Climate Dynamics
https://doi.org/10.1007/s00382-019-05017-3

The dynamics of cyclones in the twentyfirst century: the Eastern Mediterranean as an example

Assaf Hochman[1] · Pinhas Alpert[2] · Pavel Kunin[2] · Dorita Rostkier-Edelstein[3] · Tzvi Harpaz[2,4] · Hadas Saaroni[4] · Gabriele Messori[5,6]

Received: 1 April 2019 / Accepted: 14 October 2019

Abstract
The Mediterranean region is projected to be significantly affected by climate change through warming and drying. The Eastern Mediterranean (EM) is particularly vulnerable since the bulk of the precipitation in the region is associated with a specific circulation pattern, known as Cyprus Low (CL). Here, we study the influence of increased greenhouse gases on the average properties and dynamics of CLs, using a regional semi-objective synoptic classification. The classification is applied to NCEP/NCAR reanalysis data for the present day (1986–2005) as well as to eight CMIP5 models for the present day and for the end of the century (2081–2100; RCP8.5). This is complemented by a dynamical systems analysis, which is used to investigate changes in the dynamics and intrinsic predictability of the CLs. Finally, a statistical downscaling algorithm, based on past analogues, is applied to eighteen rain stations over Israel, and is used to project precipitation changes associated with CLs. Significant changes in CL properties are found under climate change. The models project an increase in CL meridional pressure gradient (0.5–1.5 hPa/1000 km), which results primarily from a strong increase in the pressure over the southern part of the study region. Our results further point to a decrease in CL frequency (− 35%, as already noted in an earlier study) and persistence (− 8%). Furthermore, the daily precipitation associated with CL occurrences over Israel for 2081–2100 is projected to significantly reduce (− 26%). The projected drying over the EM can be partitioned between a decrease in CL frequency (~ 137 mm year^{-1}) and a reduction in CL-driven daily precipitation (~ 67 mm year^{-1}). The models further indicate that CLs will be less predictable in the future.

Keywords Cyprus low · Cyclone predictability · Climate change · Cyclone dynamics · Synoptic classification · Dynamical systems · Statistical downscaling · Daily precipitation

1 Introduction

The Mediterranean Basin has been recognized as a 'hot spot' for climate change, and is projected to warm and dry in the future (Giorgi 2006; IPCC 2013; Lelieveld et al. 2016). This trend likely reflects changes in the occurrence, intensity and dynamics of Mediterranean cyclones in general (Lionello et al. 2006; Lionello and Giorgi 2007; Raible et al. 2010; Zappa et al. 2015), and of Eastern Mediterranean cyclones in particular (Peleg et al. 2015; Hochman et al. 2018a).

The majority of intense Mediterranean storms have a baroclinic life cycle typical of mid-latitude extra-tropical cyclones (Flaounas et al. 2015). In spite of their generally limited size and duration, they are associated with most extreme weather events in the region (Nissen et al. 2010, 2014). These include heavy precipitation, intense winds and sometimes severe dust storms (e.g., Tsidulko et al. 2002; Lionello 2012; Lionello et al. 2014; Drobinski et al. 2016). Mediterranean storms can thus have significant socio-economic impacts, especially on the highly populated coastal areas surrounding the basin.

The complex terrain surrounding the relatively warm waters of the Mediterranean results in several areas of cyclogenesis or cyclone intensification (Alpert et al. 1990; Trigo et al. 1999; Ziv et al. 2015; Lionello et al. 2016). The most frequent cyclogenetic area is located in the Gulf of Genoa. A second area is situated south of the Atlas Mountains

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00382-019-05017-3) contains supplementary material, which is available to authorized users.

✉ Assaf Hochman
assafhochman@yahoo.com; assaf.hochman@kit.edu

Extended author information available on the last page of the article

Published online: 02 November 2019

(Alpert and Ziv 1989; Egger et al. 1995). Other areas of high cyclonic activity are found in the North Aegean Sea and the Black Sea. In the Eastern Mediterranean, the climatological signature of cyclones appears to the east of Cyprus, such that these systems are frequently termed Cyprus Lows.

Cyprus Lows are mid-latitude disturbances that tend to develop in the lee of the Taurus Mountains, in front of upper troughs or cut-off lows (Zangvil et al. 2003). They transport cool air, originating from Eastern Europe, over the warmer Mediterranean Sea where it becomes moist and unstable (Alpert and Reisin 1986; Alpert et al. 1990; Shay-El and Alpert 1991). These lows contribute to ~ 80% of the annual precipitation in Israel, but the rainfall yield and its spatial distribution are highly sensitive to the specific location and intensity of the Cyprus Low occurrences (Enzel et al. 2003; Saaroni et al. 2010a).

Here, we identify Cyprus Lows based on the semi-objective synoptic classification of Alpert et al. (2004a). This classification was found to closely reflect the local weather conditions in the Eastern Mediterranean, especially for atmospheric patterns such as Cyprus Lows (Saaroni et al. 2010a, b; Dayan et al. 2012). Alpert et al. (2004a) have shown large inter-annual variations in the occurrence of Cyprus Lows in the second half of the twentieth century. Hochman et al. (2018a) have projected a decrease of ~ 35% in the occurrence of Cyprus Lows for the end of the twenty-first century (RCP8.5). The same authors have also shown that the seasonal timing of Cyprus Lows may significantly change in the future (Hochman et al. 2018b).

Recently, the conventional descriptions of synoptic patterns—and more generally atmospheric configurations—have been complemented by a novel approach, issued from dynamical systems theory. This is grounded in the seminal work of Lorenz (1963, 1980), and is based on metrics describing the instantaneous states of atmospheric fields (Faranda et al. 2017a). The first, local dimension (d), is a proxy for the active number of degrees of freedom of the system, and provides information on the intrinsic predictability of a given atmospheric state. The second, θ^{-1}, is a measure of persistence in phase space, which can be interpreted as persistence of a given state in time. Here, these are computed for daily atmospheric fields in the Eastern Mediterranean, grouped into synoptic classes. It has recently been shown that d and θ^{-1} provide an objective dynamical characterisation of the synoptic patterns in the region (Hochman et al. 2019a).

The purpose of this study is to estimate how the projected increase in future greenhouse gas concentrations may influence the dynamics of Eastern Mediterranean cyclones, i.e. the Cyprus Lows. The study focuses on changes in the sea level pressure patterns of Cyprus Lows, in their persistence and intrinsic predictability and in the resulting daily rainfall yield. We further elucidate the concomitant effects of these changes and of the projected reduction in the frequency of Cyprus Lows on the future precipitation regime in the region.

2 Data

Daily reanalysis data on a 2.5° × 2.5° horizontal grid are acquired from the National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis Project (NCEP/NCAR; Kalnay et al. 1996).

Model data are retrieved from the World Data Center for Climate—Deutsches Klimarechenzentrum GmbH (WDCC-DKRZ, https://cera-www.dkrz.de) data portal, for eight models participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). The list of models appears in Table 1 and follows the selection in Hochman et al. (2018a, b, 2019a, b). The spatial horizontal resolution varies from 0.94° × 1.25° to 1.9° × 3.75°, depending on the specific model (Table 1). The ability of these models to simulate annual and extreme precipitation

Table 1 The eight CMIP5 models used in the present study

Modelling center (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 Centre for Atmospheric Research, USA	NCAR	CCSM4 (CCSM)	0.94 × 1.25
Met Office Hadley Centre, England	MOHC	HadGEM2-CC (HadGEM2CC) HadGEM2-ES (HadGEM2ES)	1.25 × 1.88 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 Centre, Norway	NCC	NORESM1-M (NORESM)	1.9 × 2.5

Columns show: modelling centre (or group), institute ID, model name and horizontal resolution (°), following Taylor et al. (2012)

over the Eastern Mediterranean was previously discussed by Samuels et al. (2017). Hochman et al. (2018a, b, 2019a) found that these models successfully capture the salient qualitative features of the dynamics, frequency and annual cycle of the synoptic systems over the Eastern Mediterranean as reflected in the reanalysis data, including those of Cyprus Lows. At the same time, the models may fail to reproduce several of the reanalysis' quantitative features.

The analysis of present-day climate is based on historical (1986–2005) simulations of the CMIP5 models as well as on the NCEP/NCAR reanalysis archive for the same period. The simulated future period is the last two decades of the twentyfirst century (2081–2100). The choice of time period follows the recommendation of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013). We consider the Representative Concentration Pathway of 8.5 W/m^2 (RCP8.5) scenario, exhibiting a continuous increase in greenhouse gas concentrations throughout the twentyfirst century (Van-Vuuren et al. 2011).

The statistical downscaling algorithm for daily precipitation over Israel on days defined as a Cyprus Low is based on daily precipitation observations from a set of eighteen stations representing the primary groundwater basins of Israel, taken from the Israel Meteorological Service (IMS) database (https://ims.data.gov.il/he/ims/3; Table S1; Fig. 1b). The daily rainfall data from these stations provide a continuous long-term archive over 1991–2008, which has undergone a quality assurance procedure. This includes automated evaluation of each new data point with respect to its predecessor and cross-validation with neighboring stations, radar retrievals etc. In addition, each data point is compared to other meteorological variables and to the local climatology. For example precipitation cannot be measured when there is no cloud cover.

