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RESEARCH ARTICLE

The seasons' length in 21st century CMIP5 projections over the eastern Mediterranean

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The eastern Mediterranean (EM) is expected to be influenced by climate changes that will significantly affect ecosystems, human health and socio-economic aspects. One aspect of climate change in this vulnerable area is the length of the seasons, especially that of the rainy winter season against the warm and dry summer.

Here, the synoptic seasons' definition of Alpert, Osetinsky, Ziv, and Shafir (2004a) was applied to an ensemble of eight Coupled Model Inter-Comparison Project phase 5 (CMIP5) models, under RCP8.5 and RCP4.5 scenarios, to predict the changes in the lengths of EM seasons during the 21st century. It is shown that the ensemble adequately represents the annual cycle of the main synoptic systems over the EM.

The analysis further suggests that at the end of the 21st century, the duration of the synoptic summer, characterized by the occurrence of the Persian Trough, is expected to be lengthened by 49%, while the synoptic winter, characterized by the occurrence of the Cyprus Low, is expected to be shortened by 56% under the RCP8.5 scenario. This may lead to substantial changes in the hydrological regime and water resources, reduce the potential of dry farming, increase the risk of fires and air pollution and change the timing of seasonal health hazards.

KEYWORDS

CMIP5, Cyprus Low, Persian Trough, Red Sea Trough, season definition, Sharav Low, synoptic classification

1 | INTRODUCTION

The Mediterranean Basin is a region currently being affected by climate change and is predicted to be further influenced in the future by warming and drying (Giorgi, 2006; Intergovernmental Panel on Climate Change (IPCC), 2013; Lelieveld et al., 2016). Such changes are associated with changes in the occurrence of the prevailing synoptic systems and thus can lead to changes in the length of the seasons, which in turn may significantly affect people, economy and the ecosystems in this most vulnerable area.

The eastern Mediterranean (EM) is located on the border between mid-latitude temperate climate to its north and arid climate to the south, making it extremely vulnerable to precipitation variations (Giorgi & Lionello, 2008). The EM climate conditions are characterized by moderate air temperatures and rainy spells during the winter season (e.g., Saaroni, Halfon, Ziv, Alpert, & Kutiel, 2010) and dry and stable hot weather with low inter-diurnal variations during the summer (Ziv, Saaroni, & Alpert, 2004). The region's climate is strongly affected by external forcing of both mid-latitude and tropical origins (Alpert et al., 2005; Alpert, Baldi, et al., 2006). Ziv, Saaroni, Pargament, Harpaz, and Alpert (2014) studied the observed trends in precipitation over Israel for the recent period 1975–2010 and found a decrease over the vast majority of Israel, statistically significant only in the super-arid part. They have also shown that the length of the wet season is shortening, although not statistically significant. Peleg, Bartov, and Morin (2015) have predicted a shortening of the wet season in three global climate models for a grid point (32.5°N, 35°E) located close to the northern coast of Israel. A prolongation of the dry season will probably reduce the availability of rangelands for grazing animals in the EM (Evans, 2009; Lelieveld et al., 2012; Samuels et al., 2017). Although crop yields could potentially grow in the winter season, they may wither during the dry period, and increased risk of fires and air pollution can further aggravate the environmental stress in this vulnerable region (Giannakopoulos et al., 2009; Lelieveld et al., 2012).

Observed changes in the timing of the seasons, such as earlier onset of spring, have been widely observed in temperate areas across the Northern Hemisphere (Ruosteenoja, Raisanen, & Pirinen, 2010; Schwartz, Ahas, & Aasa, 2006). Phenological records have shown significant temporal trends in the observed time of seasonal events, from the end of the 20th century and continuing into the 21st century (Cleland, Chiariello, Loarie, Mooney, & Field, 2006). Studies have put the rate of seasons' length change measured by plant phenology in the range of 2–3 days/decade advancement in spring, and 0.3–1.6 days/decade delay in autumn, over the past 30–80 years (Sherry et al., 2007). The agricultural growing season has also expanded by 10–20 days over the last few decades (Linderholm, 2006).

Studies have suggested that the length of the seasons has substantial influence on human and animal health. For instance, multi-annual predictions of seasonal respiratory viruses were improved using the annual periodicity of the seasons and synoptic-scale parameters (Axelsen, Yaari, Grenfell, & Stone, 2014; Klausner, Klement, & Fattal, 2017; Yaari, Katriel, Huppert, Axelsen, & Stone, 2013; Zhao, Cao, Vanos, & Vecellio, 2017). These viruses have become a source of considerable human and animal morbidity and mortality (Cox & Subbarao, 2000; Peretz, Biggeri, Alpert, & Baccini, 2011). Other studies have found strong evidence relating human and animal health degradation to the length of the season (Aziz-Boaron et al., 2012; Fraenkel et al., 2017; Nevo-Shor, Kogan, Ben-Zion, & Fraenkel, 2016). From a healthcare system point of view, predictions of the magnitude and timing of upcoming epidemics could greatly assist in early preparations and developing mitigation strategies (Yaari et al., 2013). Thus, the length and timing of the seasons is of growing concern worldwide in general, and in the EM, in particular.

