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Water cycle changes over the Mediterranean: a comparison study of a super-high-resolution global model with CMIP3

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Water cycle components over the Mediterranean for both a current run (1979–2007) and a future run (2075–2099) are studied with the Japan Meteorological Agency's 20 km grid global climate model. Results are compared with another study using the Coupled Model Intercomparison Project Phase 3 ensemble model (hereafter, the Mariotti model). Our results are surprisingly close to Mariotti's. The projected mean annual change rates of precipitation (P) between the future and the current run for sea and land are −11 per cent and −10 per cent, respectively, which are not as high as Mariotti's. Projected changes for evaporation (E) are +9.3 per cent and −3.6 per cent, compared with +7.2 per cent and −8.1 per cent in Mariotti's study, respectively. However, no significant difference in the change in P–E over the sea body was found between these two studies. The increased E over the eastern Mediterranean was found to be higher than that in the western Mediterranean, but the P decrease was lower. The net moisture budget, P–E, shows that the eastern Mediterranean will become even drier than the western Mediterranean. The river model suggests decreasing water inflow to the Mediterranean of approximately 36 per cent (excluding the Nile).

Keywords: Mediterranean; water cycle; rivers; global warming

1. Introduction

The Mediterranean Sea is a marginal and semi-enclosed sea. It is located in a transitional zone where both mid-latitude and tropical dynamics play an important role (Alpert *et al.* 1990). The complex topography over the Mediterranean region yields a unique climate within this small area with steep gradients. Lack of water is a specific feature over this densely populated region, particularly over the Middle East region. The trend of global warming makes the topic of water resources particularly sensitive over the Mediterranean (Ziv *et al.* 2005), as also reported by the Intergovernmental Panel on Climate

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Change (IPCC) Fourth Assessment Report (AR4; IPCC 2007). Therefore, a better understanding of the distribution of atmospheric moisture budget components over this region is of great significance.

The dynamic factors that influence the moisture fields over the Mediterranean region are complicated. Except the regional small synoptic-scale factors, earlier studies have shown that the climate of the Mediterranean region has significant teleconnections such as the El Niño Southern Oscillation (Fraedrich 1994; Price *et al.* 1998; Diaz *et al.* 2001); variabilities of the south Asian monsoon and African monsoon (Reddaway & Bigg 1996; Rodwell & Hoskins 1996; Chou & Neelin 2003; Ziv *et al.* 2004); and the large increase in Red Sea trough frequencies (Alpert *et al.* 2004) and also tropical cyclones (Krichak *et al.* 2004). To better take all the factors into consideration, the climate model is an essential tool to study the future moisture budget and water cycle changes over this area. Several studies concerning the climate change over the Mediterranean region have been carried out based on several climate models (Gibelin & Deque 2003; Alpert *et al.* 2008; Giorgi & Lionello 2008; Mariotti *et al.* 2008). Mariotti *et al.* (2008) (hereafter, Mariotti) studied water cycle changes over the Mediterranean region, by using data from multi-model projections of the World Climate Research Program/Coupled Model Intercomparison Project Phase 3 (WCRP/CMIP3). They concluded that a transition to a drier twenty-first century is expected over the Mediterranean region, and the result is also consistent with Seager *et al.* (2007), who used ensemble climate models. However, nearly all of the model data employed for the future climate studies are of coarse resolution, with a typical horizontal spatial resolution greater than 100–200 km. Therefore, it is quite interesting to compare these results with a super-high-resolution global grid climate model.

This study aims to perform a comparison study of the changes in the future moisture budget components over the Mediterranean region between the Mariotti results and those from a super-high-resolution global climate model (GCM). Also, a brief study of predicted changes of Mediterranean Sea water discharge by using a river model is described.

2. Data and methodology

(*a*) *Super-high-resolution GCM*

To study the climate changes over the Mediterranean region, a super-high-resolution 20 km grid GCM developed at the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA) was employed. It is a climate-model version of the operational numerical weather prediction model used in the JMA. A detailed description of the model is given in Mizuta *et al.* (2006). The two runs of the 20 km GCM cover the time periods 1979–2007 for current/control and 2075–2099 for the future. The control run used the observed monthly sea surface temperatures (SSTs) and sea-ice distribution, whereas the future run used the SST and sea-ice concentration anomalies of the multi-model ensemble projected by CMIP3 under the Special Report on Emissions Scenarios A1B emission scenario. Details of the method are found in Mizuta *et al.* (2008). The JMA 20 km GCM data have been validated against past climate over the Middle East as well as over the Mediterranean region, and details can be found in Kitoh *et al.* (2008*a*).

