for the 21 countries over the model domain. The differences (Ch.), A2 − RF, for each season are shown in the last column (°C) and all changes are statistically significant. Obs/Rcm indicates the ratio between the number of the stations and the number of the RCM grid points for each country.

Temperature		Winter				Spring				Summer				Autumn			
Obs/Rcm	Countries	OBS	RF	A2	Ch.	OBS	RF	A2	Ch.	OBS	RF	A2	Ch.	OBS	RF	A2	Ch.
4/32	Albania	6.1	4.4	6.8	2.4	13.0	9.7	12.5	2.8	22.4	22.5	29.2	6.7	15.3	11.7	15.8	4.0
2/33	Armenia	−4.3	−3.9	−0.9	3.0	8.9	5.0	8.4	3.4	21.1	18.6	22.2	3.6	10.8	6.1	10.1	4.0
19/90	Azerbaijan	2.5	2.5	5.4	2.8	11.3	11.4	14.4	3.0	22.8	23.7	27.3	3.7	13.7	11.6	15.4	3.8
7/55	Bosnia	1.1	2.5	5.4	2.9	9.5	8.6	11.2	2.6	18.4	20.0	26.9	6.9	10.7	9.7	13.7	4.0
7/116	Bulgaria	1.7	2.8	5.5	2.7	11.4	10.3	13.3	3.0	21.7	22.5	28.3	5.9	12.7	10.8	14.6	3.8
2/75	Georgia	4.9	−2.2	0.5	2.7	13.5	5.4	8.3	2.9	23.2	18.0	21.7	3.8	15.0	7.0	10.9	3.9
18/147	Greece	9.9	6.6	9.1	2.4	15.3	12.8	16.2	3.4	25.2	25.3	31.0	5.6	18.3	14.2	18.1	3.9
2/57	Croatia	4.9	4.3	7.4	3.1	12.9	10.9	13.6	2.7	22.3	22.7	29.8	7.0	14.2	11.8	15.9	4.0
7/95	Hungary	−0.3	2.5	5.7	3.2	10.6	10.9	13.3	2.5	19.6	23.0	29.6	6.6	10.5	11.1	15.1	4.0
03/25	Israel	12.6	10.6	13.6	3.0	18.9	18.1	21.2	3.1	26.3	27.8	32.1	4.2	21.9	19.7	24.0	4.3
13/470	Iraq	10.6	9.3	12.4	3.1	21.4	21.8	25.6	3.8	33.7	36.3	40.5	4.2	24.0	22.1	26.6	4.5
4/97	Jordan	10.6	7.9	10.9	3.1	17.7	17.3	20.8	3.4	26.2	29.7	33.4	3.8	21.0	18.7	23.3	4.5
03/12	Lebanon	11.1	7.1	9.9	2.8	15.9	13.7	17.0	3.3	23.8	25.8	29.0	3.1	20.0	16.5	20.6	4.1
1/33	Moldova	−1.7	0.6	4.3	3.7	9.7	10.3	13.1	2.8	20.3	22.8	28.6	5.9	10.3	10.4	14.1	3.7
4/27	Macedonia	1.9	2.1	4.7	2.6	10.8	8.5	11.5	3.0	20.1	21.1	27.6	6.6	12.0	9.7	13.7	4.0
11/249	Romania	−1.7	1.0	4.2	3.2	8.7	9.2	11.9	2.6	18.5	21.1	27.3	6.2	9.6	9.6	13.5	3.9
1/23	Slovenia	0.1	1.9	5.1	3.2	10.0	8.8	11.4	2.6	18.9	19.8	26.8	7.0	10.2	9.5	13.6	4.1
11/203	Syria	8.5	6.7	9.5	2.8	17.2	16.4	20.1	3.7	28.1	31.1	34.5	3.4	19.9	18.0	22.3	4.4
36/849	Turkey	3.3	1.3	4.0	2.7	11.6	8.9	12.1	3.2	22.8	22.4	26.8	4.3	14.3	10.6	14.7	4.1
16/90	Serbia	1.2	2.9	5.7	2.9	10.9	10.1	12.7	2.7	19.7	22.1	28.7	6.6	11.2	10.6	14.6	4.0
3/17	Montenegro	4.8	1.8	4.5	2.7	12.5	7.3	9.9	2.7	16.7	19.2	25.9	6.8	14.3	8.9	13.0	4.1

1°C relative to CRU for the present-day climate. Regarding interannual variability of temperature, RegCM3's representation of the observed conditions is significantly deficient. It is unclear if this is inherited from the fvGCM or associated with deficiencies in RegCM3.

To compliment the spatial comparison of CRU and RF, we also calculated temporal averages of station observations for each country and compared the results with RF. Presenting the results in terms of individual countries is highly advantageous for the interpretation of our results. Furthermore, the averages for RF compared to the corresponding station data values agree for most of the countries (Table 1). This is a clear demonstration of the benefits of regional climate models since the resolution of most of the global climate change models is typically too coarse to resolve country transboundary differences in such a consistent manner as we have found in this study. In general the model cold bias is in the range of 1°–3°C for all seasons except summer. The agreement between the model (RF) and station-based averages is better during the summer than in the other seasons for most countries. There is some indication that the differences are more prominent for the small countries and perhaps even the larger ones where the station coverage is sparse (Table 1). The GCN dataset over Montenegro has only one station and the winter bias of RF is large (4.3°C). For winter, GHCN has three stations and the RF bias is smaller (3°C). In the case of Armenia, the spring RF bias is 7°C, which is consistent with the fact that there is only one station over the entire country. This bias reduces by about to 2°–4.9°C based for the GHCN dataset, which has two stations. Considering the size of the countries and the number of available stations, the temperature over Georgia is not likely to be representative. To compare finescale RF simulation results for places such as the Caucasus Mountains in northern Georgia, there is a need for better observational coverage. In this case the CRU dataset is more suitable for evaluating temperature bias over Georgia and the annual bias is only about 1°C. The least bias can be seen in the summer season for most of the countries except the Middle East region. In particular, the summer temperature biases over Syria, Iraq, and Jordan are higher than any other countries over the model domain. Since there are very few observational stations over desert regions for these countries, extreme dry and hot conditions during summer are not well represented by the area averages of temperature. We also note the overestimation of surface temperature by RegCM over dry regions, which has been previously reported by a number of studies (Pal et al. 2005; Krichak et al. 2007). A simulation driven by the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Pal et al. 2007) shows +4°C bias over Iraq and the Arabian peninsula. Over the same region, the summer mean

TABLE 2. Seasonal precipitation (mm) area averages of station observation, RF and A2, for 21 countries over the model domain. Percent changes (Ch.%) in the projected simulation, which are statistically significant at the 95% level of confidence for each season, are bold. Obs/Rcm indicates the ratio between the number of the stations and the number of the RCM grid points over each country.

Precipitation		Winter				Spring				Summer				Autumn			
Obs/Rcm	Countries	OBS	RF	A2	Ch.%	OBS	RF	A2	Ch.%	OBS	RF	A2	Ch.%	OBS	RF	A2	Ch.%
3/32	Albania	449	676	630	−6.8	309	417	343	**−17.8**	136	54	24	**−56.2**	425	373	324	−13.3
9/33	Armenia	72	122	130	6.4	179	196	197	0.5	146	112	109	−2.2	103	137	167	**22.4**
19/90	Azerbaijan	106	102	107	4.3	151	170	179	5.0	103	117	118	1.2	179	180	244	**35.7**
6/55	Bosnia	286	398	389	−2.2	258	325	293	−9.8	248	106	52	**−50.5**	302	284	253	−10.7
7/116	Bulgaria	112	201	154	**−23.1**	143	209	182	−13.0	140	57	36	**−37.3**	124	120	115	−3.9
17/75	Georgia	352	519	642	**23.6**	268	423	482	**13.9**	349	169	170	0.4	395	334	375	12.2
18/147	Greece	289	316	215	**−32.0**	125	185	132	**−28.6**	28	19	10	**−48.8**	182	152	138	−9.2
2/57	Croatia	206	369	359	−2.7	201	267	237	−11.1	204	93	43	**−53.7**	242	274	244	−11.2
7/10	Hungary	104	140	148	5.4	136	145	149	2.7	195	75	38	**−49.7**	126	107	100	−6.4
3/35	Israel	251	146	111	**−23.7**	74	40	36	−8.9	0	3	2	−36.1	69	45	59	32.0
9/470	Iraq	90	69	46	**−32.6**	68	26	22	−17.2	0	3	4	15.7	24	35	98	**178.0**
4/97	Jordan	162	54	39	**−29.0**	68	16	14	−9.4	0	4	4	−11.1	36	22	43	**92.3**
5/12	Lebanon	436	311	222	**−28.7**	172	144	122	−15.8	**2**	16	15	−6.0	142	93	148	**58.6**
1/33	Moldova	116	139	115	**−17.3**	128	174	149	−14.4	190	72	44	**−39.3**	113	79	81	2.8
2/27	Macedonia	128	265	229	**−13.9**	147	241	196	−18.6	116	51	35	**−32.0**	142	154	140	−8.8
11/249	Romania	111	218	228	4.2	147	248	233	−5.8	208	103	56	**−45.3**	117	146	131	−9.8
1/23	Slovenia	263	359	368	2.7	329	315	270	−14.4	**NA**	132	55	**−58.0**	380	282	247	−12.6
11/203	Syria	199	110	79	**−28.8**	95	53	43	−18.6	3	5	5	4.9	65	42	80	**90.5**
35/849	Turkey	248	287	251	**−12.5**	172	215	203	−5.5	74	31	27	−12.8	157	138	163	**18.0**
1/90	Serbia	151	194	183	−5.8	179	220	214	−2.5	208	84	50	**−40.5**	146	151	141	−6.9
1/17	Montenegro	575	780	726	−6.9	393	499	430	**−13.7**	167	93	42	**−54.6**	526	453	391	−13.7

