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Projected Changes of Etesians Regime Over Eastern Mediterranean in CMIP6 Simulations According to SSP2-4.5 and SSP5-8.5 Scenarios †

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Abstract: The Mediterranean is recognized as one of the most sensitive regions regarding climate change. The northern sector winds are a dominant feature of summer low-tropospheric circulation over the Aegean basin in eastern Mediterranean (EMed). This study is an updated assessment that uses state-of-the-art tools in order to investigate the projected changes of the meridional wind speed and Etesian regime during summer period (June-July-August) over the 21st century. The analysis is based on 17 Global Climate Models simulations (GCMs) available from Coupled Model Intercomparison Project Phase 6 (CMIP6) covering the historical period (from 1971 to 2014) and the future period (from 2015 to 2100) under two Shared Socioeconomic Pathways (SSPs), an intermediate and a very high emission scenario (SSP2-4.5 and SSP5-8.5). Additionally, results from GCMs analysis are compared to ERA5 reanalysis for the historical period from 1971 to 2000. Our findings suggest that the majority of GCMs reproduce the spatial pattern of Etesians but underestimate the meridional wind speed about 0.5 to 1.0 m/s, as compared to ERA5. During the future period, the meridional wind speed is projected to be increased over the Aegean basin, mainly during the last period of 21st century. Findings show that the majority of GCM simulations (12 out of 17) show an increase of meridional wind speed about 0.2 to 1.4 m/s for SSP5-8.5 and 0.2 to 0.6 m/s for SSP2-4.5, as compared to historical period from 1971 to 2000.

Keywords: Climate Change; Etesian winds; ERA5; GCM; CMIP6; SSP scenarios; RCP scenarios

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1. Introduction

The Sixth Assessment Report (AR6) of IPCC [1] emphasizes the vulnerability of societies on climate change highlighting the impact of global warming for our civilization. Mediterranean region warming is about 20% faster than the average earth system affecting many socioeconomic sectors [2,3]. One of the dominant tropospheric circulation features of Mediterranean is the Etesians, a permanent system of northerly winds [4]. Etesians blow during the summer period showing the maximum sign during July-August months [5,6]. The main cause of this wind system is a pressure gradient over the Aegean Sea as a result of a high and a low pressure system located over Balkan Peninsula and south EMed. Additionally, the topography of continental Greece and the Bosporus canalizes the air masses which are advected from Caspian region to the Aegean basin [7,8].

Past studies have already investigated the Etesian regime during past and future period using observations, reanalysis and model simulations data [4,5,7–10]. Dafka et al. [9] found that the intense Etesians are related with geopotential anomalies over northwest

Balkan Peninsula and the position of Jet stream. Other studies have shown that the variability of Etesians are controlled by the activity of South Asian Monsson (SAM) [5,6] via the extension of thermal low from west SAM to south EMed [11]. Misios et al. [7], using model simulations over the last millennium and 20CR data, have shown that the reduction of Etesians is associated with the weak SAM activity after post-eruption summers. For the Future period, the Etesians strengthen due to the strengthening of high pressure center, and the deepening of thermal Low over EMEd [4]. Logothetis et al. [9] and Dafka et al., [12], have shown a strengthening of Etesians during the last period of 21st century according RCP8.5 scenario due to the enhancement of the dipole that sustains the Etesian regime.

Our study investigates the projected changes of Etesian regime using state-of-the-art tools. Here, we investigate the Etesians in terms of meridional wind speed component at 10m (v10) [6,13] using 17 model simulations available from the CMIP6 project under two SSPs (SSP2-4.5 and SSP5-8.5).

2. Data and Methods

For the analysis monthly mean v10 was used. The data is obtained from CMIP6 project [13] in the frame of IPCC-AR6 [1]. In the study data of 17 simulations was analyzed covering the period from 1971 to 2000 (historical) and from 2015 to 2100 for two future emission scenarios (SSP2-4.5 and SSP5-8.5) (Table 1). SSPs are developed in the frame of CMIP6 (AR6) and describe the different pathways of atmospheric greenhouse gas emissions. There are 5 SSPs, which combined with representative concentration pathways (RCPs), describe the possible climate change under social conditions and climate features [15]. In this study, the projected changes of v10 over EMed are investigated for a "medium challenges to mitigation and adaptation" scenario (SSP2) and a "high challenges to mitigation, low challenges to adaptation" scenario (SSP5) [16]. For the CMIP6 simulations with more than one simulation available, the ensemble mean was computed. The v10 from ERA5 are retrieved during the period from 1971 to 2000, (hereafter hP) in order to compare model results to the reanalysis. The ERA5 data was retrieved in spatial resolution of 1.0°x1.0° and the model simulations regrided (bi-linear interpolation) to the common resolution.