3 Methods

The changes in the mean properties and dynamics of Cyprus Lows are studied using a variety of approaches, which we detail below.

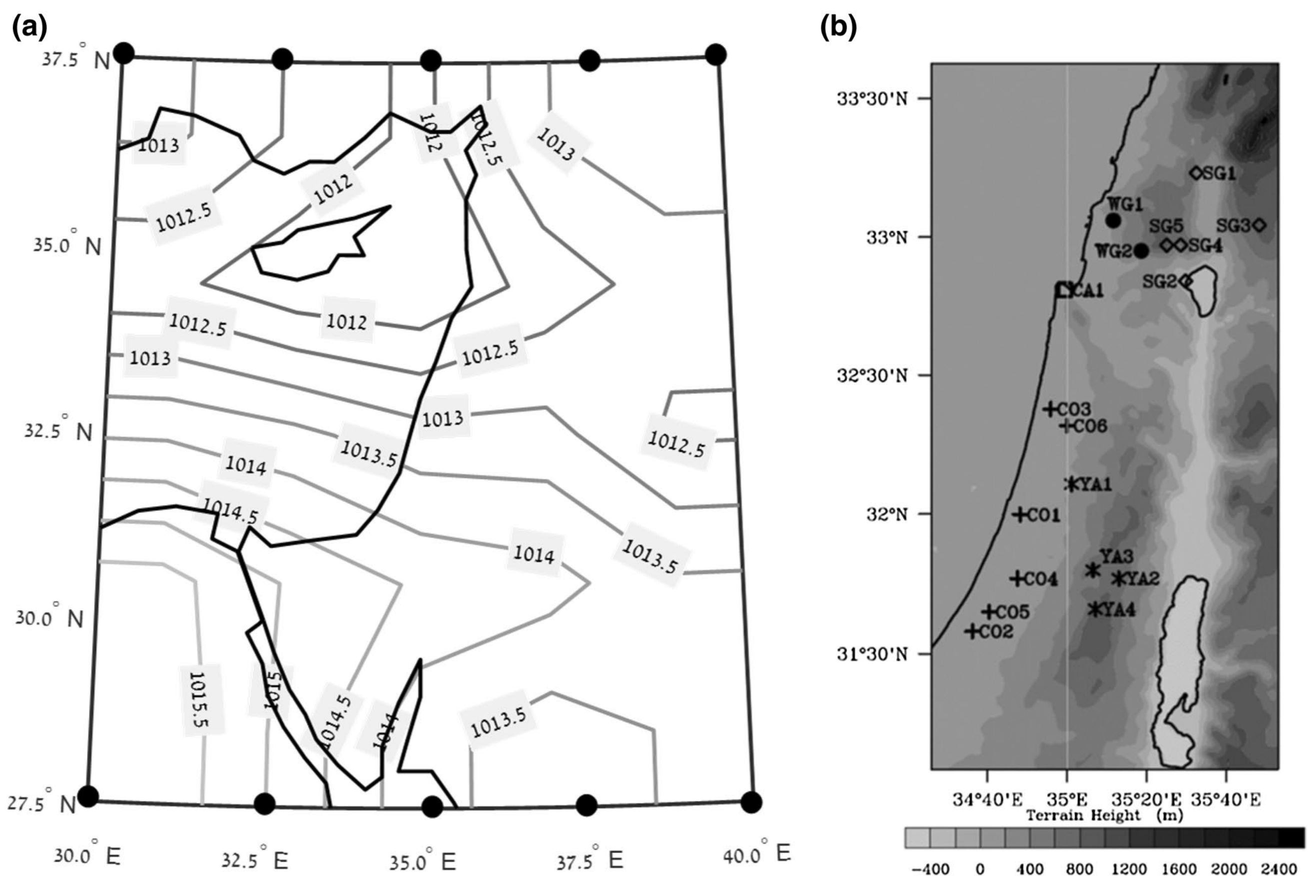

Fig. 1 The study region. **a** Composite map of the mean sea-level pressure (hPa) on days defined as Cyprus Lows over the Eastern Mediterranean. The map is based on the NCEP/NCAR reanalysis for 1986–2005. Black circles denote grid points used for calculating the meridional pressure gradient. **b** The location of the eighteen rainfall stations on top of the topography (reproduced from Rostkier-Edelstein et al. 2016)

3.1 Synoptic classification over the Eastern Mediterranean

The semi-objective synoptic classification of Alpert et al. (2004a) uses sea-level pressure, air temperature and horizontal wind components U and V at the 850 hPa level over the south-eastern part of the Eastern Mediterranean (27.5° N–37.5° N, 30° E–40° E; Fig. 1a). Five main synoptic classes are defined by Alpert et al. (2004a, b) as follows: the Persian Troughs (PT), characterizing the summer, the Red Sea Troughs (RST), peaking in the autumn, the Sharav Lows (SL) typical of spring, the High-pressure systems (H) appearing throughout the year and the Cyprus Lows (CLs), dominant in winter and the focus of this study.

3.2 Dynamical properties of Eastern Mediterranean cyclones

A recently developed method, combining extreme value theory with Poincaré recurrences, allows to compute the instantaneous properties of a dynamical system (Lucarini et al. 2016; Faranda et al. 2017a). This method is applied to daily sea-level pressure fields over the study region. The succession of daily fields is interpreted as a long trajectory in phase space. Each field corresponds to a single point along this trajectory, for which local properties are computed. Locality in phase space therefore translates to instantaneity in time. The analysis focuses on two metrics, namely the local dimension d and the persistence θ^{-1}.

The local dimension is obtained by applying the Freitas-Freitas-Todd theorem (Freitas et al. 2010, modified in Lucarini et al. 2012), and is based on recurrences of the system around the state of interest. The persistence of a state results from estimating the extremal index ϑ, which we compute here using the Süveges estimator (Süveges 2007). We then obtain the inverse persistence as $\theta = \vartheta/\Delta t$, where Δt is the time step of the dataset. The persistence θ^{-1} is therefore in units of the time step of the data. In the figures we plot θ rather than θ^{-1} to ease comparison with figures in previous studies (e.g. Faranda et al. 2017a; Hochman et al. 2019a, b). For details of the computation of the above-mentioned metrics, the reader is referred to Lucarini et al. (2016) and Faranda et al. (2019a).

As a final product, we obtain values of d and θ^{-1} for every time step in our datasets. The first is a proxy for the number of active degrees of freedom of the system about the state of interest. The second represents the mean residence time of the trajectory in the neighbourhood of said state, and ranges from 1 (low persistence, $\theta = 1$, the system leaves the neighborhood of the state of interest at the next time iteration) to infinity (a fixed point, $\theta = 0$). Both therefore have a direct link to the *intrinsic predictability* of the evolution of the atmosphere around a given state (Faranda et al. 2019b). This is in contrast to practical predictability defined relative to the performance of a numerical weather prediction model, although the two are related (Scher and Messori 2018). The dynamical systems approach, being relatively general, has been successfully applied to a variety of climate fields and datasets (e.g. Faranda et al. 2017a, b; Messori et al. 2017; Rodrigues et al. 2018; Hochman et al. 2019a). For the limits of applicability to non-stationary systems, we refer the reader to Freitas et al. (2017). A caveat is the dependence of persistence on the temporal resolution of the data used, since θ^{-1} is in units of the time step. For a very long time step, all instantaneous states will tend to $\theta^{-1} = 1$. However, as long as the time step of the dataset being used is smaller than the typical time scale of the process being studied, θ^{-1} values should be informative. Here, we use daily data and the typical persistence of a Cyprus Low is ~ 1–4 days (Alpert and Ziv 1989; Karas and Zangvil 1999).

The dynamics of Cyprus Lows are further studied using transition probability matrices, i.e., Markov chains (Gagniuc 2017). These describe the probability of occurrence of a synoptic system at time $t+1$ as a function of the synoptic system occurring at time t. The probabilities are calculated within each synoptic class, such that the frequency of each class does not influence the analysis. This is a simple complement to the dynamical systems approach, providing additional information on the evolution of the synoptic systems that govern Eastern Mediterranean weather. The above-mentioned methods successfully reflect the dynamics of the Eastern Mediterranean synoptic classes, as recently demonstrated by Hochman et al. (2019a).

3.3 Statistical downscaling of precipitation

To study the changes in precipitation yield on a Cyprus Low day, a statistical downscaling algorithm based on past analogues (Rostkier-Edelstein et al. 2016), originally proposed by Lorenz (1969), is used. In this method, a given weather state is compared with those from a long-term record. Then, the most similar weather state from the past is identified, and the matching local observations are selected as predictors for the local-scale weather (Zorita and von Storch 1999). The choice of metrics to define similarity is vast; here, analogue days are identified based on the minimal Euclidean distance (Minkowski) metric (Wilks 2011) in the space of predicted and observed vectors. The metric is calculated using twenty-five grid points and four variables at each grid point (see Sect. 3.1, above). The predicted daily precipitation at each gauge station is calculated by averaging the observed daily precipitation for three past analogues, in inverse proportion to their squared distances. Thus, the closest analogue could still not be the most similar in terms of the associated precipitation. Rostkier-Edelstein et al. (2016) tested the number of analogues to be considered in the downscaling algorithm and found that using the three closest analogues is the optimal choice, albeit with some variance deflation. The analogues method is skillful in predicting the means and quantiles of seasonal precipitation distributions, as well as in reproducing the observed inter-annual and spatial precipitation variability (with relatively high correlations of ~ 0.8; Rostkier-Edelstein et al. 2016). This provides a significant improvement over the results of coarse global models. The reader is referred to Rostkier-Edelstein et al. (2016) for further methodological details. The analogues downscaling method was recently successfully used in Hochman et al. (2019b) to downscaled *seasonal precipitation* over Israel.

