

Future Projections of Cloud Cover and Surface Relative Humidity over Greece during 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, 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, Thessaloniki, Greece

* Correspondence: ilogothe@physics.auth.gr

[†] Presented at 5th International Electronic Conference on Atmospheric Sciences, 16–31 July 2022; Available online: <https://ecas2022.sciforum.net/>.

Abstract: Greece is located over a prone region regarding the climate change. 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 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 about 5% and 5% to 8% respectively, over the continental Greece. Focusing on the winter season, the comparison between future and reference periods shows that cloud cover fraction presents a significant decrease of about 10% to 20% mainly during the last period of 21st century. Finally, surface relative humidity during 2070–2099 shows insignificant changes according low and moderate scenarios (rcp2.6 and 4.5), and limited changes for the high emission scenario (rcp8.5).

Academic Editor(s): Anthony Lupo

Published: 14 July 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

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

1. Introduction

Greece is located in the heart of one of the most susceptible region regarding climate change over the world, the Eastern Mediterranean. The increased severe climate and weather condition over this region turns the Mediterranean to a climate hot-spot [1,2]. The climate change in combination with the complex orography (the mountains and the seas) and the weather patterns over Greece increase the climate danger and vulnerability for this region. Today, it is clear that the global warming could be critically reflected on many socioeconomic and natural sectors. Some of these sectors are the land use, agriculture, food and water resources, sailing and transport, tourism, biodiversity, pollution, heat waves, fire events as well as the human health [3,4]. Regarding the economy, the Bank of Greece has estimated that the cost of climate change till 2100 can be reach €577 billion [3]. In this regard, our work studies the projected changes of cloud cover fraction and surface relative humidity during the period from 1970 to 2099 over 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 of clouds is related with warmer conditions in earth surface, consequently the air temperature increases and, this leads to even more decrease of 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 the 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 have an impact on human health, comfort sense of people and ecosystems. The global warming changes the temperature gradient between ocean—continent systems affecting the precipitation [8]. Relative humidity is usually correlated with precipitation and negatively related with 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 dynamic of 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 dynamic of atmosphere [11].

In this study, data from the 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 Greek region. The RCMs are a powerful tool that gives to scientific community the opportunity to examine the climate conditions and the mechanisms that modulate the future climate under the warming conditions [12]. Our study follows the sequent 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 conclusion (Section 4).

2. Data and Methods

In this work 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 period from 1970 to 2099 are used (Table 1).

Table 1. List of RCMs (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 in spatial resolution $0.11^\circ \times 0.11^\circ$ (about 12 Km). For the analysis composite difference maps of 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 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 21st century compared to RF. For the future projections we use the representa-

tive concentration pathways (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 clf the main changes are found during the end of 21st century according to rcp8.5 scenario. The composite difference mean maps of annual sRH (rcp8.5 scenario) for the first (F1; Figure 1a) and last period of 21st century (F3; Figure 1b) with respect to the RF (period from 1976 to 2005) are shown in Figure 1. The analysis shows that the sRH decreases mainly over the continental Greece. In particular, the sRH during the F1 compared to RF reduces about 2–3% (Figure 1a; please note that the percentage values are absolute differences). Additionally, four out of six simulations (Figure 1a/a–c,f) show a significant decrease of sRH about 2–4% over northern Greece. The majority of simulations present a limited decrease of sRH over Aegean Sea (about 1–2%; Figure 1a/b–f). The analysis shows that during the F3 the sRH reduces compared to the RF over the continental Greece (up to 8%; Figure 1b). Over the Aegean Sea the simulations show limited changes of sRH about 1–1.5% except for MPI-ESM-LR/RCA4 which shows a reduction about 3–4% over the central-east and central-west 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]. The Byrne and O’Gorman [10] show 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 show clearly that over Greek area significant changes of sRH over continental area and, limited changes of sRH over sea regions (Aegean and Ionian Sea) are projected during the future period, respectively.