temperature of the fvGCM RF simulation (Fig. 4a) is much closer to the CRU dataset than the RegCM RF simulation. Both the GCN and GHCN datasets have different numbers of observational stations for different countries. For each country we choose the dataset with better coverage based on the number of stations and locations of stations for that country.

2) PRECIPITATION

Precipitation results for RF compare well with the CRU observations (Fig. 3). RegCM3 realistically reproduced the general precipitation pattern for all the seasons. The RF results are consistent with the fact that most of precipitation over the model domain occurs along the coastal and mountainous regions. In winter and even worse for the spring time, the model overpredicts the precipitation along the Dalmatian coast, east of the Black Sea coast and southwest of Turkey's coast. All these regions have the same characteristics in terms of precipitation and they are associated with very steep topography along the coast. Because of the abundant moisture availability originating from the sea along the coastal regions and the steep topography, the model overreacts and produces unrealistically high precipitation. Higher model resolution than we used in this study is required to resolve such topographic complexity.

The climatology for autumn precipitation is reproduced more realistically by the model than for the winter and spring seasons. The model's climate during the summer season is drier than in the observations. We believe the dry conditions have been inherited by RegCM3 through the lateral boundary conditions from the fvGCM simulation, which is also very dry during summer (Fig. 4b). However, based on the CRU dataset, RegCM3 summer precipitation over northern Turkey, Romania, and Georgia is much more realistic than the fvGCM simulation.

Overall, RegCM3 realistically reproduced the annual mean precipitation and temperature for the present climate relative to the CRU observations. It is apparent that the 30-km resolution of RegCM3 that we used is satisfactory in resolving the complex topography. However, the RegCM3 resolution over the mountains may still be too coarse to resolve the gradients of the more extreme steep slopes. The validation also suffers from inadequate observational coverage in the desert and mountainous regions. We believe that both model and observational resolution contribute to the apparent model bias.

In the RF simulation, area averages of the countries agree well with spatial distributions of simulated precipitation. We also found that the station data averages and RF area averages are in good agreement for most of the countries (Table 2). The RF autumn precipitation

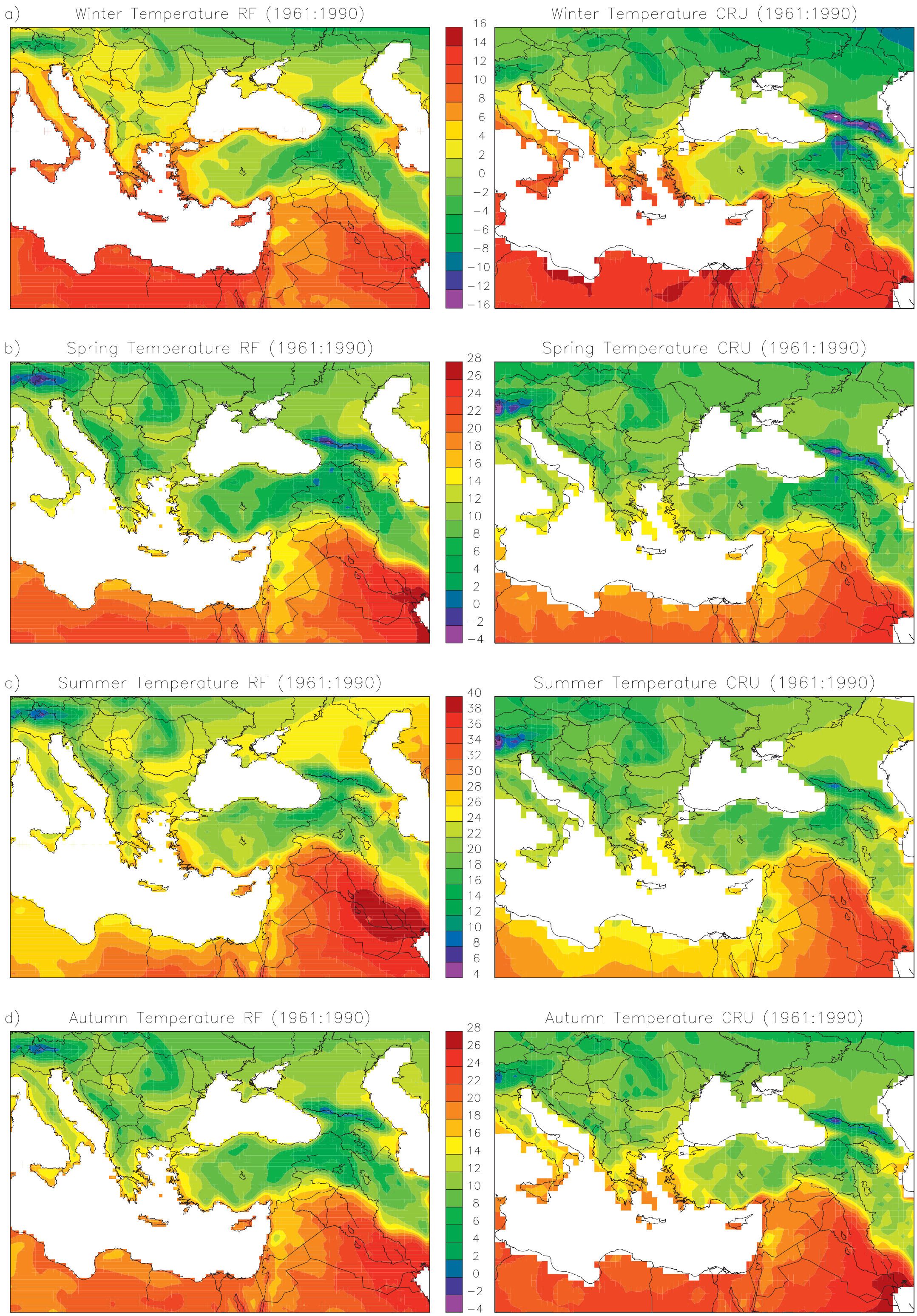

FIG. 2. Seasonal mean surface temperature (°C) comparison between (left) RF and (right) CRU for 1961–90: (a) winter, (b) spring, (c) summer, and (d) autumn.

