Chapter 9
The Projected Death of the Fertile Crescent

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Abstract Projections of rainfall and stream flow in the Mediterranean and the Fertile Crescent of the Middle East are presented here for the end of the twenty-first century. Up until recently, this has not been possible due to the lack of observed data and atmospheric models with sufficient resolution. An innovative super-high-resolution (20-km) global climate model is employed, which properly reproduces the moisture fields of the present-day climate over the study area. The model projected that the Fertile Crescent will lose its current shape and may disappear altogether by the end of this century. The annual discharge of the Euphrates River will decrease by 29–73 %, as will the stream flow in the Jordan River. Thus countermeasures for water shortages will become much more difficult.

9.1 Introduction

The Fertile Crescent is a region where ancient civilizations have developed. Population increases and intermittent dry spells in the region have resulted in agricultural innovations (Bellwood 2004). This region runs northwards from the Jordan Valley, through inland Syria, into southeastern Turkey (Anatolia), eastwards through northern Iraq, and finally southeastward along the Zagros foothills of western Iran. Prevailing climatic conditions during ancient times allowed the first rain-fed agriculture in human history. Winter rainfall and snow in high mountains in the north were the main sources of water. At present, however, most of this region requires irrigation systems to sustain agricultural production. Recent satellite images show that some of the vegetation in the fertile Mesopotamian marshlands has disappeared

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(National Geographic News 2001). The Middle East contains a heavily utilized water basin and relies upon transboundary rivers to recharge artificial reservoirs. Several counteracting international projects are underway (UNEP 2001) and the projections of future water availability are indispensable (Alpert 2004; Alpert et al. 2006, 2008; Samuels et al. 2010, 2011).

It is widely accepted that the global and regional-scale water cycle has been changing since the last century due to the accumulation of anthropogenic greenhouse gases and land use/land cover changes (IPCC 2007). The rise in the world's population (UNFPA 2005) has brought increases in water usage for food production, flood damage due to urbanization, water pollution, drought, and an increase in water demand (Vorosmarty et al. 2000). Water in the environment is an international problem because it is strongly related with the import and export of agricultural and industrial products as well as the economic and social well being of the area.

Multi-model climate change simulations for the twenty-first century showed a decrease in runoff in the Middle East of up to 30 % by 2050 (Milly et al. 2005; Mariotti et al. 2008). A 40 % decrease in the annual stream flow of the Euphrates River has also been projected (Nohara et al. 2006). However, the horizontal resolution of the climate models used for these projections (between 400 and 125 km) is not sufficient to resolve the topography in the Fertile Crescent. Thus far, only regional models have resolved the necessary topography (Evans et al. 2004). As the mountains are the source of the water that maintains the life and culture in this region, a high-resolution model that can accurately resolve topography is necessary to project future changes in water resources.

Recently, a global climate model with a horizontal grid size of about 20 km has been developed (Mizuta et al. 2006). The increased horizontal resolution allows this model to realistically represent the topography of the area. This enables us to project the hydrological impact of climate change, particularly over those water source regions containing steep mountains, such as in Eastern Turkey. The horizontal resolution of this model is even higher than that of most regional climate models used worldwide, thus orographic rainfall is represented well in this model at the regional scale (Yatagai et al. 2005). We are now entering a new era in which regional-scale climate information down to a 20-km grid interval is available without the use of regional models.

9.2 Model and Experiment

9.2.1 The General Circulation Model (GCM)

The atmospheric general circulation model (GCM) used in this study is a climate-model version of the Japan Meteorological Agency's (JMA) operational numerical weather prediction model. The simulations were performed at a triangular truncation 959 with linear Gaussian grid (TL959) in the horizontal. The transform grid uses 1920 by 960 grid cells, corresponding to a grid size of about 20 km. The model has 60 layers in the vertical with the model top at 0.1 hectopascal (hPa). A detailed description of the model is given in Mizuta et al. (2006). Mizuta et al. (2006) and Kitoh et al. (2008a) showed that modeled global distributions of the seasonal mean atmospheric circulation fields, surface air temperature, and precipitation agree well with the observations. Moreover, the model improves the representation of regional-scale phenomena. The results presented here are based on Jin et al. (2010) and Jin (2011).