Table 1. List of CMIP6 model simulations that used in this study.

Model	Institute (country)	Resolution (lon/lat)	Ensemble
ACCESS-CM2	Australian Community Climate and Earth System Simulator Climate Model Version 2 (Australia)	192 x 144	r1i1p1f1
ACCESS-ESM1-5	Australian Community Climate and Earth System Simulator Earth System Model Version 1.5	192 x 145	r1i1p1f1, r2i1p1f1, r3i1p1f1
AWI-CM-1-1-MR	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research	384 x 192	r1i1p1f1
CanESM5	Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada	128 x 64	r1i1p1f1
CMCC-CM2-SR5	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	288 x 192	r1i1p1f1
CNRM-CM6-1-HR	Centre National de Recherches Meteorologiques, Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique, France	256 x 128	r1i1p1f2
GFDL-ESM4	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, USA	360 x 180	r1i1p1f1
GISS-E2-1-G	Goddard Institute for Space Studies, USA	144 x 90	r1i1p1f2

HadGEM3-GC31-LL	Met Office Hadley Centre, UK	92 x 144	r1i1p1f3
INM-CM5-0	Institute for Numerical Mathematics, Russian Academy of Science, Russia	180 x 120	r1i1p1f1
IPSL-CM6A-LR	Institut Pierre Simon Laplace, France	144 x 143	r2i1p1f1
KACE-1-0-G	National Institute of Meteorological Sciences/Korea Meteorological Administration, Climate Research Division, Republic of Korea	192 x 144	r1i1p1f1
MIROC6	Japan Agency for Marine-Earth Science and Technology , The University of Tokyo, Japan	256 x 128	r1i1p1f1
MIROC-ES2L	Japan Agency for Marine-Earth Science and Technology , The University of Tokyo, Japan	128 x 64	r1i1p1f1
MPI-ESM1-2-HR	Max Planck Institute for Meteorology, Germany	384 x 192	r1i1p1f1
MPI-ESM1-2-LR	Max Planck Institute for Meteorology, Germany	192 x 96	r1i1p1f1
MRI-ESM2-0	Meteorological Research Institute, Japan	128 x 64	r1i1p1f1

The analysis is focused on a spatial window over EMed (17°E-31°E, 30°N-41°N; following [6]) and also over the central Aegean Sea (cAeS) where the Etesian sign is maximized (24°E-27°E, 36°N-39°N; [6]). In order to investigate the v10 spatial pattern of CMIP6 simulations, the composite mean v10 maps during hP both for model simulations and ERA5 are constructed. The bar-chart of the averaged v10 over cAeS both for simulations and reanalysis are calculated. Additionally, the agreement of averaged v10 over cAeS between ERA5 and CMIP6 simulations is estimated using the bias ratio ($\frac{\mu_{sim.}}{\mu_o}$) and the variability ratio ($\frac{s_{sim.}/\mu_{sim.}}{s_o/\mu_o}$) where μ and s are the mean and standard deviation for simulations (sim.) and reanalysis (o), respectively [17].

To study the projected changes of v10 during future period, the bar-chart of the difference of averaged v10 is calculated during two future periods (F2; 2071-2100 and F1; 2031-2060) with reference to hP, both for SSP5-8.5 and SSP2-4.5 emission scenarios. Focusing on the future period with the most significant v10 changes, the maps of composite difference of v10 between F2 and F1 periods and hP according to SSPs and hP are constructed. For the statistical significance, the two-tailed t-test was used at 95% statistical significance level.

3. Results

The mean v10 during the historical period from 1971 to 2000 (hP) for ERA5 and each one of the CMIP6 model simulations are shown in **Figure 1** (please note that in Figure 1 the spatial resolution for ERA5 is 0.25°x0.25° in order to show clearer the v10 pattern–Etesian regime over the Aegean Sea). The model simulations are regrided to 1.0°x1.0°. This analysis shows that the majority of simulations capture the spatial pattern of v10. 11 out of 17 simulations reproduce the spatial pattern of Etesian flow over the cAeS (**Figure 1c-h,j,o-r**).