Seasons can be defined in different ways. According to the astronomical definition the winter season (in the Northern Hemisphere) is defined as the period from the winter solstice (22 December) to the vernal equinox (21 March). The spring season ends at the summer solstice (22 June); the summer season lasts from the summer solstice until the autumnal equinox (23 September) and the autumn season completes the annual cycle and is between 23 September and 22 December. In meteorology, however, the four seasons are defined as four periods of 3 months each (American Meteorological Society, 2001). Trenberth (1983) defined the seasons according to the cycle of the average daily air temperature. In this definition seasons begin and end at different dates and have different lengths. This is a serious disadvantage when one defines the seasons for a given region intended for practical use, especially in the EM. To overcome the deficiencies of earlier seasonal definitions that are based on local stations data, Alpert et al. (2004a) have suggested a new definition based on the synoptic systems dominating the region. The synoptic systems classification is based on geopotential height, temperature and two horizontal wind components U and V at 1,000 hPa, in 25 grid points (27.5°–37.5°N, 30°–40°E) over the EM (Alpert, Osetinsky, Ziv, & Shafir, 2004a). Five main synoptic systems were defined as follows. The Persian Trough (PT) system characterizing the summer, Cyprus Low dominant in the winter, Red Sea Trough (RST) peaking in the autumn and the Sharav Low (SL), which is noticeable during spring (for a complete list of the synoptic systems and the specific types included in each system see Alpert et al. (2004a)). A definition of the summer season according to weather types over Greece has been earlier proposed by Maheras (1989).

Based on the synoptic definition of the seasons, the purpose of the present study is to first evaluate the ability of eight models participating in the Coupled Model Inter-Comparison Project phase 5 (CMIP5) (Taylor, Stouffer, & Meehl, 2012) in capturing the annual cycle of the different synoptic groups (i.e., PT, Cyprus Low and RST) as compared to the reanalysis. And then project the length of the seasons in the 21st century over the EM using the ensemble (ENS) mean of these models.

2 | DATA

Data were acquired from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis archive (Kalnay et al., 1996; Kistler et al., 2001). This database is available on daily or 6 hr timescales from 1948 to 2017 on a 2.5 × 2.5° grid.

Modelled data were retrieved from the World Data Center for Climate (WDCC-DKRZ, http://cera-www.dkrz.de/WDCC/ui/Index.jsp) data portal for eight models participating in the CMIP5 project (Taylor et al., 2012) previously utilized in Hochman, Harpaz, Saaroni and Alpert (2017) (for list of models see Table 1). Models' data are available on daily or 6 hr timescales for 1861–2100. Spatial resolutions vary in range from 0.94 × 1.25° to 1.9 × 3.75° (see Table 1).

TABLE 1 The eight CMIP5 models used in the present study with the following listing columns: modelling centre (or group), institute ID, model name and horizontal resolution (°), following Taylor et al. (2012)

Modelling centre (or group)	Institute ID	Model name (short name)	Resolution (°)
Canadian Centre for Climate Modelling and Analysis, Canada	CCCMA	CanESM2 (CANESM)	2.79 × 2.81
National Center for Atmospheric Research, USA	NCAR	CCSM4 (CCSM)	0.94 × 1.25
Met Office Hadley Centre, England	MOHC	HadGEM2-CC (HadGEM2CC)	1.25 × 1.88
		HadGEM2-ES (HadGEM2ES)	1.25 × 1.88
Institut Pierre-Simon Laplace, France	IPSL	IPSL-CM5A-LR (IPSL)	1.9 × 3.75
Max Planck Institute for Meteorology, Germany	MPI-M	MPI-ESM-LR (MPI)	1.87 × 1.88
Meteorological Research Institute, Japan	MRI	MRI-CGCM3 (MRI)	1.12 × 1.13
Norwegian Climate Center, Norway	NCC	NORESM1-M (NORESM)	1.9 × 2.5

The analysis representing the present period is based on the historical (1986–2005) simulations of the CMIP5 models as well as the NCEP/NCAR reanalysis archive. Future periods simulated are the mid-21st century (2046–2065) and the end century (2081–2100). This is performed for the representative concentration pathway of 8.5 W/m^2 (RCP8.5) and 4.5 W/m^2 (RCP4.5) scenarios, following the recommendation of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013). For a more complete explanation of the representative concentration pathways (RCP) scenarios, the reader is referred to Van-Vuuren, Edmonds, Kainuma, Riahi, and Weyant (2011).

3 | METHOD

The synoptic classification (SC) algorithm used by Alpert et al. (2004a) was applied to the above mentioned CMIP5 models, in order to predict the seasons' lengths for the 21st century (see section 1 on the SC method). The only difference was the use of input variables from the 850 hPa level instead of the 1,000 hPa (except for the pressure at sea level), used in the original classification, due to the lack of 6 hr data at the 1,000 hPa in CMIP5 models. The compatibility between these two levels for the SC was tested and approved by Hochman et al. (2017). This includes a full explanation and evaluation of the modified SC.

Here, we evaluated the ability of the modified classification, applied to CMIP5 models, to capture the annual cycle of the different synoptic groups, i.e., Cyprus Lows (CL) (representing the winter season), PT (for summer) and RST (autumn). These results were compared with the original SC based on 1,000 hPa input variables (Alpert et al., 2004a) applied to NCEP/NCAR reanalysis, using Taylor diagrams (Taylor, 2001). A Taylor diagram can provide a concise statistical summary of how well patterns match each other in terms of their correlation, their root-mean-square difference (RMSD) and their variance. Note that SLs, having significant climatic effect during the spring season, were not evaluated as they are a mesoscale phenomenon (Alpert & Ziv, 1989), thus, rarely captured by the relatively coarse spatial and temporal resolution of the CMIP5 models (see section 4.4 for complete discussion on the spring season).

Alpert et al. (2004a) have proposed a calculation of the length of the seasons according to the prevailing synoptic systems in the EM (see section 1 and Alpert et al., 2004a, table 1). This calculation was applied to the CMIP5 models to predict the length of the synoptic seasons in the 21st century. For every synoptic group, the daily time series of its occurrence for the study periods was obtained. Then, the total occurrence of each synoptic group in the period of 11 days (±5 days) straddling that specific day was calculated. Next, the results were averaged for every day over the historical (1986–2005), mid-century (2046–2065) and end century (2081–2100) periods. In this way, the annual cycle of each synoptic group was obtained and could be used to define the seasons. The period of 11 days for computing the frequency of occurrence was chosen after comparing between different possible periods. The use of longer periods obscured the main characteristics of the seasonal behaviour of the frequencies, whereas shorter periods led to high level of noise (Alpert et al., 2004a).

