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FUTURE PREDICTIONS OF MOISTURE BUDGET OVER THE EASTERN MEDITERRANEAN BASED ON A SUPER-HIGH-RESOLUTION GLOBAL MODEL

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ABSTRACT

Three different spatial resolution climate datasets, Era-40 reanalysis, CRU and 20 km JMA's GCM, as well as the IMS's observed dataset are employed to study the current wet season (from Oct. to Apr.) moisture field in a rectangular domain of about 3.96 $\times 10^6$ km^2 over the eastern Mediterranean and part of the Middle East region. The research time period is from 1979 to 2002. The future (2075-2099) moisture field changes based on the prediction of the 20km GCM was also carried out.

We found that among the three climate datasets, the 20km GCM better presents the current precipitation regime over the E. Mediterranean (EM) compared with the other two datasets. The precipitation is much underestimated, even by a factor of two in some places, from ERA-40. The evaporation result from ERA-40 dataset was also under-evaluated by about 200 mm/wet season compared to the 20km GCM in the EM. The future projection of the moisture field based only on 20km GCM suggests that at the end of this century, an increasing evaporation with the magnitude of 150-200, 200-250 and over 300 mm/season at the water bodies of eastern Med., Red Sea and Persian Gulf, are projected; a significant decrease of precipitation is found at the western part of Turkey, western part of Syria, entire Israel and Lebanon, with a magnitude of over 200 mm/season. The famous Fertile Crescent precipitation strip, located in the Mid-East, also becomes much drier. An increase of precipitation is projected over Iraq and part of Iran. The total moisture budget as expressed by the precipitation minus evaporation (P-E) analysis further confirmed that a drier scenario is inevitable at the end of this century for the water body area and

most of the coastline countries. Consequently, a water crisis is an inevitable challenge for the drier countries within the research region in the future.

INTRODUCTION

The Middle-East (ME) located on the border between the mid-latitudes and subtropics, is interesting both in its meteorological and climatological aspects being predominantly a semi-arid to arid region with sharp climate gradients. Lack of water is one of the greatest problems as it is a key resource affecting social health and political stability in the ME. This problem may become even more severe under global warming and make the ME extremely vulnerable to any (natural or anthropogenic) reductions in available surface water, rendering it highly sensitive to changes in climate. The IPCC fourth assessment report suggested that the eastern Mediterranean (EM) region would become significantly drier under a future climate scenario, with potentially devastating impact on the population (IPCC, 2007). Therefore, a better understanding of the distribution of the atmospheric moisture budget of this region, especially for the main two components of atmospheric moisture budget, i.e., precipitation (P) and evaporation (E), is of great significance.

The exact mechanism controlling precipitation in the ME region is complex, and precipitation amounts and distributions are largely affected by the topography and land-sea distribution (Ozsoy, 1981). However, numerous studies concerning the precipitation regime in the ME have been conducted during the past several decades by using different kinds of data sets, such as observed data, reanalysis data, satellite data, as well as the climate model data (Alpert et al., 2002; Mariotti et al., 2002a,b; Alpert et al., 2007). Based on the focus of the research of precipitation in the ME, it might be classified as dynamical, climatological or hydrological. Dynamically, Zangvil and Druian (1990) investigated the relation between the upper air trough and the location of precipitation in Israel. Price et al. (1998) even investigated the relationship between the El Niño and precipitation in Israel. Krichak and Alpert (2005) studied the relations between the EM precipitation and the indices of the East-Atlantic West Russia pattern. Climatologically, Alpert et al. (2002) have analyzed observational databases over several areas of the Mediterranean basin during the 20th century, and concluded that there exists a dominant increase in extreme daily rainfall events together with a slight decrease in total values. Seager et al. (2007) studied the climate change of the southwestern North America by using an ensemble of regional climate models; their results also suggest that the Mediterranean region will be drier at the end of this century. Hydrologically, Mariotti, et al. (2002a,b) carried out a detailed study of the hydrological cycle and water budget in the Mediterranean region.