It should be mentioned that there is little difference between the model used in Kitoh (2008a) and that in Jin et al. (2010) and Jin (2011). First, the time period for the present and future climate simulation is different. In Kitoh et al. (2008a), only a 10-year time span for the simulation was performed both for the present and the future climate study. In Jin et al. (2010) and Jin (2011), the time span is 29 years for the present (1979–2007) and 25 years for the future (2075–2099). Secondly, the future sea surface temperature (SST) used is different. In Kitoh et al. (2008a), the future SST from two climate models with different climate sensitivity, i.e. with moderate climate sensitivity (MRI-CGCM2.3.2, Yukimoto et al. 2006) and with high climate sensitivity (MIROC 3.2 (hires); K-1 Developers 2004). In Jin et al. (2010) and Jin (2011), the future SST changes are based on multi-models ensemble mean of Coupled Models Intercomparison Project Phase 3 (CMIP3) by the simulation of IPCC SRES A1B emission scenario.

9.2.2 The River Model

The river flow model used in this study is GRiveT (Global River flow model using TRIP), which was developed at MRI. The TRIP (Total Runoff Integrating Pathways) is a global river channel network in a 0.5-degree by 0.5-degree grid (Oki and Sud 1998). In the process of simulation, GRiveT distributes the runoff 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 runoff water to the river outlet along the river channel through TRIP. GRiveT does not account for any human consumption or natural losses of the river water.

9.3 Results

9.3.1 Future Changes of the Moisture Budget Components

Figure 9.1 shows the spatial distribution of the evaporation (E), precipitation (P) and P-E changes between the future (2075 to 2099) and the current climate (1979 to 2007). The evaporation's significant increase is clearly noticed over the water body with maximum values of 150–200, 200–250, and over 250 mm/season over the eastern Mediterranean, the Red Sea, and the Persian Gulf, respectively (Fig. 9.1).