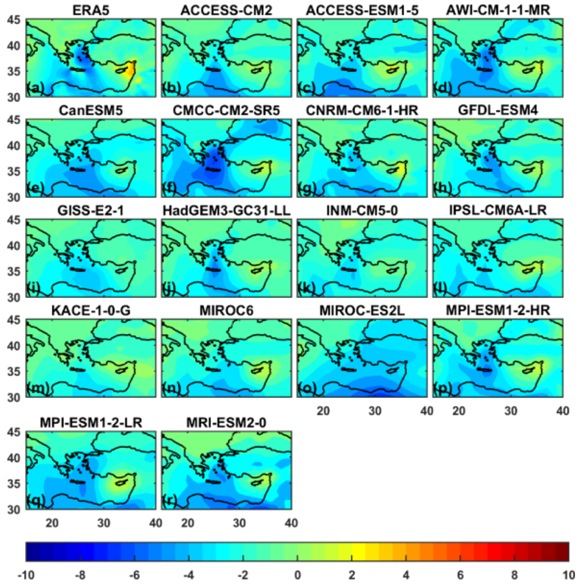

Figure 1. Composite mean of v10 (m/s) during hP for **(a)** ERA5 and **(b-r)** model simulations.

The averaged v10 over the cAeS for ERA5 and simulations are shown in **Figure 2**. 8 out of 17 simulations, compared to reanalysis, capture the average v10. In particular, the averaged CMIP6 v10 over cAeS comes into the limits of the averaged ERA5 v10 over the cAeS plus/ minus one standard deviation of ERA5 v10 distribution (namely, the AWI-CM-1-1-MR, CNRM-CM6-1-HR, GFDL-ESM4, HadGEM3-GC31-LL, MIROC-ES2L, MPI-ESM1-2-HR, MPI-ESM1-2-LR and MRI-ESM2-0). 7 out of 17 simulations underestimate the average ERA5 v10 over cAeS about 0.8m/s (namely the ACCESS-CM2, ACCESS-ESM1-5, CanESM5, CMCC-CM2-SR5, GISS-E2-1, IPSL-CM6A-LR and MIROC6) and 2 simulations show an underestimation about 1.6 to 1.9 m/s (INM-CM5-0 and KACE-1-0-G), respectively (**Figure 2**). Finally, AWI-CM-1-1-MR and MPI family simulations show better agreement with ERA5 v10 over cAeS in term of bias and variability ratio (**Figure 2b,c**).

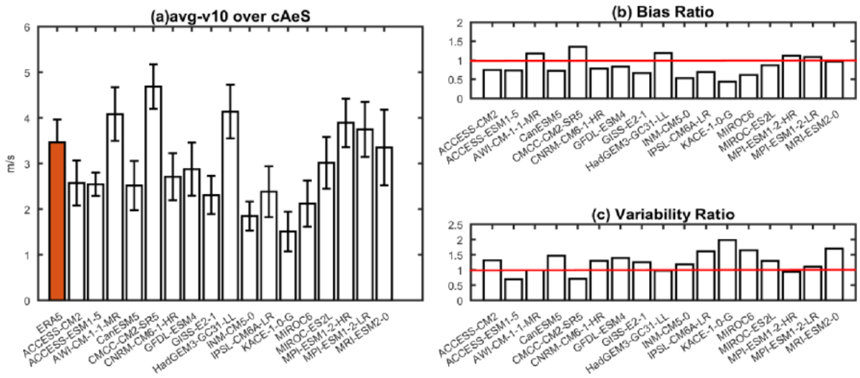

Figure 2. Bar-chart of **(a)** averaged v10 over cAeS during the hP for ERA5 (red bar) and model simulations (white bars), **(b)** bias ratio and **(c)** variability ratio for each simulation with reference to ERA5.

The difference of the averaged v10 over cAeS during F2 and F1 with reference to the hP (both for SSP5-8.5 and SSP2-4.5) are presented in **Figure 3**. The main changes are presented during the F2 (**Figure 3.a,c**). The SSP5-8.5 scenario shows the most significant changes compared to SSP2-4.5. According to SSP5-8.5, the maximum changes are presented during the F2 (compared to hP; **Figure 3a,b**). In particular, 5 out of 11 simulations show a statistical significant increase in averaged v10 over cAeS about 0.2 to 1.4 m/s and 4 (two simulations come from a common institute) out of 11 simulations show a significant decrease about 0.3 to 0.6 m/s, respectively (**Figure 3a**). For the SSP2-4.5 scenario, 5 out of 11 simulations show a significant increase in averaged v10 over cAeS about 0.2 to 0.6 m/s and two out of seventeen show a decrease about 0.3 m/s, respectively (**Figure 3c**). For the mid-21st century (F1) the averaged v10 changes over cAeS are not so significant as the last period of 21st century (**Figure 3b,d**).