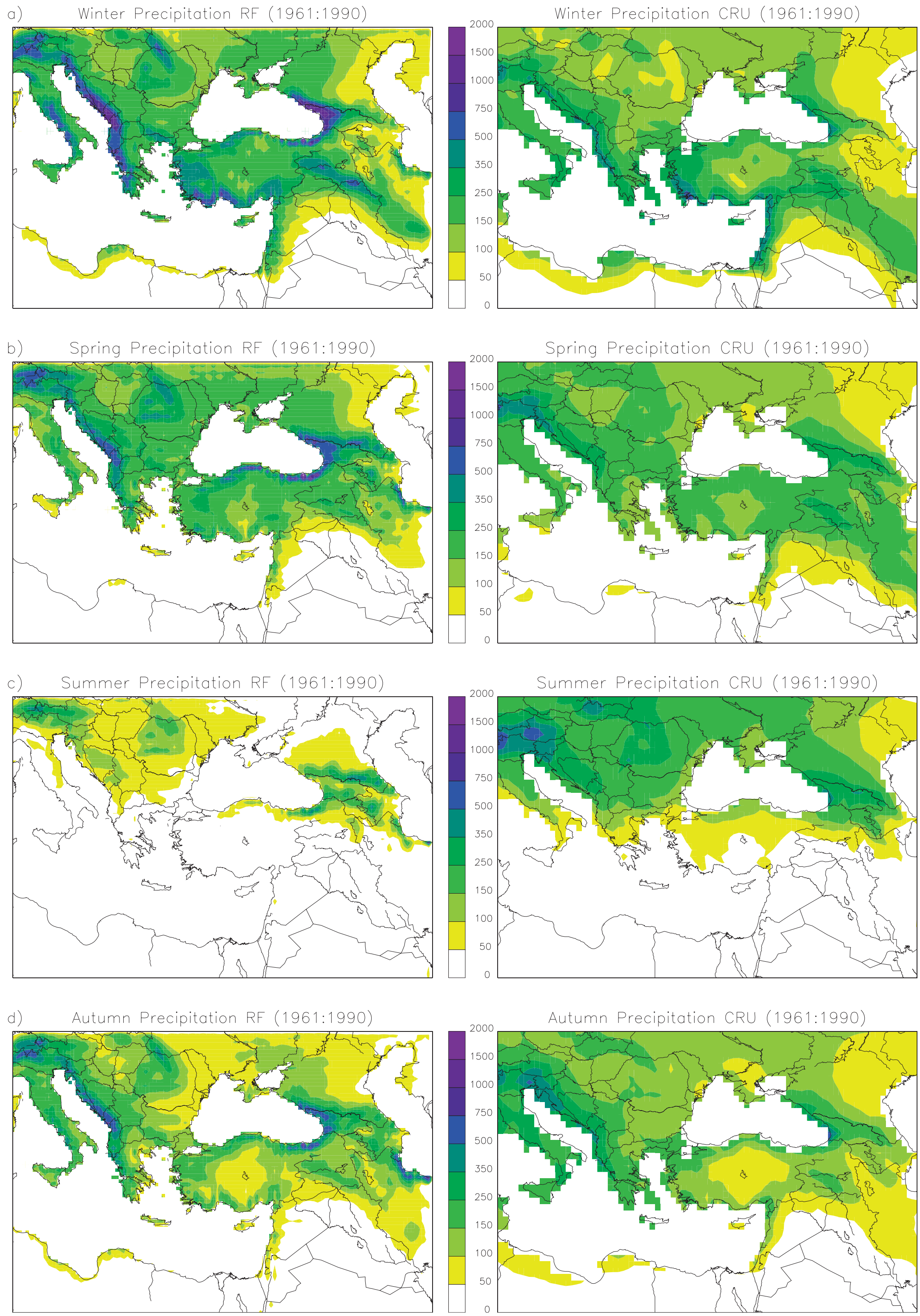

FIG. 3. Seasonal mean precipitation (mm) mean comparison between (left) RF and (right) CRU for 1961–90: (a) winter, (b) spring, (c) summer, and (d) autumn.

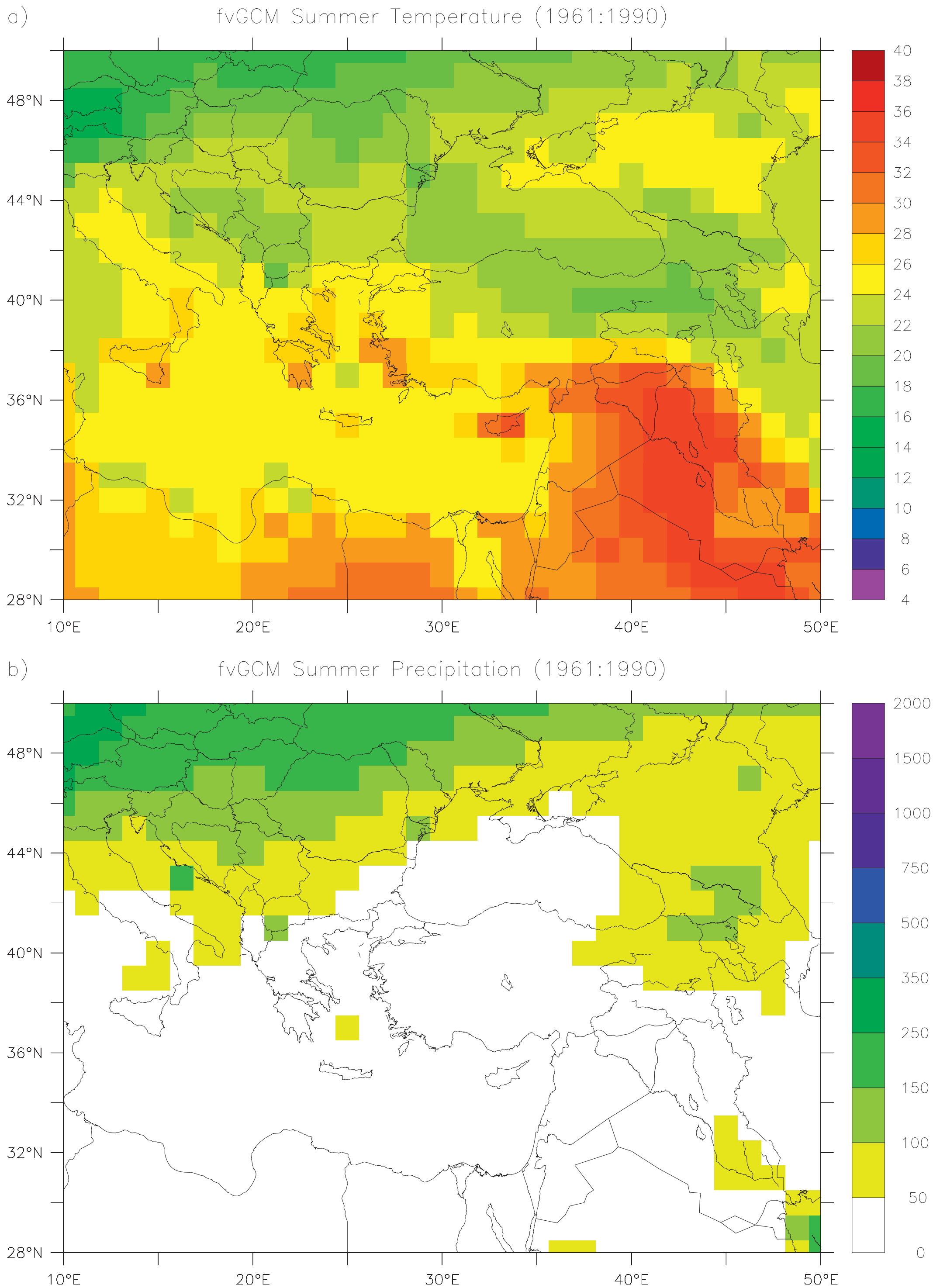

FIG. 4. (a) Summer mean temperature (°C) and (b) summer mean precipitation (mm) for the fvGCM RF simulation (1961–90).

has been realistically reproduced especially in the case of the country averages. The model has positive precipitation bias during winter and spring for the Balkan countries except for Greece and Turkey. For both countries, the model results closely match the observations.

Over Georgia and Romania the model overpredicted precipitation. As we noted earlier this may be due to a combination of sampling problems arising from both an inadequate resolution of the model and low density of observational stations particularly, over the Caucasus Mountains (Georgia) and the Carpathian Mountains (Romania). These problems may be compounded by the fact that the SUBEX large-scale precipitation scheme in the RegCM3 model does not have ice physics, which could in part be responsible for the excessive precipitation over the highlands. This may also explain some of the differences between the model precipitation and CRU during winter for the mountainous countries. In general, model bias tends to be characterized by overprediction of precipitation over the countries in the northern part of model domain and underprediction over the countries in the southern sector of the model domain.

b. *Future simulation: A2*

1) Surface temperature change

The range of the warming over EM is about 2°–5°C in winter, 2°–4°C in spring, 2°–8°C in summer, and 3°–5°C in autumn (Fig. 5). The most dramatic change occurs over the Balkan States in summer, which is as high as 8°C. The western region of Turkey is dominated by the similar heat extremes with temperature increases reaching 6°C. This summer increase is highly consistent with previous regional simulations (Gao and Giorgi 2008; Giorgi et al. 2004b; Räisänen et al. 2004). In addition, the pattern and magnitude of the changes in summer temperature produced by fvGCM (Fig. 7c) and RegCM (Fig. 5) are nearly the same. The typical difference between these two simulations is around 1°C over northern Italy, the Balkans (excluding Greece), and western Turkey. In Giorgi et al. (2004b) the differences in the RCM and GCM simulations over the Balkans is nearly 2°C in summer. Furthermore, warming over the east and southeast region of the model domain is about 3°C during the same season. Because of a more prolonged summer season, the changes in autumn surface temperature are also relatively very high. The winter and spring increases are not as high as in the case of autumn in the RegCM projection. Regarding seasonal changes, similar behavior was found in the analysis of the fvGCM simulations (Figs. 7a,b,d). Annual increase across the domain ranges between 2° and 5°C (not shown) and the temperature pattern change is still dominated by widespread summer warming through out the region. The model results show that the least increase occurs along the coast of Iskenderun Gulf and the surrounding region. Perhaps, this may be associated with the relatively small SST changes.