(*b*) *The river model*

The river flow model in this study is the global river flow model using the total run-off integrating pathways (TRIPs) (GRiveT) developed at the MRI. A TRIP is a global river channel network in a 0.5° by 0.5° grid originally designed by Oki & Sud (1998). The effective flow velocity is set at $0.40\,\mathrm{m\,s^{-1}}$ for all rivers following studies that use flow velocities ranging from 0.3 to $0.5\,\mathrm{m\,s^{-1}}$ (Oki *et al.* 1999). It should be noted here that flow velocities are not constant and can vary widely from 0.15 to $2.1\,\mathrm{m\,s^{-1}}$ (Arora & Boer 1999). In the process of simulation, GRiveT distributes the run-off water on the model grids into TRIP grids, with a weight that is estimated by the ratio of the overlaid area on both grids. GRiveT then transports the run-off water to the river outlet along the river channel through the TRIP. It should be emphasized that GRiveT does not account for any human consumption, i.e. irrigation, dam or natural losses, that is, infiltration, of the river water, which might cause some differences between the model and the observed river flow, as noted, for instance, with the Nile River flow in Egypt as analysed later.

The monthly mean of the climatological river model data from two time periods were investigated in this study: the control/current run (1979–2003) and the future projection (2075–2099).

(*c*) *Study area and season*

Following Mariotti, a domain that covers the Mediterranean, Middle East, Europe and North Africa was selected to investigate the large-scale moisture budget component changes. It was defined by the latitude 20°–60° N and longitude 20° W–70° E, with a total area of approximately $3.1\times10^7\,\mathrm{km}^2$. The Mediterranean Sea covers the domain 10° W–40° E and 28°–47° N, with a total area of water body of approximately $2.5\times10^6\,\mathrm{km}^2$. In addition, the Mediterranean Sea was subdivided into the west and east of the Mediterranean Sea region at the 15° E longitudinal line, in order to study the moisture budget for two sub-basins separately. The wet season was from October to March and the rest of the year (April–September) was the dry season.

3. Results and discussion

(*a*) *Seasonal moisture field changes over the large domain*

The seasonal change of the area mean evaporation (E), precipitation (P) and P–E between future and control runs (future minus control) over large domain results based on the 20 km GCM is shown in figure 1. In general, our results are very close to those of Mariotti. During the wet season (figure 1*a*,*c*,*e*), three belts of changing precipitation can be identified clearly from south to north (figure 1*a*), which show no significant change, a decrease and an increase in precipitation. These three belts are located below 30° N, 30°–42° N and above 42° N, respectively. The peak of the precipitation decrease is located at the northern boundary of the eastern Mediterranean Sea (EMS), with a magnitude of over $0.5\,\mathrm{mm\,d^{-1}}$ (approx. 100 mm per season). Jin *et al.* (in press) investigated the moisture budget