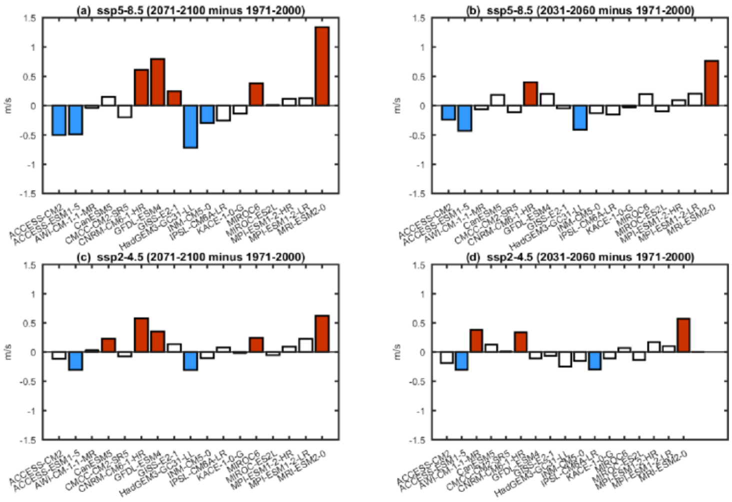

Figure 3. Bar-chart of the difference of averaged v10 (m/s) over cAeS during F2 and F1 with reference to hP **(a-b)** SSP5-8.5 and **(c-d)** SSP2-4.5. The red/ blue bars indicate the statistical significant increase/ decrease of the averaged v10 (m/s) over cAeS at 95%.

To further investigate the spatial changes of v10 over the EMed the composite difference maps of v10 between F2 (according SSP5-8.5) and hP are constructed (**Figure 4**). The analysis is focused on the last period of 21st century (F2) because the most significant changes are presented during this period. The majority of model simulations show an increase of v10 over the Aegean except the south EMed where the v10 decreases about 0.1 to 1.0 m/s. In 11 out of 17 simulations the v10 increases about 0.2 to 1.4 m/s over central Aegean (**Figure 4c,d,f-h,l-q**). Additionally, in 4 out of 17 the v10 decreases about 0.4 to 0.8 m/s over southeastern Aegean basin (**Figure 3a,b,i,e**). The other simulations show insignificant changes (**Figure 3j,k**).

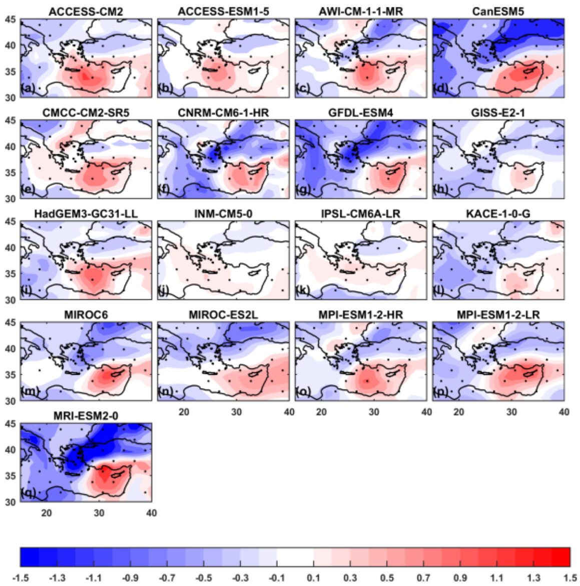

Figure 4. Mean composite difference of v10 (m/s) between F2 according SSP5-8.5 scenario and hP. The dotted area indicates the statistically significant change at 95%, as estimated using Student's t-test.

4. Conclusion

This work aims to study the projected changes of Etesian sign over Aegean Sea using CMIP6 model simulations. The half of simulations studied here captures the mean v10 over cAeS whereas the majority of the other simulations underestimate the v10. Comparing these findings with previous analysis [6] the results provide evidence that CMIP6 simulations reproduce better the Etesian sign over the central Aegean compared to CMIP5 simulations. Regarding future projections, the majority of simulations show stronger v10 (about 0.2 to 1.4 m/s for SSP5-8.5) during the last period of 21st century over central Aegean. Additionally, all simulations show a decrease of v10 over south EMed. Finally, the further investigation of EMed atmospheric circulation, using a robust tool as the CMIP6 simulations, could improve our knowledge to understand better the climate over the Mediterranean "climate hot-spot".

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