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Potential new aerosol source(s) in the Middle East

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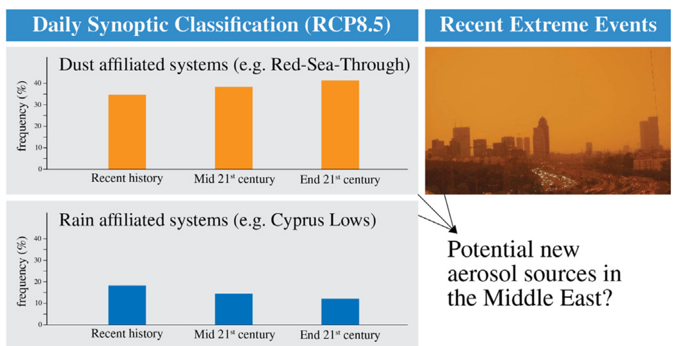
HIGHLIGHTS

- A recent extreme autumn dust storm may point to a new aerosol source in the region.
- Regional daily synoptic analysis through the 21st century is conducted.
- Dust-affiliated synoptic systems are projected to increase.
- Rain-affiliated synoptic systems are projected to decrease.
- New aerosol sources may have environmental and health implications.

GRAPHICAL ABSTRACT



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ABSTRACT

The Middle East region suffers from high levels of air pollution originating from both Saharan/Arabian mineral dust particles and pollution from East Europe. A recent extreme autumn dust storm, originating from the Middle East, highlights the potential of a new aerosol source in the region. By studying the trends of daily regional synoptic systems through the 21st century, we show that dust-affiliated systems are projected to increase significantly, i.e. Red-Sea-Trough from 35.0 to 41.6% during autumn, for RCP8.5. Whereas, rain-affiliated ones are projected to decrease (for Cyprus Lows group from 18.7 to 12.5%). Here, it is suggested that those trends, along with increased anthropogenic activities, may result in the formation of a consistent new aerosol source in the area, which could influence life in the region. This is supported by a recent study showing an increase in dust deposition over the region.

1. Introduction

The Middle East is currently experiencing an intense drought, with severe implications to various sectors, ranging from agriculture to health and wellbeing. The drought has been suggested to result in a massive migration of over a million people in Syria alone, as well as to

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trigger and accelerate the local geopolitical instability (Kelley et al., 2015). This regional drying trend is projected to continue with high intensity, with even the Fertile Crescent, a historical symbol of water abundance, may completely dry-out in this century (Kitoh et al., 2008; Alpert et al., 2014). Drought has also been linked to reduction in relative humidity and soil moisture, which in return promote dust emissions (Elmore et al., 2008; Klingmüller et al., 2016).

The Middle East region is already characterized by high levels of air pollution, including mineral dust aerosols, mostly from Saharan/Arabian origin, as well as anthropogenic ones from local sources and/or East Europe (Lelieveld, 2002; Chudnovsky et al., 2017; Provençal et al., 2017). Dust has been found to dominant in the region's megacities, responsible for over 50% of the aerosols in Cairo, Tel Aviv, Amman and Damascus, among others (Provençal et al., 2017, Fig. 8). As such, dust storms are common in the area (Ganor et al., 2010a). Consequently, dust and other anthropogenic aerosols are a major regional concern, as in the case of the drying and environmental degradation of the Dead Sea area (Kottmeier et al., 2016).

A most exceptional event was the severe dust storm that occurred during 7–13 September 2015. It had an unprecedented scale, lasting seven days, with dust concentrations reaching values over 100 times the normal (1700 μg/m^3). In addition to its intensity, the storm had a unique nature, being the only early-September dust storm recorded in the region over the last 75 years (according to the Israel Meteorological Service).

Several studies have focused on the local specification of the storm development and its behavior, showing, for example, that Syrian plumes were double layered, suggesting it was originating from multiple sources (Mamouri et al., 2016), and that the storm was accompanied/promoted by a unique westerly wind spread through the area (Parolari et al., 2016). Another study suggested that the event consisted of two simultaneous storms, the first from northern Syria and the second from the Sinai desert (Jasim, 2016). To gain more insights on the storm characteristics and dynamics, a more recent work performed a detailed investigation of the vertical structure of the storm across the whole time period using eight ceilometers in Israel (Uzan et al., 2018). Other works also discussed on the inability of the models to predict the scale/magnitude of the event (Pu and Ginoux, 2016; Gasch et al., 2017; Solomos et al., 2017).