Changes in country area averages and in the spatial distribution for temperature are highly consistent with each other. To compute the statistical significance of the change in temperature, we assumed that the simulation results are normally distributed. The Welch two sample t test was applied to the model results. We found that the changes in surface temperature are statistically significant for all the countries and seasons based on the 95% confidence level.

Temperature increase is nearly same for all the countries in winter (Table 1). The largest change occurs over Moldova (3.7°C) and the lowest changes over the neighboring countries of Greece and Albania (2.4°C). However, summer season changes are highly variable from country to country. Warming over the Adriatic countries, Albania, Montenegro, Bosnia, Croatia, and Slovenia is very high, reaching up to 7°C. Extreme warming also affects the other Balkan countries and it is highly persistent in time. Conversely, surface temperature increase over Lebanon and Syria is only 3.1° and 3.4°C, respectively. A possible explanation for this relatively modest warming is that air over the surface of the eastern Mediterranean Sea is moderated by the influence of the vast sea waters. Autumn warming over Lebanon and Syria is 1°C higher than the summer warming. Generally, the surface temperature change in autumn over the EM domain is around 4°C for all the countries in the region. The temperature change in autumn is larger than that of spring due to the fact that the summer season extends into autumn season under the climate change conditions. The extension of summer season has also been confirmed by analyzing the 30 yr of daily mean temperature.

Räisänen et al. (2004) and the present study indicate that summer temperature increases in A2 over Balkan countries and west of Turkey is in the range of 6°–8°C, which is higher than its surroundings over the model domain.

2) Precipitation change

In the A2 simulation, we note a very coherent and distinct precipitation anomaly pattern during the winter season. The results show a significant increase (10%–50%; Fig. 6) in precipitation over the Carpathian Mountains and along the east coast of the Black Sea, over the Kackar and the Caucasus Mountains. Similar amounts of winter precipitation increase (5%–25%) over the coastal regions of Black Sea and Carpathian

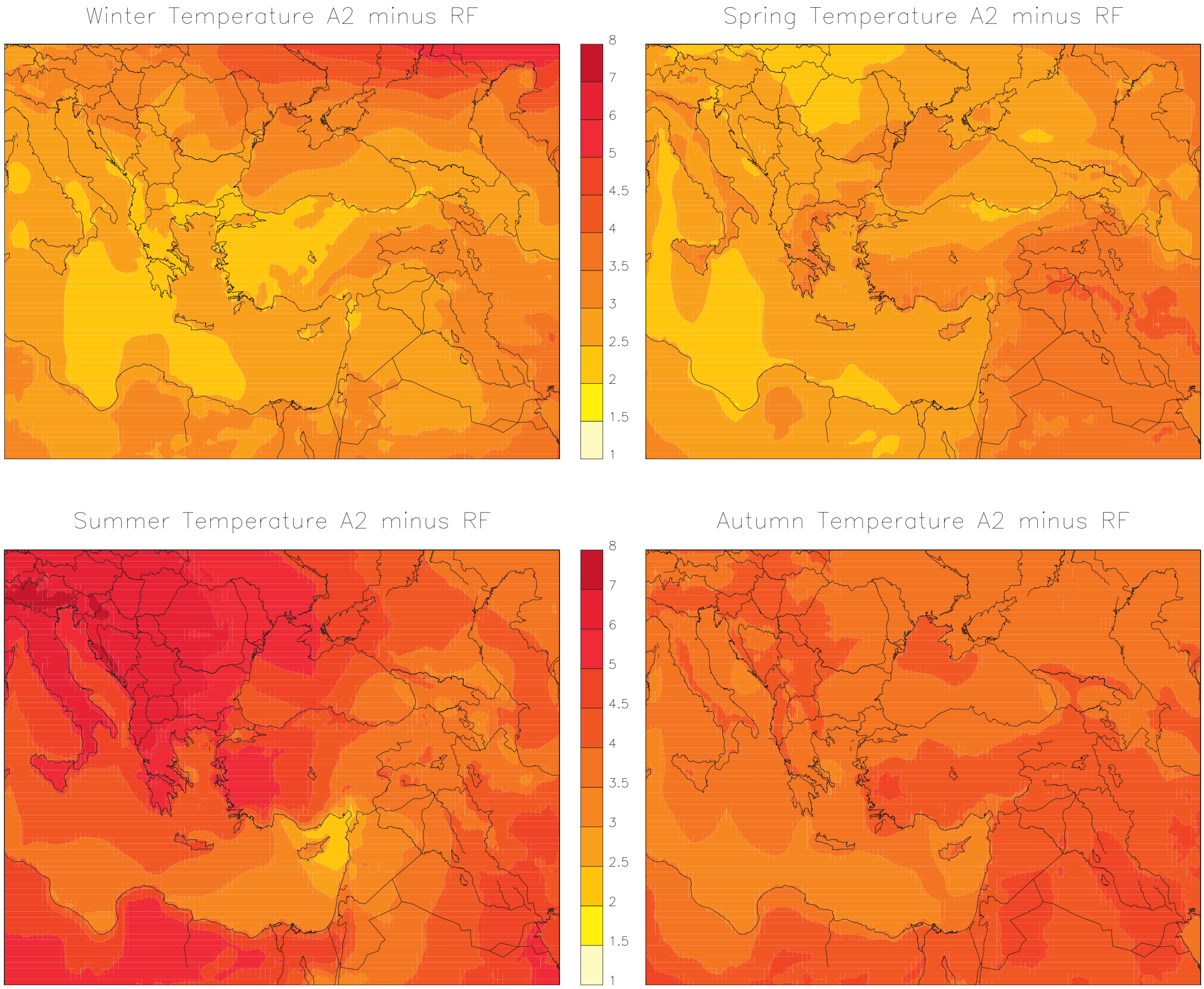

FIG. 5. Seasonal temperature change (A2 − RF) over the model domain: (top left) winter, (top right) spring, (bottom left) summer, and (bottom right) autumn.

Mountains (10% to >25%) have been simulated by Gao and Giorgi (2008). There is also large decrease (20%–60%) in precipitation over the southern and southeastern regions of Turkey, and the eastern coast of the Mediterranean Sea (Fig. 6). The decrease over the southern part of Turkey and the Balkan region is very similar to the changes found by Gao and Giorgi (2008) and Räisänen et al. (2004). Annual change of precipitation is dominated by the changes associated with the winter season. Comparison of fvGCM and RegCM3 projections for winter and spring precipitation show that the magnitude of the change the RegCM3 projection is much higher than the magnitude of the changes in the fvGCM projection (Figs. 7e,f). The contribution of the topographic effect over the Carpathians, Caucasus, Taurus, and Zagros Mountains on the changes in precipitation can be seen more clearly in the RegCM projection. In addition, resemblance of the changes in pattern in winter and autumn precipitation for these two projections (RCM and GCM) is more distinct than in the other seasons. The *P* values were calculated using the same method as the one we used for temperature and all the dominant changes we have described above are statistically significant (Fig. 8).

The change in the precipitation pattern appears to be part of a coherent climate change signal covering a much more extensive region over the Northern Hemisphere compared to the RegCM3 domain. Yin (2006) has discussed the poleward increase in the intensity and northward shift of the storm tracks for their ensemble mean of multimodel AOGCM climate change simulations. This intensification and shift over the midlatitudes was also evident in the fvGCM simulations, which were used to construct the lateral boundaries for RegCM3.