The general advantages and disadvantages of statistical downscaling have been extensively discussed in previous studies (e.g. Fowler et al. 2007; Laprise et al. 2008; Maraun et al. 2010; Warner 2011; Velasquez et al. 2015; Salvi et al. 2016; Lanzante et al. 2018). Statistical downscaling methods are computationally inexpensive compared to dynamical downscaling and, depending on the availability of high quality observations and the specific statistical techniques applied, often provide good results (Lanzante et al. 2018). Nonetheless, statistical downscaling may suffer from uncertainty due to the method itself (Maraun et al. 2010; Maraun and Widmann 2018) and may also be sensitive to the non-stationarity of the climate system. This is because the empirical relations based on observations are assumed to be stationary over time (Salvi et al. 2016). More specifically, the analogues method's disadvantage is that it cannot explore precipitation amounts that have not occurred in the past (Maraun et al. 2010). Therefore, Young (1994) proposed a perturbation of observed values to overcome this disadvantage. In this study, we are not limited to past states, but rather to the past range of the events, because we generate linear combinations of sets of three past events. The potential limitations of the resampling scheme have been extensively reviewed in the literature (Young 1994; Yates et al. 2003; Beersma and Buishand 2003).

4 Results

4.1 Sea-level pressure changes of Eastern Mediterranean cyclones

The mean sea-level pressure composite map of Cyprus Low days for the NCEP/NCAR data over 1986–2005 (Fig. 1a) is compared to the maps based on the individual CMIP5 models (Fig. 2). For the present period, the models capture relatively well the spatial pattern of the Cyprus Lows, although there is some variation in the geographical location of the sea-level pressure minima. For the end of the twentyfirst century, six out of the eight models (CCSM, HadGEM2-CC, HadGEM2-ES, IPSL, MPI and NORESM) display a significant increase in sea-level pressure across the region, peaking in the southern part of the domain (Fig. 3). This emerges clearly in the difference map of the multi model ensemble mean between the 'present' and the 'future' periods (Fig. 3e). Although the models do not unanimously indicate an increase in sea-level pressure (Fig. 3a, h) they do agree that the average meridional pressure gradient across the ~ 1000 km domain considered here, will increase in the future by ~ 0.5–1.5 hPa (Fig. 3). The change in the meridional pressure gradient force per unit mass $\frac{F_y}{m}$ can then be calculated according to:

$$\Delta\frac{F_y}{m} = \frac{-1}{\rho}\frac{\Delta p}{\Delta y}$$

where ρ is the density of air ≈ 1.2 kg m^{-3}, Δp is the difference between pressures and Δy is the distance between the pressures used in Δp (km). In our case, this means an increase of the meridional pressure gradient force of up to 0.012 km s^{-2} (equivalent to an increase of up to ~ 25% for a Cyprus Low), due to increased greenhouse gas concentrations. Thus, it is assumed that future Cyprus Lows may be associated, on average, with stronger zonal winds. We further note that the meridional pressure gradient force increase primarily results from a pressure increase in the south of the domain rather than a deepening of the low pressure centre in the north.

4.2 Future dynamics of Eastern Mediterranean cyclones

Changes in the dynamics of Cyprus Lows under increased greenhouse gas concentrations are investigated using transition probability matrices and dynamical systems metrics (see Sect. 3.2). Figure 4 shows the changes in the transition probabilities for the five synoptic systems characterizing the Eastern Mediterranean region according to the eight CMIP5 models considered here. In the multi model ensemble mean, the Persian Trough and the Cyprus Low systems display the largest changes in self-transitions, i.e., transitions from PT to PT or from CL to CL. The changes are about + 16% for PTs and − 8% for CLs. These changes are significant at the 5% significance level under a binomial test (Fig. 4e; bold numbers are significant). Furthermore, a significant reduction is projected in the transitions from other synoptic systems to the Cyprus Lows (Fig. 4e). These results are mostly consistent across the eight models (Fig. 4).

The dynamics of Cyprus Lows are further analyzed using the d and θ metrics. Figure 5 shows the Cumulative Distribution Functions (CDFs) on Cyprus Low days for the present and future periods. The ensemble of CMIP5 models show an increase in d (Fig. 5a) and θ (i.e. decrease in persistence, Fig. 5b). These are significant at the 5%

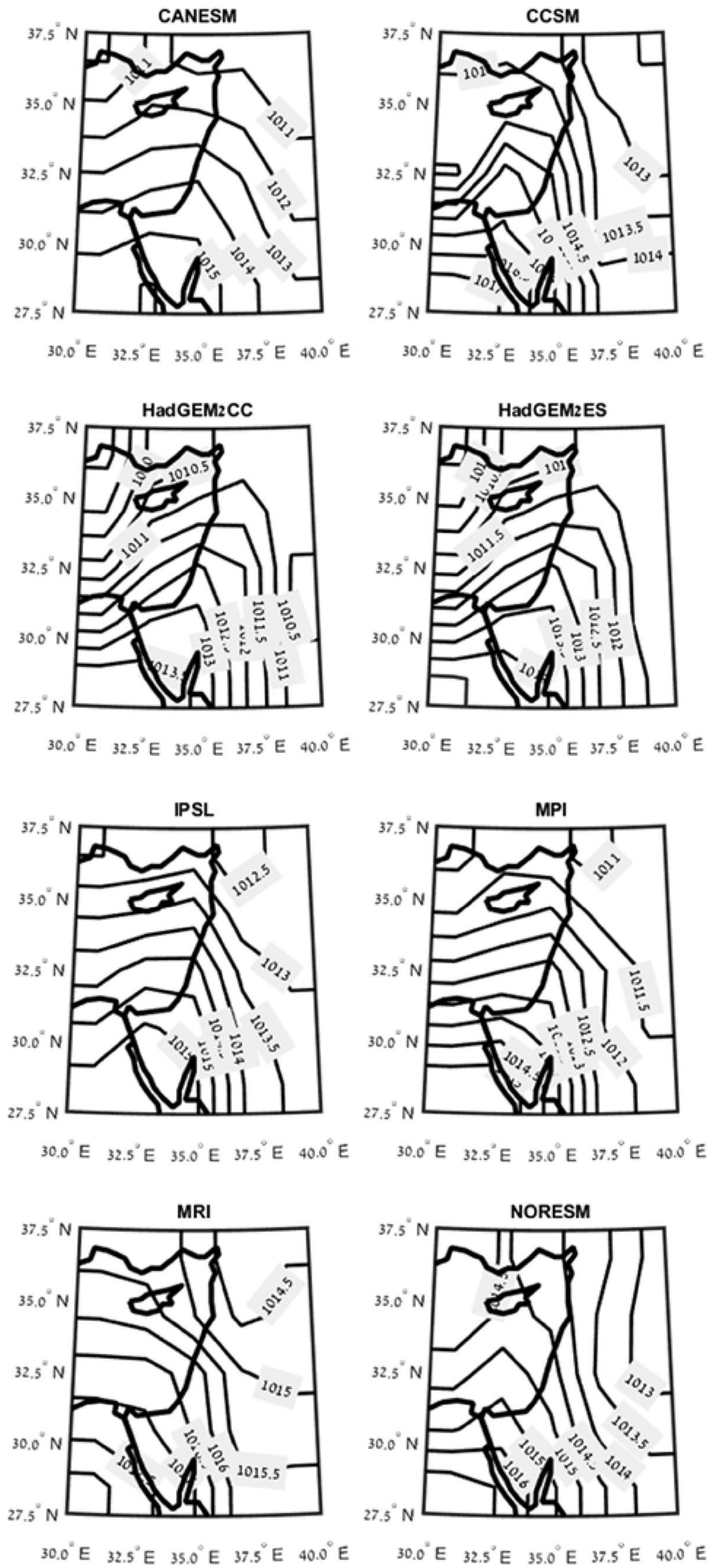

Fig. 2 Composite maps of the mean sea level pressure (hPa) over the Eastern Mediterranean on Cyprus Low days, based on CMIP5 models (see Table 1), for 1986–2005

