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Future Projections of Cloud Cover and Surface Relative Humidity Over Greece during the 21st Century Based on EURO-CORDEX Simulations †

Ioannis Logothetis [1,2,*], Kleareti Tourpali [1] and Dimitrios Melas [1]

1 Laboratory of Atmospheric Physics, Department of Physics, Faculty of Sciences, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; tourpali@auth.gr (K.T.); melas@auth.gr (D.M.)
2 Centre for Research and Technology Hellas, Chemical Process and Energy Resources Institute, 57001 Thermi, Greece
* Correspondence: ilogothe@physics.auth.gr
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Abstract: Greece is located over a climate-change-prone region. The aim of this study is to investigate the projection of cloud cover fraction and surface relative humidity during the period from 1970 to 2099. In this analysis, we use six high-resolution regional climate model simulations (RCMs) available from the EURO-CORDEX program. The RCMs include the historical period from 1970 to 2005 and the future period from 2006 to 2099 under the influence of the representative concentration pathway (rcp) scenarios rcp2.6, rcp4.5, and rcp8.5. Results show significant projected changes mainly during the last period of the 21st century according to the rcp8.5 scenario. In particular, during the 2070–2099 period, with respect to a reference period (1976–2005), both the cloud cover fraction and the surface relative humidity are reduced by about 5% and 5% to 8%, respectively, over continental Greece. Focusing on the winter season, the comparison between future and reference periods shows that the cloud cover fraction presents a significant decrease of about 10% to 20% mainly during the last period of the 21st century. Finally, the surface relative humidity in 2070–2099 shows insignificant changes according the low and moderate scenarios (rcp2.6 and 4.5) and limited changes for the high emission scenario (rcp8.5).

Keywords: climate change; future projections; cloud cover fraction; surface relative humidity; rcp scenarios; EURO-CORDEX simulations; Eastern Mediterranean; Greece

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1. Introduction

Greece is located in the heart of one of the regions most susceptible to climate change in the world, the Eastern Mediterranean. The increased severe climate and weather condition over this region turns the Mediterranean into a climate hot spot [1,2]. Climate change in combination with the complex orography (the mountains and the seas) and the weather patterns over Greece increases the climate danger and vulnerability of this region. Today, it is clear that global warming could be critically reflected in many socioeconomic and natural sectors. Some of these sectors are land use, agriculture, food and water resources, sailing and transport, tourism, biodiversity, pollution, heat waves, fire events, and human health [3,4]. Regarding the economy, the Bank of Greece has estimated that the cost of climate change till 2100 can be reach EUR 577 billion [3]. In this regard, our work studies the projected changes of cloud cover fraction and surface relative humidity during the period of 1970 to 2099 over the Greek area.

Cloud cover variability is considered as a key climatic element because it drastically influences the radiation budget and the transfer of energy affecting the atmospheric circulation and weather [5,6]. Previous studies have shown that changes in cloud cover are associated with climate sensitivity [5,7]. Generally, the decrease in clouds is related to warmer conditions in the earth surface; consequently, the air temperature increases, and this leads to an even more decrease in clouds [6]. The complexity of the cloud cover and heat flux mechanisms increases the uncertainty regarding the feedbacks between cloud cover and global warming [8]. In this context, the scientific community considers as a major issue further investigations of future projections of cloud cover and the related feedback mechanisms in the atmosphere [4].

The warming climate also afflicts the relative humidity. Generally, relative humidity has an impact on human health, the comfort sense of people, and ecosystems. Global warming changes the temperature gradient between ocean and continent systems, affecting precipitation [8]. Relative humidity is usually correlated with precipitation and negatively related to temperature [9]. These points indicate that there is a relation between global warming and relative humidity (and vice versa). Changes in humidity and temperature in ocean–continent systems affect the moist static energy, having as a result changes in the dynamics of the atmosphere [10]. The alternation of relative humidity in a warmer future can possibly modulate the cloud fraction and precipitation patterns. Finally, in a warmer climate, the relative humidity and cloud cover are modulated by changes in atmospheric circulation and the dynamics of the atmosphere [11].