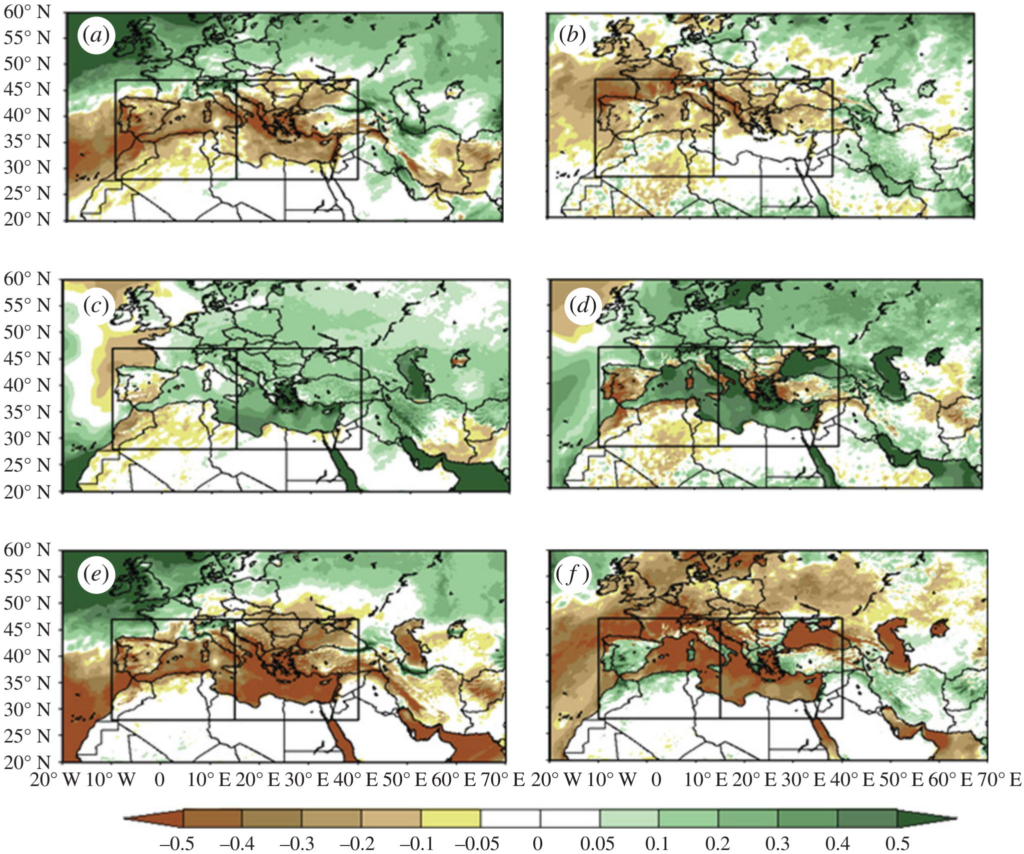

Figure 1. Mediterranean water cycle changes by 2075–2099 compared with 1979–2007 for the (a,c,e) 'wet' and (b,d,f) 'dry' seasons based on MRI 20 km GCM. (a,b) Precipitation, (c,d) evaporation and (e,f) precipitation minus evaporation. Unit, mm d^{-1}. The box broadly depicts the western and eastern Mediterranean region.

over the Middle East by using 20 km GCM data and demonstrated that the 20 km GCM credibly simulates the current precipitation regime over the eastern Mediterranean region.

Comparing present and future simulations, during the dry season, when compared with the wet season, the belt of precipitation decrease moves slightly to the north (figure 1b), probably because of the northward shift of the Hadley cell. Detailed discussion of poleward widening of the Hadley cell based on different datasets can be found in Held & Soden (2006), Lu *et al.* (2007) and Johanson & Fu (2009). They have also discussed some differences in the Hadley cell expansion as seen in the observations and reanalysis data. This causes most of the southern and central European countries, which are adjacent to the Mediterranean Sea, to become drier in the summer season in the future. For the change in evaporation, E, both wet and dry seasons show a similar pattern (figure 1c,d). However, a significant difference can be found over the north Mediterranean coast, i.e. an increasing E during the wet season (figure 1c) but decreasing E during the dry

Table 1. Mediterranean mean evaporation (E), precipitation (P) and precipitation minus evaporation (P–E) anomalies in future (2075–2099) relative to current (1979–2007) values separated by the sea and land areas. In each column, relative (%, left) and absolute (mm d^{-1}, right) values are reported based on a 20 km GCM.

area	parameter	annual	wet season	dry season
sea	E	9.3/0.35	5.7/0.24	13.6/0.45
	P	−11/−0.19	−10/−0.24	−11.4/−0.12
	$P-E$	−26.2/−0.54	−25.4/−0.48	−25.4/−0.57
land	E	−3.6/−0.04	1.4/0.01	−5.8/−0.09
	P	−10/−0.14	−10/−0.14	−9.2/−0.12
	$P-E$	−43.5/−0.10	−21.7/−0.15	−13/−0.03

season (figure 1*d*). As expected, all the water bodies show evaporation increases consistent with the SST and air temperature increases, based on the A1B emission scenario. A change in the net moisture budget, i.e. P–E, for both the wet and dry seasons shows that the Mediterranean Sea becomes drier (figure 1*e*,*f*). A major difference is that the P–E is projected to decrease during the wet season, but to increase during the dry season over the north Mediterranean coast. This could be the consequence of changes in E over the same area, as discussed earlier. This finding cannot be identified in Mariotti. In addition, limited by the spatial resolution, the change in P, E and P–E for the famous ‘Fertile Crescent’, which is located at the Middle East, can be easily identified in the 20 km GCM, but is not clear in Mariotti, as suggested previously by Kitoh *et al.* (2008*a*).