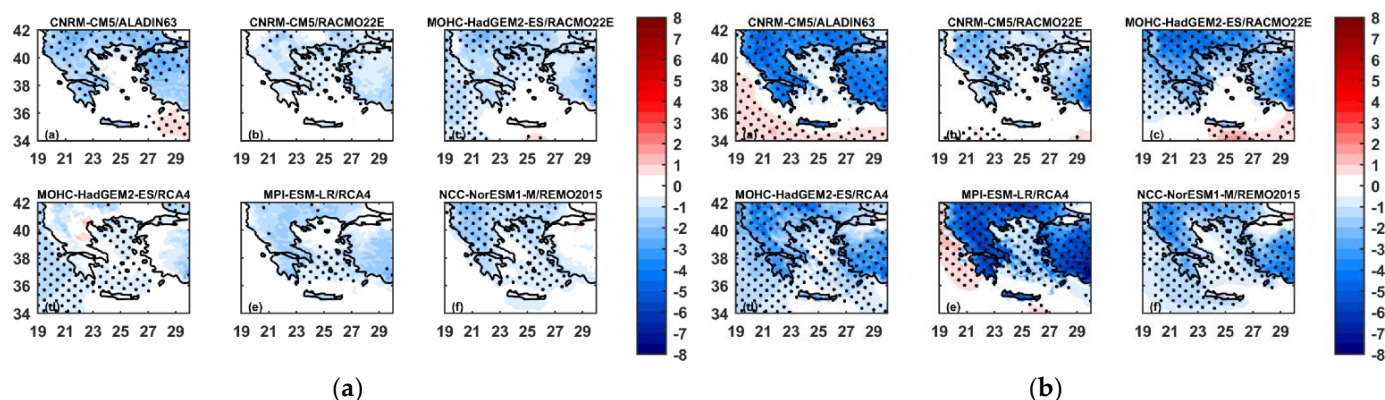


Figure 1. Annual mean sRH composite difference according to rcp8.5 scenario of (a) F1 and RF and (b) F3 and RF for each simulation. The dotted points denote statistical significance at 95%.

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 to the other future scenarios (rcp2.6 and rcp4.5; not shown). Generally, the ccf reduces in future projections over Greece. In particular, the F3 shows the most significant reduction of ccf (rcp8.5 scenario). The simulations show that the ccf reduction varies from 1% to 8% depending to the region of the continental Greece (please note that the percentage values are absolute differences; Figure 2b). Additionally, during the F1 only two out of six simulations show that the ccf reduces about 1–3% (Figure 2a/a,f). Sanchez-Lorenzo et al. [15] have shown that the ccf decreases during the recent past period (from 1971 to 2005), using observations, satellite and reanalysis data. Furthermore,

the ccf presents a decreasing trend for the Mediterranean region and the sign of reduction is maximized during 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 the ccf, over the Greek region, reduces especially over the continental area during the rcp8.5 scenario.

According the rcp8.5 scenario, simulations show that about 38% of the years of the RF shows sRH larger than the mean sRH for the whole period (from 1970 to 2099). For the future, the number of years reduces correspondingly about 30%, 20% and 13% for F1, F2 and F3. The common analysis for the ccf shows about 37% for the RF as well as 31%, 21% and 10% for the F1, F2 and F3, respectively. To summarize, our findings emphasize the reduction of sRH and ccf over continental Greece during the end of 21st century especially in the rcp8.5 scenario. These changes alter the energy radiation budget and affect the weather systems, the atmospheric dynamic as well as 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.