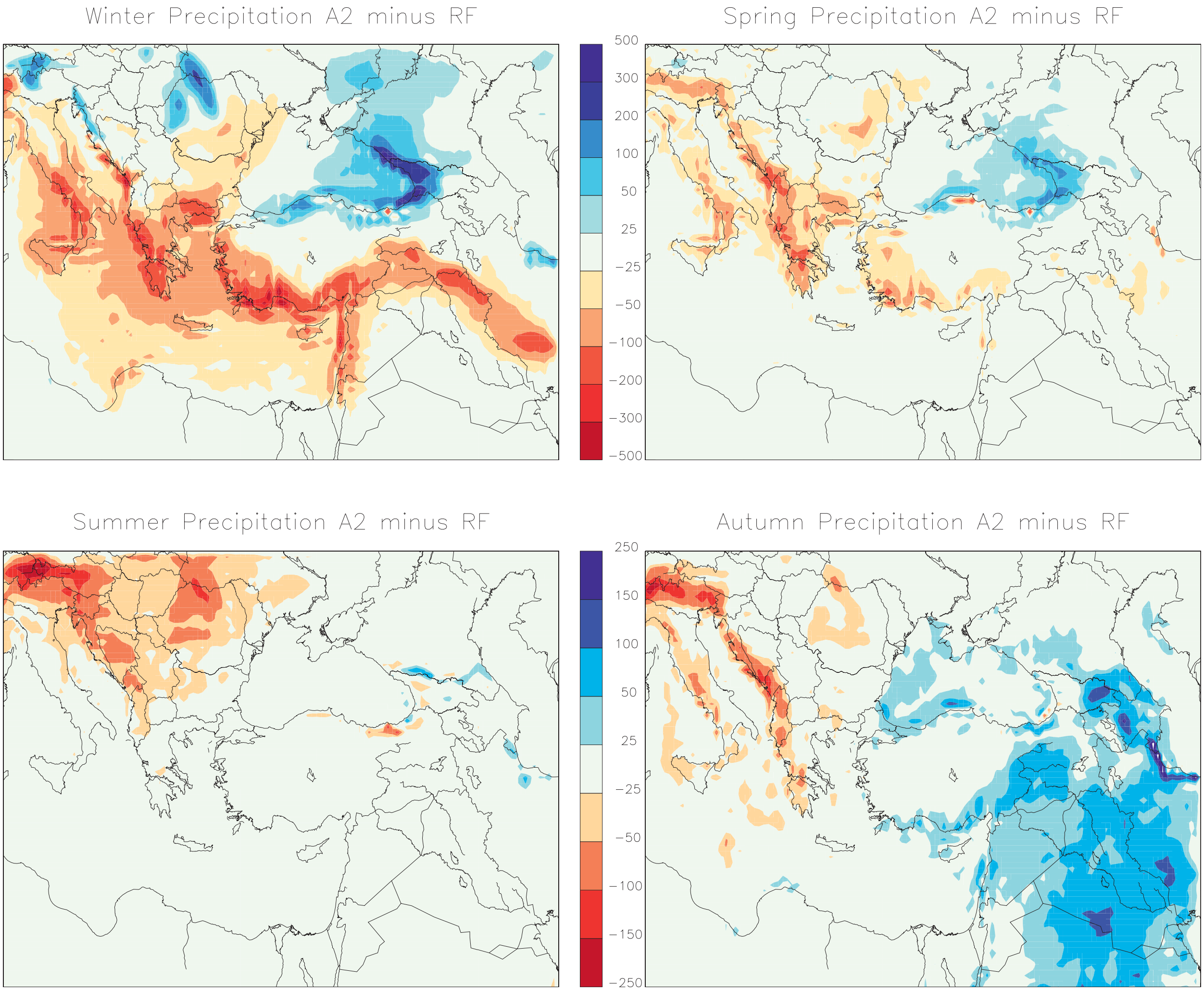

FIG. 6. Seasonal precipitation change (A2 − RF, mm) over the model domain: (top left) winter, (top right) spring, (bottom left) summer, and (bottom right) autumn.

Figure 9 is generated by embedding the low-level winds and the precipitation changes of the RegCM3 domain onto the FvGCM general circulation changes for winter. The local precipitation changes resolved by RegCM3 because of its fine spatial resolution (30 km) are consistent with the large-scale atmospheric circulation changes in the fvGCM over the EM region. Based on visual inspection, it is evident that the sharp topographic gradients resolved by RegCM3 are responsible for the localized intensification superimposed on the fvGCM background changes in climate. Enhanced 850-mb winds in A2 over the northern part of the domain appear to augment the amount of precipitation due to orographic forcing over the Black Sea coastal regions (Fig. 9; blue). Further inspection of the results indicates that the changes in the 850-mb wind in A2, over the southern part of the domain, interact with orography to reduce precipitation (Fig. 9; red). Correlation between changes in the 850-mb zonal wind and precipitation is very high (0.7–1) except over southern Turkey, which is more related to the meridional component of the wind (not shown).

Another important change in precipitation occurs in autumn and it is associated with the expansion of precipitation over the southeastern sector of the model domain in the A2 simulation. The primary sources of water for this region are the Euphrates and Tigris Rivers and net precipitation change over the basin of these rivers can directly affect streamflow discharge. This region, which includes Iraq, Syria, and southern Turkey, is generally very dry (less than 100 mm for the season) and the climatology of the region was well simulated in RF (Fig. 3). It is apparent that the change in large-scale circulation in A2 simulation is responsible

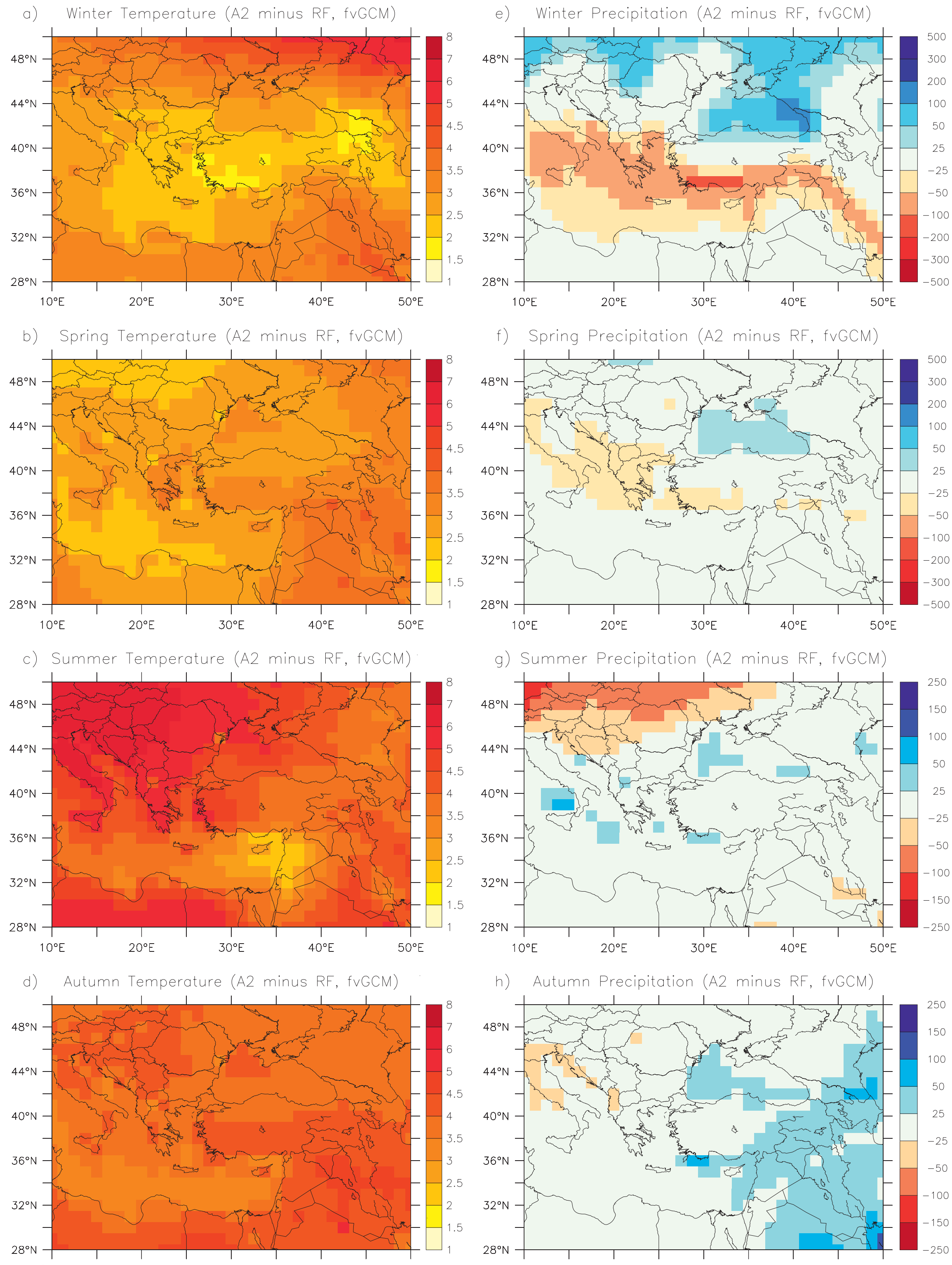

FIG. 7. (a)–(d) FvGCM seasonal temperature (°C) and (e)–(h) precipitation (mm) change (A2 − RF) over the domain of interest.