It should be expected that using inputs from the 850 hPa pressure level instead of the original 1,000 hPa pressure level would over/underestimate the cold/warm low-pressure systems, since cold/warm low-pressure systems tend to deepen/shallow with height, respectively (Holton, 2004). As mentioned in section 1, the effect of this process was evaluated in Hochman et al. (2017) and it was found that the synoptic systems are well represented using the data from the 850 hPa pressure level, although with different occurrences. Therefore, the proposed subjective rules of Alpert et al. (2004a) for calculating the length of the seasons had to be modified, using the occurrences that are based on the 850 hPa data. The suggested rule for defining the summer, dominated by the PT, was changed to 1/11 days instead of 6/11 days in the original classification (based on the 1,000 hPa). For the winter, dominated by CLs, the rule was changed to 4.3/11 days instead of 3/11 days in the original classification. The beginning and ending dates of spring and autumn result from the winter and summer dates, following the original suggestion by Alpert et al. (2004a).

The above mentioned thresholds were found by minimizing the differences between Alpert et al. (2004a) synoptic seasons lengths based on 1,000 hPa inputs (Table 2, first column from left) and the CMIP5 synoptic seasons lengths based on 850 hPa inputs (Table 2, second column from left). This means that a few options were examined so that the lengths of the seasons in CMIP5 will be as close as possible to the observations. Furthermore, the defined thresholds do not significantly influence the changes in the seasons' lengths in the future, which is the focus of this study.

The next section presents the projected changes in the lengths of each synoptic season in the 21st century as compared to the present period.

4 | PROJECTED LENGTH OF THE SYNOPTIC SEASONS

4.1 | Summer

The PT is a low-pressure system originating in the Persian Gulf extending to Greece with the associated Etesian winds penetrating the EM and the Levant (Maheras, 1980, 1977; Ziv et al., 2004). This system, along with the subtropical high-pressure system from south, is responsible for the lack of precipitation over the EM and Israel during the summer (Alpert, Abramsky, & Neeman, 1990; Saaroni & Ziv, 2000; Ziv et al., 2004; Harpaz, Ziv, Saaroni, & Beja, 2014).

Figure 1 displays an evaluation of the ability of the eight CMIP5 models (Table 1) and their mean ENS in capturing the annual cycle of the occurrence of the PT compared to the original NCEP/NCAR reanalysis SC, for the historical period (1986–2005). The models capture relatively well the annual cycle of the PT with correlation (*R*) of 0.7–0.9, RMSD of 2–4/11 days and relatively low standard deviations (*SD*), of about 1–3 *SD*, compared to the NCEP/NCAR reanalysis annual cycle (except for Meteorological Research Institute (MRI) model which shows *SD* ~ 0.2). As the PT is a warm low-pressure system and tends to shallow with

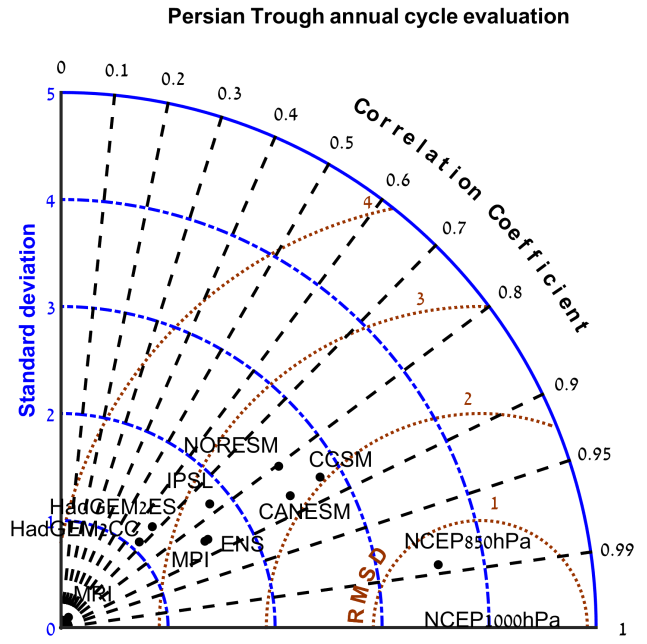

FIGURE 1 A Taylor diagram (Taylor, 2001) evaluation of the annual cycle of the occurrence of the PT over the EM for the eight CMIP5 models (Table 1), for the ENS mean and for NCEP/NCAR at 850 hPa with respect to the NCEP/NCAR reanalysis at 1,000 hPa, for the historical period, 1986–2005 [Colour figure can be viewed at wileyonlinelibrary.com]

height, the CMIP5 850 hPa SC underestimates its occurrence compared to the NCEP/NCAR 1,000 hPa SC. The ENS mean of the eight CMIP5 models captures well the PT annual cycle with a correlation coefficient of 0.85 with the NCEP/NCAR reanalysis. The evaluation for the NCEP reanalysis PT annual cycle at the 850 hPa level is also displayed for reference and it shows that the 850 hPa classification is doing quite well.

Figure 2 shows the annual cycle of the mean ENS of PT occurrence for the historical period 1986–2005, and for two periods in the future, 2046–2065 and 2081–2100. The models' spread around the ENS mean, for the RCP8.5 scenario, is shown in Figures S1–S3, Supporting information, respectively. As can be well seen, the length of the synoptic summer season is expected to increase by 25% in the near future (2046–2065) and by 49% at the end of the 21st century (2081–2100), under the RCP8.5 scenario (Figure 2a). In comparison with the RCP4.5 scenario approximately the same change is shown by mid-century with only small additional changes by the end of the century (Figure 2b). First signs of this change are shown in NCEP reanalysis, comparing the periods 1977–1996 and 1997–2016 (Figure S4).