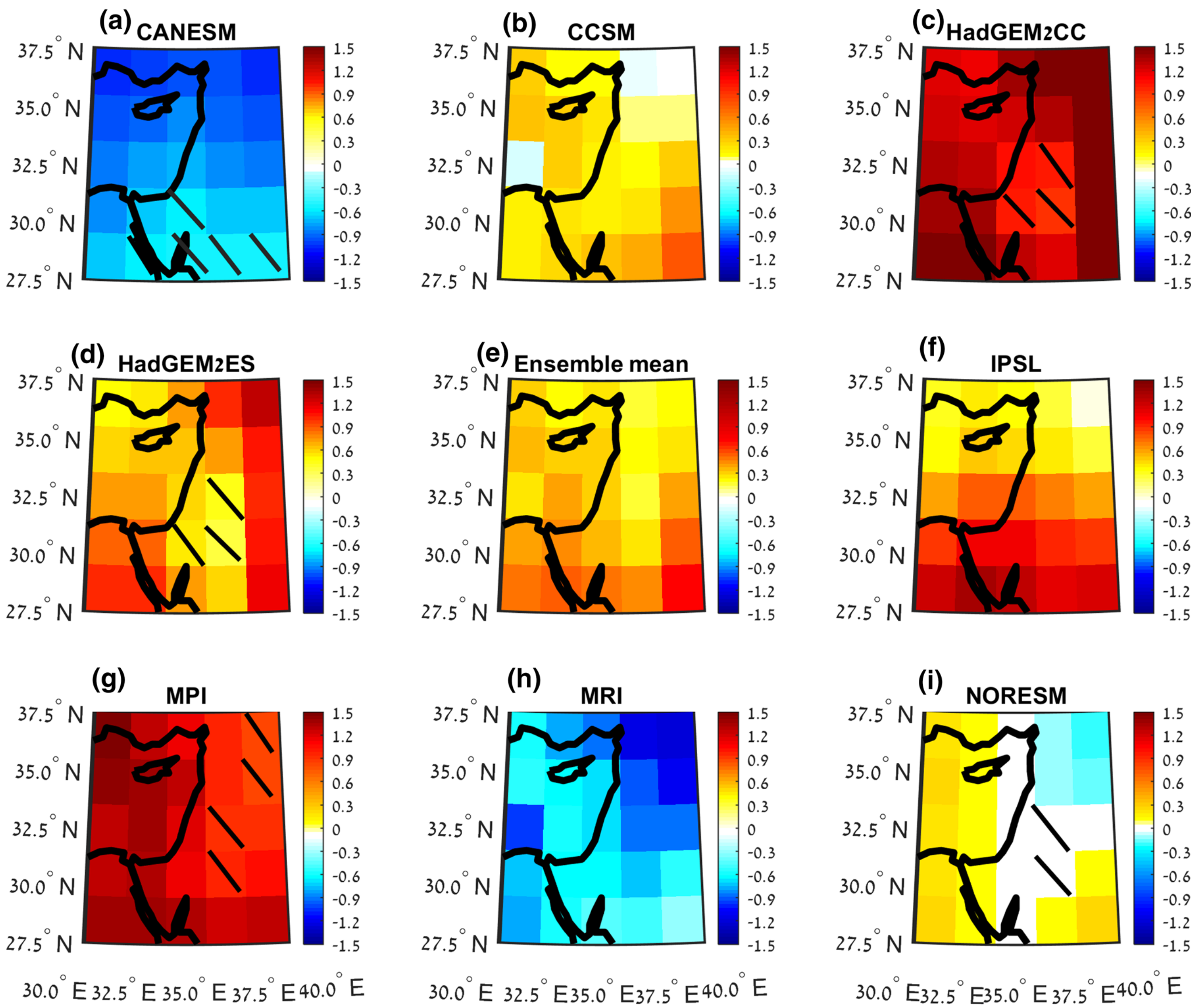

Fig. 3 Difference between the mean sea-level pressure (hPa) of Cyprus Low composites for the 2081–2100 (RCP8.5) versus 1986–2005 periods as simulated by CMIP5 models (panels **a**–**i**). The multi model ensemble mean sea-level pressure difference is shown in panel **e**. All grid points are significant at the 5% significance level using the Student's t-test, except for grid points with black diagonal lines

significance level under the Kolmogorov–Smirnov (for the CDFs) and Wilcoxon Rank-Sum (for the median values) tests. Less persistent systems, characterized by a larger number of active degrees of freedom, imply that the intrinsic predictability of Cyprus Lows is projected to decrease under global warming. A more detailed inspection of the CDFs suggests that the increase in d arises from a shift of the full distribution (Fig. 5a), whereas the increase in θ originates mostly from the lower percentiles (Fig. 5b). The changes in d and θ for the individual models partly support the results found for the multi model ensemble mean. Four of the models display a significant increase in d and θ under both the Kolmogorov–Smirnov (for the CDFs) and Wilcoxon Rank-Sum (for the median values) tests at the 5% significance level (Fig. 6).

4.3 Future daily precipitation associated with Eastern Mediterranean cyclones

Changes in Cyprus Low dynamics and in the sea-level pressure mean properties can have a profound influence on the precipitation regime over Israel. Figure 7 shows the downscaled daily precipitation CDFs associated with Cyprus Lows in model and reanalysis data, for the two periods considered here. The models capture the shape of the CDFs comparatively well, albeit with an underestimation of the upper percentiles and an overestimation of the lower percentiles of the distributions (Fig. 7e). Moreover, most models struggle to capture the finer details of the CDFs, with only CCSM actually matching the NCEP/NCAR distribution mean, according to a bootstrapping test at the 5%

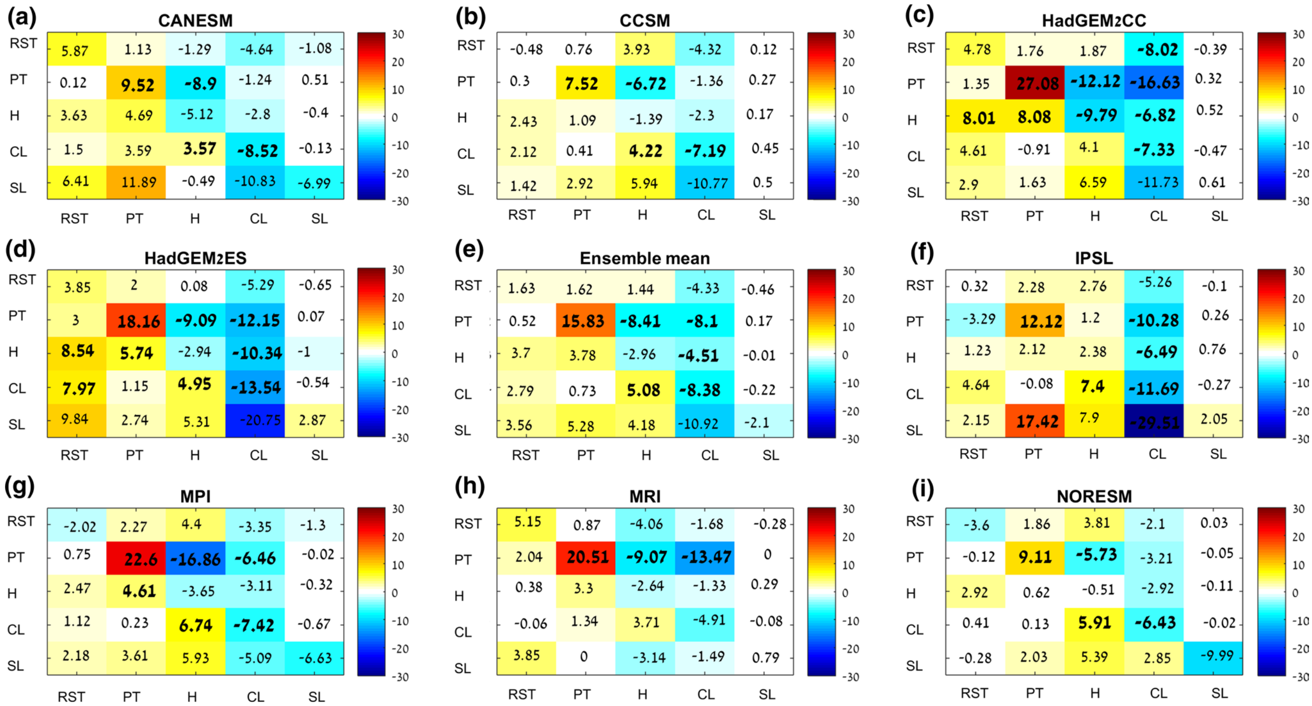

Fig. 4 The synoptic classes transition matrices, expressed as % difference between 2081–2100 (RCP8.5) and 1986–2005 for CMIP5 models (panels **a**–**d**, **f**–**i**; Table 1), and for the multi model ensemble mean (panel **e**). The bold numbers are significant at the 5% significance level under a binomial test. The five synoptic systems are: Red Sea Troughs (RST), Persian Troughs (PT), Highs (H), Cyprus Lows (CL) and Sharav Lows (SL)

significance level. The average daily precipitation over Israel for Cyprus Lows is nonetheless relatively well captured, with values of 3.25 mm/d and 3.37 mm/d for the multi model ensemble mean and the NCEP/NCAR data, respectively (Table 2).

According to the NCEP/NCAR reanalysis for the present period, 36% of Cyprus Low days do not produce precipitation over Israel, whereas most CMIP5 models underestimate this number—a known general deficiency of the models (e.g. Sillman et al. 2013; Samuels et al. 2017). For the future, five out of the eight models show an increase in the probability of Cyprus Low days with no precipitation. Four of these (CCSM, MRI, NORESM and HadGEM2CC) project a significant increase in this probability at the 5% significance level under a binomial test. Moreover, all models agree on a statistically significant reduction in the average daily precipitation on Cyprus Low days, from 3.25 mm/d to 2.39 mm/d (~ − 26% on average), according to a bootstrapping test at the 5% significance level (Fig. 7 and Table 2).