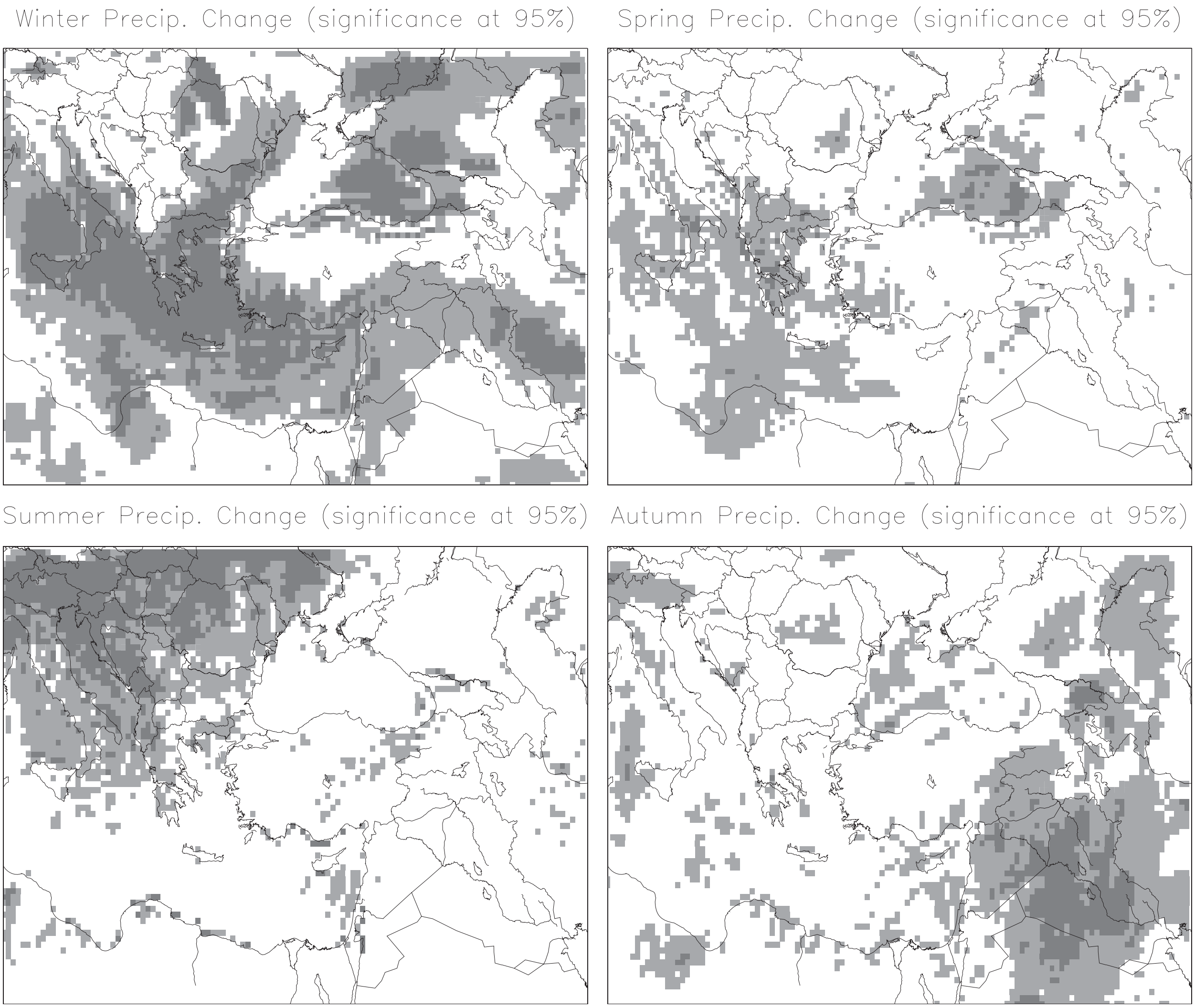

FIG. 8. Statistical significant areas for seasonal precipitation change at 95% (light gray) and 99% (dark gray) levels of confidence: (top left) winter, (top right) spring, (bottom left) summer, and (bottom right) autumn.

for weakening the high over the border region between Iraq and Saudi Arabia. Consequently, enhanced moisture entrainment from the Mediterranean Sea, the Red Sea, and the Persian Gulf into the region is likely to be responsible for the increase in precipitation over this region during autumn (Fig. 10). It is apparent that the changes in the large-scale circulation (Fig. 10; blue) are responsible for precipitation increase over the EM domain. Changes in the general circulation in the presence of orographic forcing (Fig. 10; red) are consistent with the decrease in precipitation over the Dalmatian coast. In the fvGCM projection, the magnitude of change in autumn precipitation (Fig. 7h) over the same region is very weak, which is probably the reason for the weaker response to orographic forcing. Moreover, the summer season is very dry virtually over the entire EM region and projected changes are not statistically significant except over the Alpine region. Consistent decrease in summer precipitation over the northwestern part of the model domain has been found in both RCM and GCM A2 simulations.

The high consistency between the RegCM3 and the fvGCM circulation changes is testimony to the fact that the distortion of flow across the lateral boundaries is minimum and that the exponential relaxation method employed in the nesting procedure works very well over the buffer zone (Figs. 9 and 10). This provides further confidence in the formulation of the RCM boundary conditions and its ability to deal with the transition from the fvGCM to the RegCM3 domains. This graphical approach, which we have developed specifically for the present study, shows the suitability of embedding a nested

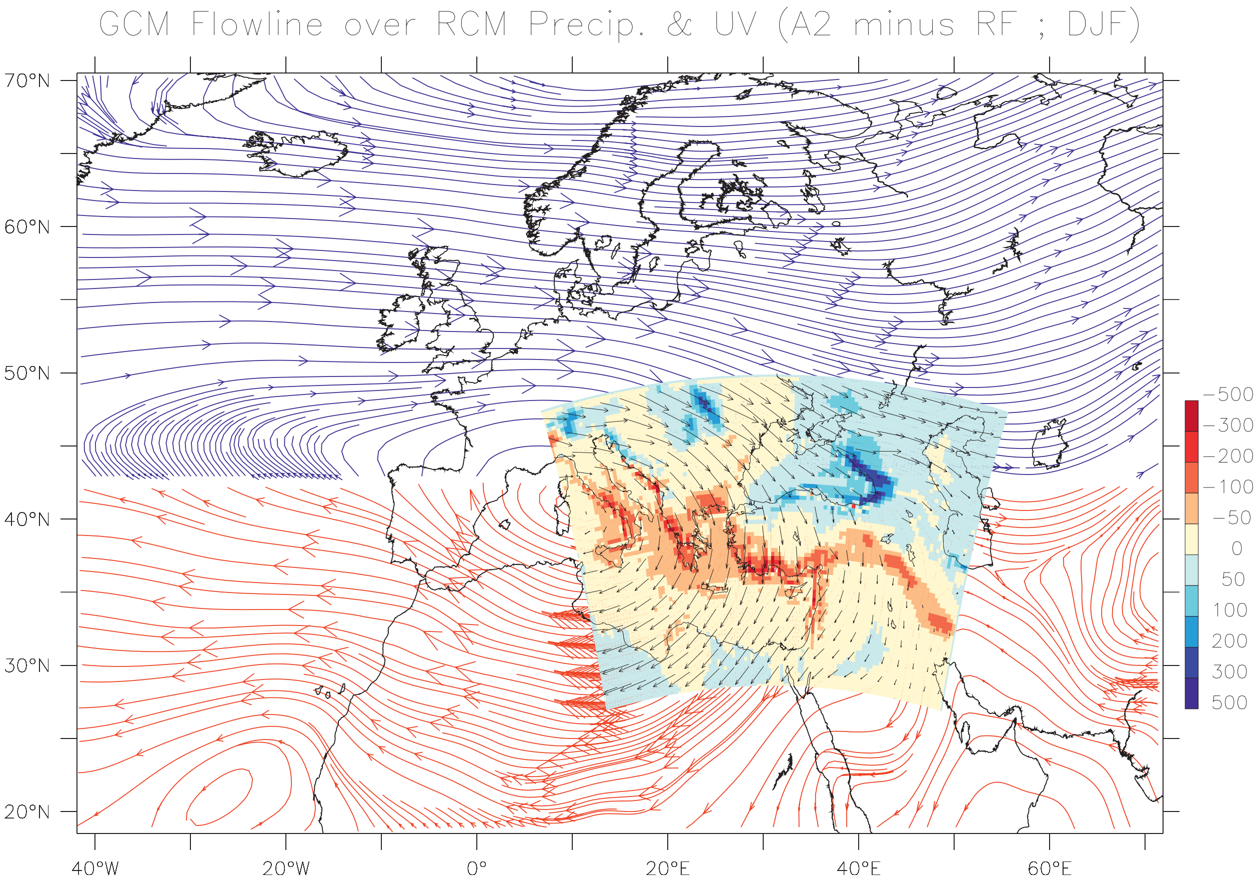

FIG. 9. RegCM3 (nested domain) precipitation and 850-mb wind change (A2 − RF) and fvGCM (outer domain) 850-mb flow line change (A2 − RF) in winter. The flow line in the outer domain corresponds to increased (blue) and decreased (red) precipitation in the nested domain.

grid into the GCM grid without distorting the background flow patterns. We believe it is very promising for the customization of regional climate models and we recommend it as a universal method for regional model customization.