Table 1 shows the projected future changes in the mean P, E and P–E, separated for annual, wet and dry seasons and also for the land and sea bodies over the Mediterranean region. When compared with Mariotti (Mariotti’s results are in parentheses), the annual changes in P for sea and land from the 20 km GCM are −11 per cent (−15%) and −10 per cent (−15.5%), respectively. The smaller decreases in P in this study are perhaps due to different time periods for the control run used between these two studies, which are 1979–2007 and 1950–2000, respectively. The annual changes in E for sea and land areas are 9.3 per cent (7.2%) and −3.6 per cent (−8.1%), respectively. The reason for the big difference in E changes over land between these two studies might be the different features of models used in each study. However, the annual projected change of P–E for the sea body is quite close, i.e. −26 per cent (−24%). For the wet season, the projected changes in P, E and P–E in these two studies agree quite well, both qualitatively and quantitatively, except for the change in E over the land area. For the dry season, in contrast, there are distinct differences in the projected changes in E and P. These differences also result in the annual differences between these two studies, as discussed earlier. Another factor contributing to the differences between the two studies comes certainly from the very different spatial resolutions of the models. However, it is hard to ascertain which factor is the key in determining these differences.

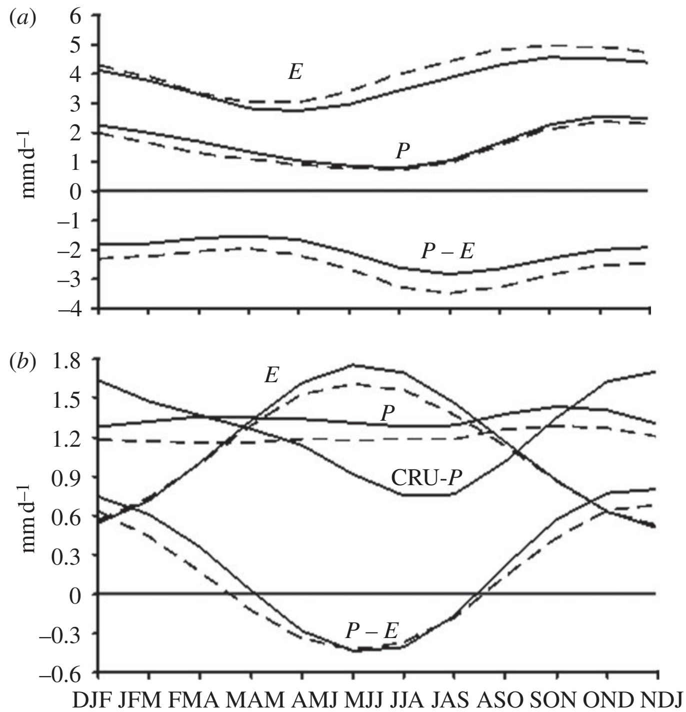

Figure 2. Mediterranean water cycle in 1979–2007 (solid line) compared with 2075–2099 (dashed line) based on the MRI 20 km GCM. The seasonal cycles (three-month running mean) of precipitation (P), evaporation (E) and precipitation minus evaporation ($P - E$) are shown (mm d^{-1}). The same CRU precipitation for 1979–2002 is added for comparison: (*a*) sea only and (*b*) land only.

(*b*) *Changes in monthly running means of E, P and P–E over the Mediterranean*

Figure 2 shows the seasonal cycles (three-month running mean) of E, P and P–E for the sea and land areas separately. Again, the results generally fit those of Mariotti, especially for the sea area (figure 2*a*). However, there are some interesting differences. For instance, the simulated summer P over the land area from the 20 km model is larger than that of Mariotti by a factor of about 2 (figure 2*b*). The same analysis using the Climate Research Unit (CRU) data, which are derived from observations, exhibits a pattern similar to that of Mariotti, but somewhat overestimates the precipitation for the winter season (figure 2*b*). It seems that the 20 km run overestimates the summer P of the land area. A plausible explanation is that the total land area over our research domain is relatively small, and the topographically forced precipitation has a significant influence over the complex water–land region, particularly in the summer, as the local forcing plays an important role in precipitation genesis. In contrast, no significant difference in land precipitation in the winter was found between these two studies, probably because winter precipitation is mostly influenced by synoptic systems. Jin *et al.* (in press) showed that, compared with the CRU, the 20 km GCM performs better in capturing the land area precipitation. Hence, coarse resolution models seem to be unable to capture the detailed precipitation