The climate models have been widely used to do both global and regional scale of climate study since it has been introduced, particularly with some high temporal and spatial resolution climate models. However, the global climate model (GCM) is usually with relative coarse spatial resolution, about 100 km to 300 km; therefore, it cannot capture well the small scale factors which have an important influence on the local climate, particularly over the Mediterranean. On the other hand, the regional climate model (RCM) has relative fine spatial and temporal resolution, but besides being computationally expensive, it also needs the lateral boundary condition data, which usually comes from the GCM to drive the RCM. The very high spatial resolution GCM model employed here addresses the disadvantages that exist in both the GCM and RCM. It avoids the problems of the unfit-in-scale of the lateral boundary condition, but also can incorporate interactions between global scale and regional scale explicitly. Here, we study except for several traditional datasets, also a high-resolution 20km grid GCM, which was developed in the Japan Meteorological Agency (JMA) in order to investigate the current and future precipitation regime in the ME.

METHODS

Data

To study the current precipitation regime of the EM, several datasets have been used here. These include, first, the global time series dataset based on rain gauge measurements (land only) from the climate research unit (CRU, in brevity; Mitchell and Jones, 2005). The grid horizontal resolution is 0.5×0.5 degree, and the time period is available from 1901 to 2002. Second is the The European Center for Medium-range Weather Forecast (ECMWF) reanalysis dataset (ERA-40, in brevity; Kallberg et al., 2004). This data covers the time period from mid-1957 until 2002. Originally, ERA-40 has a spectral representation based on a triangular truncation at wave number 156 or at 1.125 degree. horizontal resolution using a Gaussian grid (Gibson et al., 1997). However, the spatial resolution of ERA-40 data used in this study is 2.5 ×2.5 degree. The third database is based on daily precipitation for several selected observed stations inside Israel from the Israel Meteorological Service (IMS) with different time periods. The fourth database is the Japanese Meteorological Agency's (JMA) super-high spatial resolution (about 20 km) grid GCM, which is a climate-model version of a GCM. A detailed description of the model is given in Mizuta et al. (2006). Two runs of the 20km GCM cover the time periods 1979-2007 for current/control run and 2075-2099 for the future run. The monthly mean precipitation taken from datasets 1, 2 and 4 are used here while the daily mean precipitation is also available for dataset 4. Since the current 20km run covers the time period 1979-2007, while the ERA-40 and CRU data are available only until 2002, the time period selected for the current atmospheric moisture budget research is 1979-2002, in order to make all main three datasets cover the same period.

Research Area and Study Time Period

The study area covers the main part of the EM and a good part of the ME, and was chosen to be 27°-41°N and 22°-50°E with a total area of about 3.96×10^6 km^2. Also, in order to study the moisture field over the ME, a sub-region within this area was defined by the latitude 30°-37°N and longitude 30°-40°E with Israel located approximately in the center of this area.

Since the main rainy season in the EM region is October-April, only this 7 month wet season period over 23 years was chosen to study the precipitation regime, as the remaining dry season has only very little influence on the total annual precipitation.

RESULTS OF THE MOISTURE BALANCE COMPONENTS AND DISCUSSIONS

Seasonal Precipitation

The average total precipitation for the wet season (Oct.-Apr.) of the ME and zoomed in of the EM from 1979 to 2002 is given in Fig 1. In general, the less than 50 mm precipitation contour line can be clearly defined from these three charts with more or less the same locations. The latitudinal gradient is the predominant feature of precipitation in the EM. A clear precipitation strip with one peak zone of precipitation, approximately located at 37°N, forms the famous "Fertile Crescent"strip due to the rain shadow effects generated by the mountains of Taurus, Elburz and Zagros in this area. However, the peak of total precipitation of the crescent strip from ERA-40, CRU and 20km GCM are different, with the corresponding values of 500-700, 700-900 and 900-1100 mm, respectively. Another maximum of average total precipitation also can be identified along the eastern and northern coastlines of EM, with the amount of precipitation of 350-500, 500-700 and over 1100 for the ERA-40, CRU and 20km GCM, respectively. The zoomed-in ME in Fig.1 shows the more detailed distribution of the precipitation in this region, with a sharp eastward decreasing gradient of precipitation that starts from the eastern coastline of the Mediterranean. This gradient can be explicitly defined only in the CRU and 20km GCM, with the 20km with sharper patterns to be discussed later in comparison with rain gauges. The 20km GCM further shows its two centers of peak precipitation in the east and north coast line of EM with the value over 1100 mm/season, but the results from CRU and ERA-40 are significantly lower compared to values in the 20km GCM. Does the over evaluated amount of precipitation from 20km GCM reflect the reality of precipitation regime in this area?