The noticeable predicted lengthening of the summer may be explained by the expected strengthening of the South Asian monsoon under increased greenhouse gases concentrations in the future (Li, Ting, Li, & Henderson, 2015), which dominates the upper-level subsidence over the EM during the summer (Rodwell & Hoskins, 1996; Ziv et al., 2004). Also, the expected expansion of the Hadley cell towards the Pole in a warmer climate (Lu, Vecchi, &

TABLE 2 The length (number of days) of the synoptic seasons according Alpert et al. (2004a) and the ENS mean of the eight CMIP5 models for the historical period (1986–2005) and the change (in number of days) in two future periods (2046–2065 and 2081–2100) for the RCP8.5 scenario

Season	Length of seasons' according Alpert et al. (2004a) (days)	Length of seasons' according CMIP5 for 1986–2005 (days)	Change seasons' length for 2046–2065 in % (days)	Change seasons' length for 2081–2100 in % (days)
Summer	115	94	+25% (23)	+49% (46)
Winter	114	166	−25% (42)	−56% (93)
Autumn	75	73	+24% (17)	+59% (43)
Spring	61	27[a]	+12% (3)	+23% (6)

[a] Refer to section 4.4 for a complete discussion on the reasons for a short spring.

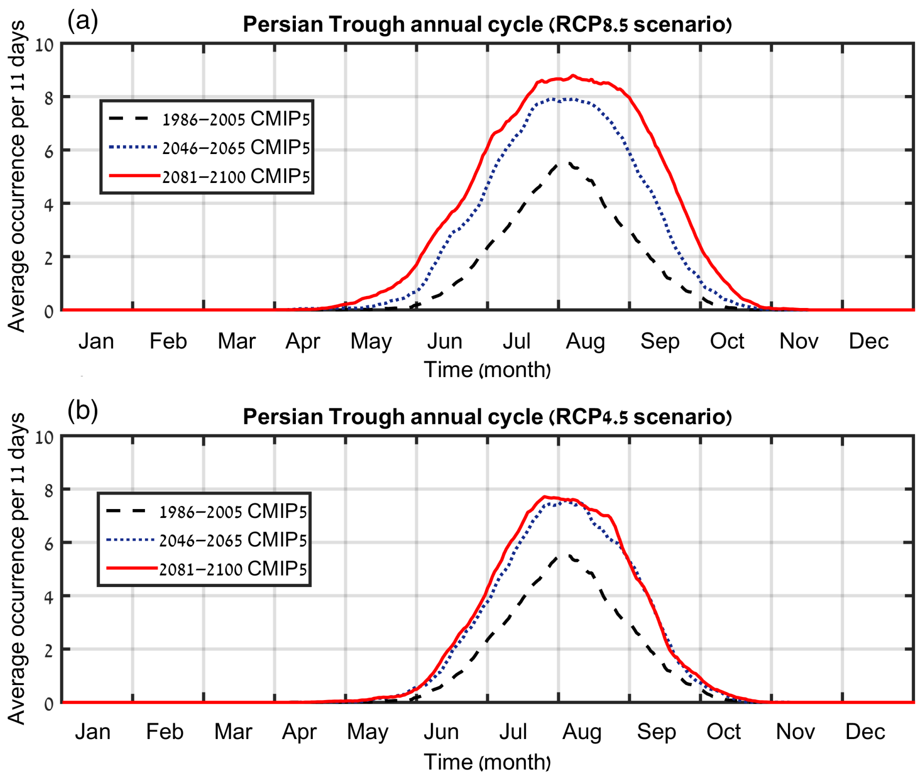

FIGURE 2 The ENS average of the eight CMIP5 models (a) RCP8.5 and (b) RCP4.5 of the annual cycle for the occurrence of the PT over the EM; for the historical (1986–2005, dashed), mid-century (2046–2065, dotted) and end century (2081–2100, full) periods [Colour figure can be viewed at wileyonlinelibrary.com]

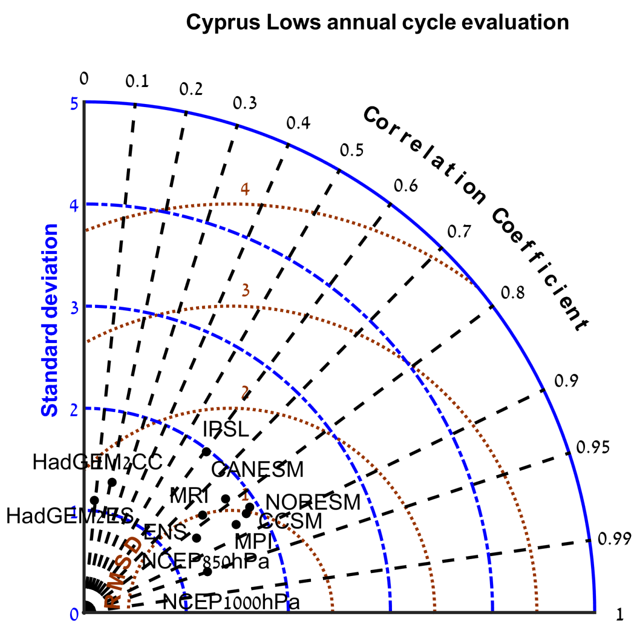

FIGURE 3 Same as Figure 1 but for the occurrence of the CL [Colour figure can be viewed at wileyonlinelibrary.com]

Reichler, 2007; Seidel, Fu, Randel, & Reichler, 2008) supports the results.