In general, recent Middle East aerosol trends, extreme events and droughts have been the focus of numerous studies (e.g. Seager et al., 2014; Kelley et al., 2015; Notaro et al., 2015; Klingmüller et al., 2016; Parolari et al., 2016; Chudnovsky et al., 2017). Table 1 summarizes different approaches and the proposed drivers. These can be attributed to either global, i.e. global warming or Greenhouse gas (GHG) increases, or local factors, e.g. irrigation, local land-cover/land-use changes (see Alpert and Mandel, 1986; Shafir and Alpert, 2011 for further discussion on the separation of the global and local contributions).

The aim of this study is to investigate the potential emergence of new aerosol sources in the Middle East, employing the daily regional synoptic variations. We will study the temporal changes of the 21st century daily Middle East synoptic systems, which are the drivers of the regional climate and weather. A major advantage of employing synoptic systems is that they encapsulate the weather phenomena that are associated with them. This is particularly beneficial when the actual weather information may not be available.

For this purpose, eight CMIP5 (Coupled Model Inter-Comparison Project phase 5) models of the 21st century projections for RCP4.5 and RCP8.5 scenarios (Representative Concentration Pathway of 4.5 and 8.5 W/m^2; IPCC, 2013), will be synoptically analyzed. Emphasis will be given to the autumn season (September–October-November; SON), when the Red-Sea-Trough (RST) systems peak throughout the year (Alpert et al., 2004). The RST originates from the interaction of upper level trough with the East African or Saudi Arabian mountains and extending to the Middle East (Krichak et al., 1997a, 1997b). These systems are often associated with dust storms over the Middle East (e.g. Dayan et al., 2008; Ganor et al., 2010a, 2010b), including the most severe 2015 extreme storm. Ganor et al. (2010b, Table 2, Figs. 1, 2) have shown large differences in atmospheric profiles of dusty RST days, such as an increase in wind intensities and a drop in humidity. A novel method was recently suggested for accurate identification of the RST (Saaroni et al., 2019).

Table 1
Different approaches and proposed sources for Middle East drought and aerosols origin due to anthropogenic activities with either global or local focus.

Reference	Physical drivers for recent aerosol/drought trends	Local or Global Focus
Klingmüller et al. (2016)	Positive aerosol optical depth (AOD) trends (2000–2015) in the Middle East (Saudi-Arabia, Iran, Iraq) are explained by the following main factors: soil moisture, precipitation and wind speed trends, and not directly due to local anthropogenic aerosols.	Global
Parolari et al. (2016)	Analysis of the 2015 extreme dust storm shows "that land cover changes associated with the ongoing conflict were unlikely to be at the origin of increased erodibility of the soil surface and suggests meteorological conditions as the more probable driver for enhanced dust uplift and transport"	Global
Chudnovsky et al. (2017)	Sources of aerosols in Iraq are a combination of natural and anthropogenic. The majority of areas were dominated by mineral dust from storms; in some locations, fine particles from anthropogenic sources dominate.	Local
Kelley et al. (2015)	Recent extreme Middle East droughts are primarily the result of GHG emissions and are enhanced by 3 local drivers; un-proportional demand increase (both in agriculture and population), groundwater buffer depletion and successive droughts.	Local/Global

The synoptic approach presented here can be seen as intermediate between local and global scales, and has the advantage and disadvantage of probable effects from both. Synoptic systems are naturally connected to the large scale circulations, but several studies have previously shown they are also directly influenced by local surface conditions, such as sea surface temperature and land-sea temperature gradients (Stein and Alpert, 1991; Alpert and Ziv, 1989). Although the synoptic global/local interactions are not always well understood, a few studies have attempted isolating them, e.g. Shafir and Alpert (2011) in the separation of local from global effects on the Dead Sea evaporation.

By adopting a regional synoptic approach, this study could thus provide a new dimension to the ongoing study and discussion on the Middle East regional weather events and climate.

2. Materials and methods

2.1. Data

The CMIP5 data of eight models were obtained from the World Data Center for Climate data portal (WDCC-DKRZ, available at http://cera-www.dkrz.de/WDCC/ui/Index.jsp) (Taylor et al., 2012). These eight models have been previously used in synoptic classification studies by Hochman et al. (2017, 2018).

In this study, the data were used for the analysis of three time periods: historical (1986–2005), mid-21st century (2046–2065) and end of 21st century (2081–2100). The analyzed future projections were for the RCP4.5 and RCP8.5 scenarios (IPCC, 2013).