To ascertain that the average total seasonal precipitation that results from the three different datasets fits with the observed data, six points are selected sequentially from south to north, which make an approximate south-to-north cross-section along the EM coast, and covers the countries of Egypt, Israel, Lebanon and Turkey. The detailed information about these six points is shown in Table 1. The reason for selecting these six stations, which are all located near the coast line, was as follows. Both the land-sea interaction and the significant change of topography from sea to land have a strong influence on the precipitation regime of the coastal area. Fig. 2 shows that the seasonal averaged total precipitation of the six selected stations results from ERA-40 are significantly underestimated compared to the observation data, except for the stations of Cairo and Beer-Sheva. ERA-40 even catches less than the half of the total precipitation in Tel-Aviv and Beirut.

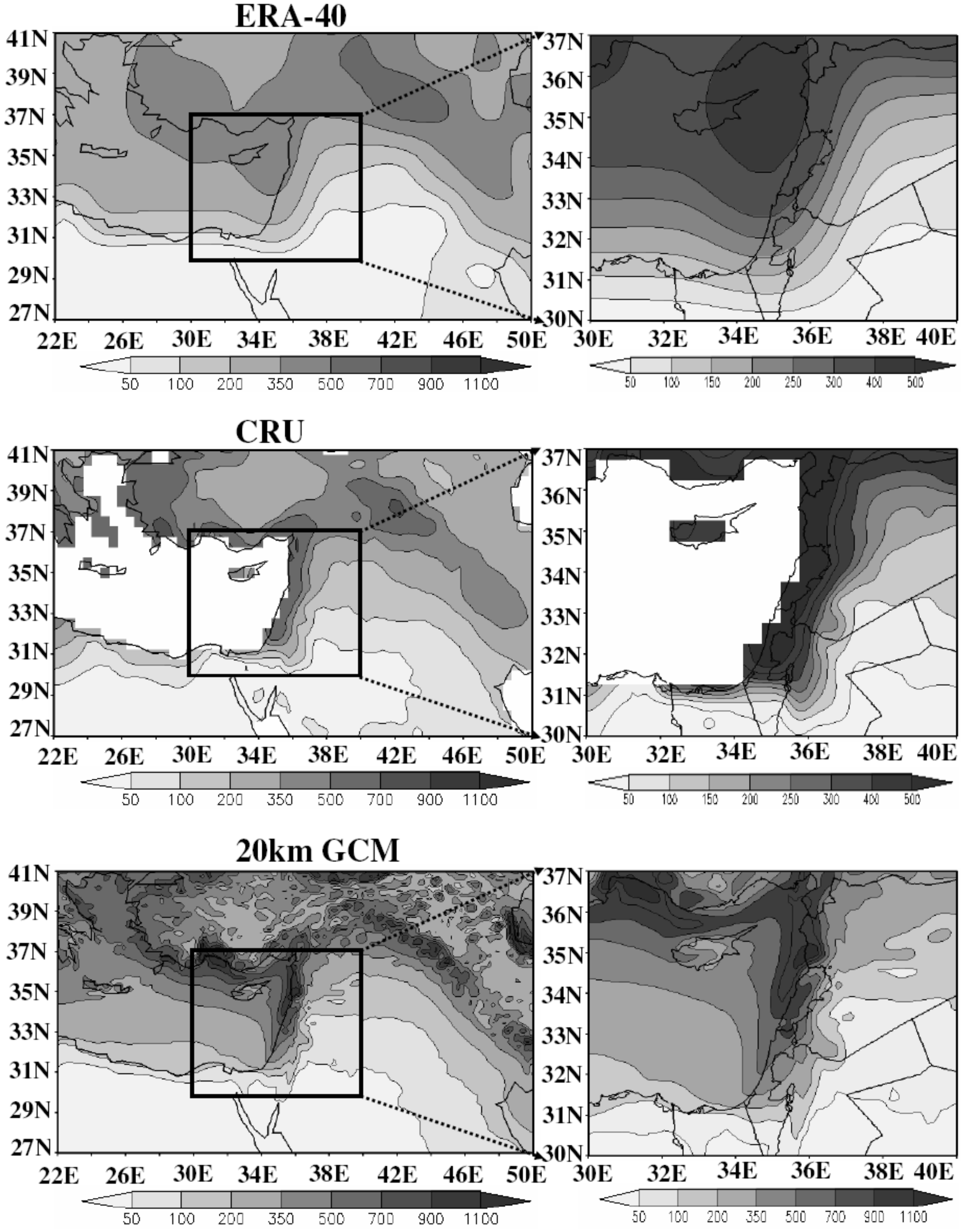

Fig. 1: Total seasonal (Oct.-Apr.) precipitation for the Eastern Mediterranean(EM) and the Middle-East (left panel) and zoomed in over the EM (right panel). Averaging time period is 1979 - 2002. Unit: mm/season.

This finding is consistent with Mariotti et al. (2002a), in which several IPCC datasets were used to study the hydrological circle of the Mediterranean. The CRU and the 20km GCM results show a better estimation, and the 20km GCM's results are quite close to the observed data. The standard deviation of errors for each model is shown in Table 1 and further confirms this fact. However, the CRU is unable to reproduce the peak precipitation in Beirut, but with an error of over 150 mm. It can be concluded that the 20km GCM better captures the total amounts of precipitation for the selected six stations.