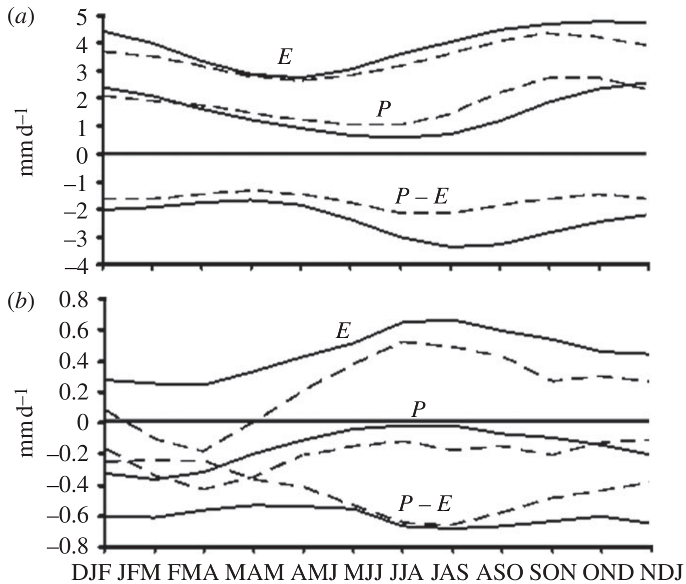

Figure 3. Sea area water cycles for western Mediterranean (dashed line) and eastern Mediterranean (solid line) regions based on the MRI 20 km GCM. The seasonal cycles (three-month running mean) of precipitation (P), evaporation (E) and precipitation minus evaporation ($P-E$) are shown (mm d^{-1}): (a) current (1979–2007) and (b) future (2075–2099) minus current.

information over such a small land area, i.e. only several grid point data can be obtained from the coarse data. The P–E curves suggest that both the land and sea areas of the Mediterranean region will become more arid in the future, and the sea area will experience even greater decreases in precipitation than the land area.

(c) *Comparing west and east Mediterranean*

The quite different geographical positions of the western Mediterranean Sea (WMS) and the EMS, which neighbour the huge moist Atlantic Ocean on the west and the arid Middle East on the east, respectively, make it interesting to compare the moisture budgets in both. Figure 3a shows, not surprisingly, that the current (present climate) evaporation of the EMS is higher than that of the WMS, with annual average values of 3.9 and 3.5 mm d^{-1}, respectively. This is probably due to the EMS being closer to the hot climate of the arid Middle East as well as the Indian monsoon, leading to significant subsidence over the EMS in summer, as reported by Rodwell & Hoskins (1996) and further discussed by Ziv *et al.* (2004). It should also be noticed that the maximum evaporation for the EMS and WMS appears during the winter and autumn seasons. This result is consistent with Jin & Zangvil (2009), who employed NASA reanalysis data. For the current precipitation, except for the central winter season (December–January), the average EMS precipitation is lower than the WMS precipitation (figure 3a), with mean annual values of 1.5 and 1.8 mm d^{-1}, respectively. This result is probably related to the WMS receiving more moisture from the Atlantic

Ocean than the EMS area. Another reason is that the northern part of the WMS is further north and therefore closer to the baroclinic zone. The P–E of the current period run for the EMS and WMS again indicates that the EMS is significantly drier than the WMS, especially during the summer and autumn seasons (figure 3*a*).

Figure 3*b* shows the model-projected changes in P, E and $P-E$ over the water body of the EMS and WMS between 1979–2007 and 2075–2099. The E changes show a dominant increasing E trend for both regions, except for some decrease in E for the WMS in the spring (March). The magnitude of the E increase in the EMS is higher than that of the WMS, with average values of $+0.45$ and $+0.22\,\mathrm{mm\,d^{-1}}$, respectively. It is not clear why an E decrease is projected in the spring season for the WMS in the future. Another finding is that, despite a projected P decrease in both the EMS and the WMS, the magnitudes in the WMS are higher than those of EMS, with mean values of -0.21 and $-0.16\,\mathrm{mm\,d^{-1}}$, respectively, except for the winter season (figure 3*b*). However, $P-E$ still shows that the EMS becomes drier than the WMS in the future, with mean values of $P-E$ changes of -0.61 and $-0.43\,\mathrm{mm\,d^{-1}}$, respectively. This means that the already drier EMS is projected to become even drier compared with the WMS.