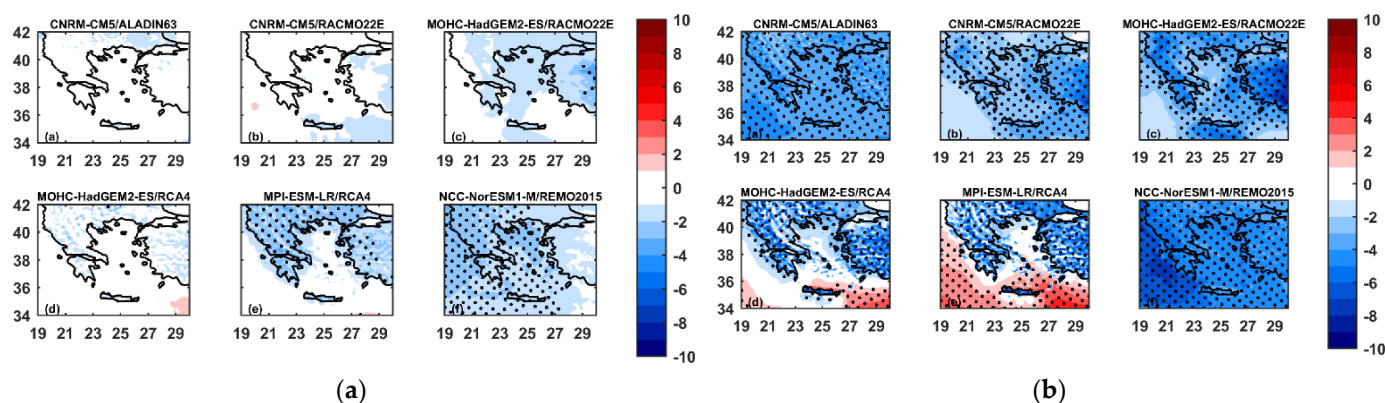


Figure 2. Annual mean ccf composite difference according to rcp8.5 scenario of (a) F1 and RF and (b) F3 and RF for each simulation. The dotted points denote statistical significance at 95%.

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. Results of the analysis indicate that the changes of sRH are insignificant for rcp2.6 and rcp4.5 scenarios (Figure 3a/a–l). Some limited changes are found over the northwest continental Greece in the rcp8.5 scenarios. In particular, four out of six simulations show a small reduction of sRH (Figure 3a/m–r) over north-west continental Greece and two out of six simulations show an increase of sRH about 4–6% over west 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) 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 of ccf over continental Greece, respectively (Figure 3b/b,e). Finally, for the moderate scenario (rcp4.5), the ccf in three out of six simulations shows a relative decrease (about 4–8%) especially over the sea region of 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 the F3, however, these differences are not clear for the RCMs because the sign varies among the simulations (for example: Figures 3a/m–o and 3a/p,q). Additionally, the ccf decreases during the DJF, mainly during the end of 21st century (F3), according to the rcp8.5 scenario. Finally, the results of the future projections over continental Greece according to rcp2.6 and rcp4.5 scenarios are insignificant and in

some cases the findings show a different sign among the simulations (for instance: Figures 3b/b–d and 3b/e,f).