In this study, data from state-of-the-art regional climate model simulations (RCM EURO-CORDEX) are used to investigate the future projections of cloud cover fraction and relative humidity in the Greek region. RCMs are a powerful tool that gives the scientific community an opportunity to examine the climate conditions and the mechanisms that modulate the future climate under warming conditions [12]. Our study follows the sequential structure. In Section 2, we present the material and methods. Section 3 shows our findings, and finally, we sum up the main points of this study in the conclusion (Section 4).

2. Data and Methods

In this work, the annual mean and seasonal mean values (calculated from daily data) of cloud cover fraction (ccf; in %) and surface relative humidity (sRH; in %) of six RCM simulations during the period from 1970 to 2099 are used (Table 1).

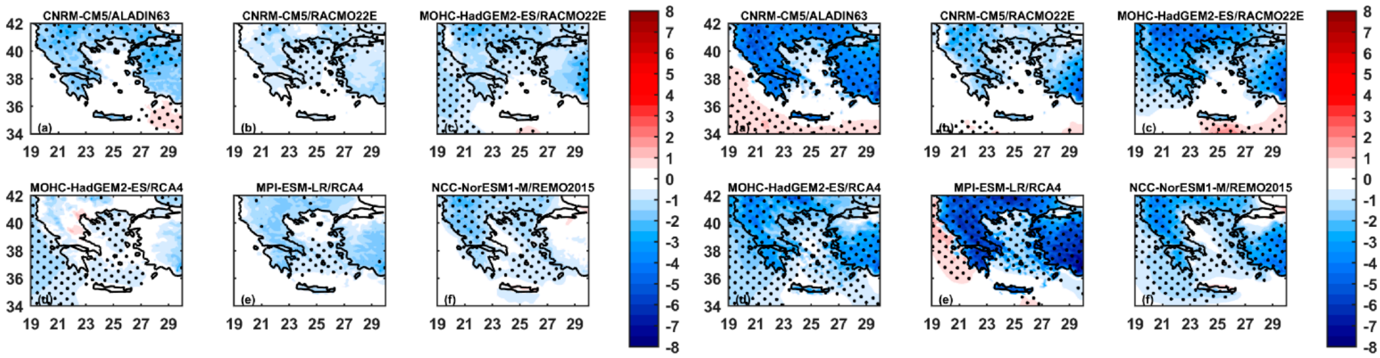
Table 1. List of RCM (EURO-CORDEX) simulations used in this study.

RCM	Driving GCM	Experiment	hist	rcp2.6	rcp4.5	rcp8.5
ALADIN63.v2	CNRM.CNRM-CERFACS-CNRM-CM5	r1i1p1	×	×	×	×
RACMO22E.v2	CNRM.CNRM-CERFACS-CNRM-CM5	r1i1p1	×	×	×	×
RACMO22E.v2	KNMI.MOHC-HadGEM2-ES	r1i1p1	×	×	×	×
RCA4.v1	SMHI.MOHC-HadGEM2-ES	r1i1p1	×	×	×	×
RCA4.v1	SMHI.MPI-M-MPI-ESM-LR	r1i1p1	×	×	×	×
REMO2015.v1	GERICS.NCC-NorESM1-M	r1i1p1	×	×	×	×

The data are retrieved from the EURO-CORDEX project at a spatial resolution of 0.11° × 0.11° (about 12 km). For the analysis, composite difference maps of the annual and seasonal mean of sRH and ccf are calculated over the Greek region (19° E–29° E, 34° N–42° N). The projected changes are investigated by comparing three future periods with a reference historical period (RF: 1976–2005). In particular, we investigate the climate changes of sRH and ccf for the near (F1: 2010–2039), middle (F2: 2040–2069), and late (F3: 2070–2099) future period of the 21st century compared with RF. For the future projections, we use the representative concentration pathway (rcp2.6, rcp4.5, and rcp8.5) scenarios. The rcp's depict the additive radiation forcing (W/m^2) in 2100 regarding the preindustrial period, and they measure the impact of greenhouse gas emissions on climate change [4]. The statistical significance of the composite differences is calculated at the 95% confidence level using the two-tailed *t*-test [13].