Table 1. Geographic location of the stations used for the models' evaluation. Observed total seasonal (Oct.-Apr.) precipitation is based on sources listed under the Table. The right-most column shows the standard-deviation of the errors for each model. The accurate values of precipitation were obtained by the same interpolation method (GrADS). For comparison, the ERA-40, CRU and 20km GCM run are listed in units of mm/season.

	Cairo	Beer-Sheva	Tel-Aviv	Haifa	Beirut	Adana	SD(E)
Longitude	31.37°E	34.90°E	34.77°E	34.98°E	35.51°E	35.32°E	-
Latitude	30.05°N	31.25°N	32.02°N	32.82°N	33.98°N	37°N	-
Observed	26*	201**	527**	534**	840***	550***	0
ERA-40	8	165	245	320	380	425	167
CRU	21	220	560	520	680	670	91
20kmGCM	39	210	480	590	780	550	43

*WeatherUnderground **Israel Meteorological Service *** Weatherbase.com

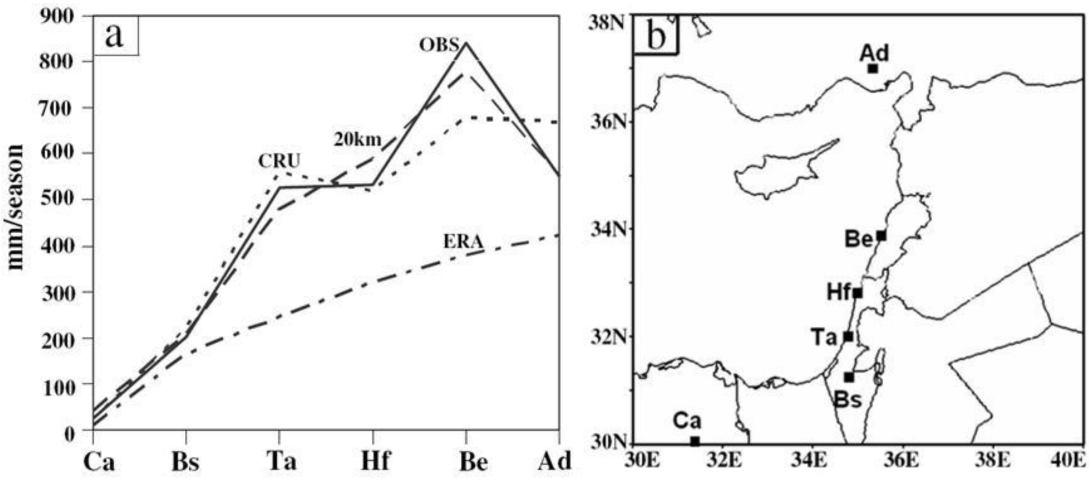

Fig 2: (a) Comparison of average total observed seasonal precipitation with three model data for the selected 6 stations, which make an approximate south-to-north cross-section along the EM coast. The six stations are from south-to-north, Egypt---Cairo (Ca,); Israel---Beer-Sheva (Bs), Tel-Aviv (Ta), Haifa (Hf); Lebanon---Beirut (Be) and Turkey---Adana (Ad). The three models are the European reanalysis (ERA, — - —), the Climate Research Unit (CRU, - - - -) and Japanese Meteorological Agency's 20km GCM run (20km, — —). Unit: mm/season. (b) Eastern Mediterranean map indicating the location of the six stations.