Area averages over individual countries are perhaps more useful in evaluating precipitation changes for the purpose of impact studies (Table 2). The most dramatic change in winter precipitation is projected to occur over Greece (32% decrease), which is also statistically significant at the 99% level of confidence. Another Balkan state, Bulgaria, which is also directly affected by the changes in the large-scale circulation, is projected to suffer from a reduction of 23% in precipitation due to climate change. Over the Middle East countries, Syria, Iraq, Lebanon, and Israel, the reduction in precipitation is in the range of 24%–32% in winter and it is statistically significant. However, most of the annual precipitation deficit over these countries is compensated by autumn rains. In spring, the neighboring countries of Albania and Macedonia experience drying conditions with an 18% decline in rainfall observed in A2. In this season, Greece still has the most dramatic drop of 28%. All over the Balkan countries the summer season is dominated by drier conditions (40%–60% reduction), which is highly consistent with previous regional climate change studies (Gao and Giorgi 2008; Giorgi et al. 2004b; Räisänen et al. 2004). Georgia is the only country with consistent precipitation increase for all seasons except summer. The most dramatic and statistically significant increase will occur in winter (24%) for Georgia and it is important to note that this is climatologically the wettest season of year.

The simulated changes are larger in our study (driven by fvGCM), than in the projections obtained by Giorgi et al. [2004b; driven by the Hadley Centre Atmosphere-Only Model (HadAM3H).] This is consistent with another regional climate change modeling study by Räisänen et al. (2004) based on two different GCMs (HadAM3H and ECHAM4). Their model domain covers part of the EM region and with similar projected precipitation results for both summer and winter seasons

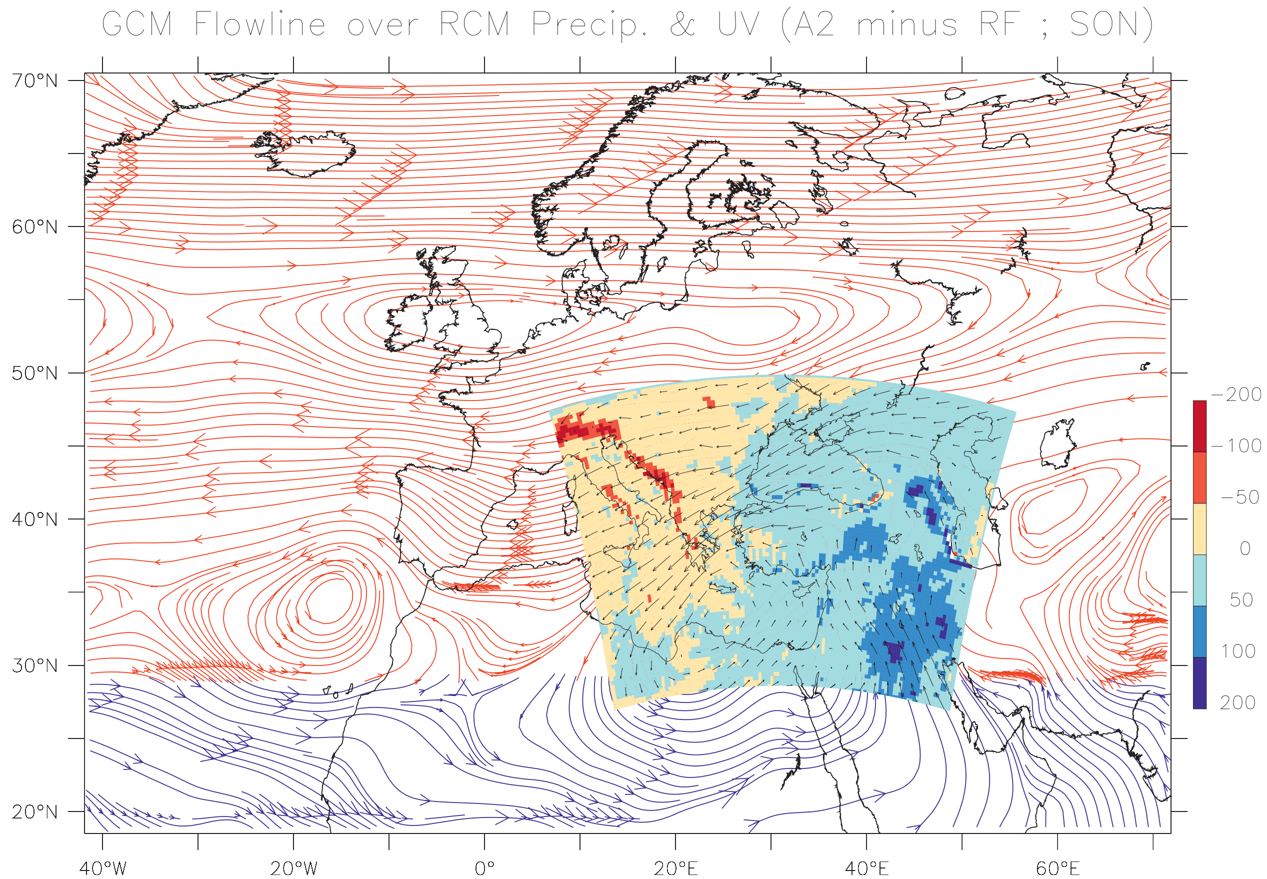

FIG. 10. As in Fig. 9, but for autumn.

over the Balkans and southern Turkey. With regard to Räisänen et al. (2004) downscaling, which was based on two different GCMs, it is noteworthy that our fvGCM-driven projections are more consistent with their ECHAM4-driven results compared to the corresponding HadAM3H-driven projections. In both studies (fvGCM and ECHAM4 driven), the reduction of precipitation in winter and summer for A2 simulations over Greece and the south of Turkey is in the range of 20%–50% and 30%–60%, respectively.

4. Conclusions

We have investigated the projected climate change over the EM region using the RegCM3 regional climate model for the RF and A2 IPCC scenario. Highlights of this study include the following: (i) use of relatively fine resolution (30 km) than many previous studies to reduce computational bias particularly in the presence on complex orography; (ii) investigation of confidence in the model by adopting a systematic multifacet comparison among the model reference/projection (RF/A2) simulation results, CRU gridded observational data at 0.5° resolution, and station data, which confirm that the model bias is significantly smaller than the projected climate change signal; (iii) confirmation of the robustness of the model projections by ascertaining that our results are consistent with previous studies over the regions where the model numerical domains overlap; (iv) presentation of evidence of the ability of the regional model downscaling approach to simulate important and realistic spatial climatic details, which GCMs cannot reproduce; (v) aggregation of climate change results in context of individual countries to enhance interpretability of the climate change projection results; and (vi) development and successful implementation of a new graphics method to confirm seamless nesting of the RegCM3 grid into the GCM grid without any apparent distortion of the flow patterns across the two models.

The model simulation of the present-day climate is realistic except over Caucasus Mountains in winter and over southern Iraq in summer (+4°C bias). This is an important source of reassurance in the RegCM3 performance considering such complex topography and heterogeneous surface conditions over the EM region. In particular, model climatology for summer temperature and autumn precipitation is accurately reproduced over most of the model domain. However, we have noted some significant differences between the RF control run and the observations for the spring season precipitation over the Black Sea region in Turkey, and for the temperature for all the seasons of the year. There is some indication, in part, that the differences may be attributed to observational deficiencies. However, model shortcomings could be the dominant source of the systematic bias, particularly over the Black Sea region during spring.

The projected climate change, especially during the summer season over the Balkan states and western Turkey, is characterized by an increase in temperature in the range of 5°–7°C, which is 3°–4°C higher than the eastern part of the domain. In winter, temperature change over the entire domain is less than 3°C thus resulting in a very large interseasonal temperature range between the winter and summer seasons over the Balkan states and western Turkey. We infer that the 4°C increase in the interseasonal temperature difference could significantly shift the timing of the transition of the seasons.

The changes in the precipitation patterns are perhaps the most conspicuous feature in the projected climate change. They are particularly important regarding the availability of water resources in the future. The change in the winter precipitation over EM is related to the change in the anticyclonic circulation over Europe in the A2 case, which is also in good agreement with the previous study of Giorgi et al. (2004b). The largest decrease in winter precipitation, which is in excess of 30%, occurs over Greece and southern Turkey. We note the strong resemblance of our simulated climate change pattern (A2 minus RF) in winter over EM, and the North Atlantic–eastern Mediterranean teleconnection pattern obtained by Eshel and Farrell (2000). Their study of contemporary climate variability was based on observational analysis of the (National Centers for Environmental Prediction) NCEP–NCAR reanalysis and stations data. We infer that climate change over EM will manifest itself in terms of the modulation of North Atlantic Oscillation by global warming.