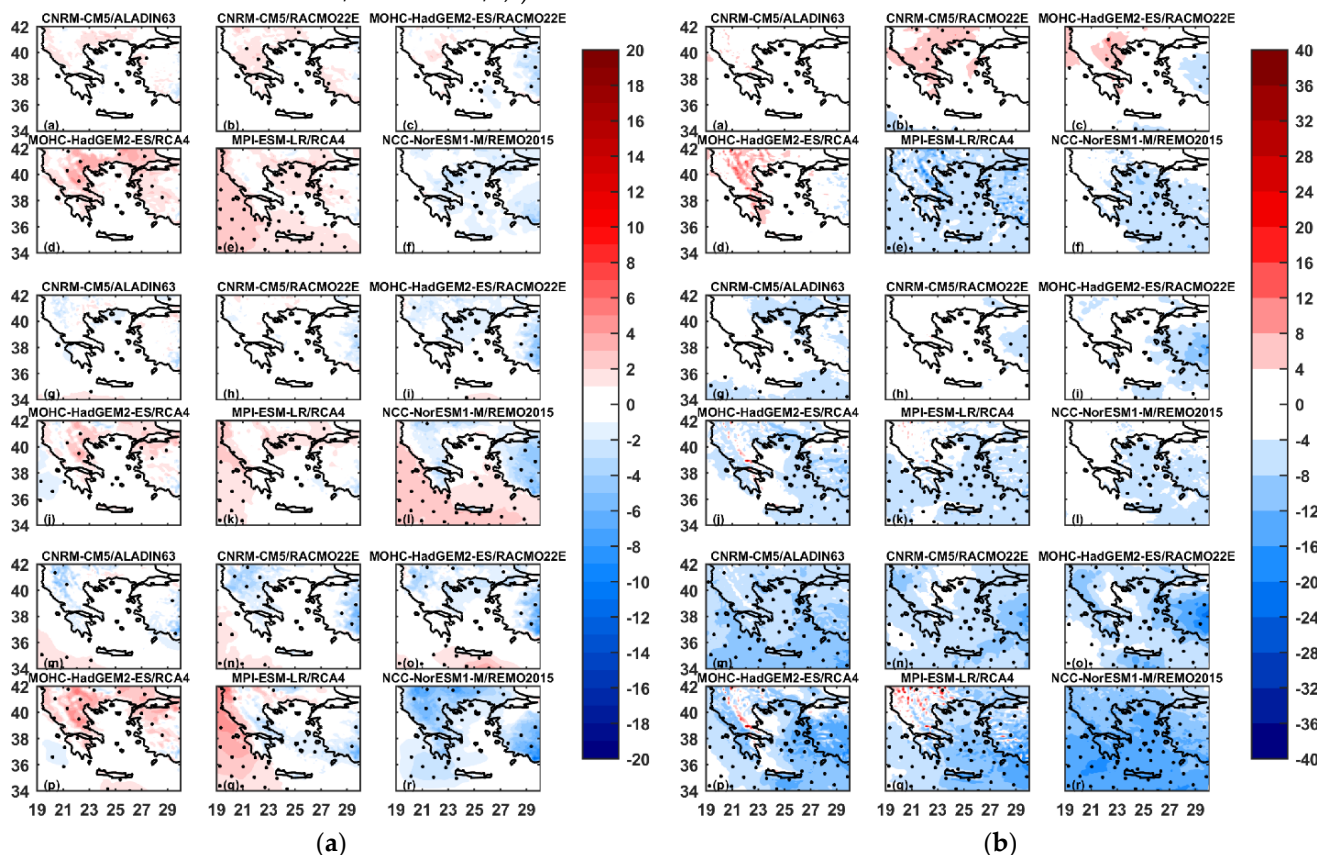


Figure 3. Winter (DJF) season relative composite difference (%) of (a) sRH of F3 according to (a–i) rcp2.6, (g–l) rcp4.5 and (m–r) rcp8.5 scenarios with respect to RF and (b) ccf of F3 according to (a–i) rcp2.6, (g–l) rcp4.5 and (m–r) rcp8.5 scenarios with respect to RF for each simulation. The dotted points denote a 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 21st century. In particular, the sRH decreases during 2070–2099 with respect to reference period about 5%–8% and the ccf about 4%–6%, respectively. These changes are mainly found over the continental Greece. The simulations show a different sign of change over south Aegean and Ionian Sea indicating some differences to the simulations results over the sea area. During winter period (DJF) the main changes are found during the end of 21st century both for sRH and ccf. Generally, the simulations show a different sign of sRH changes over Greece. The majority of simulations presents a small relative reduction of sRH over northwestern Greece. The ccf shows a relative reduction about 10%–20% compared to reference period over the Greek domain. Finally, the further investigation both of ccf and sRH are of great importance for the eastern Mediterranean because these climate parameters contribute to the mechanisms of the energy transfer over the atmosphere and precipitation.

Author Contributions: Conceptualization, I.L. and K.T.; methodology, I.L.; software, I.L.; validation, I.L.; formal analysis, I.L.; investigation, I.L.; resources, I.L.; data curation, I.L.; writing—original draft preparation, I.L.; writing—review and editing, I.L., K.T. and D.M.; visualization, I.L.; supervision, K.T. and D.M.; project administration, K.T. and D.M.; funding acquisition, D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Network on Climate Change and its Impacts—CLIMPACT, code number 98807, funded by the Public Investment Program of Greece, General Secretary of Research and Technology—Ministry of Development and Investments.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: <https://esgf-data.dkrz.de/search/cordex-dkrz/>.