4.2 | Winter

CLs are mid-latitude disturbances that tend to either develop or deepen in the Levantine Basin when upper-air troughs or cut-off lows penetrate the EM (e.g., Alpert, Neeman, & Shay-El, 1990b; Trigo, 2006; Bartholy, Pongrácz, & Margit, 2009; Flocas et al., 2010; Ziv, Harpaz, Saaroni, & Blender, 2015). CLs transport cold air, originating from eastern Europe that becomes moist and unstable while passing over the warm Mediterranean Sea (Alpert & Reisin, 1986; Shay-El & Alpert, 1991). These lows contribute ~90% of the annual precipitation in Israel (Goldreich, Moses, & Rosenfeld, 2004; Saaroni et al., 2010; Zangvil, Karas, & Sasson, 2003). The rainfall yield and its spatial distribution over Israel are highly sensitive to the location of the CL as well as to its track and intensity (Saaroni et al., 2010; Zangvil et al., 2003). It was earlier shown that CLs have a regular bell-shaped occurrence during winter with peaks centring over specific calendar dates, often entitled as calendaricities (Osetinsky & Alpert, 2006).

Figure 3 displays a Taylor diagram evaluation for the annual cycle of the occurrence of CLs for the historical period. Six out of the eight CMIP5 models excel in capturing the CL annual cycle, with correlation coefficient >0.6, RMSD of 0.9/11 days to 1.5/11 days and a *SD* similar to that found in the NCEP/NCAR reanalysis (1.5 *SD*). The ENS mean of the CMIP5 models captures well the annual cycle of the CLs, in all three evaluated parameters. The evaluation for the NCEP reanalysis CL annual cycle at the 850 hPa level is also displayed for reference and it shows that the 850 hPa classification is performing quite well.

Figure 4 presents the annual cycle of CLs mean ENS for the historical and future periods. The models' spread around the ENS mean, for the RCP8.5 scenario, is shown in Figures S5–S7, respectively. The length of the synoptic

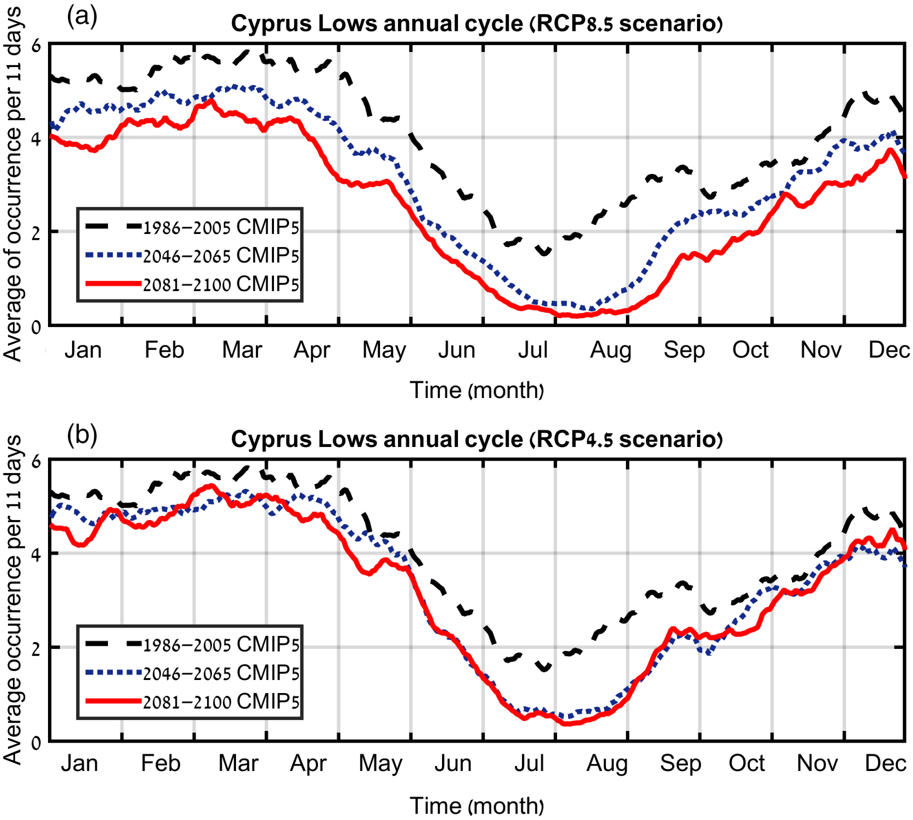

FIGURE 4 Same as Figure 2 but for the occurrence of the CL [Colour figure can be viewed at wileyonlinelibrary.com]

winter season is expected to decrease by 25% in the near future (2046–2065) and by 56% at the end of the 21st century (2081–2100), under the RCP8.5 scenario (Figure 4a). In comparison with the RCP4.5 scenario approximately the same change is shown by mid-century with only small additional changes by the end of the century (Figure 4b). First signs of this change are shown in NCEP reanalysis, comparing the periods 1977–1996 and 1997–2016 (Figure S8).

The sharp decrease predicted in the occurrence of CLs reinforces the expected expansion of the Hadley cell in a warmer climate (Lu et al., 2007; Seidel et al., 2008) and the increase in the positive phase of the North Atlantic Oscillation (NAO) that is related with northwards migration of the cyclone tracks (Eichler, Gaggini, & Pan, 2013; Tamarin-Brodsky & Kaspi, 2017). Note that the modified SC captures a small number of CLs during the summer period. These detected CLs can be related to the small number of rainy events developing over the Levant during summer (Saaroni & Ziv, 2000). This feature should not influence the changes in the occurrence of the CL system as the same classification procedure was applied to all periods.