(*d*) *Change of river discharge over the Mediterranean region*

In order to obtain a more complete picture of the water cycle budget for the Mediterranean region, it is interesting to examine the projected changes in river discharges, although they have a close relation with the precipitation regime, especially for those main rivers flowing into the Mediterranean Sea.

Figure 4 shows the changes in the run-off over land and the changes in the river flow rates between future (2075–2099) and current (1979–2003) periods based on the MRI river model. Figure 4*a* shows a clear decrease in the run-off over the continent of the north Mediterranean region, with a mean value of approximately $-10\,\mathrm{m^3\,s^{-1}}$, primarily as a result of the decreasing precipitation in the region. As a consequence, the flow rate of most of the rivers over this area is decreasing (figure 4*b*). It is interesting to note that the river model also shows that the Nile River is projected to have an increased flow rate in the future. This is due to the projected increase in rainfall in the tropics discussed in detail by Kitoh *et al.* (2008*a*).

To further investigate the change in river discharge, several large rivers flowing into the Mediterranean Sea were selected in a manner similar to that of Mariotti. The rivers' names and the countries where the estuaries are located are as follows: Ebro in Spain; Rhone in France; Po in Italy; Maritsa in Turkey; and the Nile River in Egypt. In addition, the Jordan River, as the only river which does not flow into the Mediterranean, was selected in order to examine its change in flow rate at the estuary of the Dead Sea. The reason for doing this is that the Jordan River is not only the main water resource for the bordering countries in the East Mediterranean, but also a significant influence on the water balance of the Dead Sea and hence on life in this sensitive region.

Instead of calculating the mean flow rate of the rivers, only the flow rates at the estuaries for each river were examined because of our great concern for potential variations in the river discharges into the Mediterranean Sea.