5 Discussion and conclusions

Understanding changes in Eastern Mediterranean cyclones, often named Cyprus Lows, is a key step for projecting future climate in the region. Here, the influence of increased greenhouse gas concentrations on the dynamics and average properties of Cyprus Lows is studied. We use eight CMIP5 models for the present day and the end of the century under the RCP8.5 scenario. The analysis is based on the conventional parameters of the cyclone, such as pressure gradient force and precipitation yield, as well as on two recently developed dynamical systems metrics.

Several studies have investigated changes in cyclone activity over the Mediterranean Basin under increased greenhouse gas concentrations (e.g., Carnell and Senior 1998; Lionello et al. 2002; Geng and Sugi 2003; Pinto et al. 2006; Leckebusch et al. 2006; Bengtsson et al. 2006; Pinto et al. 2007; Zappa et al. 2015; Hochman et al. 2018a; González-Alemán et al. 2019). There is a consensus that the number of cyclones in this region will be reduced. However, there is still no clear agreement regarding the influence global warming will have on the intensity and dynamics of these cyclones as reflected by the large spread among the models and tracking methods concerning future variability and trends (Ulbrich et al. 2009; Raible et al. 2010; Nissen et al. 2014; Zappa et al. 2015).

We find a number of important changes in the dynamics and precipitation associated with Cyprus Lows under future climate conditions. The CMIP5 models, on average, project an increase in the region-wide sea-level pressure and the meridional pressure gradient force on Cyprus Low days.

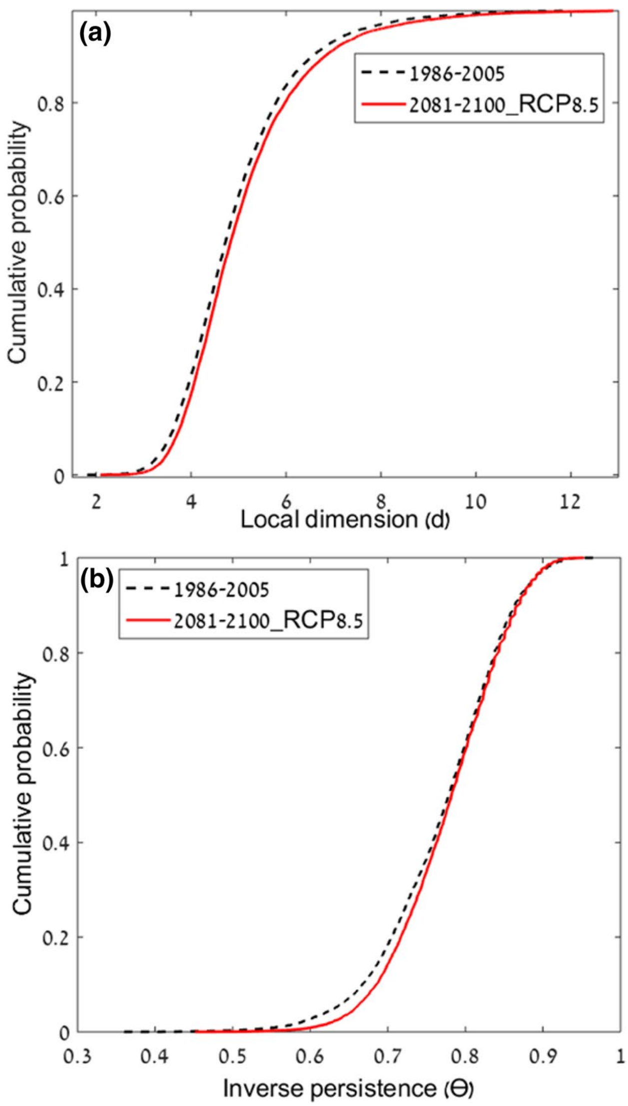

Fig. 5 Cumulative Distribution Functions (CDFs) of the Cyprus Low days in the CMIP5 multi model ensemble mean for: **a** local dimension (*d*) and **b** inverse persistence (*θ*). The periods simulated are 1986–2005 (dotted line) and 2081–2100 (RCP8.5, continuous line). The distributions are significantly different at the 5% significance level, using the Kolmogorov–Smirnov test (for the CDFs) and Wilcoxson Rank-Sum test (for the medians)

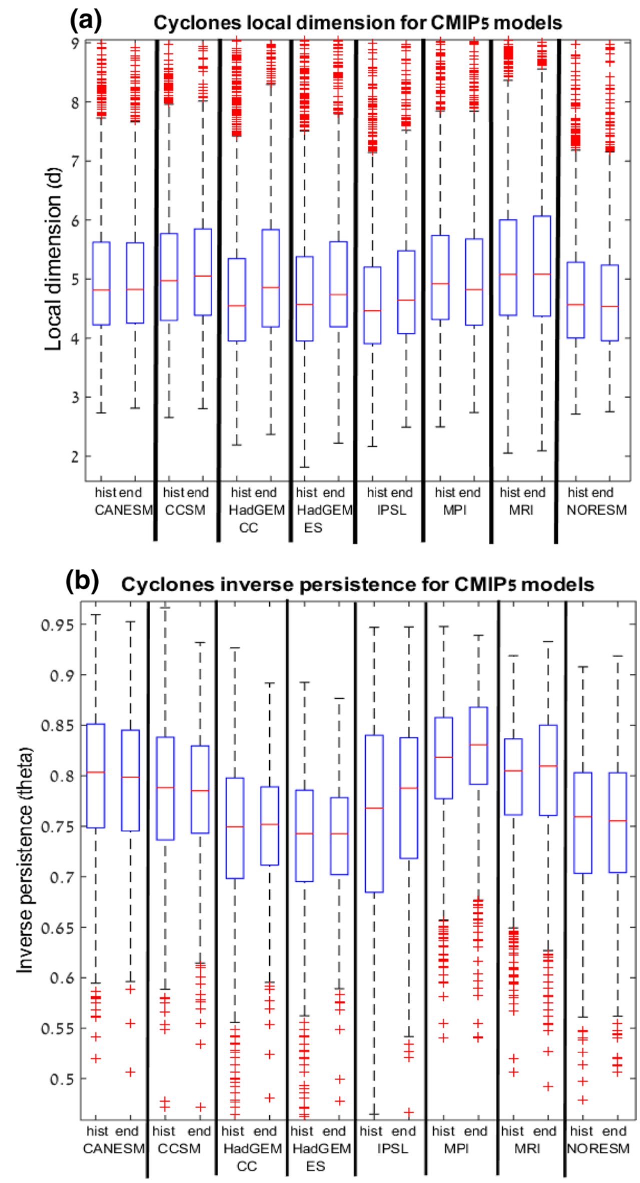

Fig. 6 Cyprus Low days' local dimension (**a**) and inverse persistence (**b**) for the CMIP5 models (Table 1). The periods simulated are 1986–2005 (denoted: hist) and 2081–2100, under the RCP8.5 scenario (denoted: end)

The latter stems mainly from the large pressure increase projected in the southern part of the Eastern Mediterranean. Under the RCP8.5 scenario, this will increase the horizontal advection across the warm Mediterranean waters, which is a key component of the precipitation associated with Cyprus Lows. Intuitively, one could therefore expect an increase in the precipitation yield of the Cyprus Lows. However, the CMIP5 models considered here indicate that the number of Cyprus Low days with no precipitation over Israel will significantly increase and the average precipitation associated with Cyprus Lows will significantly decrease in the future. Specifically, an analogues statistical downscaling algorithm applied to the CMIP5 simulations, suggests that the daily precipitation yield of Cyprus Lows over Israel will decrease on average by ~ 26% relative to present-day. This may result not only from changes in the cyclones' intensity, but also from a change in their location, which exerts a strong control on precipitation in Israel (Zangvil et al. 2003; Saaroni et al. 2010a). The expected expansion of the Hadley Cell in a warmer climate (Lu et al. 2007; Seidel et al. 2008) and the expected increase in the positive phase of the North Atlantic Oscillation (Hoerling et al. 2001; Karpechko 2010;