3. Results

Both for sRH and ccf, the main changes are found during the end of the 21st century according to the rcp8.5 scenario. The composite difference mean maps of annual sRH (rcp8.5 scenario) for the first (F1; Figure 1A) and last periods of the 21st century (F3; Figure 1B) with respect to the RF (period from 1976 to 2005) are shown in Figure 1. The analysis shows that sRH decreases mainly over continental Greece. In particular, sRH during F1 compared with RF reduces by about 2–3% (Figure 1A; please note that the percentage values are absolute differences). Additionally, four out of the six simulations (Figure 1A(a–c,f)) show a significant decrease in sRH by about 2–4% over northern Greece. The majority of the simulations present a limited decrease in sRH over the Aegean Sea (about 1–2%; Figure 1A(b–f)). The analysis shows that during F3, sRH reduces compared with RF over continental Greece (up to 8%; Figure 1B). Over the Aegean Sea, the simulations show limited changes of sRH of about 1–1.5% except for MPI-ESM-LR/RCA4, which shows a reduction of about 3–4% over the central-eastern and central-western Aegean Sea (Figure 1B(e)). Previous studies have shown that global warming leads to the reduction of relative humidity in tropical and middle latitudes. Additionally, there is a complex direct–indirect relation between the changes in relative humidity and cloud cover pattern [11,14]. Byrne and O'Gorman [10] showed that the main changes of specific humidity are mainly located over continental areas for the geographical window from 40° S to 40° N. In line with this, our findings clearly show that, over the Greek area, significant changes of sRH over the continental area and limited changes of sRH over the sea regions (Aegean and Ionian Sea) are projected during the future period, respectively.



(**A**) (**B**)

Figure 1. Annual mean sRH composite difference according to the rcp8.5 scenario of (**A**) F1 and RF and (**B**) F3 and RF for each simulation. The dotted points denote statistical significance at 95%.

Figure 2 shows the calculation of mean composite difference maps as in Figure 1, but for ccf. Our analysis shows that the most significant differences are presented for the rcp8.5 scenario compared with the other future scenarios (rcp2.6 and rcp4.5; not shown). Generally, ccf reduces in future projections over Greece. In particular, F3 shows the most significant reduction of ccf (rcp8.5 scenario). The simulations show that the ccf reduction varies from 1% to 8%, depending on the region of continental Greece (please note that the percentage values are absolute differences; Figure 2B). Additionally, during F1, only two out of the six simulations show that ccf reduces by about 1–3% (Figure 2A(a,f)). Sanchez-Lorenzo et al. [15] showed that ccf decreased during the recent past period (from 1971 to 2005), using observations, satellite, and reanalysis data. Furthermore, ccf presents a decreasing trend for the Mediterranean region, and the sign of reduction is maximized during the winter and spring seasons. Recent studies, using CMIP5 model simulations, have shown a negative trend of ccf for the Mediterranean region during the future period [16,17]. Our results are in line with these works, indicating that ccf, over the Greek region, reduces especially over the continental area during the rcp8.5 scenario.

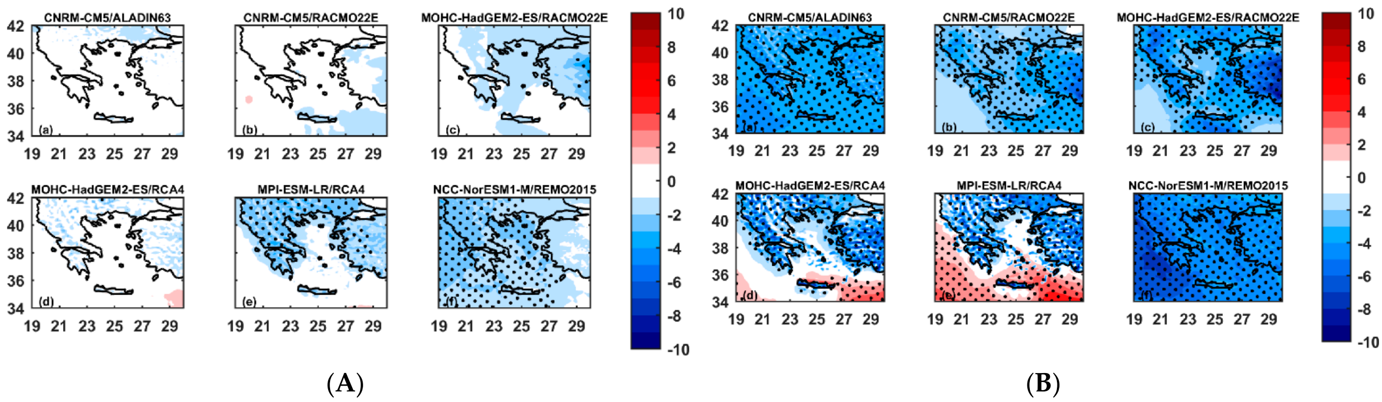


Figure 2. Annual mean ccf composite difference according to the rcp8.5 scenario of (**A**) F1 and RF and (**B**) F3 and RF for each simulation. The dotted points denote statistical significance at 95%.