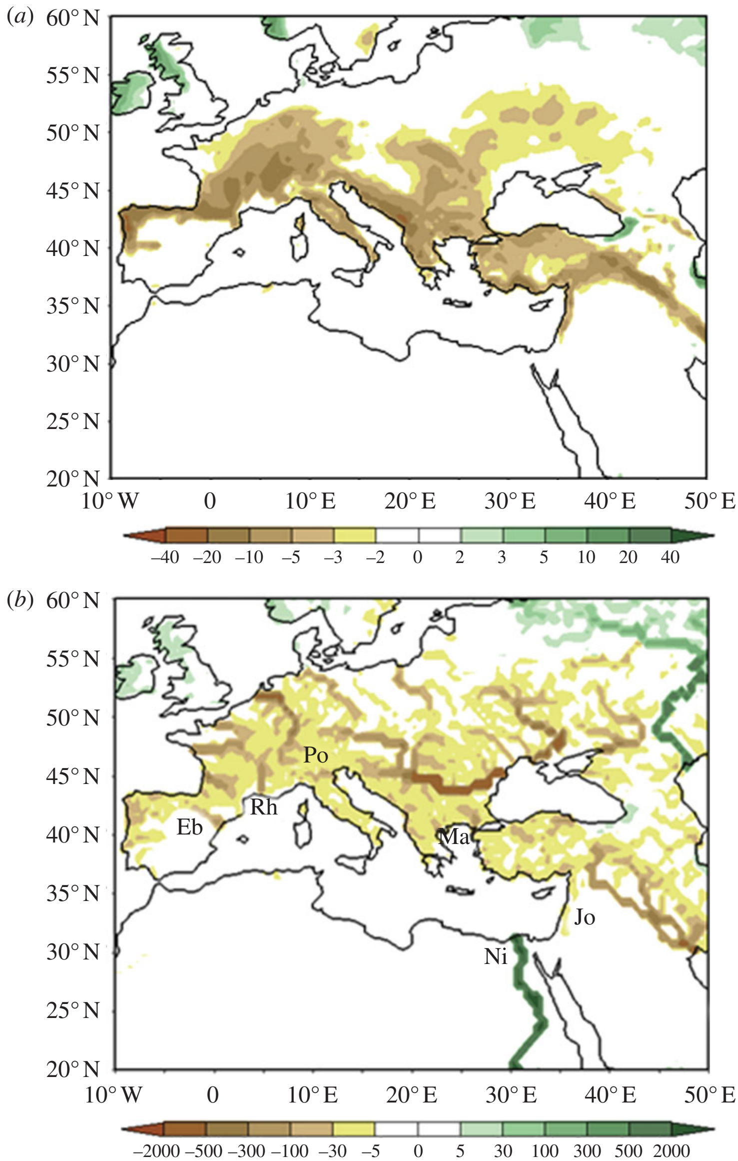

Figure 4. Changes in run-off and river discharge by 1979–2003 compared with 2075–2099: (*a*) run-off and (*b*) river discharge. Six rivers are marked as Ebro (Eb), Rhone (Rh), Po (Po), Maritsa (Ma), Jordan (Jo) and Nile (Ni). Unit, $m^3 s^{-1}$.

Figure 5 shows that, except for the Nile River, a decreasing trend of monthly mean river discharges is projected for the future. The most dramatic decrease in river discharge is found for the rivers Ebro and Maritsa and for the Jordan River. The decreasing magnitudes of the annual average discharge for the rivers Ebro, Rhone, Po and Maritsa and the Jordan River are 108, 307, 146, 184 and $19 m^3 s^{-1}$, corresponding to 46 per cent, 26 per cent, 18 per cent, 54 per cent and 85 per cent, respectively. The decrease in discharge for the East Mediterranean river

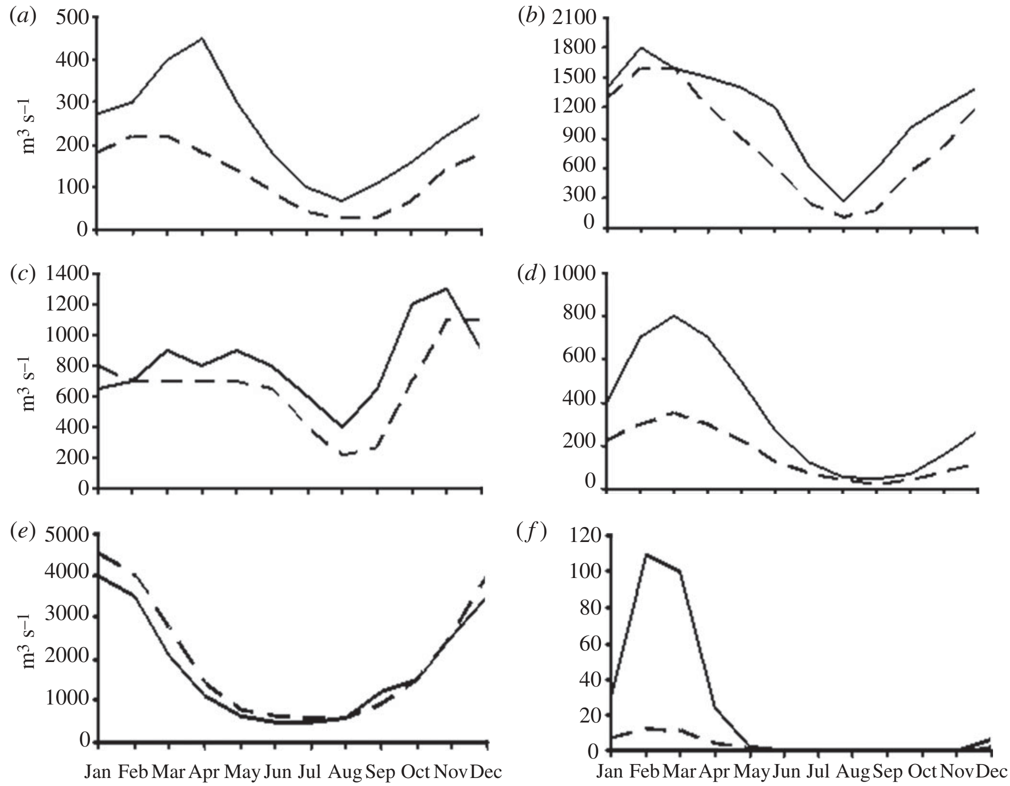

Figure 5. Changes in monthly mean river discharge of six rivers by (1979–2003) compared with (2075–2099). Except for the Jordan River, all rivers flow into the Mediterranean ($m^3\,s^{-1}$). Solid lines are for the current climate, whereas dashed lines are for the future climate. (*a*) Ebro; (*b*) Rhone; (*c*) Po; (*d*) Maritsa; (*e*) Nile; (*f*) Jordan. Notice the very different ordinate scales for all the rivers.