Monthly Distribution of Rainfall

It is also interesting how the 20km GCM captures the monthly precipitation regimes. The state of Israel was selected, not only because it is a transition zone between hyper-arid and relatively humid regions, but also because it is a complicated topographic zone for this small country. Therefore, the region of Israel was arbitrarily divided into three parts, northern, centeral and southern parts, see Fig.3. For each part, two stations are selected to calculate the monthly mean precipitation based on rain gauge data with the time period from 1979 to 2002. Fig. 4 shows that, in general, there is a good agreement between the precipitation from the rain gauge and the 20km GCM, with the correlation coefficient for the monthly precipitation between northern, centeral, southern parts and the 20km GCM -0.97, 0.93 and 0.96, respectively, with 99% level of statistical significance. The model credibly describes the dry period from May to August when only very little precipitation amounts are observed. However, Fig. 4 shows that the model underestimated the precipitation of the autumn, and a larger error can be seen in Jerusalem at an altitude of 750 meters, probably due to the fact that the spatial resolution of the model is still not fine enough to accurately describe the orographic rainfall. The importance of the high-resolution in Jerusalem was highlighted by Shafir and Alpert (1990). Another model deviation is its overestimation of the precipitation for most of the wet seasons in Elat. But the absolute quantity of precipitation in Elat is very small. Overall, it can be concluded that the 20km GCM performs very well in simulating the current monthly rainfall distribution in the research region.

Fig.3 : Geographic map indicating the selected six stations focused on Israel. Empty squares denote northern stations, cross (+) for central stations and solid squares for the southern part of Israel. Contour lines show the topography (m) with 200 m interval.