According to the rcp8.5 scenario, simulations show that about 38% of the years of RF show sRH larger than the mean sRH for the whole period (from 1970 to 2099). For the future, the number of years reduces correspondingly by about 30%, 20%, and 13% for F1, F2, and F3. The common analysis for ccf shows about 37% for RF and 31%, 21%, and 10% for F1, F2 and F3, respectively. To summarize, our findings emphasize the reduction of sRH and ccf over continental Greece during the end of the 21st century especially in the rcp8.5 scenario. These changes alter the energy radiation budget and affect the weather systems, the atmospheric dynamics, and the circulation of the atmosphere. The projected changes in combination with the increased temperature over Eastern Mediterranean can drastically unbalance the climate and weather patterns of this sensitive region.

We focus the analysis on the winter (DJF) season because it is the season with the maximum ccf and sRH in Greece. Figure 3 shows the relative composite difference (%) of DJF between F3 and RF for all rcp scenarios. The results of the analysis indicate that the changes of sRH are insignificant for the rcp2.6 and rcp4.5 scenarios (Figure 3A(a–l)). Some limited changes are found over northwestern continental Greece in the rcp8.5 scenarios. In particular, four out of the six simulations show a small reduction of sRH (Figure 3A(m–r)) over northwestern continental Greece, and two out of the six simulations show an increase in sRH by about 4–6% over western Greece (Figure 3A(p,q)).

For the future projections of (DJF) ccf, the main changes are presented in the rcp8.5 scenario. This analysis shows a relative reduction (with respect to RF) of about 10–20% over the Greek domain (Figure 3B(m–r)). According to the rcp2.6 scenario, the simulations show insignificant changes (Figure 3B) except for CNRM-CM5A/RACMO22E and MPI-ESM-LR/RCA4 simulations, which present a limited relative increase and decrease in ccf over continental Greece, respectively (Figure 3B(b,e)). Finally, for the moderate scenario (rcp4.5), ccf in three out of the six simulations shows a relative decrease (about 4–8%) especially over the sea region of the Greek domain (Figure 3B(g–l)).

To sum up, the sRH projections show that the maximum (DJF) changes are found according to the rcp8.5 scenario during F3; however, these differences are not clear for the RCMs because the sign varies among the simulations (for example, Figure 3A(m–q)). Additionally, ccf decreases during DJF, mainly during the end of the 21st century (F3), according to the rcp8.5 scenario. Finally, the results of the future projections over continental Greece according to the rcp2.6 and rcp4.5 scenarios are insignificant, and in some cases, the findings show a different sign among the simulations (for instance, Figure 3B(b–f)).

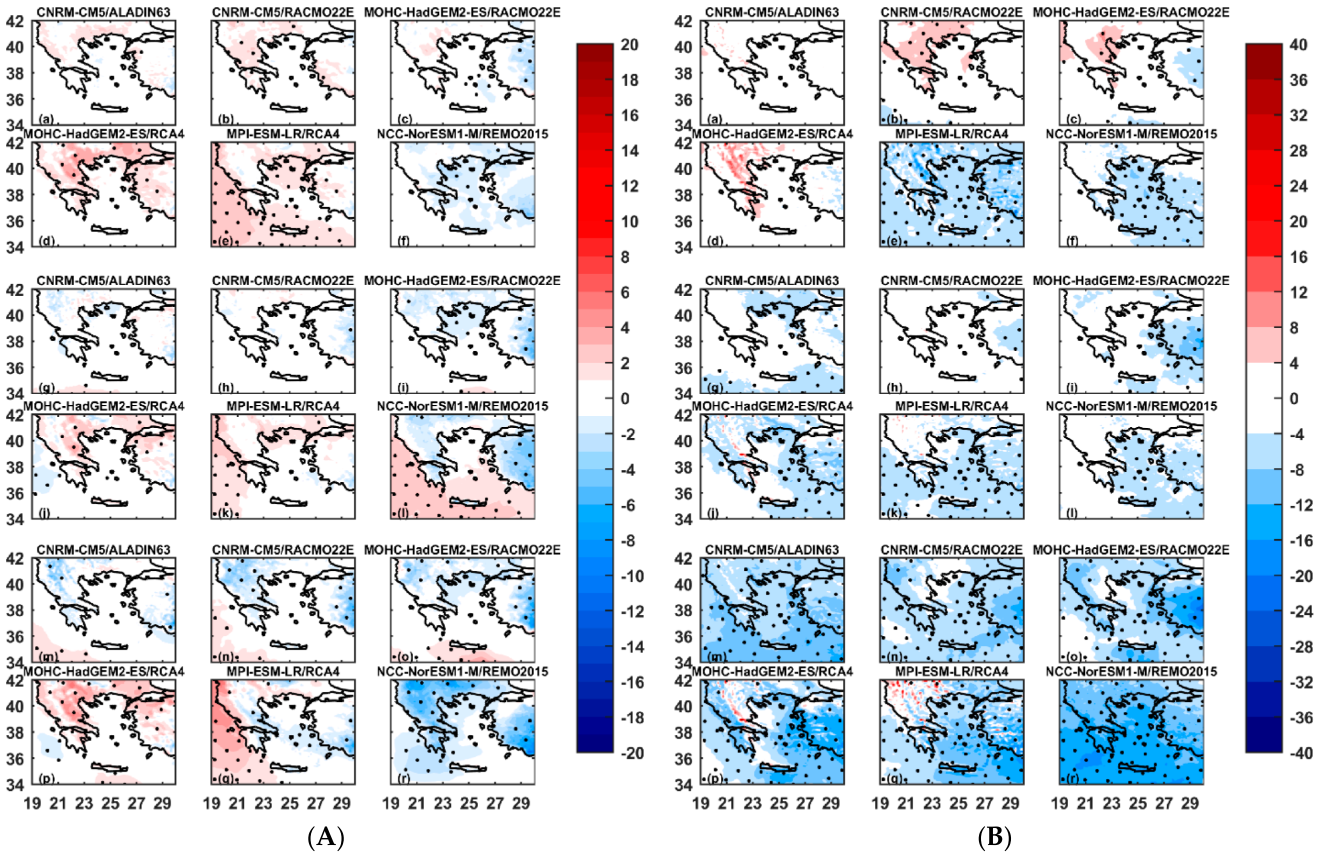


Figure 3. Winter (DJF) season relative composite difference (%) of (**A**) sRH of F3 according to the (**a**–**i**) rcp2.6, (**g**–**l**) rcp4.5, and (**m**–**r**) rcp8.5 scenarios with respect to RF and (**B**) ccf of F3 according to the (**a**–**i**) rcp2.6, (**g**–**l**) rcp4.5, and (**m**–**r**) rcp8.5 scenarios with respect to RF for each simulation. The dotted points denote statistical significance at 95%.

4. Conclusions

This work studies the future changes of cloud cover fraction (ccf) and surface relative humidity (sRH) over Greece during the period from 1970 to 2099 using data from EURO-CORDEX. Significant changes of ccf and sRH are found mainly in the rcp8.5 scenario and during the last period of the 21st century. In particular, sRH decreases in 2070–2099 with respect to the reference period by about 5–8%, and ccf by about 4–6%, respectively. These changes are mainly found over continental Greece. The simulations show a different sign of change over the southern Aegean and Ionian Sea, indicating some differences in the simulations results over the sea area. During the winter period (DJF), the main changes are found during the end of the 21st century both for sRH and ccf. Generally, the simulations show a different sign of sRH changes over Greece. The majority of simulations present a small relative reduction of sRH over northwestern Greece. The ccf shows a relative reduction of about 10–20% compared with the reference period over the Greek domain. Finally, further investigations both of ccf and sRH are of great importance for Eastern Mediterranean because these climate parameters contribute to the mechanisms of the energy transfer over the atmosphere and precipitation.

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