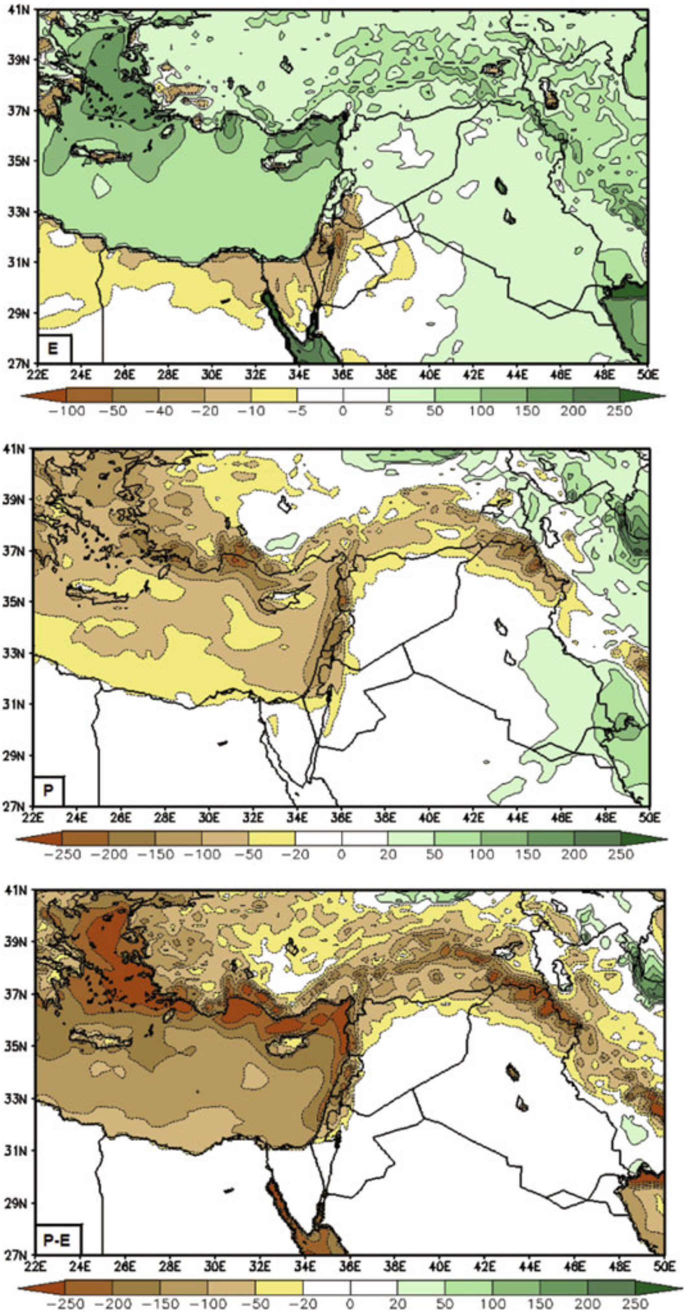

Fig. 9.1 Difference of seasonal (October-April) total evaporation (**E**), precipitation (**P**), and precipitation minus evaporation (**P-E**) between the future (2075 to 2099) and current (1979 to 2007) time periods in the 20-km global super high-resolution runs. Dashed contour lines indicate the negative changes, i.e. reduction in the future. The measurement is mm/season. (The figures follow Jin et al. 2010)

The center of the evaporation's increases in the eastern Mediterranean is located along the northern boundary with the magnitude of 150–200 mm. A slight increasing of evaporation over the Fertile Crescent can also be seen. A dramatic decreasing of evaporation is found over the Sinai Peninsula, Israel, and Jordan, with the maximum value exceeding 100 mm/season.

The precipitation differences show that the precipitation (P) of the entire eastern Mediterranean is decreasing with an average value of over 100 mm/season, with maximum precipitation decrease over the northern and eastern coastline areas of the eastern Mediterranean at a magnitude of above 250 mm/season (Fig. 9.1). 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. (2008a). Figure 9.1 suggests that the eastern coastline countries, i.e. Israel, Lebanon, and the western part of Syria will become much 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 precipitation increases is perhaps due to the fact that the increasing evaporation over the surrounding region generates more local-source moisture that becomes available over this area.

The total moisture budget represented by the precipitation minus the evaporation, P-E shows that the Red Sea and the Persian Gulf region will have a moisture deficit due to the increased evaporation in the future in spite of no change of precipitation over these areas (Fig. 9.1). This is an important result that is ignored in some studies that focus only on the rainfall changes. A completed Fertile Crescent strip is even clearer than that of the precipitation difference chart in further emphasizing the drying tendency in the future of this region.

9.3.2 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 necessary to examine the projected changes of the river discharges, though it has a close relation with the precipitation regime especially for those main rivers flowing into the Mediterranean Sea.

Figure 9.2 shows the changes in the runoff of the land precipitation and the changes in the river flow rates between future (2075 to 2099) and current (1979 to 2007) periods based on the MRI river model (Jin et al. 2010). Figure 9.2 shows a clear decrease of the runoff over the continent of the north Mediterranean region with a mean value of about $-10\,\mathrm{m}^3/\mathrm{s}$, which is primarily as a result of the decreasing precipitation over the region that was simulated by the 20-km model. As a consequence, the flow rates of most of the rivers in this area are decreasing (Fig. 9.2). It is interesting to note that the river model shows that the Nile River is increasing its flow rate in the future. This is probably due to the tropical area projected to be wetter as suggested by some studies, which is discussed also by Kitoh et al. (2008a).

In the moderate climate change run of Kitoh et al. (2008a), (future moderate, i.e., FM run), the projected decrease in precipitation is concentrated in the Mediterranean

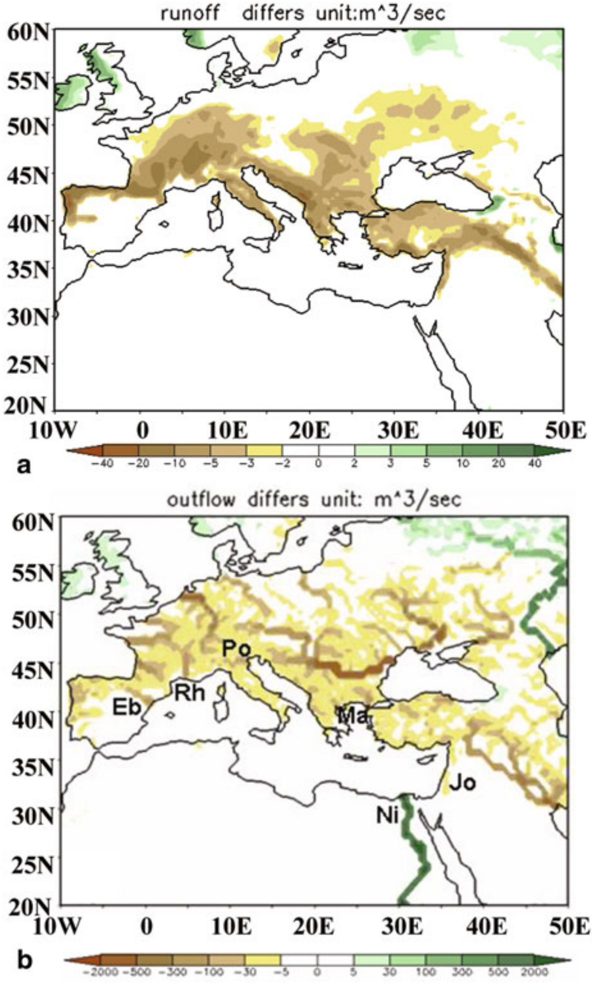

Fig. 9.2 Changes of runoff and river discharge by 2075–2099 as compared to 1979–2007 in terms of (**a**) runoff (**b**) river discharge. The six rivers are marked as Ebro (*Eb*), Rhone (*Rh*), Po (*Po*), Maritsa, Jordan (*Jo*), and Nile (*Ni*)

Sea and coastal areas of Southern Turkey, Syria, Lebanon, and Israel. This decrease in precipitation is mainly projected in the winter and spring. Annual precipitation is projected to increase in the future over the Caucasus Mountains and the gulf coastal region. This increase in precipitation is projected mainly in fall, thus detailed investigation is needed to clarify regional differences between the projected precipitation changes.

At the end of the twenty-first century, evaporation generally increases. Therefore, even in the areas where precipitation increases, an increase in evaporation may overcompensate for the increase in precipitation, leading to decreased surface runoff.

For this reason, trends in the stream flow are not always the same as that of the precipitation. Using the monthly runoff, simulated stream flow is calculated at 0.5-degree by 0.5-degree grids.

Figure 9.2 illustrates the simulated annual mean stream flow changes in the future. It shows that the stream flow decreases in most of rivers in the East Mediterranean region and increases in the Nile River and the Caucasus Mountain region. It also clearly illustrates that the annual stream flow is projected to decrease in the future in all rivers over the Middle East. Kitoh et al. (2008a) show that the annual discharge for the Euphrates River will decrease by 29 % in a moderate climate change and by 73 % in the higher climate change (FM & FH respectively there). In both runs, the decrease is largest during the high-water season. Percentage decrease in river discharge is larger at the Ceyhan River region in Turkey where the FM run projects 39 % decrease and the FH run projects 88 % decrease. Along this river, tremendous decreases in stream flow accompanied with greater warming demands a thorough countermeasure against agricultural and other uses of water in this southeast Turkey region. The situation is much worse in Jordan. Although uncertainty in projections is large in such a small drainage area, the modest warming case of the FM run projects an 82 % decrease. The high warming (and less precipitation) case (FH) projects that the stream flow will almost disappear throughout the year (98 % decrease). Since the water of the Jordan River is already a matter for high tension and conflict for the bordering countries (Alpert 2004), attention to this region is indispensable.

To further investigate the change of river discharge, several large rivers flowing into the Mediterranean Sea were selected (following Mariotti et al. 2008). 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, respectively. In addition, the Jordan River, as the only river that does not flow into the Mediterranean, was also selected in order to examine its change of flow rate and potential influence 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 some countries in the East Mediterranean, but also it has significant influence to the water balance of Dead Sea and plays a special role on life in this sensitive region.

Figure 9.3, following Jin et al. (2010), shows that except for the Nile River, a decreasing trend of monthly mean river discharges is found in the future. As can be seen in Table 9.1, a most dramatic decrease of river discharge is found for the rivers Ebro, Maritsa, and the Jordan River, as projected by the model. The decrease of discharge for the East Mediterranean rivers Maritsa and the Jordan River is particularly large, i.e., even over a half as compared to the current rate.

It should be mentioned that, compared to the observed data, the current simulation of the river discharge from the river model shows similar fluctuation patterns from month to month. For instance, the Ebro River has a peak in March/April and minimum in July/August. However, the results from the river model underestimate the flow rate by a factor of two compared with the observed data, except for the Nile River where the deviation is much larger. Possible explanations for this deviation might be due to the simplified river model, which relies on the estimation of the runoff and the still relatively coarse spatial resolution of the river model. This flow deviation can be reduced to some degree when we focus on the difference of the river discharge