2.2. Methodology

Following the procedure detailed in Hochman et al. (2017), the semi-objective synoptic classification algorithm by (Alpert et al., 2004) was applied to the CMIP5 data for the autumn and the full year time frames. The implementation was similar to the original study, with the exception that here the input variables are at 850 hPa, compared to 1000 hPa in the original study (excluding sea level pressure). This stems from the lack of hourly 1000 hPa CMIP5 data, which are required for the synoptic classification algorithm. Hochman et al. (2017, 2018) conducted data validation and verification for the classification outcomes by comparing to the original classification using Taylor diagrams, and found the modified classification to be consistent with the original and to well represent the regional synoptics. One should note that using 850 hPa data compared to 1000 hPa, may result in over/under estimation of the cold/warm low-pressure systems, due to the tendency of cold/warm low-pressure systems to deepen/shallow with height (Holton, 2004). This issue was tested and discussed in Hochman et al. (2017).

3. Results and discussion

3.1. Full year synoptic trends for the 21st century

Future synoptic trends that account for the full year are presented in Fig. 1 according to their dominant area over four Middle Eastern regional quarters. We find that the regional dust-affiliated groups, over the two easterly quarters, i.e., the Persian-Trough (PT) and Red-Sea-Trough (RST), are projected to increase. The PT is involved with no rain, especially during the summer (Saaroni and Ziv, 2000). PT systems (and E Lows) are projected to increase by 3.0–4.0% by mid-21st century (2046–2065), and by 3.4–6.2% by the end of the century. The RST systems, which were previously linked to droughts and the generation of dust storms (e.g. Alpert et al., 2004; Uzan et al., 2018), are projected to increase by 0.6–1.7% over the whole century. In contrast, regional rain-affiliated synoptic groups over the two westerly quarters, i.e., Cyprus Low (CL) and occasionally also Sharav Low (SL, Alpert and Ziv, 1989), are projected to decrease. The CL systems contribute ~80–90% of the total yearly precipitation in the East Mediterranean (Shay-El and Alpert, 1991; Zangvil et al., 2003). The CL and W Lows are projected to drop by 3.7–4.9% in the first half of the century, and by 4.1–6.8% by its end. The spring SL is projected to have a moderate negative trend. The negative trends in both CL and SL indicate that the number of rainy days is expected to decline, a trend that has already been observed in the region during recent decades (Ziv et al., 2014; Yosef et al., 2019).

3.2. Autumn synoptic trends for the 21st century

The described synoptic groups' trends were also found to be prominent in the autumn months of September–November (SON), particularly noticed for the RST (SE quarter) as shown in Fig. 2. The observed 21st century increasing trend of the dust-affiliated RST is projected to be considerably high (3.1–6.6%), whereas an opposite decreasing trend is projected for the rain-affiliated CL (2.9–6.2%). The different trends observed in CL between 2046-2065 and 2081–2100 in the RCP4.5 scenario could be explained by the fact that in the RCP4.5 scenario the change is more pronounced in the second half of the century (Hochman et al., 2017). In addition, one can see that during autumn PT systems drop in percentage (−2.7%), this can be explained by the