The winter precipitation is projected to decrease by 24% in A2 over southeastern Turkey, which is upstream of the Euphrates and Tigris River basins. These two rivers are the main sources of water supply for the region. The results indicate that over the same region there will be an increase of 48% in the autumn precipitation, which could help to compensate for the winter deficit and therefore reduce the net change during the annual cycle. The change in the autumn flow pattern in A2 will also result in the expansion of the seasonal rains into Syria and Iraq, which currently do not get any rainfall during this time of the year. All the major precipitation changes are statistically significant over the model domain.

The comparison of RCM and GCM circulation based on overlying the nested and outer domains is very instructive in the interpretation of the results. Our analysis shows that the seamless continuity of the circulation change simulated by RegCM3 and fvGCM across the boundary of the two domains confirms the effectiveness of the nested procedure. This particular feature of our analysis tools may be universally helpful for the evaluation of the downscaling method and useful for determining appropriate domains and boundaries in other nesting studies.

In this study, pattern and magnitude changes over EM for temperature (summer) and precipitation (winter) in A2 simulation are quite similar with the changes found in previous regional climate change studies (Gao et al. 2006; Gao and Giorgi 2008; Giorgi et al. 2004b; Räisänen et al. 2004). In these studies several GCMs (e.g., HadAHM, ECHAM4, and fvGCM) were used to drive RCMs simulations. The consistency among those studies and our results is positive testimony regarding the robustness of the regional climate modeling approach in general, and RegCM3 in particular for investigating climate change over the EM region.

Considering the social economic diversity of the EM region, our climate change projections indicate potential for increased stress on the future water-dependant socioeconomic activities of the region. Although there are always some inherent uncertainties associated with climate change scenario studies we believe that the results of our investigation could have important implications in the development of strategies for addressing the climate change problem for the EM region.

Acknowledgments. This research was supported by the NSF/Climate Dynamics Program, Project ATM-0438116. We extend our gratitude to Jared H. Bowden, Neil Davis, Richard Anyah, and Nihat Cubukcu for their assistance, which significantly helped to improve this paper. We thank the ICTP staff for providing us with the fvGCM data and their continuous assistance throughout the study. The postprocessing of data was carried out partly at the CLIMLAB Laboratory at North Carolina State University.

REFERENCES

Alpert, P., I. Osetinsky, B. Zivb, and H. Shafir, 2004: Semi-objective classification for daily synoptic systems: Application to the eastern Mediterranean climate change. *Int. J. Climatol.,* **24,** 1001–1011.

Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment, part I. *J. Atmos. Sci.,* **31,** 674–701.

Chen, M., D. Pollard, and E. J. Barron, 2003: Comparison of future climate change over North America simulated by two regional models. *J. Geophys. Res.,* **108,** 4348, doi:10.1029/2002JD002738.

Christensen, J. H., and O. B. Christensen, 2007: A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Climatic Change,* **81,** 7–30.

——, T. R. Carter, and F. Giorgi, 2002: PRUDENCE employs new methods to assess European climate change. *Eos, Trans. Amer. Geophys. Union,* **83,** 147.

——, ——, M. Rummukainen, and M. Amanatidis, 2007: Evaluating the performance and utility of regional climate models: The PRUDENCE project. *Climatic Change,* **81,** 1–6.

Coppola, E., and F. Giorgi, 2005: Climate change in tropical regions from high-resolution time-slice AGCM experiments. *Quart. J. Roy. Meteor. Soc.,* **131,** 3123–3145.

Déqué, M., and Coauthors, 2007: An intercomparison of regional climate simulations for Europe: Assessing uncertainties in model projections. *Climatic Change,* **81,** 53–70.

Dickinson, R. E., A. Henderson-Sellers, and P. J. Kennedy, 1993: Biosphere–Atmosphere Transfer Scheme (BATS) version 1E as coupled to the NCAR Community Climate Model. NCAR Tech. Rep. NCAR/TN-387+STR, 72 pp.

Diffenbaugh, N. S., J. S. Pal, R. J. Trapp, and F. Giorgi, 2005: Fine-scale processes regulate the response of extreme events to global climate change. *Proc. Natl. Acad. Sci. USA,* **102,** 15 774–15 778.

Duffy, P. B., and Coauthors, 2006: Simulations of present and future climates in the western United States with four nested regional climate models. *J. Climate,* **19,** 873–895.

Eshel, G., and B. F. Farrell, 2000: Mechanisms of eastern Mediterranean rainfall variability. *J. Atmos. Sci.,* **57,** 3219–3232.

Evans, J. P., R. B. Smith, and R. J. Oglesby, 2004: Middle East climate simulation and dominant precipitation processes. *Int. J. Climatol.,* **24,** 1671–1694.

Gao, X., and F. Giorgi, 2008: Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Global Planet. Change,* **62,** 195–209.

——, J. S. Pal, and F. Giorgi, 2006: Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation. *Geophys. Res. Lett.,* **33,** L03706, doi:10.1029/2005GL024954.

Giorgi, F., C. Shields, and G. T. Bates, 1994: Regional climate change scenario over the United States predicted with a nested regional climate model. *J. Climate,* **7,** 375–399.

——, L. O. Mearns, C. Shields, and L. McDaniel, 1998: Regional nested model simulations of present day and 2 x CO_2 climate over the central plains of the U.S. *Climatic Change,* **40,** 457–493.

——, B. Xunquiang, and J. S. Pal, 2004a: Mean, interannual variability and trends in a regional climate change experiment over Europe. I: Present-day climate (1961–1990). *Climate Dyn.,* **22,** 733–756.

——, ——, and ——, 2004b: Mean interannual variability and trends in a regional climate change experiment over Europe. II: Climate change scenarios (2071–2100). *Climate Dyn.,* **23,** 839–858.

Graham, L. P., 2004: Climate change effects on river flow to the Baltic Sea. *Ambio,* **33,** 235–241.

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.,* **121,** 764–787.

Hewitt, C., 2005: The ENSEMBLES Project—Providing ensemble-based predictions of climate changes and their impacts. *EGU Newsletter,* No. 13, 22–25. [Available online at http://www.the-eggs.org/data/eggs_13.pdf.]

Hirakuchi, H., and F. Giorgi, 1995: Multi-year present and 2 x CO_2 simulations of monsoon climate over Asia and Japan with a regional climate model nested in a general circulation model. *J. Geophys. Res.,* **100,** 105–126.

Krichak, S. O., and P. Alpert, 2005: Decadal trends in the east Atlantic-west Russia pattern and Mediterranean precipitation. *Int. J. Climatol.,* **82,** 27–39.

——, M. Tsidulko, and P. Alpert, 2000: Monthly synoptic patterns associated with wet/dry conditions in the eastern Mediterranean. *Theor. Appl. Climatol.,* **65,** 215–229.

——, P. Alpert, K. Bassat, and P. Kunin, 2007: The surface climatology of the eastern Mediterranean region obtained in a three-member ensemble climate change simulation experiment. *Adv. Geosci.,* **12,** 67–80.

Leung, L. R., Y. Qian, X. Bian, W. M. Washington, J. Han, and J. O. Roads, 2004: Mid-century ensemble regional climate change scenarios for the western United States. *Climatic Change,* **62,** 75–113.

Lin, S.-J., 2004: A ''vertically Lagrangian'' finite-volume dynamical core for global models. *Mon. Wea. Rev.,* **132,** 2293–2307.

McGregor, J. L., and K. Walsh, 1994: Climate change simulations of Tasmanian precipitation using multiple nesting. *J. Geophys. Res.,* **99,** 20 889–20 905.

Pal, J. S., E. E. Small, and E. A. B. Eltahir, 2000: Simulation of regional-scale water and energy budgets: Representation of subgrid cloud and precipitation processes within RegCM. *J. Geophys. Res.,* **105,** 29 579–29 594.

——, F. Giorgi, and X. Bi, 2004: Consistency of recent European summer precipitation trends and extremes with future regional climate projections. *Geophys. Res. Lett.,* **31,** L13202, doi:10.1029/2004GL019836.

——, and Coauthors, 2007: Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET. *Bull. Amer. Meteor. Soc.,* **88,** 1395–1409.

Räisänen, J., and Coauthors, 2004: European climate in the late twenty-first century: Regional simulations with two driving global models and two forcing scenarios. *Climate Dyn.,* **22,** 13–31.

Yin, J. H., 2005: A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophys. Res. Lett.,* **32,** L18701, doi:10.1029/2005GL023684.