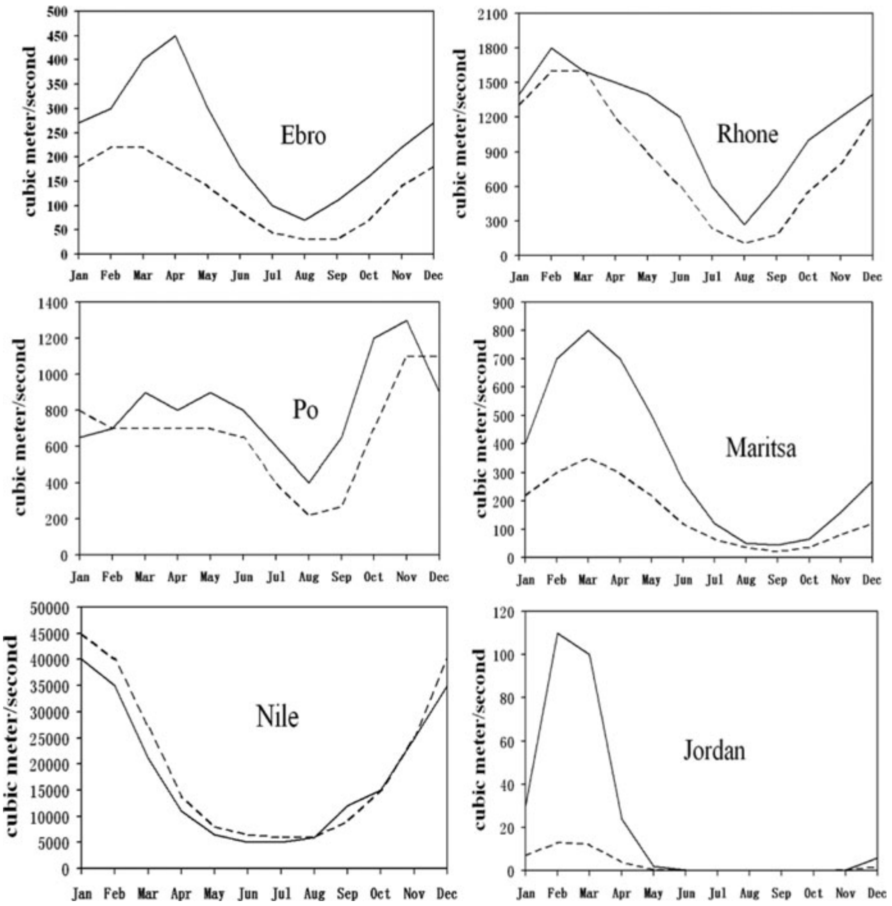

Fig. 9.3 Changes in monthly mean river discharge of six rivers by 1979–2007 compare to 2075–2099. Except to the Jordan River, all of the rivers flow into the Mediterranean. *Bold* lines are for current climate while *dashed* lines represent the future. (Jin 2011; Jin et al. 2010)

between the future and the current. An increasing trend of discharge with the value of about 2090 m^3/s was calculated only for the Nile. It should be also noted that the river model does not take into account any anthropogenic influences into the model consideration. Therefore, there are additional discrepancies for the river discharge between the model and observed result. For example, the river discharge for the Nile from the model is much higher than the observed data due to the huge Aswan dam that was constructed across the river in Egypt (Kitoh et al. 2008b). In addition, the Nile is the largest river that flows into the Mediterranean, and it has a crucial role in the balance of the river discharges in the region. 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 the model errors mentioned above, there are still numerous

Table 9.1 Changes in annual average discharge rates for large rivers that flow into the Mediterranean sea

River feeding the Mediterranean sea	Decreasing magnitude of discharge rates (m^3/s)	Percent of discharge reduction (%)
Ebro	108	46
Rhone	307	26
Po	146	18
Maritsa	184	54
Jordan	19	85

small rivers (over 20) over the European continent and isolated islands that flow into the Mediterranean, and all of those rivers were projected to have a decrease in their discharge (Fig. 9.2). The Mariotti et al. (2008) study also showed similar decreases of river discharges for some rivers based on the observed data. Therefore, a future water deficit is probably projected in the future over the Mediterranean. Moreover, researches have shown that the salinity of the Mediterranean is increasing steadily from the observed data even in the recent decades (Millot et al. 2006). These results might be due to the combined effect of decreasing of precipitation, increasing of evaporation, and the deficit water discharge in the Mediterranean region.

9.4 Discussion

This study clearly shows that the super-high resolution model simulates orographic rainfall very well. The 20-km mesh AGCM reproduces a regional maxima of rainfall along the coastal regions of the East Mediterranean and the Black Sea as well as along the south coast of the Caspian Sea. Lower resolution models used in climate projection studies, such as in Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report, show much smoother maximum of precipitation over the Caucasus Mountains (IPCC 2007). Precipitation over the Fertile Crescent region is also well reproduced by the 20-km mesh AGCM, with the local maxima of orographic rainfall along the Zagros Mountains (also in comparison to a new high resolution observed database over the Mid-East, Yatagai et al. 2008). Projected changes in precipitation also differ qualitatively between the 20-km mesh model and the lower resolution models. The run shows increased precipitation over the Caucasus Mountains and some parts of Gulf Coast states. These differences in precipitation resulted in stream flow changes in these regions. The current climate model projects decreasing precipitation in the Fertile Crescent region. Changes in stream flow will become more severe, which may result in substantial damage to rain-fed agriculture in the Mesopotamia area. Ancient rain-fed agriculture enabled the civilizations to thrive in the Fertile Crescent region, but this blessing is soon to disappear due to human-induced climate change. The fate of people in this politically vulnerable region depends on global management of the limited available water. Countermeasures have been planned for a long time, and global climate models that sufficiently represent the Fertile Crescent and project its future change can now be utilized for such purposes.

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