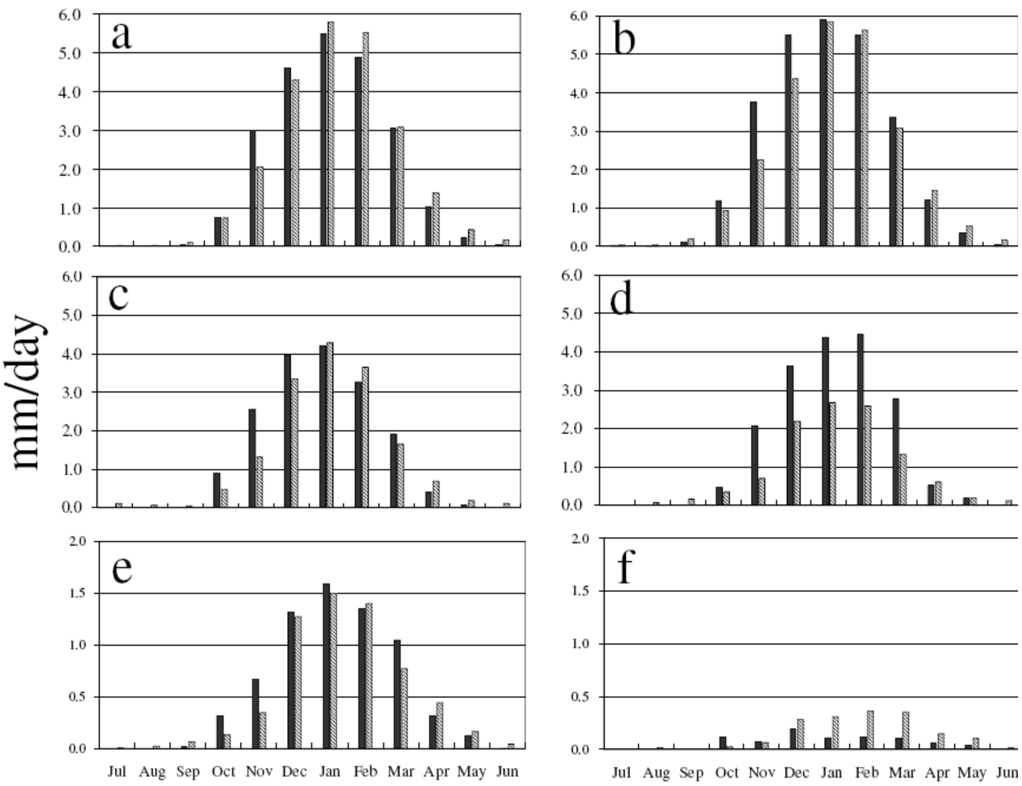

Fig. 4: Comparison of monthly mean precipitation from observed rain gauges (black column) and 20km GCM (grey column) for selected six stations in Israel based on their locations. Unit: mm/day. The selected stations are: *Northern Israel*: (a) Har-Knaan, (b) Eilon; *Center Israel*: (c) Tel-Aviv, (d) Jerusalem; *Southern Israel*: (e) Beer-Sheva, (f) Elat.

Evaporation

Fig. 5 shows the evaporation (E) results from the ERA-40 and the 20km GCM. As expected, the water body shows larger evaporation values than the land area. The ERA-40 does not show the sharp land-sea boundary as in the 20km. Three maxima centers of evaporation over the ME are noticed, Red Sea and Persian Gulf can be obviously seen both in the ERA-40 and the 20km GCM. The E peak is located at the center of the EM in the ERA-40, but it is located in the northeast corner of EM in the 20km GCM. It looks reasonable that the maximum evaporation is located where the maximum precipitation is as seen from the 20km GCM simulation. The maximum evaporation in the EM is 900-1100 mm/season in the ERA-40 compared to over 1100 mm/season in the 20km GCM. This suggests that the E is underestimated in the reanalysis data over the Mediterranean region as also suggested by Mariotti et al. (2002a).