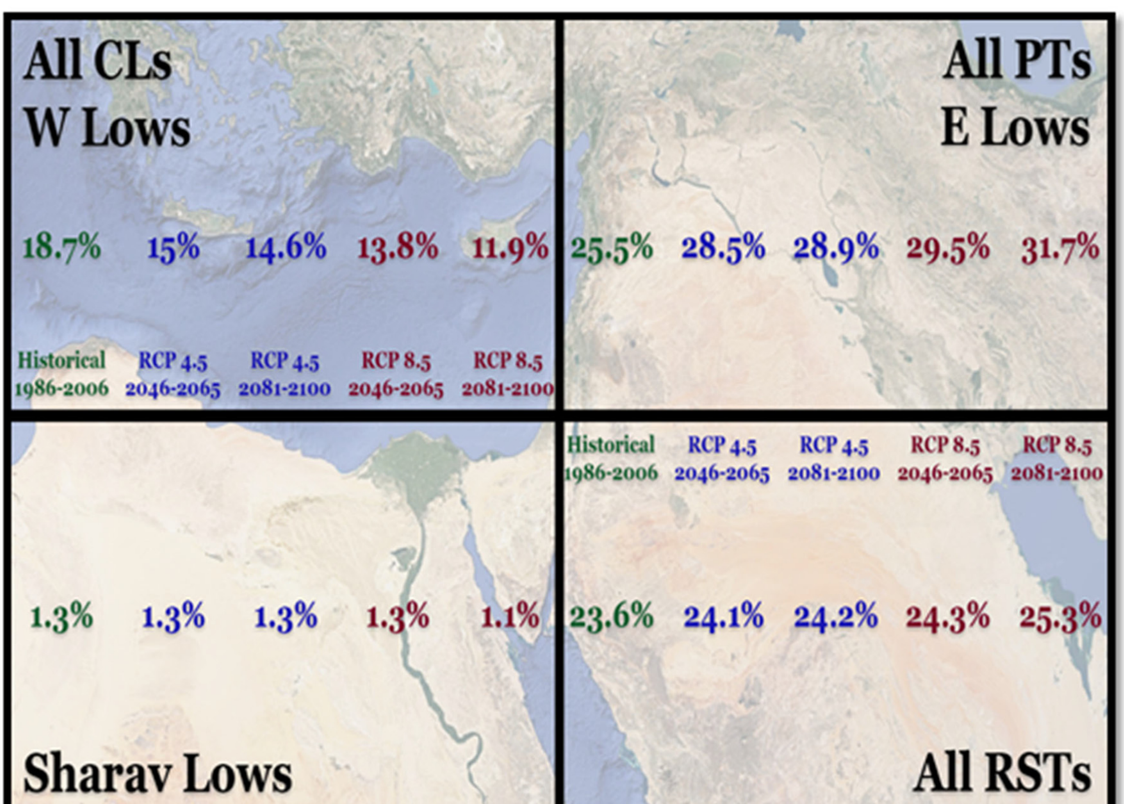

Fig. 1. Cyclone and trough annual distribution changes over four Middle East regional quarters based on 8-member ensemble CMIP5 projections. Highs are not included. In each quarter, the fraction of the stated synoptic group is mentioned for the historical time period (1986–2006, in green) as well as for the future 21st century periods (2046–2065, 2081–2100) for both RCP4.5 (blue) and RCP8.5 (red) scenarios. These are indicated with matching colors in the upper-left and lower-right quarters. The four main synoptic systems are as follows (Alpert et al., 2004). The Red-Sea-Trough (RST) originates from the interaction of upper level trough with East African or Saudi Arabian mountains and extends to EM; The Persian Trough (PT) originates from the Asian Monsoon region, through the Persian Gulf and westward to the EM; Cyprus Lows (CL) result from the penetration of extra-tropical cyclones to the EM or their interactions within the EM region; Sharav Lows originate in the lee side of the Atlas Mountains, moves to the east along the southern coast of the Mediterranean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