4.3 | Autumn

The RST is a low-pressure trough that extends from East Africa or Saudi Arabia towards the EM and the Levant (e.g., Alpert et al., 2004a; Ashbel, 1938; Kahana, Ziv, Enzel, & Dayan, 2002; Tzvieli & Zangvil, 2005, 2007). The physical mechanism responsible for the RST generation was shown to be the interaction of the westerly jet with the E. African Mountains (Krichak, Alpert, & Krishnamurti, 1997a, 1997b). The lower-level trough is commonly accompanied by upper-level westerlies or anticyclonic flow. When this combination of dry air at the lower levels and absence of upper-level dynamic ascent exist, the RST is a non-rainy system (Dayan, Ziv, Margalit, Morin, & Sharon, 2001; Ziv, Dayan, & Sharon, 2005). It is mostly accompanied by transport of relatively hot and dry air from the Arabian Peninsula and its surroundings towards the Levant (e.g., Lionello, 2012; Saaroni, Ziv, Bitan, & Alpert, 1998) and in some cases, dust storms develop (e.g., Dayan, Ziv, Shoob, & Enzel, 2008; Ganor, Osetinsky, Stupp, & Alpert, 2010; Ganor, Stupp, Osetinsky, & Alpert 2010), as for example the latest extreme event of 8–10 September 2015 (Gasch et al., 2017; Mamouri et al., 2016; Parolari, Li, Bou-Zeid, Katul, & Assouline, 2016; Uzan, Egert, & Alpert, 2017). When a sharp upper-level trough or even cut-off low develops over the Nile Delta, pronounced instability develops throughout the entire troposphere. The implied mid-level southerly winds transport tropical moist air from equatorial Africa or from the Arabian Sea into the Levant, resulting in severe rain and flood events (Dayan et al., 2001; Kahana et al., 2002; Shalev, Saaroni, Izsak, Yair, & Ziv, 2011; Tzvieli & Zangvil, 2005, 2007; Ziv et al., 2005). It should be noted that the current study of the seasons' length does not distinguish between an active and a non-active RST. Thus, it is not yet possible to determine the projected frequency and timing of RST-related floods.

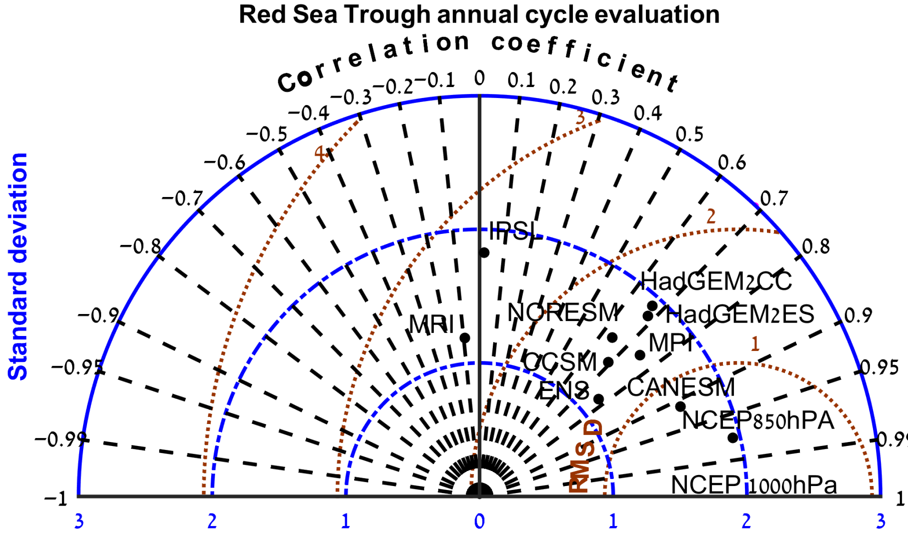

FIGURE 5 Same as Figure 1 but for the occurrence of the RST [Colour figure can be viewed at wileyonlinelibrary.com]

According to the semi-objective SC of Alpert et al. (2004a), the RST system has an annual frequency of 19% of the days, mainly in the autumn season, considerably during the winter, and exhibiting fade-out by mid-spring. Figure 5 shows a Taylor diagram evaluation for the annual cycle of the occurrence of the RST, for the historical period. Six out of the eight CMIP5 models capture well the annual cycle of the RST, with correlation coefficient >0.6, RMSD of 0.8/11 days to 1.5/11 days and *SD* comparable to that of the NCEP/NCAR reanalysis (2 *SD*). The ENS mean of the CMIP5 models presents a correlation coefficient of ~0.8 and RMSD of ~1.2/11 days. The evaluation for the NCEP reanalysis RST annual cycle at the 850 hPa level is also displayed for reference and it shows that the 850 hPa classification is performing quite well.

The length of the synoptic autumn, defined as the difference between the end of summer and the beginning of winter, is expected to increase by 24% in the near future (2046–2065) and by 59% at the end of the 21st century (2081–2100), under the RCP8.5 scenario (Table 2). The models spread around the ENS mean, for the RCP8.5 scenario, are shown for reference in Figures S9–S11. Figure 6 presents the annual cycle of the RST for the historic and future periods. An increase in the occurrence of RST days is expected during the autumn, the winter and the spring seasons, and a decrease is noted during the

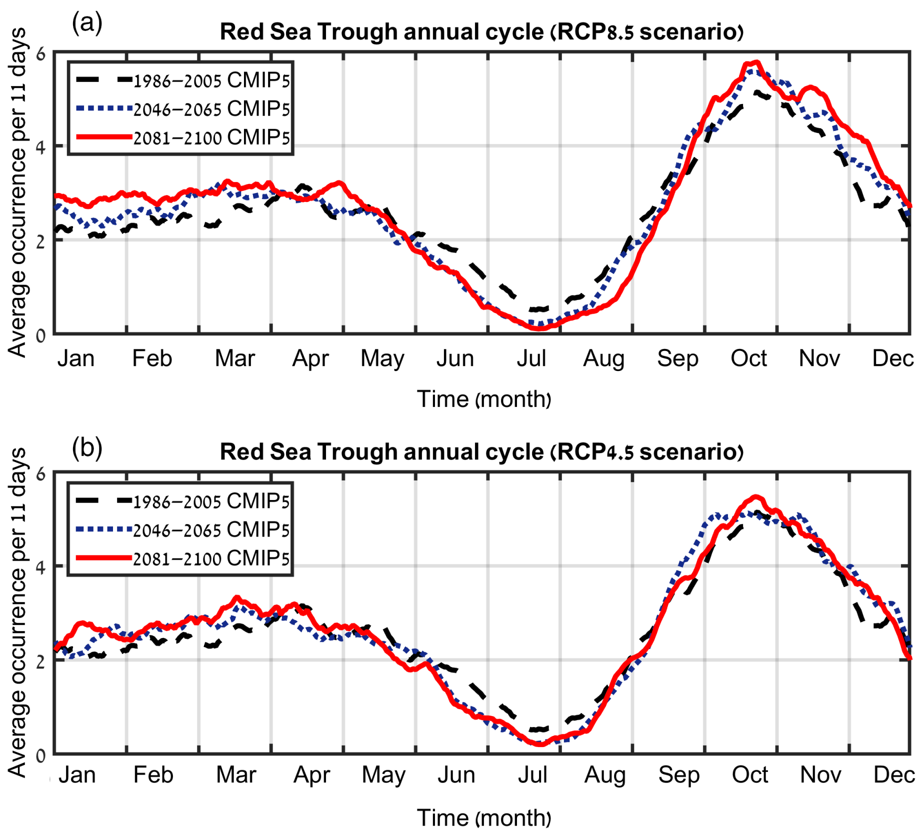

FIGURE 6 Same as Figure 2 but for the occurrence of the RST [Colour figure can be viewed at wileyonlinelibrary.com]

summer. No significant difference is shown between RCP8.5 and RCP4.5 scenarios (Figure 6a,b, respectively). First signs of this change are shown in NCEP reanalysis, comparing the periods 1977–1996 and 1997–2016 (Figure S12).

These results go in line with the predicted decrease in the occurrence of CLs during the winter and the transitional seasons (Figure 4) and the increase in the occurrence of the PT during the summer (Figure 2). The latter may result from the expected strengthening of the South Asian monsoon (Li et al., 2015). The decrease in the occurrence of CLs may be related to migration of the Mediterranean storm track northwards (Chang, Guo, & Xia, 2012; Eichler et al., 2013; Tamarin-Brodsky & Kaspi, 2017), associated also with the Hadley cell expansion (Lu et al., 2007; Seidel et al., 2008). These changes are related with variations in the intensity of large-scale oscillations known to modulate the CLs such as the NAO and the East Atlantic Western Russia (EA-WR) patterns (Black, 2012). A reduction in the occurrence of CLs enables penetration of the RST towards the Levant, resulting in a predicted increase in their occurrence during the autumn, the winter and the spring.

4.4 | Spring

The SL is a low-pressure system generated in the lee of the Atlas Mountains, migrating from west to east on the southern coast of the Mediterranean during the spring (Egger, Alpert, Tafferner, & Ziv, 1995; Prezerakos, 1990). The spring season is very short, and the SLs' reach their peak (~5% of the days) in April (Alpert et al., 2004a). The SL natural average occurrence is about once per week during high spring (Alpert & Ziv, 1989). There are several reasons why the modified SC used in this study mostly missed the SLs', resulting in a short spring definition (27 days) (Table 2). SLs' move quickly over the southern coast of the Mediterranean, sometimes within less than a day and usually at night time (Alpert, Neeman, & Shay-El, 1990a). Thus, the appearance of a SL may fall between the classification sampling times, which is currently once daily at 12Z. Additionally, the relatively coarse resolution of the CMIP5 models rarely capture mesoscale phenomena such as the SL, which is about 200–500 km in size. Furthermore, the averaging process over 20 years, which may include the peak of the SL occurrence at slightly different times, is probably smoothing out the peak or even removing it completely. Note that an earlier objective season's definition resulted in the complete disappearance of the spring (Alpert et al., 2004a).

In addition, the current modified classification in which a different pressure level is employed, i.e., 850 hPa instead of 1,000 hPa, contributed to this spring result. As explained in section 1 the warm low-pressure systems tend to shallow with height, thus, the low natural occurrence of SLs' at the surface is even further reduced in the 850 hPa level. Finally, the SL is associated with an upper-level trough to the west of Cyprus (Alpert & Ziv, 1989), which is captured by the modified classification during April as a peak in CL occurrences (Figure 4). Because of the above mentioned reasons the SLs' were not evaluated and predicted separately in this

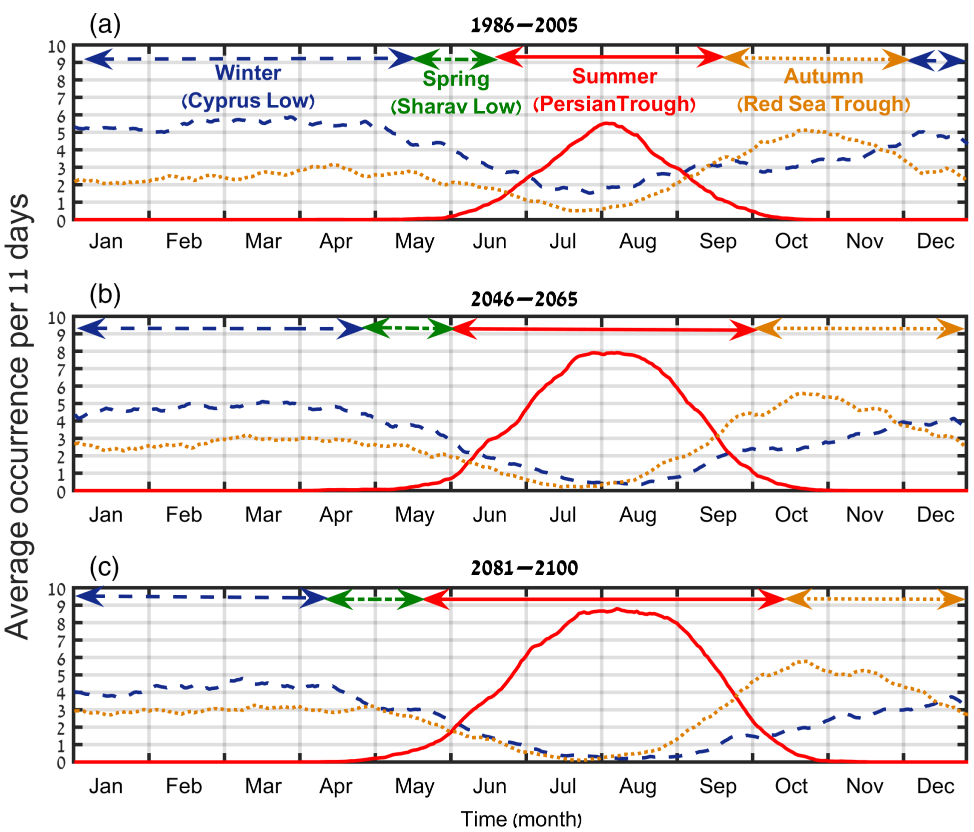

FIGURE 7 A summary of the seasons lengths' according to the synoptic definition of Alpert et al. (2004a). The average ENS of the eight CMIP5 models is presented for the annual cycle of the occurrence of the PT (representing the summer, full line), CL (representing the winter, dashed line) and the RST (representing the autumn, dotted line). The periods shown are: (a) 1986–2005, (b) 2046–2065 and (c) 2081–2100, under the RCP8.5 scenario [Colour figure can be viewed at wileyonlinelibrary.com]

study. Nevertheless, Alpert et al. (2004a) defined the spring as the period between winter and summer. According to this definition, here, the spring's length is 27 days expected to increase by 12% (2046–2065) and 23% (2081–2100) under the RCP8.5 scenario (Table 2 and Figure 7a–c).

The cyclogenesis of SLs is basically the result of classic baroclinic instability (Alpert & Ziv, 1989; Egger et al., 1995). Furthermore, the synoptic baroclinic instability is not sufficient to produce the high occurrence of the SL during spring. Only by adding low-level baroclinicity due to significant sea-land temperature contrast the peak of SL occurrence in spring is obtained (Alpert & Ziv, 1989). Since the temperature difference between land and sea is expected to increase due to a more rapid increase in land surface temperature relative to the increase in sea surface temperature under warming scenarios (Alpert, Krichak, Dayan, & Shafir, 2006; Sutton, Dong, & Gregory, 2007). This may explain the expected lengthening of the spring season (Table 2 and Figure 7a–c) with the associated uncertainties.

5 | SUMMARY AND CONCLUSIONS

The study investigates future changes in the length of the seasons, mainly the winter and the summer, over the EM, based on the ensemble mean of eight CMIP5 models. The seasons were defined following the definition of Alpert et al. (2004a) that is based on the occurrence of the prevailing synoptic systems. The CMIP5 models were found to capture relatively well the annual cycle of the prevailing synoptic systems for the present period (1986–2005). For the future period, under the RCP8.5 scenario, it was found that the length and timing of the synoptic seasons are expected to change significantly (Table 2 and Figure 7a–c). The warm and dry summer season is expected to last for a longer period, while the cooler and wetter part of the year is expected to shorten (Table 2 and Figure 7a–c). The length of the summer season is predicted to increase by 25% in the mid-21st century and by 49% at the end of the century. The opposite holds for the winter season; predicted to decrease by 56% in length by the end of the century. The opposite trends predicted for the length of the summer and the winter results in a pronounced increase in the length of autumn by 59% at the end of the 21st century. Regarding the spring, defined according the occurrence of the often mesoscale SL, hardly detected by the relatively coarse temporal and spatial resolution of the CMIP5 models. Nonetheless, defined here as the period between the end of summer and the beginning of winter. The length of the spring is predicted to increase by 23% by the end of the century. Comparing the results of the RCP8.5 and RCP4.5 scenarios reveal that the RCP4.5 scenario projects approximately the same changes by mid-century with only small additional changes by the end of the century. This is in line with the definition of the RCP4.5 scenario, in which greenhouse gas concentrations will peak at 2040 and then start to decline.

The changes in the synoptic seasons' lengths are a result of the expected strengthening of the South Asian monsoon during summer under increased greenhouse gases concentrations, the expected expansion of the Hadley cell towards the Poles in a warmer climate and the positive phase of the NAO migrating cyclone tracks northwards during winter. This polewards shift of synoptic systems finds expression in the increase of RST frequencies during autumn, winter and spring. The decreases in RSTs during summer are related to the strengthening of the South Asian Monsoon under increased greenhouse gases concentrations, thus, reducing the number of RST's with respect to an increase in PT occurrence. Finally, the temperature difference between land and sea is expected to increase due to a more rapid increase in land surface temperature relative to the increase in sea surface temperature in a warming scenario. This factor was found to be most significant in cyclogenesis of SLs and might explain the predicted lengthening of the spring season, with the associated uncertainties.

The lengthening of the summer season together with the shortening of the winter season may lead to substantial environmental changes, including deficit in the water resources and the hydrological regime, increased risks for agriculture, fires and air pollution, as well as health risks.

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