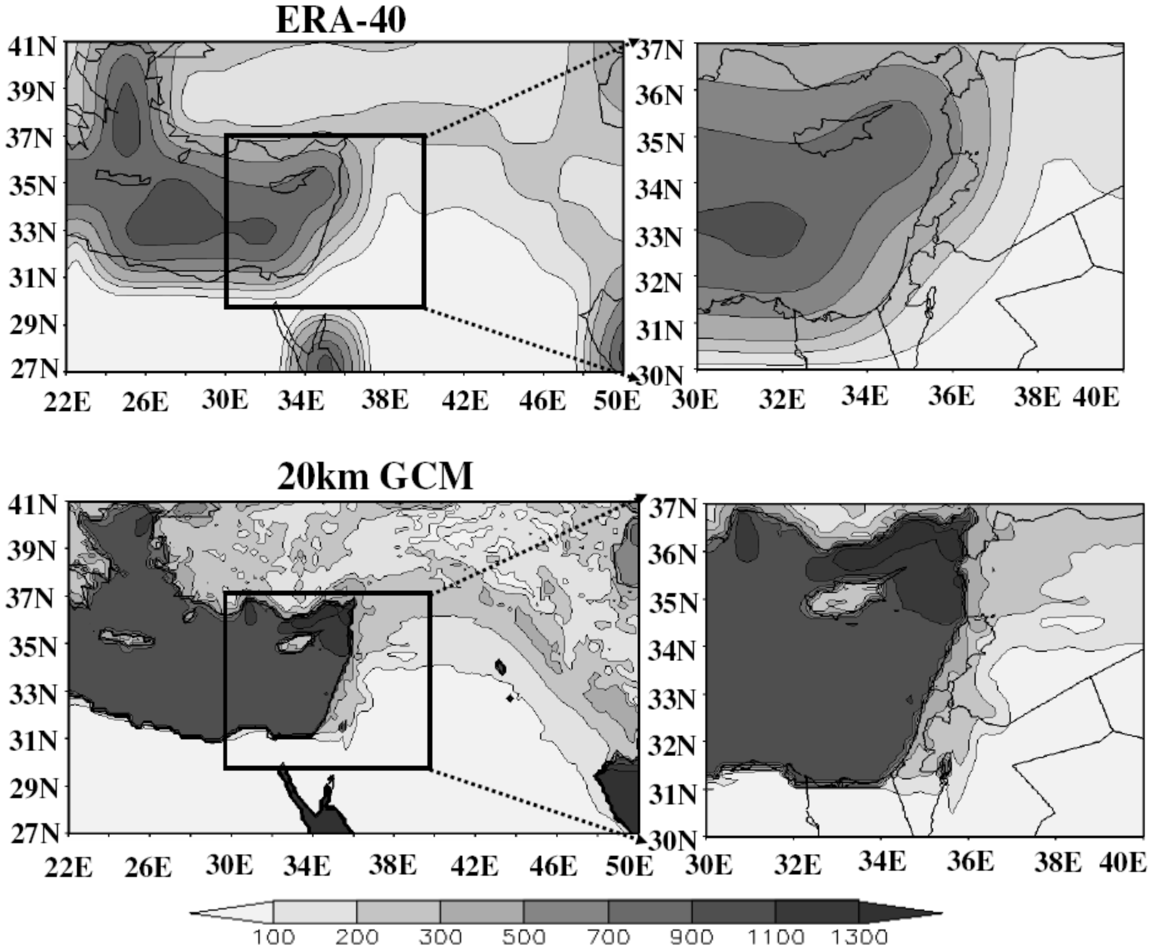

Fig.5: Same as Fig. 1 but for evaporation.

Future Changes of E, P and P-E

Fig. 6 shows the difference of E, P and P-E between the future (2075-2099) results from a certain emission scenarios defined by IPCC and current climate (1979-2007). The E increase is clearly noticed over the water body, with maximum value of 150-200, 200-250 and over 300 mm/season at the EM, Red Sea and the Persian Gulf, respectively (Fig. 6a). The center of E increases in the EM is located along the northern boundary with the magnitude of 150-200 mm. A small increasing area over the “Fertile Crescent” can also be seen. There are small changes in North Africa and most of the inland Middle East countries. An evaporation decrease can only be found in some islands inside the EM, i.e., island of Crete and Cyprus, as well as the joint boundary between Israel and Jordan.

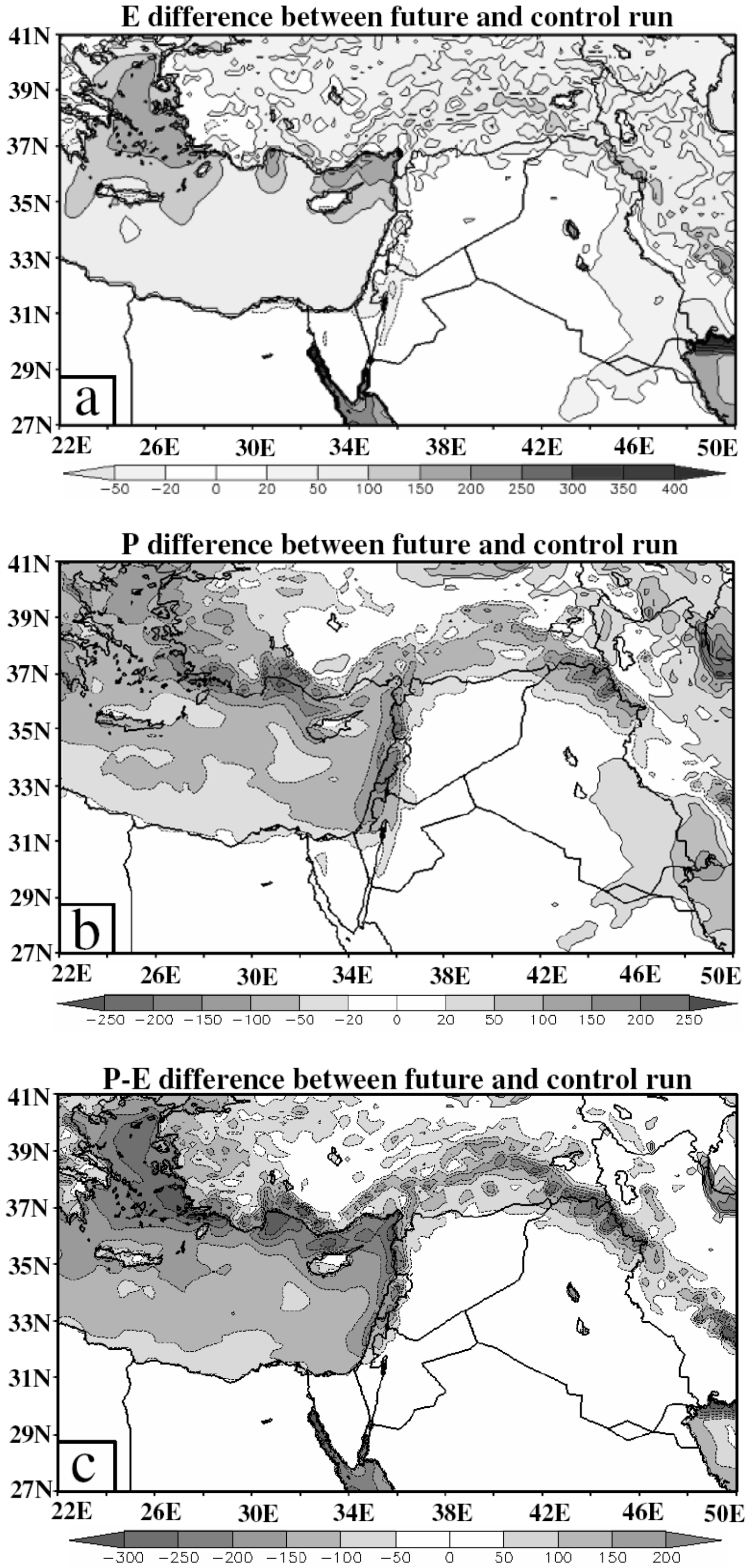

Fig.6: Difference of seasonal total E, P and P-E between the future (2075-2099) and current (1979-2002) 20 km GCM runs. Dashed contour lines indicate the negative changes, i.e., reduction in the future. Unit: mm/season.

P differences show (Fig.6b) that the P of the entire EM is decreasing with an average value of over 100 mm/season, with maximum P decreases located at the northern and eastern coastline area of the EM with a magnitude of over 250 mm/season. The western part of Turkey and most part of the "Fertile Crescent" are also projected to be drier, as reported also by Kitoh et al., (2008). Fig. 6b suggests that the eastern coastline countries, i.e., Israel, Lebanon and the western part of Syria, will become drier in the future by about 200 mm/season. On the other hand, a precipitation increase belt is found at the most easterly part of research region, including the eastern part of Iraq and western part of Iran. A potential explanation for the P increases there is that they are perhaps due to the evaporation increases over the water bodies surrounding this area, which increased the available moisture; also, the mountain region provides strong orographic forcing.

P-E is an important indicator in study of long term climate changes of the moisture fields. The advantage of using the P-E term is that it shows the moisture sinks or sources by the sign of P-E. As the moisture budget equation shows. P-E exactly equals the vertical integrated moisture convergence term (E-P equals the divergence term). The difference of P-E between future and current climate is shown in Fig.6c. Area with negative P-E changes indicates that the area will lose moisture. In general, it has the similar pattern as the precipitation difference in Fig.6b. However, when examined carefully, it can be found that the region with the precipitation increase in Fig. 6b has shrinked dramatically. The Red Sea and the Persian Gulf region show a negative value which can not be seen from the P difference chart, suggesting that these two water bodies also become drier, though the precipitation in this area has no clear index to change, but the evaporation field changed significantly. A completed "Fertile Crescent" strip, clearer than that of the P difference chart ,further proved the drying tendency in the future of this region.

CONCLUSIONS

The main conclusions can be summarized as follows:

1) JMA's 20km GCM shows its high capability in simulating the current two main moisture budget components - precipitation and evaporation - in the research region.

2) Both precipitation and evaporation are underestimated by the coarser resolution ERA-40 data, especially noticed in the relatively large errors for the estimation of the observed precipitation distribution in the research area.

3) The main three water bodies, EM, Red Sea and Persian Gulf are projected to be drier at the end of this century, i.e., reduced P-E.

4) The famous Fertile Crescent will become dramatically drier at the end of this century.

5) Most of the EM adjacent Middle East countries, such as the western part of Turkey, western part of Syria, entire Israel and Lebanon are projected to be drier; however, the east part of Iraq and part of Iran will become wetter by the end of this century.

6) The EM and ME topographic rainfall forcing as well as physiographical changes (like land-sea, land-use etc.) effects on rainfall are quite dominant. Therefore, high-resolution modeling plays a critical role in atmospheric processes. This seems to be true for the whole Mediterranean region, e.g., Lionello et. al. (2006).

7) A water crisis probably is an evitable challenge for the drier countries within the research region in the future.

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