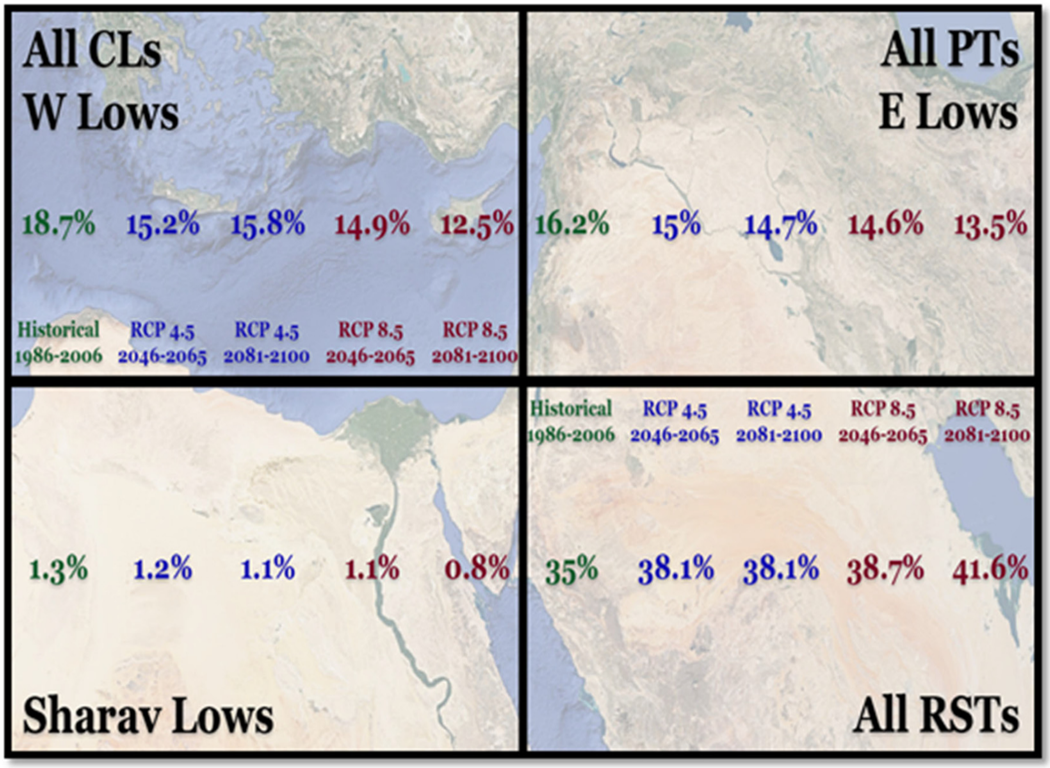

Fig. 2. As Fig. 1, but for the autumn season (September –November).

dramatic increase in the autumn RST (+6.6%). For the full year, PT significant increases (+6.2%) were shown to be tied with the extension of the summer period (Hochman et al., 2018).

3.3. Spread of CMIP5 lows and RST autumn synoptic trends

Analyzing projections of the different eight CMIP5 models, the picture is similar, where an overall negative trend in the Middle East Lows is observed throughout the 21st century (Fig. 3). This negative trend was shown to be directly associated with the decrease of both recently observed as well as future rainfall predictions over the region (Hochman et al., 2020). Notably, the models mostly agree that the RCP8.5 decrease in the second half of the 21st century is equivalent to the decrease since the end of the 20th century until mid-21st century (~5%). However, this drop occurs on a shorter time scale of ~40 years, compared to 60 years in the earlier period. Notice that in Hochman et al. (2017) a similar figure was presented for the full year, showing a drop of −12.9% compared to −11.6% in the present autumn figure.

Conversely, an overall significant positive trend in the Middle East RST is observed throughout the 21st century (Fig. 4). The significance of the ensemble RST trend was illustrated for the full year in Hochman et al. (2017), while the autumn increases presented here are even larger

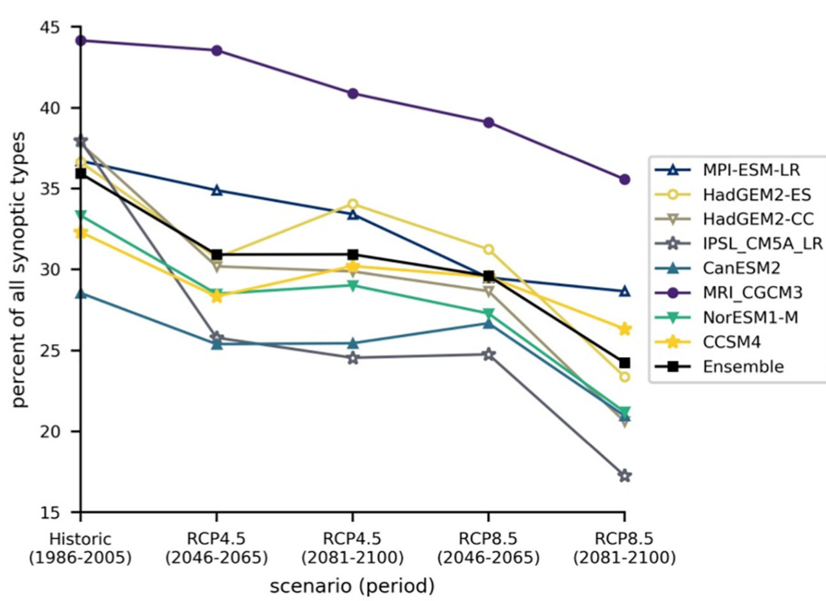

Fig. 3. Middle East Lows 21st century projections of eight models for the autumn season.

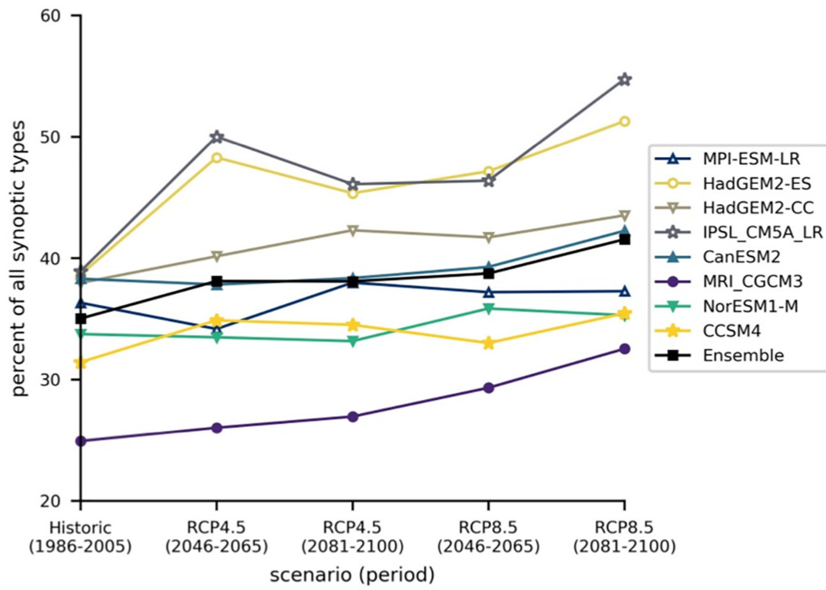

Fig. 4. Middle East RST 21st century projections of eight models for the autumn season.

(+6.6% from the historic value to the end of 21st century for the autumn period, compared to +1.7% for the full year). Most models agree on RST increases in the first half of the 21st century (compared to historical values) for both RCP4.5 and RCP8.5. It is interesting to note that in the RCP4.5 scenario, the RST increases until the mid-century and then becomes stable, whereas for RCP8.5, most models show increases in the second half of the 21st century.

3.4. Discussion on recent observed regional aerosol trends

While our focus here is on future projections, several studies have analyzed the recent aerosols trends in the region. Positive trends were observed throughout the region using ground measurements as well as remote sensing tools (for years 2000–2015, Klingmüller et al., 2016; for years 1958–2006, Ganor et al., 2010a). Other works showed moderate decreases in urban zones, with a recent study suggesting a decrease in Cyprus aerosol levels during 2010–2015 (Pikridas et al., 2018). However, for a longer time period of 17 years (1998–2015), this trend is not well pronounced. Moreover, slight increases were observed in some stations during 2012–2015, which suggest the necessity for longer periods in order to determine solid aerosol trends. Another work, which analyzed aerosol distribution and trends in the world's largest cities, using the MERRAero reanalysis, showed moderate negative dust trends for some regional cities (2003–2015, Provençal et al., 2017). However, opposite positive trends are observed in the newer reanalysis model, i.e., MERRA-2, due to the incorporation of aerosol data assimilation in the newer model. MERRA-2, in fact shows positive trends in the Middle East dust AOD during 2003–2012, similar to regional observations (A. Rocha-Lima, personal communication). Either way, the issue of recent dust trends in the region, employing different instrumentation and tools requires further investigation.

Most interesting, a recent finding which strongly supports the idea of a new aerosol source in the north east (NE) of Israel is presented in a 14-year study (2006–2019) on desert dust deposition (DDD) from a high-resolution 0.3^{o} (~30 km) horizontal grid DREAM (Dust REgional Atmospheric Model) model (Kishcha et al., 2020; KISH20). A most significant DDD increase over north Israel is shown for recent years, particularly during autumn (November). Moreover, the spatial correlations of DDD indicate that the NE positive trends originate from a different source than the southern areas (KISH20, Table 2). From the DDD mapping over the region, separate areas of deposition can be observed particularly at the beginning of the study period (2006–2009). Over the years, this NE deposition gradually spreads towards the south (KISH20, Fig. 15).

4. Conclusions

A most severe autumn dust storm during 2015, which originated from the Middle East, highlights the potential of a new aerosol source in the region. In this work, a regional 21st century daily synoptic analysis is performed by applying the semi-objective synoptic classification algorithm on eight CMIP5 models. We show that RST systems, which have been linked to regional dust events, are projected to increase, particularly during autumn. At the same time, CL systems, which are associated with regional precipitation, are projected to decrease. Overall, by conducting this regional synoptic analysis, the potential for a new aerosol source in the Middle East, is proposed, which may be enhanced by local anthropogenic activities. Such an additional dust source could impact the regional climate and environment, but also the health and wellbeing of the local population, regional agriculture and other sectors (Incecik et al., 2014). This can exert additional pressure on the region, which was shown to be vulnerable to climatic impacts and is expected to become significantly warmer and drier (Giorgi, 2006; Kitoh et al., 2008; Lelieveld et al., 2012; Zittis et al., 2019).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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