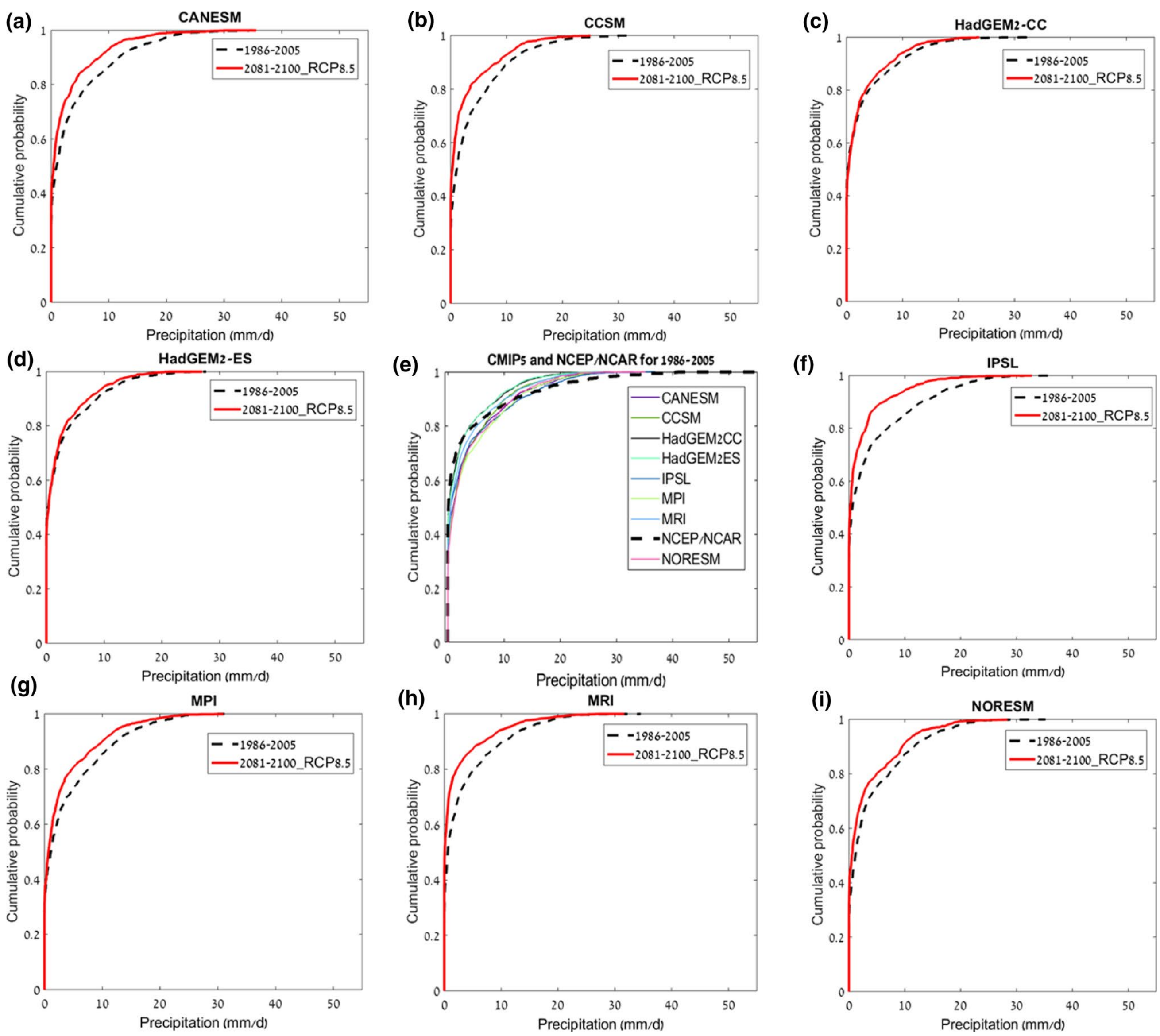

Fig. 7 Daily precipitation CDFs (mm d^{-1}) on Cyprus Low days according the CMIP5 models downscaled by the analogues' method, for 1986–2005 and 2081–2100 (RCP8.5; panels **a**–**d**, **f**–**i**). **e** The evaluation of the models with respect to the NCEP/NCAR Reanalysis for 1986-2005. Daily precipitation is calculated as the average of eighteen rain stations over Israel (Fig. 1b; Table S1). All models agree on a statistically significant reduction in the average daily precipitation on Cyprus Low days according to a bootstrapping test at the 5% significance level

Gillet and Fyfe 2013), would correspond to the northward migration of the mid-latitude cyclone tracks (Eichler et al. 2013; Tamarin-Brodsky and Kaspi 2017). This, in turn, may favour changes in the location and characteristics of Cyprus Lows and the associated rain yield over Israel (Peleg et al. 2015). Elucidating this result is somewhat problematic in coarse-gridded global GCMs, and motivates future regional simulations to further investigate its robustness and underlying drivers.

The transition probability matrices for the future highlight a significant decrease in self-transitions of Cyprus Lows, pointing to a decreased persistence of these cyclones. This is mirrored by a reduced persistence (increased θ) in the dynamical systems analysis, which is especially evident for the longer-lived systems (Fig. 5b), and is consistent with a significant reduction in Cyprus Low frequency in the future, by ~ 35% (Hochman et al. 2018a). The present-day average frequency of Cyprus Lows is ~ 120 d $year^{-1}$ and the average precipitation yield on a Cyprus Low day in Israel is 3.25 mm day^{-1}, according to the CMIP5 models (Table 2). The model simulations project a future reduction in the total annual precipitation of ~ 137 mm $year^{-1}$ due to a decrease in

Table 2 Downscaled average daily precipitation associated with Cyprus Lows over Israel for the historical (1986–2005) and end-of-century (RCP8.5; 2081–2100) periods

Model	1986–2005 (mm/d)/fraction of dry days (%)	2081–2100 (RCP8.5, mm/d)/ fraction of dry days	Difference (%)
NCEP/NCAR	**3.37/36**		
CCSM	3.38/22	2.17/31	– 36*/+9**
CANESM	3.6/24	2.40/30	– 33*/+6**
NORESM	3.61/21	3.11/26	– 14*/+5
MRI	3.02/22	1.97/34	– 35*/+12**
IPSL	3.74/25	1.92/26	– 49*/+1
MPI	3.75/26	3.07/25	– 18*/– 1
HadGEM2-ES	2.48/38	2.32/33	– 6*/– 5
HadGEM2-CC	2.47/38	2.14/30	– 13*/– 8**
Multi model average	**3.25/27**	**2.39/29.4**	**– 26*/+2.4****

The NCEP/NCAR reanalysis downscaled value is shown for reference. The models are ranked according to the difference between their mean daily precipitation values and the NCEP/NCAR values

*A significant change using bootstrapping at the 5% significance level. The fraction of dry days is also shown (precipitation = 0)

**A significant change using a binomial test at the 5% significance level

Cyprus Low frequency (assuming an unchanged precipitation yield of a Cyprus Low day). An additional reduction, of ~ 67 mm year^{-1}, is projected due to reduction in daily precipitation yield (computed relative to the decreased frequency). The reader is referred to Figure S1 in the supplementary information for the complete calculation. This is in agreement with Peleg et al. (2015), who found a reduction in frequency and duration of wet events over the Eastern Mediterranean by the mid-twentyfirst century. Similarly, Zappa et al. (2015) found a strong decrease in precipitation associated with cyclones in the Eastern Mediterranean by the end of the twentyfirst century, resulting from a combination of decreases in frequency and in precipitation yield of the individual cyclones.

The dynamical systems analysis suggests that precipitation events associated with Cyprus Lows, while becoming rarer, will also become less predictable. Previous analysis has highlighted a connection between intrinsic predictability in a dynamical systems sense and both spread in ensemble weather forecasts and unskilful forecasts for extreme events in the Eastern Mediterranean (Scher and Messori 2018; Hochman et al. 2019a). This is consistent with recent studies arguing for a general decrease in synoptic predictability in the mid-latitudes in the future (Faranda et al. 2019b; Scher and Messori 2019). From a thermodynamic viewpoint, an important factor influencing the generation and intensification of Cyprus Lows are sea-surface fluxes (Stein and Alpert 1991; Alpert et al. 1995). Under increased greenhouse gas concentrations, these may significantly change due to a warmer sea (Schultz et al. 2019). More intense sea-surface-fluxes may shorten the lows' life span; in particular the genesis of Cyprus Lows is expected to be faster. Thus, we hypothesize that this process may in turn influence the intrinsic predictability of Cyprus Lows in the future.

The above results provide a clear outline of the climatic challenges that may face the Eastern Mediterranean in the future, such as substantial alterations in the water resources and hydrological regime of the region, reduced agricultural potential and increased risk of forest fires and harmful air pollution. They may therefore be used as a baseline for priority setting and policy formulation towards water management and climate change adaptation. An extension of this work to high-resolution regional simulations, coupled to a hydrological model, would provide a stimulating avenue for future policy-relevant research. Moreover, the analysis tools adopted in this study are directly applicable to other regions, which may be particularly affected by climate change.

Acknowledgements We thank Tel-Aviv University's President and the Mintz foundation. This study was also partially supported by cooperation within the international virtual institute DESERVE (Dead Sea Research Venue), funded by the German Helmholtz Association, the Israel Science Foundation (ISF Grant no. 1123/17) and the Water Authority of Israel. G. Messori was partly supported by a grant from the Department of Meteorology of Stockholm University and by the Swedish Research Council Vetenskapsrådet, under Grant no. 2016-03724. This paper is a contribution to the Hydrological Cycle in the Mediterranean Experiment (HyMeX) community.