Acknowledgments: We would like to acknowledge all institutes and efforts that have a contribution to EURO-CORDEX. Additionally, we would like to thank the ESGF nodes regarding the distribution and store of EURO-CORDEX data. Finally, the authors would like to thank MSc. Ourania Hasiltzoglou for English Language editing.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Giorgi, F. Climate change hot-spots. *Geophys. Res. Lett.* **2006**, *33*, L08707. <https://doi.org/10.1029/2006GL025734>.
2. Cramer, W.; Guiot, J.; Fader, M.; Garrabou, J.; Gattuso, J.P.; Iglesias, A.; Lange, M.A.; Lionello, P.; Llasat, M.C.; Paz, S.; et al. Climate change and interconnected risks to sustainable development in the Mediterranean. *Nat. Clim. Chang.* **2018**, *8*, 972–980. <https://doi.org/10.1038/s41558-018-0299-2>.
3. CCISC. *The Environmental, Economic and Social Impacts of Climate Change in Greece*, Climate Change Impacts Study Committee, Bank of Greece: Athens, Greece, 2011; pp. 1–520, ISBN:978-960-7032-49-2.
4. IPCC. Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK, 2021, in press.
5. Bony, S.; Stevens, B.; Frierson, D.C.; Jakob, M.; Kageyama, R.; Pincus, T.G.; Shepherd, S.C.; Sherwood, A.P.; Siebesma, A.H.; Sobel, M.W.; et al. Clouds, circulation and climate sensitivity. *Nature Geosci.* **2015**, *8*, 261–268. <https://doi.org/10.1038/ngeo2398>.
6. Mendoza, V.; Pazos, M.; Garduño, R.; Mendoza B. Thermodynamics of climate change between cloud cover, atmospheric temperature and humidity. *Sci Rep.* **2021**, *11*, 21244. <https://doi.org/10.1038/s41598-021-00555-5>.
7. Groisman, P.Y., Bradley, R.S.; Sun, B. The Relationship of Cloud Cover to Near-Surface Temperature and Humidity: Comparison of GCM Simulations with Empirical Data. *J. Clim.* **1999**, *13*, 1858–1878.
8. Byrne, M.P.; O’Gorman, P.A. Understanding Decreases in Land Relative Humidity with Global Warming: Conceptual Model and GCM Simulations. *J. Clim.* **2019**, *29*, 9045–9061. <https://doi.org/10.1175/JCLI-D-16-0351.1>.
9. Mawonike, R.; Mandonga, G. The effect of temperature and relative humidity on in Gokwe region, Zimbabwe: A factorial design perspective. *Int. J. Multidiscip. Acad. Res.* **2017**, *5*, 2.
10. Byrne, M.P.; O’Gorman, P.A. Trends in continental temperature and humidity directly linked to ocean warming. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4863–4868.
11. Sherwood, C.; Ingram, W.; Tsushima, Y.; Satoh, M.; Roberts, M.; Vidale, P.L.; O’Gorman, P.A. Relative humidity changes in a warmer climate. *J. Geophys. Res.* **2010**, *115*, D09104. <https://doi.org/10.1029/2009JD012585>.
12. Georgoulas, A.K.; Akritidis, D.; Kalisoras, A.; Kapsomenakis, J.; Melas, D.; Zerefos, C.S.; Zanis, P. Climate change projections for Greece in the 21st century from high-resolution EURO-CORDEX RCM simulations. *Atmospheric Res.* **2022**, *271*, 106049. <https://doi.org/10.1016/j.atmosres.2022.106049>.
13. Wilks, D.S. Forecast verification. In *Statistical Methods in the Atmospheric Sciences*; Academic Press: New York, NY, USA, 1995.
14. Mitchell, J.F.B.; Ingram, W.J. Carbon dioxide and climate: Mechanisms of changes in cloud. *J. Clim.* **1992**, *5*, 5–21.
15. Sanchez-Lorenzo, A.; Enriquez-Alonso, A.; Calbó, J.; González, J.-A.; Wild, M.; Folini, D.; Norris, J.R.; Vicente-Serrano, S.M. Fewer clouds in the Mediterranean: Consistency of observations and climate simulations. *Sci. Rep.* **2017**, *7*, 41475.
16. Wild, M.; Folini, D.; Henschel, F.; Fischer, N.; Müller, B. Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems. *Sol. Energy* **2015**, *116*, 12–24.
17. Enriquez-Alonso, A.; Sanchez-Lorenzo, A.; Calbó, J.; González, J.A.; Norris, J. Cloud cover climatologies in the Mediterranean obtained from satellites, surface observations, reanalyses, and CMIP5 simulations: Validation and future scenarios. *Clim. Dyn.* **2016**, *47*, 249–269.