Maritsa and the Jordan River is particularly large, i.e. more than half compared with the current rate. It should be mentioned here that, compared with the observed data, the current simulation of river discharge by the river model shows a similar seasonal course from month to month. For instance, the Ebro River peaks in March/April and reaches its minimum in July/August. However, the results from the river model underestimate the flow rate by a factor of 2 compared with the observed data except for the Nile River, where the deviation is much larger. Possible explanations for the error might be the simplified river model, which relies on the model estimation of the run-off, and the still relatively coarse spatial resolution of the river model. This error can be reduced to some degree when we focus on the difference in the river discharge between the future and the current periods. For further discussion on the Nile results, see Kitoh *et al.* (2008*b*).

An increasing trend of discharge with a value of approximately $2090\,m^3\,s^{-1}$ was calculated only for the Nile. It should also be noticed here that the river model does not take into account any anthropogenic influences. Therefore, there are additional discrepancies for the river discharge between the model and observed data. For example, the river discharge for the river Nile from the model is higher than the observed data owing to the huge Aswan dam constructed across the river in Egypt (Kitoh *et al.* 2008*b*). In addition, the Nile is the largest river that flows into the Mediterranean, and it has a crucial role in the balance of river discharges in the Mediterranean. However, as the model showed, the absolute value of increasing discharge from the Nile River only is larger than the sum of all decreasing discharges from the other four rivers. Hence, it may seem that an overall surplus of river discharge was projected by this analysis. But, we should keep in mind that, except for the model errors mentioned earlier, there are numerous other small rivers over the European continent and isolated islands that flow into the Mediterranean, and all of these rivers are projected to experience a decrease in their discharge (figure 4*b*).

In agreement with this study, the Mariotti study showed a decrease in the river discharges for some rivers based on the observed data. Therefore, a future water deficit is projected over the Mediterranean. Moreover, research has shown that the salinity of the Mediterranean is increasing steadily from the observed data even in recent decades (Millot *et al.* 2006). These results might be caused by the combined effect of decreasing P, increasing E and the deficit water discharge in the Mediterranean region.

4. Summary

The JMA 20 km grid GCM data were introduced to make a comparison study with Mariotti *et al.* (2008) of water cycle components over the Mediterranean region. On a large spatial scale, results from these two studies are similar to each other, but there are some important differences. Future decreases in precipitation are projected by both studies, but the decrease in precipitation both for land and for sea from the 20 km resolution model is not as high (4% lower) as that predicted by the Mariotti study for the annual time scale. The seasonal cycle of precipitation, evaporation and precipitation minus evaporation over the land and sea areas of the Mediterranean region from these two studies is similar. In contrast, there are some significant differences between these two studies. For example, the water cycle change over the famous 'Fertile Crescent' is simulated quite well by the 20 km run compared with the coarser Mariotti model; and the summer seasonal cycle of precipitation from the 20 km run, which is larger than in the study by Mariotti, differs by a factor of about 2. The comparison of the water cycle over the water bodies of the western and the eastern Mediterranean shows that, for the current climate, the evaporation of the eastern Mediterranean is higher than that of the western Mediterranean with an average value of $0.4\,\mathrm{mm\,d^{-1}}$, with the opposite true for precipitation, i.e. less than in the WMS with an average value of $0.32\,\mathrm{mm\,d^{-1}}$. For the future, the evaporation increases over the eastern Mediterranean are higher than for the western Mediterranean, with average values of 0.45 and $0.22\,\mathrm{mm\,d^{-1}}$, respectively. The precipitation future decreases for the western Mediterranean are higher than those for the eastern Mediterranean, with average values of -0.21 and $-0.16\,\mathrm{mm\,d^{-1}}$. The change in precipitation minus evaporation ($P-E$) shows that the eastern Mediterranean becomes even drier than the western Mediterranean.

Results from the river model indicate that most of the rivers over the north Mediterranean region decrease their flow rate in the future. Further study of some key rivers that flow into the Mediterranean Sea shows that some rivers, such as the Ebro in Spain and the Maritsa in Turkey, become much drier in the future. Notably, the discharge of the Jordan River to the Dead Sea decreases by a very high value of 85 per cent projected by the model.

It can be concluded from these two studies that a drier climate transit might be inevitable over the Mediterranean by the end of the twenty-first century. Hence, a water crisis may become a big challenge in the future for the study area.

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