References

Alpert P, Reisin T (1986) An early winter polar air mass penetration to the Eastern Mediterranean. Mon Weather Rev 114:1411–1418

Alpert P, Ziv B (1989) The Sharav cyclone—observations and some theoretical considerations. J Geophys Res 94:18495–18514

Alpert P, Neeman BU, Shay-El Y (1990) Climatological analysis of Mediterranean cyclones using ECMWF data. Tellus 42A:65–77

Alpert P, Stein U, Tsidulko M (1995) Role of sea-fluxes and topography in Eastern Mediterranean cyclogenesis. Glob Atmos Ocean Syst 3:55–79

Alpert P, Osetinsky I, Ziv B, Shafir H (2004a) Semi-objective classification for daily synoptic systems: application to the Eastern Mediterranean climate change. Int J Climatol 24:1001–1011

Alpert P, Osetinsky I, Ziv B, Shafir H (2004b) A new seasons' definition based on classified daily synoptic systems: an example for the Eastern Mediterranean. Int J Climatol 24:1013–1021. https://doi.org/10.1002/joc.1037

Beersma JJ, Buishand TA (2003) Multi-site simulation of daily precipitation and temperature conditional on the atmospheric circulation. Clim Res 25:121–133

Bengtsson L, Hodges KI, Roeckner E (2006) Storm tracks and climate change. J Clim 19:3518–3543

Carnell RE, Senior CA (1998) Changes in mid-latitude variability due to increasing greenhouse gases and sulphate aerosols. Clim Dynam 14:369–383

Dayan U, Tubi A, Levy I (2012) On the importance of synoptic classification methods with respect to environmental phenomena. Int J Climatol 32:681–694

Drobinski P, Alpert P, Cavicchia L, Flaounas E, Hochman A, Kotroni V (2016) Strong winds. In: Sabrie ML, Gilbert-Brunet E, Mourier T (eds) The Mediterranean region under climate change—a scientific update. Institut de Recherche pour le Développement, Marseille, pp 115–122

Egger J, Alpert P, Tafferner A, Ziv B (1995) Numerical experiments on the genesis of Sharav cyclones: idealized simulations. Tellus 47A:162–174

Eichler TP, Gaggini N, Pan Z (2013) Impacts of global warming on Northern Hemisphere winter storm tracks in the CMIP5 model suite. J Geophys Res Atmos 118(10):3919–3932. https://doi.org/10.1002/jgrd.50286

Enzel Y, Bookman R, Sharon D, Gvirtzman H, Dayan U, Ziv B, Stein M (2003) Late Holocene climates of the Near East deduced from Dead Sea level variations and modem regional winter rainfall. Quat Res 60(3):263–273. https://doi.org/10.1016/j.yqres.2003.07.011

Faranda D, Messori G, Yiou P (2017a) Dynamical proxies of North Atlantic predictability and extremes. Sci Rep 7:412782017b. https://doi.org/10.1038/srep4127

Faranda D, Messori G, Alvarez-Castro MC, Yiou P (2017b) Dynamical properties and extremes of Northern Hemisphere climate fields over the past 60 years. Nonlinear Processes Geophys 24(4):713–725

Faranda D, Messori G, Vannistem S (2019a) Attractor dimension of time-averaged climate observables: insights from a low-order ocean-atmosphere model. Tellus A. https://doi.org/10.1080/16000870.2018.1554413

Faranda D, Alvarez-Castro MC, Messori G, Rodrigues D, Yiou P (2019b) The hammam effect or how a warm ocean enhances large scale atmospheric predictability. Nat Commun 10(1):1316

Flaounas E, Raveh-Rubin S, Wernli H, Drobinski P, Bastin S (2015) The dynamical structure of intense Mediterranean cyclones. Clim Dyn 44:2411–2427

Fowler HJ, Blenkinsop S, Tebaldi C (2007) Linking climate change modeling to impacts studies: recent advances in downscaling techniques for hydrological modeling. Int J Climatol 27:1547–1578. https://doi.org/10.1002/joc.1556

Freitas ACM, Freitas JM, Todd M (2010) Hitting time statistics and extreme value theory. Probab Theory Relat Fields 147:675–710

Freitas ACM, Freitas JM, Vaienti S (2017) Extreme Value Laws for non-stationary processes generated by sequential and random dynamical systems. Annales de l'Institut Henri Poincaré, Probabilités et Statistiques 53(3):1341–1370

Gagniuc PA (2017) Markov chains: from theory to implementation and experimentation. John Wiley, Hoboken

Geng Q, Sugi M (2003) Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols—study with a high-resolution AGCM. J Clim 16:2262–2274

Gillet NP, Fyfe JC (2013) Annular mode changes in the CMIP5 simulations. Geophys Res Lett 40:1189–1193. https://doi.org/10.1002/grl.50249

Giorgi F (2006) Climate change hot spots. Geophys Res Lett 33:L08

González-Alemán JJ, Pascale S, Gutierrez-Fernandez J, Murakami H, Gaertner MA, Vecchi GA (2019) Potential increase in hazard from Mediterranean hurricane activity with global warming. Geophys Res Lett 46(3):1754–1764

Hochman A, Harpaz T, Saaroni H, Alpert P (2018a) Synoptic classification in 21st century CMIP5 predictions over the Eastern Mediterranean with focus on cyclones. Int J Climatol 38:1476–1483. https://doi.org/10.1002/joc.5260

Hochman A, Harpaz T, Saaroni H, Alpert P (2018b) The seasons' length in 21st century CMIP5 projections over the Eastern Mediterranean. Int J Climatol 38(6):2627–2637. https://doi.org/10.1002/joc.5448

Hochman A, Alpert P, Harpaz T, Saaroni H, Messori G (2019a) A new dynamical systems perspective on atmospheric predictability: Eastern Mediterranean weather regimes as a case study. Sci Adv. https://doi.org/10.1126/sciadv.aau0936

Hochman A, Kunin P, Alpert P, Harpaz T, Saaroni H, Rostkier-Edelstein D (2019b) Weather regimes and analogues downscaling of seasonal precipitation for the 21st century; A case study over Israel. Int J Climatol. https://doi.org/10.1002/joc.6318 **(in press)**

Hoerling MP, Hurrel JW, Xu T (2001) Tropical origins for recent North Atlantic climate change. Science 292:90–92. https://doi.org/10.1126/science.1058582

IPCC (2013) Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change [Stocker T.F. Qin D. Plattner G. K. Tignor M. Allen S.K. Boschung J. Nauels A. Xia Y. Bex V. and Midgley P.M. (eds)]. Cambridge University Press, Cambridge, and New York, 1535 pp. https://doi.org/10.1017/cbo9781107415324

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–471

Karas S, Zangvil A (1999) A preliminary analysis of disturbance tracks over the Mediterranean basin. Theor Appl Climatol 64:239–248

Karpechko AY (2010) Uncertainties in future climate attributable to uncertainties in future annular mode trend. Geophys Res Lett 37:L20702. https://doi.org/10.1029/2010GL044717

Lanzante JR, Dixon KW, Nath MJ, Whitlock CE, Adams-Smith D (2018) Some pitfalls in statistical downscaling of future climate. Bull Am Meteorol Soc 99:791–803. https://doi.org/10.1175/BAMS-D-17-0046.1

Laprise R et al (2008) Challenging some tenets of regional climate modelling. Meteorol Atmos Phys 100:3–22

Leckebusch GC, Koffi B, Ulbrich U, Pinto JG, Spangehl T, Zacharias S (2006) Analysis of frequency and intensity of winter storm events in Europe on synoptic and regional scales from a multi-model perspective. Clim Res 31:59–74

Lelieveld J, Proestos Y, Hadjinicolaou P, Tanarhte M, Tyrlis E, Zittis G (2016) Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. Clim Change 137:245–260. https://doi.org/10.1007/s10584-016-1665-6

Lionello P (ed) (2012) The climate of the Mediterranean region, from the past to the future. Elsevier, Amsterdam, p 502

Lionello P, Giorgi F (2007) Winter precipitation and cyclones in the mediterranean region: future climate scenarios in a regional simulation. Adv Geosci 12:153–158
Lionello P, Dalan F, Elvini E (2002) Cyclones in the Mediterranean region: the present and the doubled CO2 climate scenarios. Clim Res 22:147–159
Lionello P, Malanbotte-Rizzoli P, Boscolo R (2006) Mediterranean climate variability. Developments in earth and environmental sciences, vol 4. Elsevier, Amsterdam, pp 325–372
Lionello P, Gacic AF, Planton M, Trigo SR, Ulbrich U (2014) The climate of the Mediterranean region: research progress and climate change impacts. Reg Environ Change 14:1679–1684
Lionello P, Trigo IF, Gil V, Liberato ML, Nissen KM, Pinto JG, Raible CC, Reale M, Tanzarella A, Trigo RM, Ulbrich S (2016) Objective climatology of cyclones in the Mediterranean region: a consensus view among methods with different system identification and tracking criteria. Tellus A 68:1–18
Lorenz EN (1963) Deterministic non periodic flow. J Atmos Sci 20:130–141
Lorenz EN (1969) Atmospheric predictability as revealed by naturally occurring analogues. J Atmos Sci 26:636–646. https://doi.org/10.1175/1520-0469(1969)26%3c636:APARBN%3e2.0.CO;2
Lorenz EN (1980) Attractor sets and quasi-geostrophic equilibrium. J Atmos Sci 37:1685–1699
Lu J, Vecchi GA, Reichler T (2007) Expansion of the Hadley cell under global warming. Geophys Res Lett 34:L06805. https://doi.org/10.1029/2006GL028443
Lucarini V, Faranda D, Wouters J (2012) Universal behavior of extreme value statistics for selected observables of dynamical systems. J Stat Phys 147:63–73
Lucarini V, Faranda D, Freitas ACM, Freitas JM, Holland M, Kuna T, Nicol M, Todd M, Vaienti S (2016) Extremes and Recurrence in dynamical systems. Pure and applied mathematics: a wiley series of texts, monographs and tracts. Wiley, Hoboken, pp 126–172
Maraun D, Widmann M (2018) Statistical downscaling and bias correction for climate research. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781107588783
Maraun D, Wetterhall F, Ireson AM, Chandler RE, Kendon EJ, Widmann M, Brienen S, Rust HW, Sauter T, Themessl M, Venema VKC, Chun KP, Goodess CM, Jones RG, Onof C, Vrac M, Thiele-Eich I (2010) Precipitation downscaling under climate change. Recent developments to bridge the gap between dynamical models and the end user. Rev Geophys 48:3003
Messori G, Caballero R, Faranda D (2017) A dynamical systems approach to studying mid-latitude weather extremes. Geophys Res Lett 44(7):3346–3354
Nissen KM, Leckebusch GC, Pinto JG, Renggli D, Ulbrich S, Ulbrich U (2010) Cyclones causing wind storms in the Mediterranean: characteristics, trends and links to large-scale patterns. Nat Hazards Earth Syst Sci 10:1379–1391
Nissen KM, Leckebusch GC, Pinto JG, Ulbrich U (2014) Mediterranean cyclones and windstorms in a changing climate. Reg Environ Change 14:1873–1890
Peleg N, Bartov M, Morin E (2015) CMIP5-predicted climate shifts over the East Mediterranean: implications for the transition region between Mediterranean and semi-arid climates. Int J Climatol 35(8):2144–2153
Pinto JG, Spangehl T, Ulbrich U, Speth P (2006) Assessment of winter cyclone activity in a transient ECHAM4-OPYC3 GHG experiment. Meteorol Z 15:279–291
Pinto JG, Ulbrich U, Leckebusch GC, Spangehl T, Reyers M, Zacharias S (2007) Changes in storm track and cyclone activity in three SRES ensemble experiments with the ECHAM5/MPIOM1 GCM. Clim Dyn 29:195–210
Raible CC, Saaroni H, Ziv B, Wild M (2010) Winter cyclonic activity over the Mediterranean Basin under future climate, based on the ECHAM5 GCM. Clim Dyn 35:473–488
Rodrigues D, Alvarez-Castro MC, Messori G, Yiou P, Robin Y, Faranda D (2018) Dynamical properties of the North Atlantic atmospheric circulation in the past 150 years in CMIP5 models and the 20CRv2c reanalysis. J Clim 31:6097–6111. https://doi.org/10.1175/JCLI-D-17-0176.1
Rostkier-Edelstein D, Kunin P, Hopson TM, Yubao L, Givati A (2016) Statistical downscaling of seasonal precipitation in Israel. Int J Climatol 36:590–606
Saaroni H, Halfon N, Ziv B, Alpert P, Kutiel H (2010a) Links between the rainfall regime in Israel and location and intensity of cyprus lows. Int J Climatol 30:1014–1025
Saaroni H, Ziv B, Osetinsky I, Alpert P (2010b) Factors governing the inter-annual variation and the long-term trend of the 850-hPa temperature over Israel. Q J R Meteorol Soc 136:305–318
Salvi K, Ghosh S, Ganguly AR (2016) Credibility of statistical downscaling under nonstationary climate. Clim Dyn 46:1991–2023. https://doi.org/10.1007/s00382-015-2688-9
Samuels R, Hochman A, Baharad A, Givati A, Levi Y, Yosef Y, Saaroni H, Ziv B, Harpaz T, Alpert P (2017) Evaluation and projection of extreme precipitation indices in the Eastern Mediterranean based on CMIP5 multi model ensemble. Int J Climatol 38(5):2280–2297. https://doi.org/10.1002/joc.5334
Scher S, Messori G (2018) Predicting weather forecast uncertainty with machine learning. Q J R Meteorol Soc. https://doi.org/10.1002/qj.3410
Scher S, Messori G (2019) How global warming changes the difficulty of synoptic weather forecasting. Geophys Res Lett 46(5):2931–2939
Schultz DM, Bosart LF, Colle BA, Davies HC, Dearden C, Keyser D, Martius O, Roebber PJ, Steenburgh WJ, Volkert H, Winters AC (2019) Extratropical cyclones: a century of research on meteorology's centerpiece. Meteorol Monogr 59:16.1–16.56. https://doi.org/10.1175/amsmonographs-d-18-0015.1
Seidel DJ, Fu Q, Randel WJ, Reichler TJ (2008) Widening of the tropical belt in a changing climate. Nat Geosci 1(1):21–24. https://doi.org/10.1038/ngeo.2007.38
Shay-El Y, Alpert P (1991) A diagnostic study of winter adiabatic heating in the Mediterranean in relation to cyclones. Q J R Meteorol Soc 117:715–747
Sillman J, Kharin VV, Zhang X, Zwiers FW, Bronaugh D (2013) Climate extreme indices in the CMIP5 multi-model ensemble: part 1. Model evaluation in the present climate. J Geophys Res 118:1716–1733
Stein U, Alpert P (1991) Inclusion of sea moisture flux in the Anthes-Kuo cumulus parametrization. Contrib Atmos Phys 64:231–243
Süveges M (2007) Likelihood estimation of the extremal index. Extremes 10(1–2):41–55
Tamarin-Brodsky T, Kaspi Y (2017) Enhanced poleward propagation of storms under climate change. Nat Geosci. https://doi.org/10.1038/s41561-017-0001-8
Taylor KER, Stouffer J, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498
Trigo IF, Davies TD, Bigg GR (1999) Objective climatology of cyclones in the Mediterranean region. J Clim 12:1685–1696
Tsidulko M, Krichak SO, Alpert P, Kakaliagou O, Kallos G, Papadopoulos A (2002) Numerical study of a very intensive eastern Mediterranean dust storm, 13–16 March 1998. J Geophys Res 107(D21):4581. https://doi.org/10.1029/2001JD001168
Ulbrich U, Leckebusch GC, Pinto JG (2009) Extra-tropical cyclones in the present and future climate: a review. Theor Appl Climatol 96:117–131. https://doi.org/10.1007/s00704-008-0083-8

Van-Vuuren DP, Edmonds JA, Kainuma M, Riahi K, Weyant J (2011) A special issue on the RCPs. Clim Change 109:1–4. https://doi.org/10.1007/s10584-011-0157-y

Velasquez JA, Troin M, Caya D, Brissette F (2015) Evaluating the time-invariance hypothesis of climate model bias correction: implications for hydrological impact studies. J Hydrometeorol 16:2013–2026. https://doi.org/10.1175/JHM-D-14-0159.1

Warner TT (2011) Quality assurance in atmospheric modeling. Bull Am Meteorol Soc 92:1601–1610. https://doi.org/10.1175/BAMS-D-11-00054

Wilks DS (2011) Statistical methods in the atmospheric sciences. Academic Press, San Diego

Yates DS, Gangopadhyay BR, Strzepek K (2003) A technique for generating regional climate scenarios using a nearest neighbor algorithm. Water Resour Res 39(7):1199. https://doi.org/10.1029/2002WR001769

Young K (1994) A multivariate chain model for simulating climatic parameters from daily data. J Appl Meteorol 33(6):661–671

Zangvil A, Karas S, Sasson A (2003) Connection between Eastern Mediterranean seasonal mean 500 hPa height and sea-level pressure patterns and the spatial rainfall distribution over Israel. Int J Climatol 23:1567–1576

Zappa G, Hawcroft MK, Shaffrey L, Back E, Brayshaw D (2015) Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models. Clim Dyn 45:1727–1738. https://doi.org/10.1007/s00382-014-2426-8

Ziv B, Harpaz T, Saaroni H (2015) A new methodology for identifying daughter cyclogenesis—application for the Mediterranean Basin. Int J Climatol 35(13):3847–3861

Zorita E, von Storch H (1999) The analog method—a simple statistical downscaling technique: comparison with more complicated methods. J Clim 12:2474–2489

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Assaf Hochman[1] · Pinhas Alpert[2] · Pavel Kunin[2] · Dorita Rostkier-Edelstein[3] · Tzvi Harpaz[2,4] · Hadas Saaroni[4] · Gabriele Messori[5,6]

[1] Department of Tropospheric Research, Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany

[2] Department of Geophysics, Porter School of the Environment and Earth Sciences, Tel-Aviv University, 69978 Tel-Aviv, Israel

[3] Department of Applied Mathematics, Environmental Sciences Division, Israel Institute for Biological Research, Ness-Ziona, Israel

[4] Department of Geography and the Human–Environment, Porter School of the Environment and Earth Sciences, Tel-Aviv University, 69978 Tel-Aviv, Israel

[5] Department of Earth Sciences, Uppsala University, Uppsala, Sweden

[6] Department of Meteorology and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden