ISTANBUL TECHNICAL UNIVERSITY ★ EURASIA INSTITUTE OF EARTH SCIENCES

SUSTAINABILITY PROBLEM OF THE EUPHRATES - TIGRIS BASIN WATER RESOURCES UNDER A CHANGING CLIMATE

M.Sc. THESIS

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Department of Climate and Marine Sciences

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To my family and environmental lovers

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ABBREVIATIONS

ETB	**:** Euphrates - Tigris Basin
IPCC	**:** Intergovernmental Panel on Climate Change
GCM	**:** Global Climate Model
RCM	**:** Regional Climate Model
BCM	**:** Billion Cubic Meter
MCM	**:** Million Cubic Meter
CMIP	**:** Climate Model Intercomparision Project

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SUSTAINABILITY PROBLEM OF THE EUPHRATES - TIGRIS BASIN WATER RESOURCES UNDER A CHANGING CLIMATE

SUMMARY

The global and regional hydrological cycle can be affected by temperature changes in the coming years. In the regions where the water cycle depends on the snowmelt, these fluctuations can be more than other areas due to the effects of increasing temperature on snow cover and seasonal runoff. There are many studies about the consequences and threats of climate change on water sustainability and hydrological cycle around the world. However, the quantity and quality of the data that can be used in related studies has been affected by the insufficient measurement networks and trouble of upkeep of the accessible hydro-meteorological stations. Moreover, regional conflicts and local disputes can seriously complicate field survey in some of these regions. The Euphrates and Tigris River Basin (ETB) has been affected by climate change, and it suffers from all the aforementioned shortcomings. The ETB is a single transboundary watercourse system located in the Middle East. The basin includes two snow-fed rivers called the Euphrates and Tigris rivers, and its water recourses are used for different aims including domestic use, irrigation, hydroelectric power generation, etc. Turkey, Syria, Iraq and Iran are the main riparian countries in the ETB. These countries have started development projects in the basin since 1960s. In this sense, the Southeastern Anatolian Project (GAP) by Turkey has been started for agricultural and hydropower development in the region. These anthropogenic factors and increasing population, together with negative impacts of climate change, will cause mismatches between water demand and water supply in the basin. This study, by utilizing the outputs of GCM (Global Climate Model) and RCM (Regional Climate Model) simulations, aims to contribute to the understanding of future climate variations and their effects on the future of the water resource sustainability in the ETB. Annual time series of climate data provided by Royal Netherlands Meteorological Institute (KNMI) and Coordinated Regional Climate Downscaling Experiment (CORDEX) were used to determine the impacts of climate change in the ETB. In other words, outputs of GCMs and RCMs were used to understand the effects of the climate change on regional water budget in the future (periods of 2016-2035, 2041-2060 and 2081-2100) with respect to past climate (period of 1986-2005). Analysis of the changes in the hydrometeorological parameters (temperature, precipitation, evapotranspiration and net water flux output) were provided using the the outputs from the global and regional climate models based on the territories of the riparian countries in the ETB (i.e., Iran, Syria, Turkey and Iraq). Moreover, the changes in 10 climate indices based on riparian country territories in the ETB were analyzed using output of CMIP5 models for all three periods. These parameters include maximum length of dry spell (CDD), maximum length of wet spell (CWD), daily temperature range (DTR), number of tropical nights (TR), growing season length (GSL), annual total precipitation when daily precipitation >99th percentile

(R99pTOT), maximum consecutive 5-day precipitation (Rx5day), simple precipitation intensity index (SDII), warm nights index (TN90p) and warm days index (TX90p).

The most striking point is that increasing temperature which is more pronounced for 2081-2100 period may have profound implications for the snow cover and runoff in the basin. According to global and regional simulations, temperature in the whole Euphrates - Tigris basin increases. Simulations indicate 1 °C increase in surface temperature for 2016-2035 period whereas it is about 3°C and 6 °C for 2041-2060 and 2081-2100 periods, respectively. The consequence of this increase in temperature in the regional hydrological cycle is the reduction in snow cover and temporal shifts to earlier days in melting of snow in the highlands. In terms of precipitation, there is a wide harmony between the simulations, and it decreases up to 15% in Turkey and Syria for the 21 century. Precipitation in Iraq and Iran are projected to increase by 5% for 2016-2035 and 2041-2060 periods, whereas simulations produce a decrease by 15% for 2081-2100 period. Predicted changes in the evapotranspiration indicate generally increases in the basin for the early period in response to the increasing temperatures, however it decreases by the end of the century because of decreasing precipitation. Based on different experiments, the surface runoff is found to decrease about 10-50% in Turkey and Iran by the end of the 21st century. Surface runoff in Syria and Iraq also decreases by140% and 250%, respectively. Investigation of climate indices in the ETB indicates that climate extremes will become more intense in the future. Investigation of climate changes in the ETB based on the riparian country territories indicates that Turkey will undergo the most changes. The changes in the surface runoff is projected to be by 20-50% reduction in Turkey by the end of the present century. But down-stream countries, especially Iraq and Syria which are dependent on the water released by the upstream Turkey will experience more stress for the water crisis in the future. The climate change in the ETB may lead to other natural hazards such as salinization and desertification. The ETB has faced severe droughts in the past years. For instance, the severe drought in the winter of 2007 - 2008 had a big effect on the agricultural production in the region. The initiation of development projects by the riparian countries since 1960s which are uncoordinated with water availability in the ETB and crisis in water demand management and inefficient water policy of the riparian countries within the national framework are the main causes of water mismatch between supply and demand in the ETB. On the other hand, changes in hydroclimatic parameters can exacerbate water disputes in the region due to increased water demand and supply imbalance. Important solutions to this problem include coordinated regional actions and assessment of the factors for water allocation.

İKLİM DEĞİŞİKLİĞİ ŞARTLARI ALTINDA DİCLE-FIRAT HAVZASINDA SU KAYNAKLARININ SÜRDÜREBİLİRDİĞİ SORUNU

ÖZET

Küresel ve bölgesel hidrolojik döngü önümüzdeki yıllarda sıcaklık değişimlerinden etkilenebilir. Su döngüsünün kar erimesine bağlı olduğu bölgelerde, bu dalgalanmalar artan sıcaklığın kar örtüsü ve mevsimsel akış üzerindeki etkileri nedeniyle diğer alanlardan daha fazla olabilir. İklim değişikliğinin bu bölgelerde su kaynakları sürdürülebilirliği ve hidrolojik döngü üzerindeki etkileri hakkında birçok çalışma var. Bununla birlikte, ilgili çalışmalarda kullanılabilecek verilerin miktarı ve kalitesi, yetersiz ölçüm ağından ve erişilebilir hidro-meteoroloji istasyonlarının bakım sıkıntısından etkilenmiştir. Ayrıca, bölgesel çatışmalar ve yerel anlaşmazlıklar, bu bölgelerden bazılarında yapılan saha araştırmasını ciddi şekilde zorlaştırabilir. Orta Doğu'daki Dicle ve Fırat nehri havzası, iklim değişikliğinden çok etkilene bölgelerden biridir ve tüm bu eksikliklerden muzdariptir. Dicle ve Fırat nehri havzası, Ortadoğu'da bulunan tek sınır aşan su yolu sistemidir. Havzada Dicle ve Fırat nehirleri adında iki kar beslemeli nehir bulunmaktadır ve su kaynakları evsel kullanım, sulama, hidroelektrik enerji üretimi dahil olmak üzere farklı amaçlar için kullanılmaktadır. Türkiye, Suriye, Irak ve İran, havzadaki başlıca nehir kenarı ülkeleridir. Bu ülkeler 1960'lı yıllardan beri havzada kalkınma projelerine başlamıştır. Bu anlamda, bölgedeki hidroelektrik enerji ve tarımsal gelişim için Türkiye Cumhuriyeti tarafından Güneydoğu Anadolu Projesi (GAP) başlatılmıştır. Bu insan kaynaklı faktörler ve artan nüfus ile birlikte iklim değişikliğinin olumsuz etkileri, havzada su talebi ile su arzı arasında uyumsuzluğa neden olacaktır. Bu çalışmanın temel amacı, havzada iklim değişkenliğininin su kaynaklarının sürdürülebilirliğine etkilerini anlamak için GCM'lerin (Küresel İklim Modelleri) ve RCM'lerin (Bölgesel İklim Modelleri) simülasyonlarının çıktılarını analiz etmektir. Havzadaki iklim değişikliğinin etkilerini belirlemek için Hollanda Kraliyet Meteoroloji Enstitüsü (KNMI) ve Koordineli Bölgesel İklim Ölçeklendirme Deneyi (CORDEX) tarafından sağlanan yıllık iklim verileri kullanılmıştır. Diğer bir deyişle, GCM'lerin ve RCM'lerin çıktısı, geçmiş döneme (1986-2005) göre gelecekteki (2016-2035, 2041-2060 ve 2081-2100 dönemi) iklim değişikliğinin bölgesel hidroloji üzerindeki etkilerini anlamak için kullanılmıştır. Hidrometeorolojik parametrelerdeki (sıcaklık, yağış, buharlaşma ve akış) değişikliklerin değerlendirilmesi, ülkelerin (örneğin, Irak, İran, Suriye ve Suriye Türkiye) havzadaki alanlarına göre küresel ve bölgesel iklim modellerinden elde edilen çıktılar kullanılarak sağlanmıştır. Dahası, havzada nehir kenarı ülkelerinin sınırlarına göre 10 iklim indisindeki değişiklikler üç dönem boyunca CMIP5 verileri kullanılarak analiz edildi. Bu indisler beş günlük maksimum yağış (Rx5day), tropikal geceler sayısı (TR), sıcak günler yüzdesi (TX90p), ılık geceler yüzdesi (TN90p), basit yağış şiddet indisi (SDII), aşırı yağışlı günler yağışı (R99pTOT), büyüme dönemi uzunluğu (GSL), günlük sıcaklık aralığı (DTR), günlük sıcaklık aralığı (CDD) ve en uzun yağışlı dönem (CWD)'yi içerir. En çarpıcı nokta, 2081-2100 dönemi için daha belirgin olan sıcaklık artışının havzada

kar örtüsü ve kar erimesi ile oluşan akış için derin etkileri olabileceğidir. Küresel ve bölgesel simülasyonlara göre Dicle-Fırat havzasında sıcaklık artmaktadır. Simülasyonlar, 2016-2035 dönemi için yüzey sıcaklığında 1 °C'lik bir artış gösterirken, 2041-2060 ve 2081-2100 dönemleri için sırasıyla yaklaşık 3 °C ve 6 °C'dir. Bölgesel hidrolojik döngüde sıcaklıktaki bu artışın sonucu, kar örtüsünün azalması ve dağlık bölgelerde karların erimesinin zamansal olarak önceki günlere kaymasıdır. Türkiye ve Suriye'de yağış miktarının 21. yüzyılın sonuna kadar % 15'e kadar azalması yönünde simülasyonlar arasında geniş bir uyum vardır. Irak ve İran'da yağışların 2016-2035 ve 2041-2060 dönemleri için % 5 artacağı tahmin edilirken, 2081-2100 dönemi için %15 oranında azalması beklenmektedir. Evapotranspirasyonda öngörülen değişiklikler, dönem başında genel olarak artış ve büyük olasılıkla yağışta öngörülen değişikliklerle ilgili olarak yüzyılın sonuna kadar bölge'de artış şeklindedir. Farklı model simülasyonları yüzey akışının Türkiye ve İran'da 21. yüzyılın sonuna kadar yaklaşık %10-50 oranında azalacağını öngörmektedir. Suriye'de yüzeysel akış %140 ve Irak'ta %250 arasında düşüyor. Havzadaki iklim değişikliğinin nehir kıyı ülkeleri arasında en fazla Türkiye'yi etkileyeceği anlaşılmaktadır. Havzanın Türkiye kısmında yüzey akışının bu yüzyılın sonuna kadar %20-50 oranında azalması öngörülmektedir. Ancak aşağı ülkeler, özellikle de Türkiye'nin saldığı suya bağımlı olan Irak ve Suriye, gelecekte su kaynakları açısından daha fazla stres altında olacaktır. Havzada iklim değişikliği, tuzlanma ve çölleşme gibi diğer doğal tehlikelere de yol açabilir. Havza son yıllarda ciddi kuraklıklarla karşı karşıya kaldı. Örneğin, 2007 - 2008 kışında meydana gelen şiddetli kuraklık, bölgedeki tarımsal üretim üzerinde büyük bir etkiye sebep oldu. Öte yandan, hidroklima parametrelerindeki değişiklikler bölgedeki su uyuşmazlıkları ve arz-talep dengesizliği nedeniyle su uyuşmazlıklarını daha da kötüleştirebilir. Bu sorunun çözümü için bölgesel eylemlerin koordine edilmesi ve su tahsisi için faktörlerin değerlendirilmesi önemlidir.

1. INTRODUCTION

The global and regional hydrological cycle can be affected by temperature changes in the coming years (IPCC, 2007). In the regions where the water cycle depends on the snowmelt, these fluctuations could be more than other areas due to the effects of increasing temperature on snow cover and seasonal runoff (Stewart et al., 2005; Adam et al., 2009; Özdoğan, 2011; Sen et al., 2011). There are many studies about the impacts of climate change on water sustainability and hydrological cycle in such regions (Xu, 1999; Hayhoe et al., 2007; Sorooshian et al., 2008; Chenoweth et al., 2011). These areas are relatively least developed regions, and as a result, they are known as arguably the best places to understand the global climate change signal that is not affected by anthropogenic factors such as urban heat island effect (Sen et al., 2011). However, the quantity and quality of the data that could be used in related studies has been affected by the insufficient measurement network and trouble of upkeep of the accessible hydro-meteorological stations. Moreover, regional conflicts and local disputes can seriously complicate field survey in some of these regions.

The Euphrates and Tigris river Basin (ETB) in the Middle East is one of the regions that are being highly affected by climate change, and it suffers from all the aforementioned shortcomings (Kibaroğlu, 2015). Atmospheric and hydrological models are used to overcome problems related to the lack of data and hydrometeorological stations (Kavvas et al., 2011). These models are used to generate both historical analysis and projections on the future changes in different scales. Global Circulation Models (GCMs) are generally used in large-scale climate change impact studies. Their data are easily accessible by researchers and they are good tools for understanding future climate changes (Fujihara et al., 2008). On the other hand, the GCMs can provide valuable but limited information about the effects of climate change on water recourses at sub-regional scales. This is mainly due to their low spatial resolution, which could not resolve the structure of the earth's surface at the sub-regional scales (Bozkurt and Sen, 2013). Regional Climate Models (RCMs) with different emissions scenarios have been used in many studies to understand the impacts of climate change on water resources around the world (Wilby et al., 2000; Hay et al., 2002; Christensen et al., 2004). These models are one of the common tools to dynamically reduce the scale of GCM outputs and provide fine scale information.

The ETB is a single transboundary watercourse system located in the Middle East. The basin includes two snow-fed rivers naming the Euphrates and Tigris rivers and its water recourses are used for different aims including domestic use, irrigation, hydroelectric power generation, etc. Turkey, Syria, Iraq and Iran are the main riparian countries in the ETB. These countries have started the development projects in the basin since 1960s. In this sense, the Southeastern Anatolian Project (GAP) by Turkish Republic has been started for hydropower and agricultural development in the region. This project is the fourth largest irrigation project in the world, and it is also known as the largest investment for regional development in the history of Turkey. The riparian countries have different views about the allocation of water resources of the basin and this disagreement is likely to worsen in the coming years. The arid and semi-arid climate of the basin has contributed to these unfavorable conditions. The inherent characteristics of the prevailing climate has caused drought events in the basin. In addition, the effects of population growth and global climate change intensify water conflicts in the basin (Morvaridi, 1990; Unver, 1997; Kibaroglu and Unver, 2000; Altınbilek, 2004). Global climate change, caused by the increase in the concentration of greenhouse gases in the Earth's atmosphere, has become even more noticeable in recent years due to its major impacts on society and ecosystems. The reports of Intergovernmental Panel on Climate Change (IPCC, 2007) emphasized the role of anthropogenic factors in the increasing of concentrations of greenhouse gases. It would lead to variations in precipitation patterns and temperature changes in different parts of the world. The climatic factors affect the hydrological cycle, and any changes in these factors, especially in precipitation and streamflow, affect the quality and quantity of water resources. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007) discusses about the interaction between climate change and different aspects of hydrological cycles. According to this report, climate change and global warming are the main reasons behind the changes in the large-scale hydrological cycle such as; decreasing snow cover, changing patterns of precipitation, increasing atmospheric water vapor content, changing runoff and soil moisture, etc. Observed records and model-based climate projections indicate a lot of evidence that the consequences of climate change on freshwater resources can affect the ecosystems and human societies. Further information about the effects of climate change on different scales of hydrological cycles are available at Bou-Zeid and El Fadel (2002), Chen et al. (2007) and Loukas et al. (2007). These studies indicate a significant decreasing trend in precipitation and increasing trend in temperature over the past decades and highlight the problem of water shortages in different regions.

The effects of climate change scenarios on agricultural water consumption has been investigated by Mizyed (2009) for the West Bank in the eastern Mediterranean region. According to the results of this study, the agricultural water demand could be increased by up to 17 % due to increasing temperature, and the groundwater discharge could be reduced by up to 21%. Also, there are many studies related to the effects of climate change on water resources of Turkey. Fujihara et al. (2007) indicated the effects of decreasing precipitation and streamflow in the Seyhan river basin in the southern Turkey. Sen et al. (2011) used the streamflow data of 7 stations located in the Euphrates and Tigris river basin to indicate the significant changes in the snowmelt runoff in the basin. Their results indicated the effects of increasing temperature on the shifts of the timing of springtime snowmelt toward earlier times. A regional hydroclimate model was developed by Kavvas et al. (2011) to model water balance of the ETB from 1957 to 1969. This period was selected because it represents the period before the construction of large dams in the basin. Based on the results of this study, Turkey accounts for about 90% of the Euphrates and 46% of the Tigris flow origin. Akyurek et al. (2011) used MODIS snow product to analyze the snow cover area changes in the upper part of the Euphrates Basin in Turkey between 2000 and 2009. Their results didn’t show any significant change in the area of snow-covered parts. Ozdogan (2011) used a hydrological model and GCM outputs to investigate the effects of climate change on the variations of the water stored in snowpack in the ETB. The results of this study, especially under the A2 scenario, indicated 10 - 60% decline in the available snow water until the end of the 21st century. Furthermore, the regions in lower elevations will face with greatest changes. The results of Ozdogan (2011) emphasized on the negative effects of climate change on the water resources of the basin and increasing disputes among the riparian countries in ETB. Bozkurt et al. (2015) used global and regional climate models to analyze the effects of climate change on future discharges in the ETB. They concluded that the outputs of the RCMs were more accurate and better than low-resolution GCMs for reproducing the seasonal discharge cycle. Their results showed that the mean annual discharge for the ETB will decrease about 19-58% by the end of the century. Bozkurt and Sen (2013) used outputs of ECHAM5, CCSM3 and HadCM3 with different emissions scenarios including A1FI, A2 and B1 to determine the hydro-climatic impacts of future climate change in the ETB. Their results indicated that in contrast to increasing winter surface temperature in all parts of the basin, precipitation decreases in northern parts and highlands and it increases in the southern parts of the ETB. Accordingly, the annual surface runoff of the main headwaters area will face with substantial decline ranging between 25 and 55%.

1.1 Objectives and Hypothesis

Water has played a substantial role in the history and civilizations of the ETB especially Mesopotamia (the land located between the Euphrates and Tigris rivers). Lack of coordination between riparian countries has led to an intensification of the water crisis in the region. Climate change and human activities such as construction of several canals and dams for energy generation and agricultural development in the basin will lead to increasing evapotranspiration and decreasing runoff in the region. Ilisu dam on the Tigris river is the best example to illustrate the negative impacts of human activities in the basin. This dam has impacted the heritage of Hasankeyf, which hosts a unique habitat in the ETB (Sekercioglu et al., 2011). These anthropogenic factors and increasing population together with negative impacts of climate change will cause mismatches between water demand and water supply in the basin. Figure 1.1 and Table 1.1 indicate the water crisis in the basin as a result of human activities and climate change. According to Table 1.1, the demand for irrigation in Turkey will increase from 6.3 BCM to 19.5 BCM in the future and as a result, the remaining water will decrease from 20.07 BCM to 6.62 BCM. Therefore, Turkey will not be able to provide water for the downstream countries (Yilmaz et al., 2019).

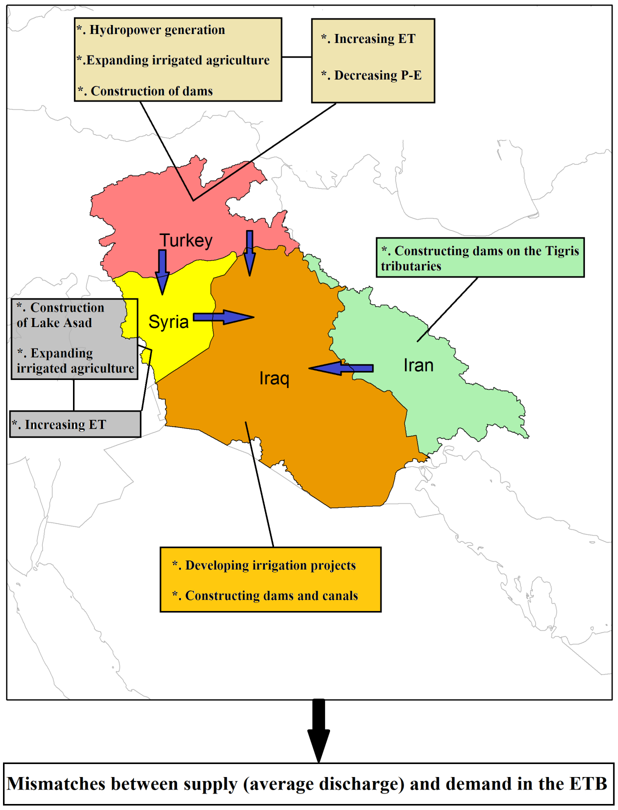

Figure 1.1: Problem diagram in the ETB due to climate change and anthropogenic factors.

The main objective of this study is to analyze the outputs of GCMs and RCMs scenario simulations to understand future climate change in the basin and its possible effects on the future of the water sustainability. The hypothesis of this study states that the ETB will face water availability and water sustainability problem in the future due to negative impacts of climate change in the region, and that water conflict will increase between riparian countires.

Table 1.1: Model-based estimations of mismatch between supply and demand in the ETB due to agricultural development in Turkey (Yilmaz et al., 2019).

	Present	**Future**
Available water (P-E)	26.37 BCM/y	26.12 BCM/y
Irrigation	6.3 BCM	19.5 BCM
Remaining water	20.07 BCM	6.62 BCM
Releasing water	15.8 BCM	15.8 BCM

2. MATERIALS AND METHODS

In this study, annual climatological time series data provided by Royal Netherlands Meteorological Institute (KNMI) and Coordinated Regional Climate Downscaling Experiment (CORDEX) were used to determine the impacts of climate change in the ETB. In other words, the outputs of GCMs and RCMs were used to understand the effects of changing climate on regional hydrology in the future. The KNMI Climate Explorer is a web application started in the 1999 to analyze climate data. Regional climate downscaling (RCD) techniques are used to provide high-resolution climate data from contemporary global climate models.

For a diagnostic study of changes in the ETB climate, this investigation used annual temperature, precipitation, evapotranspiration and net water flux time series output from various global circulation model simulations which are involving more than 40 climate models of CMIP5 (Table A.1) with RCP8.5 scenario for three 20-year periods in the future (2016-2035, 2041-2060, 2081-2100) with respect to a 20-year reference period of 1986-2005. This application comprises all of the model simulations and takes an average of these simulations. In this study, we consider the changes in the hydro-meteorological parameters for the four sections separated based on the riparian country borders.

Global Climate Models (GCMs) are used to provide reliable prediction information about natural hazards such as floods, droughts and other extreme events on very larges scales about 1000 by 1000 km covering different types of landscapes. Regional Climate Models (RCMs) driven by GCMs are used to provide detailed information over limited areas on much smaller scales. Both GCMs and RCMs are used in many vulnerable regions of the world for natural disaster planning and crisis management. For these reasons, in addition to global climate model output analysis, this study provided assessments of the changes in hydrometeorological parameters (temperature, precipitation, evapotranspiration and net water flux output) using the outputs from the regional climate models based on the country territories in the ETB (i.e., Iraq, Iran, Syria and Turkey). The RCM dataset is provided from the output of

18 climate models (Table A.2) - emissions scenario (RCP8.5) simulations. These data are in three 20-year periods (2016-2035, 2041-2060, 2081-2100) with reference period of 1986-2005. The mean of simulations (total 18) enables an analysis taking into account the RCP8.5 emission scenario simulations for four different riparian countries.

This research has also assessed the changes in 10 climate indices based on riparian country borders in the ETB using the CMIP5 climate model outputs for all three periods. These parameters include CDD, CWD, DTR, TR, GSL, Rx5day, SDII, R99pTOT, TN90p and TX90p.

3. STUDY AREA

The Euphrates and Tigris River Basin is a large transboundary basin that covers an area of about 800,000 km^2 in five countries, Iraq (46%), Turkey (22%), Iran (19%), Syria (11%), Saudi Arabia (1.9%) and Jordan (0.03%). Iran is a stockholder only to the Tigris, and Jordan and Saudi Arabia are stockholders only to the Euphrates (Bozkurt and Sen, 2013; Kibaroğlu et al, 2017). The ETB is known by the two long rivers that mainly fed by winter snow. The Euphrates river with 2700 km length is the longest river and the Tigris river with 1840 km length is the second longest river in the Middle East. In the eastern highlands of Turkey Karasu and Murat rivers are joining together in Kharput in Turkey to form The Euphrates River at their confluence. The Tigris River originates in the Taurus Mountains in Turkey near Lake Van, south of the Anatolian Highlands and the city of Elazig. It is formed by the confluence of two headwater tributaries, the Batman and the Botan (Bozkurt and Sen, 2013).

Nearly 90% of the runoff belonging to the Euphrates is originated within the highlands of eastern Turkey, with the remaining 10% contribution coming from the Syria. Turkey provides almost 40% of the flow of the Tigris while the rest of its flow is provided by tributaries from Zagros Mountains of Iran and Iraq. The average annual discharge of the Euphrates is 32 BCM, whereas that of the Tigris and its tributaries is 50 BCM. Due to natural climate characteristics in the basin, a significant part of the water flow in the rivers evaporates and increases water salinization and water loss in major reservoirs in the three riparian countries. The rivers in the long run merge at the Shatt al-Arab and finally flow into the Persian Gulf (Yurekli, 2015). But both rivers are linked together by building several canals in Iraq before joining in Shatt al-Arab. Climatic and topographic conditions are not the same throughout the Euphrates and Tigris basin but an important characteristic of the basin is high mountainous topography especially in the north and east, elevation mostly exceeding 2000 m. Figure 3.1 indicates the location map of the Euphrates and Tigris rivers in the basin.

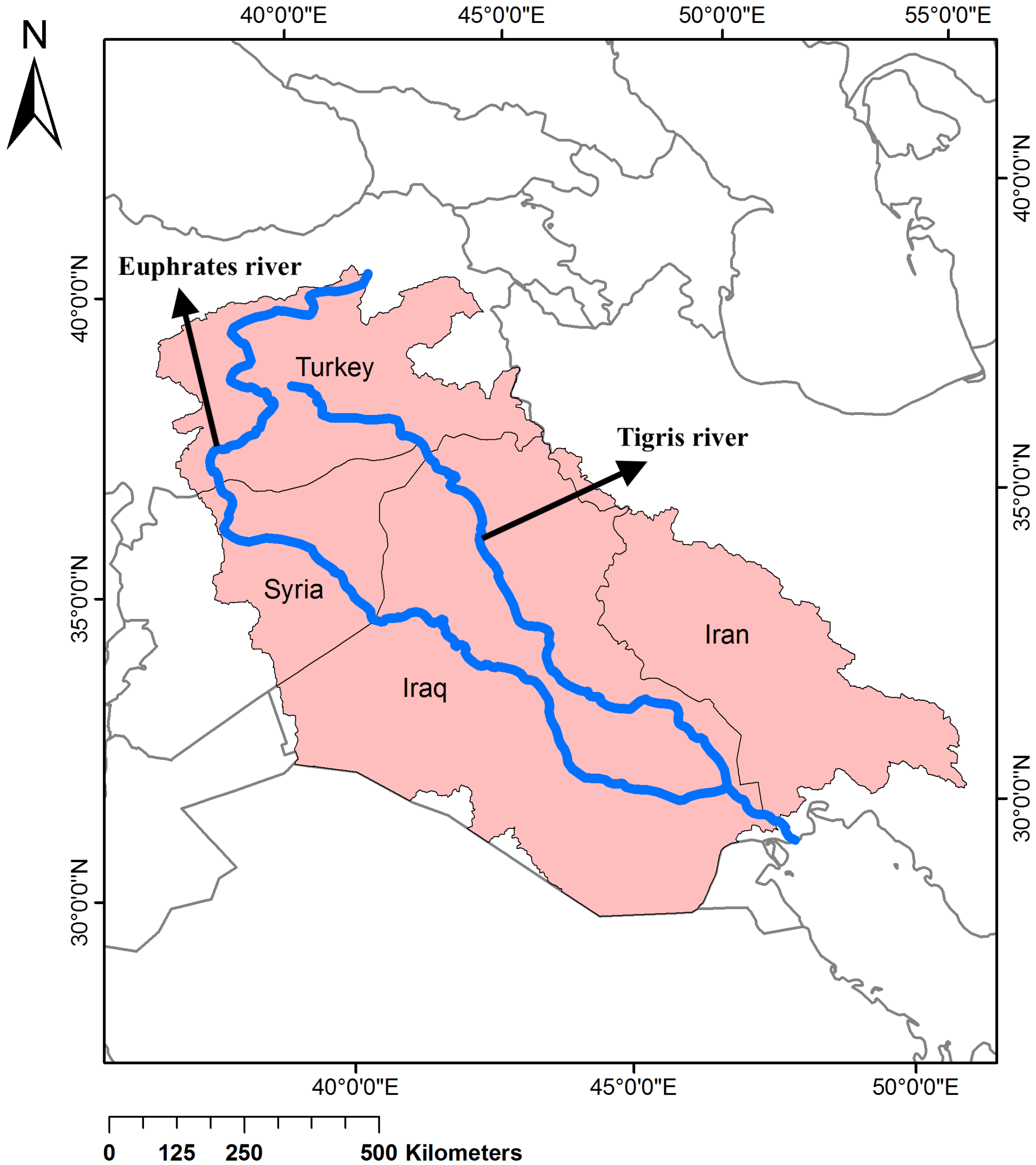

Figure 3.1 : Map of the Euphrates and Tigris rivers in the ETB

There are extensive lowlands in the south and east of the basin. The rivers flow on their route southward from the highlands of eastern Anatolia in Turkey, the Syrian valleys and the Iraqi plateaus, and then they enter the arid plain of Mesopotamia (Bozkurt and Sen, 2013). The ETB climate is mostly subtropical Mediterranean climate. The winters are damp and the summers are dry. The annual average temperature in the basin ranges between 20 °C and 9 °C (Bozkurt and Sen, 2013). Average minimum air temperature of the basin is about 5 °C - 11 °C in January and mean maximum temperature of the basin is between 31 °C and 37 °C in July (Bozkurt and Sen, 2013). Precipitation, which forms the main source of water of the two rivers in the Euphrates and Tigris basin, is often in the form of snow over the highlands of the basin and often occurs in winter and in the months of October to April. Winter snowfall remains solid at highlands until they begin to melt as the temperature rises up in the spring and early summer (Yurekli, 2015). The average annual precipitation in the basin is about 335 mm and it varies across the basin area (Bozkurt and Sen, 2013). The annual precipitation in Mesopotamian is above 200 mm and it reaches to 1045 mm in other places of the basin. About 23 million people live in the Euphrates basin. Iraq, Syria and Turkey contain 44%, 25% and 31% of this population, respectively. The total population of the Tigris basin is approximately 23.4 million. Only 50,000 people live in the Syrian part of the basin and Iraq, Turkey and Iran contain 18 million, 3.5 million and 1.5 million of the remaining population, respectively.

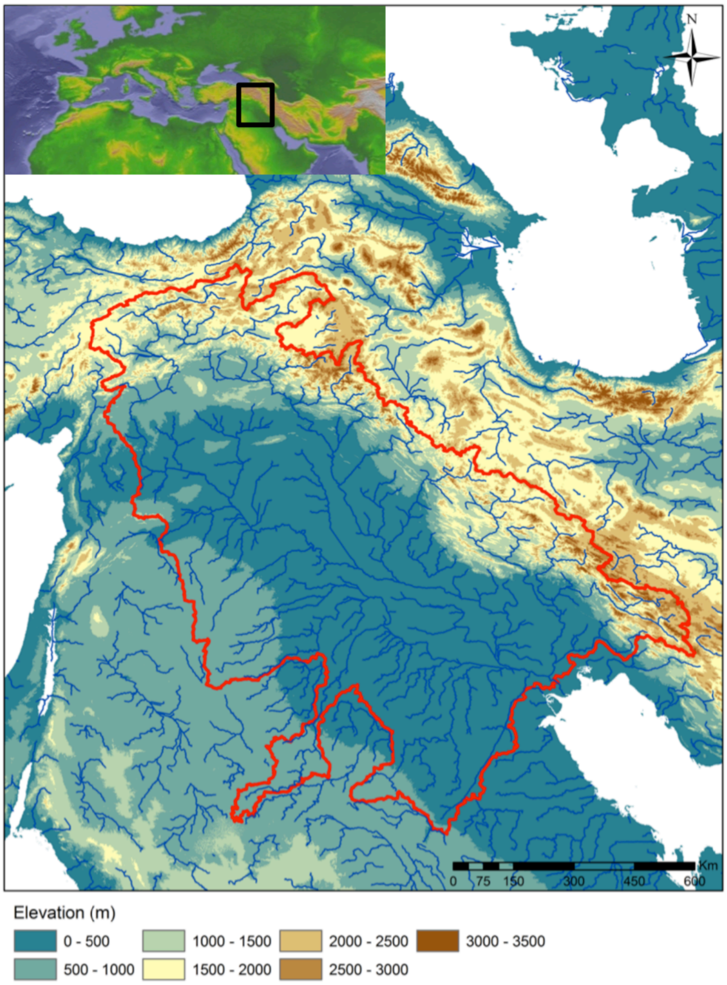

Figure 3.2: Map of the ETB on digital elevation map derived from GTOPO30, Global 30 Arc-Secon Elevation Data (Bozkurt et al., 2014).

The Khabour, Sajur and Balikh rivers originated from Syria are the main contributors of Euphrates flow while the most part of Tigris flow depends on the numerous tributaries originated from Zagros Mountatins. The Southeastern Anatolian Project (GAP), a 30-billion-dolar investment in Turkey, is known as one of the largest agricultural development projects in the world, which affects the water availability and sustainability in the basin. Euphrates and Tigris rivers are the essential parts of this project and Turkey aims to generate energy and develop agricultural lands in southeastern Turkey via constructing 22 dams and 19 hydropower plants (SAPRDA, 2009). On the other hand, Iraq has constructed many dams and diversion projects on the Tigris such as Tharthar Canals between the Euphrates and Tigris. These human activities in the ETB have led to international disputes between riparian countries over water use and availability. Figure 3.2 shows the map of ETB on digital elevation map derived from GTOPO30, Global 30 Arc-Secon Elevation Data (Bozkurt, 2014).

4. WATER RESOURCES MANAGEMENT IN THE ETB

Water management in the Euphrates Basin started about 6000 years ago, when the the irrigation networks changed the Mesopotamian landscape for agricultural development in the region. In the 20th century, the basin faced with many plans such as building new dams and reservoirs for agricultural development, drinking water supply and generation of electricity (Table 4.1). Agricultural sector accounts for more than 70% of water consumption in the basin (FAO, 2009; UN-ESCWA and BGR, 2013). The natural flow regime on the river in the upper basin has been affected by Southern Anatolia Project over the past decades (Sahan et al, 2001; UN-ESCWA and BGR, 2013). The natural annual flow volume of Euphrates river is about 30 BCM, while the maximum storage capacity of the major reservoirs and dams on the river is more than 144 BCM.

The Tigris Basin has witnessed with many water resources development schemes like the Euphrates basin. Many diversion structures and major dams with a maximum capacity of 116.5 BCM have been built in the Tigris Basin to serve multiple purposes since the 1930 (Table 4.2).

Turkey has dramatically affected water rosurces in the ETB by starting new water exploitation projects and changing the natural flow regime in the ETB since the 1970s. The Keban dam was the first large water exploitation project of Turkey on the Euphrates. The Karakaya dam was the first dam of GAP, which was compeleted in 1987. After that, The Ataturk dam was built in 1992. The Birecik and Karkamis dams were the other dams, which were constructed on the Euphrates river as a part of GAP. In total, 11 hydroelectric power plants and 14 dams were built on the Euphrates and its tributaries as part of GAP. These human-induced activites made the upper Euphrates as the largest part of GAP (Sahan et al., 2001; UN-ESCWA and BGR, 2013).

Figure 4.1 indicates the Euphrates river basin and the location map of water exploitation projects in this basin (UN-ESCWA and BGR, 2013).

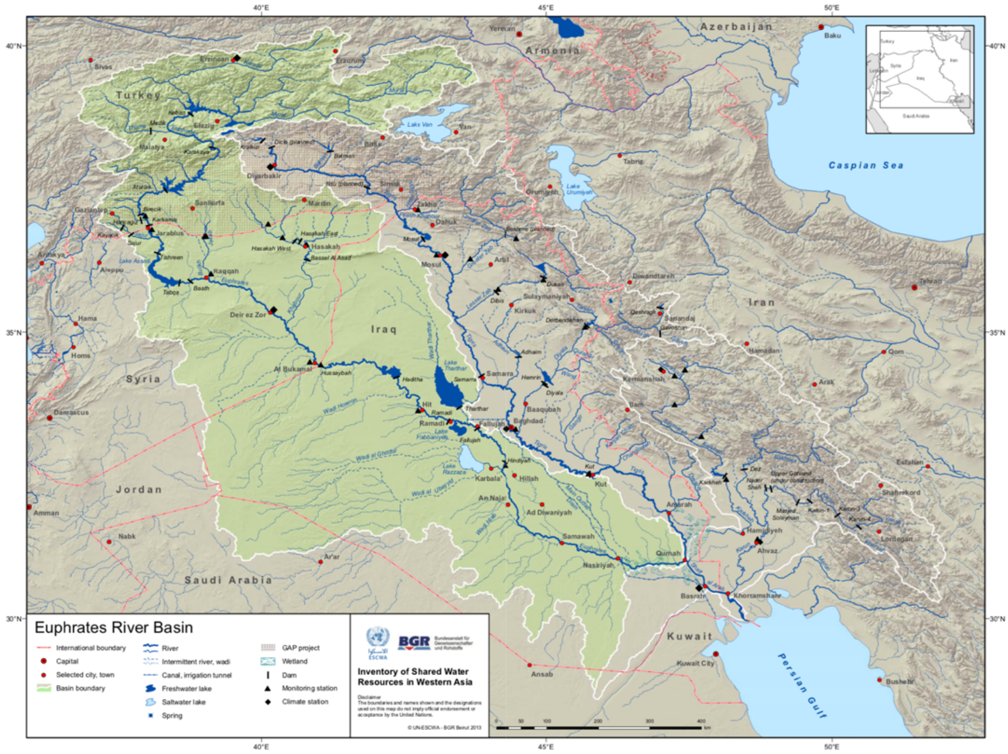

Figure 4.1: Euphrates River Basin and water exploitation projects in this basin (UN-ESCWA and BGR, 2013).

The geographic conditions of Tigris river basin in Turkey made it difficult to be exploited and the water resources management projects in Tigris basin were developed after Euphrates basin. In total, 8 hydroelectric power plants and 8 large dams were built on the Tigris river basin as part of GAP. In order to flow regulation in Tigris river basin, Turkey plans to establish a reservoir system on the upper Tigris river. Ilisu dam project generates about 1200 MW hydroelectric power and is at the center of this project.

Turkey plans to develop agricultural activities along with hydropower generation, especially in southeastern Anatolia. GAP aims to irrigate the area of about 1.8 million ha using water resources in the ETB. At present time, about one third of these irrigated lands (600,000 ha) is operational (Yilmaz et al., 2019). The Ataturk dam uses the Urfa tunnels to provide water to irrigate Urfa-Harran agricultural development project.

Syria started water exploitation from Euphrates basin by establishment of Tabqa dam (Euphrates) in the 1970s. The country developed major agricultural development plans along the Euphrates river (UN-ESCWA and BGR, 2013). This dam has an important role in providing enery needs and development of irrigated lands in Syria.

Table 4.1: Main dams and barrages on the Euphrates river in chronological order of construction (UN-ESCWA and BGR, 2013). Irrigation (I), Hydropower (HP), Flow Diversion (FD) and Flood Control (FC).

COUNTRY	NAME	COMPLETION YEAR	CAPACITY (MCM)	PURPOSE	BACKGROUND INFORMATION
Iraq	Hindiyah	1914	-	I, HP	This regulator was built in the Euphrates Basin when Iraq was a part of the Ottoman Empire. It was the first modern water diversion structure and the old structure was replaced by the new one in the 1980s. This regulator is used to produce electricity too.
Iraq	Ramadi	1948	3,300 (Lake Habbaniyeh)	FC, I	This barrage is used to regulate the Euphrates flow regime using the Warrar Regulator. The Warrar Regulator is used to discharge excess flood water into the Lake Habbaniyeh. The stored water in the lake is diverted to Lake Razzaza or released back to the Euphrates. The Mujarra Regulator (constructed in 1957) is used to divert the stored water.
Turkey	Keban	1974	31,000	HP, FC	Reservoir area: 675 km^2
Syria	Tabqa	1975	14,000	HP, I	The other names of this dam are Euphrates dam or Revolution dam. This dam is the largest earth-fill dam around the world. This dam aims to provide irrigation water and produce hydropower.
Iraq	Fallujah	1985	-	FD, I	This dam was built next to the riverbed to store the Euphrates river water.
Iraq	Haditha (Al Qadisiyah)	1987	8,280	FC, I, HP	This dam was jointly built with the Soviet Union. Lake Qadisiyah with an area of about 500 km^2 was created using this 10 km-long earth fill dam.
Syria	Baath	1987	90	HP, FC	This dam is used to regulate water flow from the Tabqa dam and generate electricity.
Turkey	Karakaya	1987	9,580	HP	This dam with an area of about 268 km^2 is a part of GAP.
Turkey	Atatürk (Originally Karababa	1992	48,700	HP, I	This dam is known as one of the largest dams around the world and it is the third-largest lake in Turkey. It is located about 80 km far from the Syrian border. It is the main water reservoir for developing GAP in Turkey. The Atatürk dam with a maximum capacity of 48,700 MCM can store the entire annual discharge of the Euphrates. Turkey started to fill this dam in 1990.
Syria	Tishreen	1999	1,900	HP	-
Turkey	Karkamis	1999	160	HP, FC	This dam, which is part of GAP, is located 4.5 km far from Syrian border.
Turkey	Birecik	2000	1,220	HP, I	This dam with an annual average capacity of 2,500 GWh is used to produce hydroelectric power.

The establishment of the Tabqa dam led to the construction of Lake Assad, which is the largest water reservoir in Syria and irrigates an area of about 640,000 ha (UN-ESCWA and BGR, 2013). The Baath dam, which is the third-largest dam on the

Euphrates river in Syria, was built in 1987. This dam regulates flow from the upstream Tabqa dam. The Tishreen dam was established in 1999 to generate hydropower. Syria developed many projects such as Great Khabour Irrigation project in the Euphrates basin for irrigation. In total, three dams were established in the Great Khabour Irrigation project on the Khabour river to provide water for irrigation and generate hydropower. Syria is a minor Tigris riparian country and the Tigris river crosses from a small part of the Syrian-Turkish border. The country uses the Tigris river for demostic use and development of small-scale agricultural lands. The country started to exploit water from Tigris river using an irrigation project in 2010.

Table 4.2: Main dams on the Tigris River in chronological order of construction (UN-ESCWA and BGR, 2013). Irrigation (I), Hydropower (HP), Flow Water Supply (WS) and Flood Control (FC).

COUNTRY	NAME	COMPLETION YEAR	CAPACITY (MCM)	PURPOSE	BACKGROUND INFORMATION
Iraq	Kut	1939	-	I	This barrage was built in the city of Kut for agricultural development.
	Tharthar (Samarra Barrage)	1954	85,000	FC, I, HP	This barrage diverts flood water to Lake Tharthar using a 64 km canal. Then, a 37 km canal with a capacity of 550 m^3/s is used to convey the water to the Euphrates. The area of this reservoir is about 2,400 km^2 and the estimated evaporation from it is about 2.86 km^3/yr.
	Mosul (Chambarakat, formerly Saddam Dam)	1985	11,100	HP, FC, I	This dam is the largest dam of Iraq, located near Mosul. It is used to produce electricity for about 1.7 million people in Mosul.
Turkey	Goksu	1991	600	I	This dam is used to irrigates an area of 3,582 ha (Cinar-Goksu Irrigation Project).
	Kralkizi	1997	1,900	HP	Hydropower capacity: 90 MW
	Tigris (Dicle)	1997	6,000	HP, I, WS	Hydropower capacity: 110 MW Projected irrigated area: 128,080 ha
	Batman	1999	1,200	I, HP, FC	Hydropower capacity: 198 MW Projected irrigated area: 37,744 ha
	Garzan	-	-	HP, I	Hydropower capacity: 89 MW Projected irrigated area: 60,000 ha
	Ilisu	2018	10.41	HP, I, FC	Planned hydropower capacity: 1.200 MW

Based on the agreement between Iraq and Syria in 2002, Syria was authorized to pump annually 1,250 MCM water from the Tigris river (Kibaroglu et al., 2008; UN-ESCWA and BGR, 2013). This water is used to develope irrigated lands and generate hydroelectricity. An inter-basin water transfer has been used to irrigate about 150,000 ha in Hasakah Governorate in the upper part of the Khabour basin (UN-ESCWA and BGR, 2013).

Iraq developed engineering projects in the Euphrates basin as a first riparian country. This country was the main user of Euphrates river before the development of water exploitation projects in Turkey and Syria. The area of irrigated lands in this country was more than 5 times of the irrigated lands in Syria and about 10 times of irrigated lands in Turkey (UN-ESCWA and BGR, 2013). However, these projects have been affected by Turkish and Syrian irrigation projects since 1960s. The Ramadi-Razzaza Regulator and Hindiyah dam were established in Iraq for agricultural development via canal systems and flood prevention. Iraq also constructed the Haditha dam, with a maximum capacity of 8.2 BCM on the Euphrates river in 1987. Furthermore, Iraq developed many water exploitation projects such as network of canals on the Euphrates to transfer water from the Euphrates to other reservoirs like Lake Tharthar and Lake Habbaniyeh for various purposes.

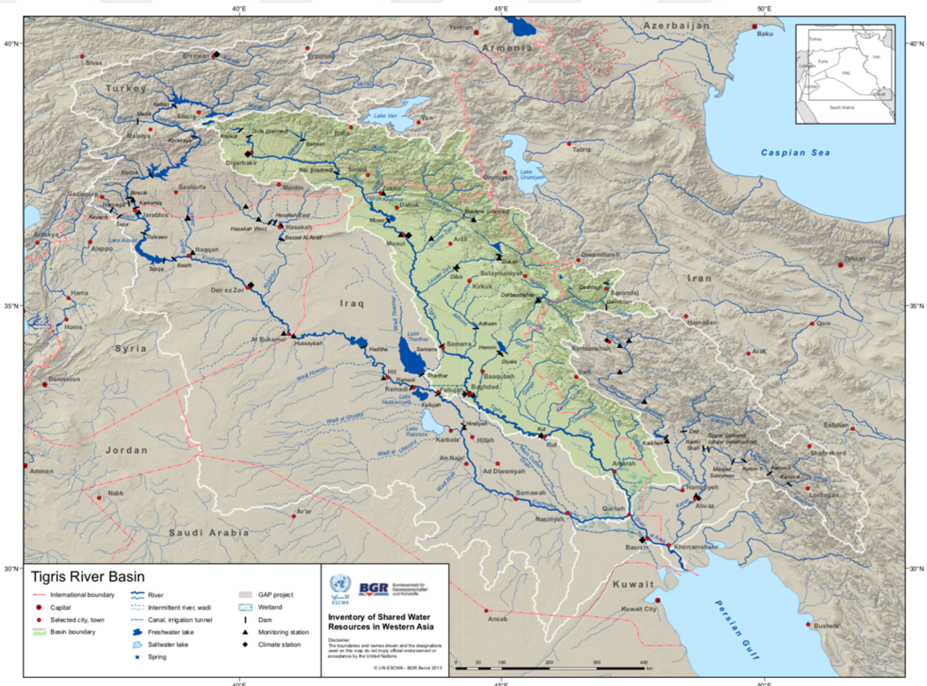

Figure 4.2: Tigris River Basin and water exploitation projects in this basin (UN-ESCWA and BGR, 2013).

Figure 4.2 shows the Tigris River Basin and water exploitation projects in this basin (UN-ESCWA and BGR, 2013). Kut Barrage and Tharthar System Barrage, started in 1939 and 1956, respectively, were the first engineering projects of Iraq in the Tigris basin. Iraq built regulating structures and reservoirs such as the Derbendikhan dam on the Diayal, Dukan and Dibis dams on the Lesser Zab on the eastern tributaries of the Tigris between the 1960s and 1980s. Mosul dam was another water reservoir which was built in 1985. This dam, which is one of the largest dams in Iraq, is used for a various of purposes including hydropower generation, irrigation and flood control (Table 4.2). The Tharthar Canal is the main factor of developing water resources systems in Iraq.

This canal connects the Tigris to the Euphrates and it solves the problem of water shortages in the Euphrates basin by transferring water from the Tigris river to the Euphrates river. The capacity of Lake Tharthar in Iraq is twice the capacity of Atatürk dam in Turkey.

5. COUNTRY BASED ANALYSIS OF CLIMATE CHANGE IN THE BASIN

The water availibity will be affected greatly by climate change and human activities in the arid and semi-arid regions around the world. In the ETB water availability and sustainability are the most important issues for the riparian countries. Therefore, a country-based analysis was performed in this study to investigate the changes in the hydroclimatic parameters including temperatue, evapotranspiration, precipitation, surface water and climate indices. The country borders were determined in the basin and projected annual temperature, evapotranspiration, precipitation, surface runoff and climate indices of four countries including Turkey, Iraq, Syria and Iran were calculated and compared based on the GCMs and RCMs outputs for three periods including 2016-2035, 2041-2060 and 2081-2100.

Table 5.1 gives the projected changes of annual temperature, evapotranspiration, precipitation and net water flux in the ETB based on the riparian country territories. The temperature increases in all countries, while precipitation generally decreases in the basin. Annual evapotranspiration initially increases in the basin in response to increasing temperatures. Towards the end of the century, however, it tends to decrease in response probably to decreasing precipitation. The net water flux in Turkey indicates a significant decreasing trend due to increase in temperature and decrease in precipitation. In the other three countries net water flux also decreases by the end of century.

5.1 Temperature

The regional hydrological cycle can be affected by temperature changes over the mountainous areas. Increasing temperature in these regions causes decreasing snow cover and temporal shifts in snowmelt surface runoff timing. Furthermore, it affects the climate dynamics of the region by disrupting snow-albedo feedbacks in the regional-scales.

Table 5.1: Annual values of reference period (1986-2005) and percentage or amount of changes for future periods (2016-2035, 2041 2060 and2081-2100) for temperature, evapotranspiration, precipitation and net water flux in the ETB based on the riparian countries includingTurkey, Syria, Iraq and Iran.

Parameter	Dataset	Turkey				Syria				Iraq				Iran			
		1986-2005	2016-2035	2041-2060	2081-2100	1986-2005	2016-2035	2041-2060	2081-2100	1986-2005	2016-2035	2041-2060	2081-2100	1986-2005	2016-2035	2041-2060	2081-2100
		Actual value	Percentage /Amount change	Percentage /Amount change	Percentage /Amount change	Actual value	Percentage /Amount change	Percentage /Amount change	Percentage/ Amount change	Actual value	Percentage /Amount change	Percentage /Amount change	Percentage /Amount change	Actual value	Percentage /Amount change	Percentage /Amount change	Percentage /Amount change
Temperature (Celsius)	CMIP5	12.365	1.237	2.691	5.339	19.891	1.198	2.612	5.236	21.377	1.212	2.692	5.407	14.786	1.212	2.686	5.436
	CORDEX	8.607	1.441	3.022	6.131	18.603	1.253	2.633	5.369	21.443	1.345	2.801	5.712	15.186	1.482	3.031	6.088
Evapotranspiration	CMIP5	422.045 mm/yr	1.138%	-1.093 %	-7.34%	124.608 mm/yr	-0.212%	-2.4%	-9.789%	187.478 mm/yr	3.292%	2.45%	-0.223%	326.615 mm/yr	2.527%	2.972%	-0.437%
	CORDEX	428.889 mm/yr	4.411%	5.147%	5.147%	182.908 mm/yr	0%	-8.620%	-13.793%	167.140 mm/yr	1.886%	-1.886%	-3.773%	321.667 mm/yr	2.941%	0%	0%
Precipitation	CMIP5	538.751 mm/yr	-0.821%	-5.395%	-14.587%	123.193 mm/yr	-0.285%	-2.887%	-11.329%	190.025 mm/yr	4.079%	2.309%	-0.859%	384.764 mm/yr	2.3386%	1.381%	-2.045%
	CORDEX	706.406 mm/yr	0%	-6.696 %	-13.839%	192.369 mm/yr	0%	-13.114%	-18.032%	170.294 mm/yr	1.851%	-7.407%	-11.111%	441.504 mm/yr	0.714%	-5.714%	-11.428%
P-E, Net Water Flux	CMIP5	117.794 mm/yr	-10.03%	-25.38%	-47.44%	1.199 mm/yr	-12.94%	-20.58%	-31.39%	2.453 mm/yr	-19.55%	-10.82%	-10.62%	60.310 mm/yr	6.3%	-4.06%	-8.64%
	CORDEX	277.516 mm/yr	-7.954%	-23.863%	-43.181%	9.460 mm/yr	-33.333%	-100%	-133.333%	6.307 mm/yr	0%	-100%	-250%	119.836 mm/yr	-7.894%	-23.684%	-39.473%

Figure 5.1a shows bar plot analysis of annual mean temperature changes in the Euphrates-Tigris basin based on riparian country territories for the three period of 2016-2035, 2041-2060, 2081-2100 relative to the reference period of 1986-2005. The bar plots were formed by averaging the output of GCMs within each countries. Mean temperature increases are between 1 and 6 °C (Table 5.1) for the entire basin. There is a striking change in temperature for the three periods, especially for the end of century. However, although the CMIP5 dataset is treated as more reliable to assess the climate changes as it possesses more model simulations, this dataset might have poor representation of main climate variables because of low spatial resolution which do not adequately resolve the structure of the earth's surface at these scales. Therefore, in addition to analysis of this dataset a regional dataset that has higher spatial resolution was used. Figure 5.1b demonstrates the annual mean temperature changes from CORDEX dataset. As it is observed in CMIP5, mean temperature in the whole basin indicates a striking increase (between 1-6 °C) in the three future periods relative to the reference period. The most striking point is that increasing temperature, which is more pronounced for the 2081-2100 period, may have profound implications for the snow cover and snowmelt runoff in the Turkey because the snow-covered mountains are mostly located in the main headwaters of the basin.Figure 5.2 shows the projected mean surface temperatures for each country in the ETB. The annual mean temperature in Turkey ranges between 10-15 °C which is lower than lowland riparian countries. The annual mean temperature is about 15-20 °C for Iran and about 20-25 °C for Syria and Iraq. In general, there is a broad agreement in the changes among the simulations, which indicates increase in the temperature in all four countries of the ETB.

5.2 Evapotranspiration

Figure 5.3a shows the annual mean evapotranspiration changes in the Euphrates-Tigris basin based on CMIP5 dataset for the three periods of 2016-2035, 2041-2060, 2081-2100 relative to the reference period of 1986-2005. Annual evapotranspiration amount changes in the basin ranges between -10% and %5 (Table 5.1), which usually indicate an increase in the earlier period and a decrease in the later periods.

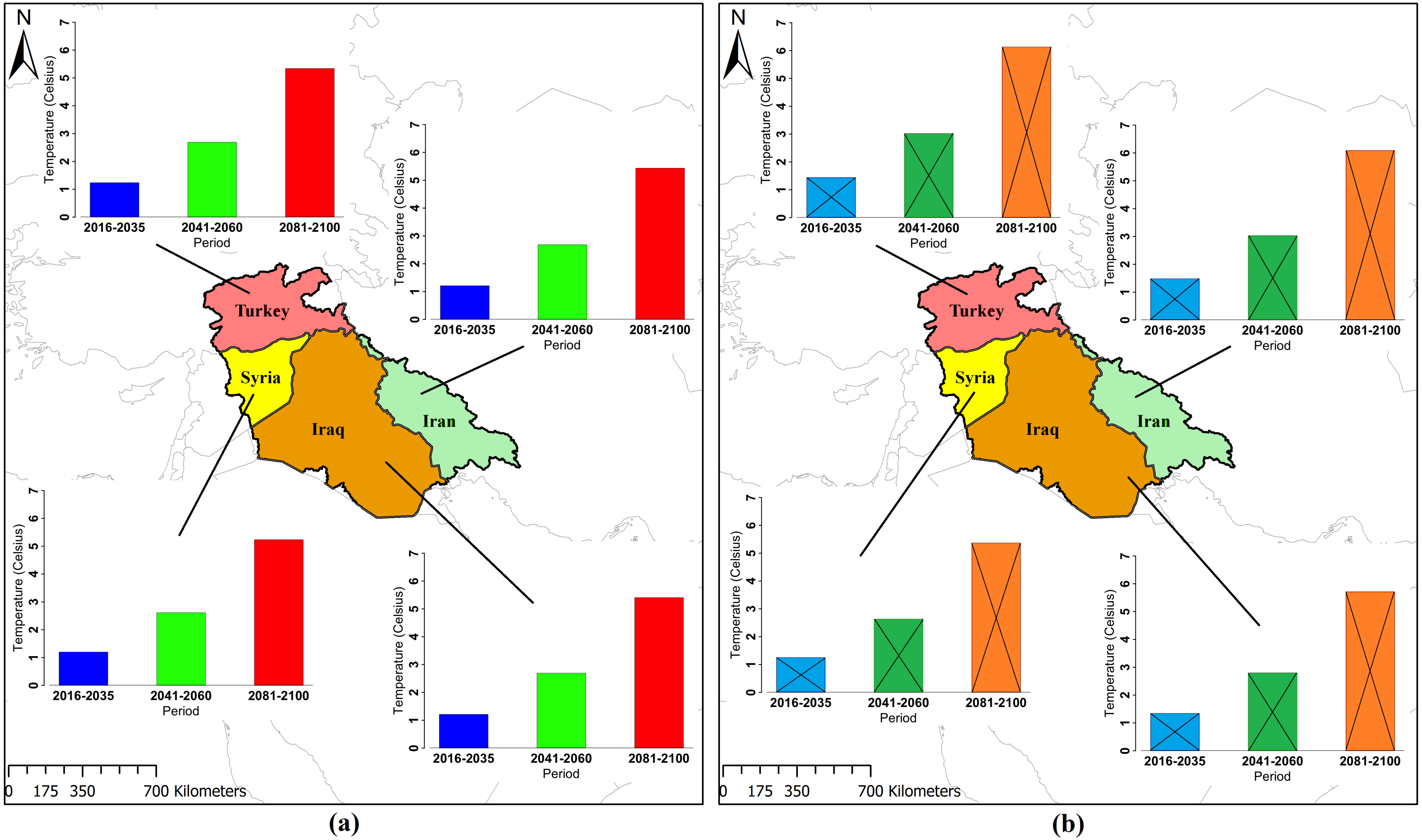

Figure 5.1:Temperature changes for the riparian countries in the ETB. a) CMIP5. b) CORDEX.

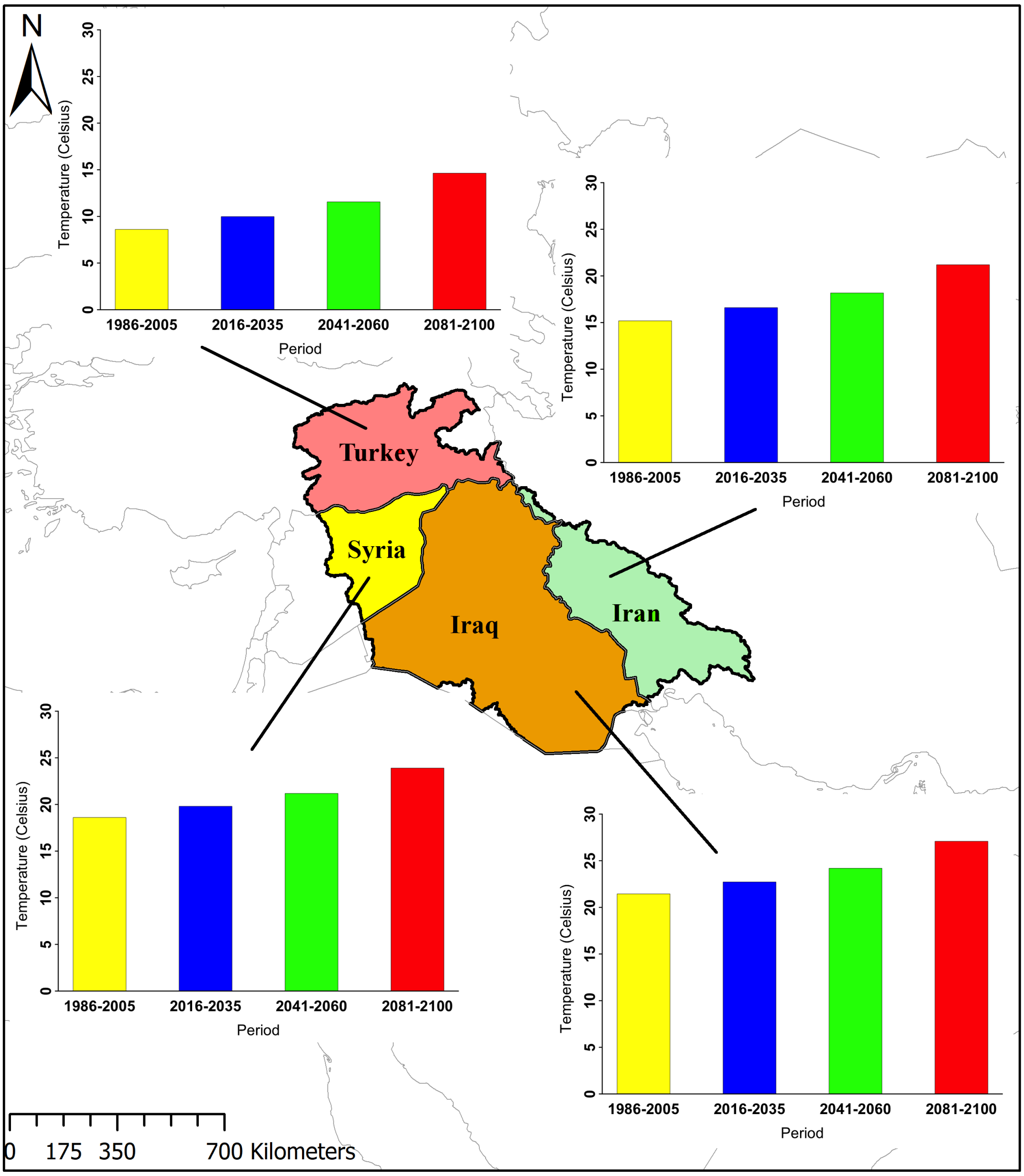

Figure 5.2: Annual mean temperature values from CORDEX ensemble for the riparian countries in the ETB.

Figure 5.3b shows the annual mean evapotranpiration changes in the Euphrates – Tigris Basin based on CORDEX dataset for each riparian countries in the three period of 2016-2035, 2041-2060, 2081-2100 relative to the reference period of 1986-2005. Evapotranspiration increases up to 5% in Turkey by the end of the century. A decrease can be seen in evapotranspiration between 0% and 15% in Syria. In Iraq, annual mean evapotranspiration increases up to 2% in 2016-2035 period, but after this period it decreases about 4%. In Iran evaporation increases for 2016-2035 period about 4%, but there is a striking decrease in it beginning from 2041 (Table 5.1).

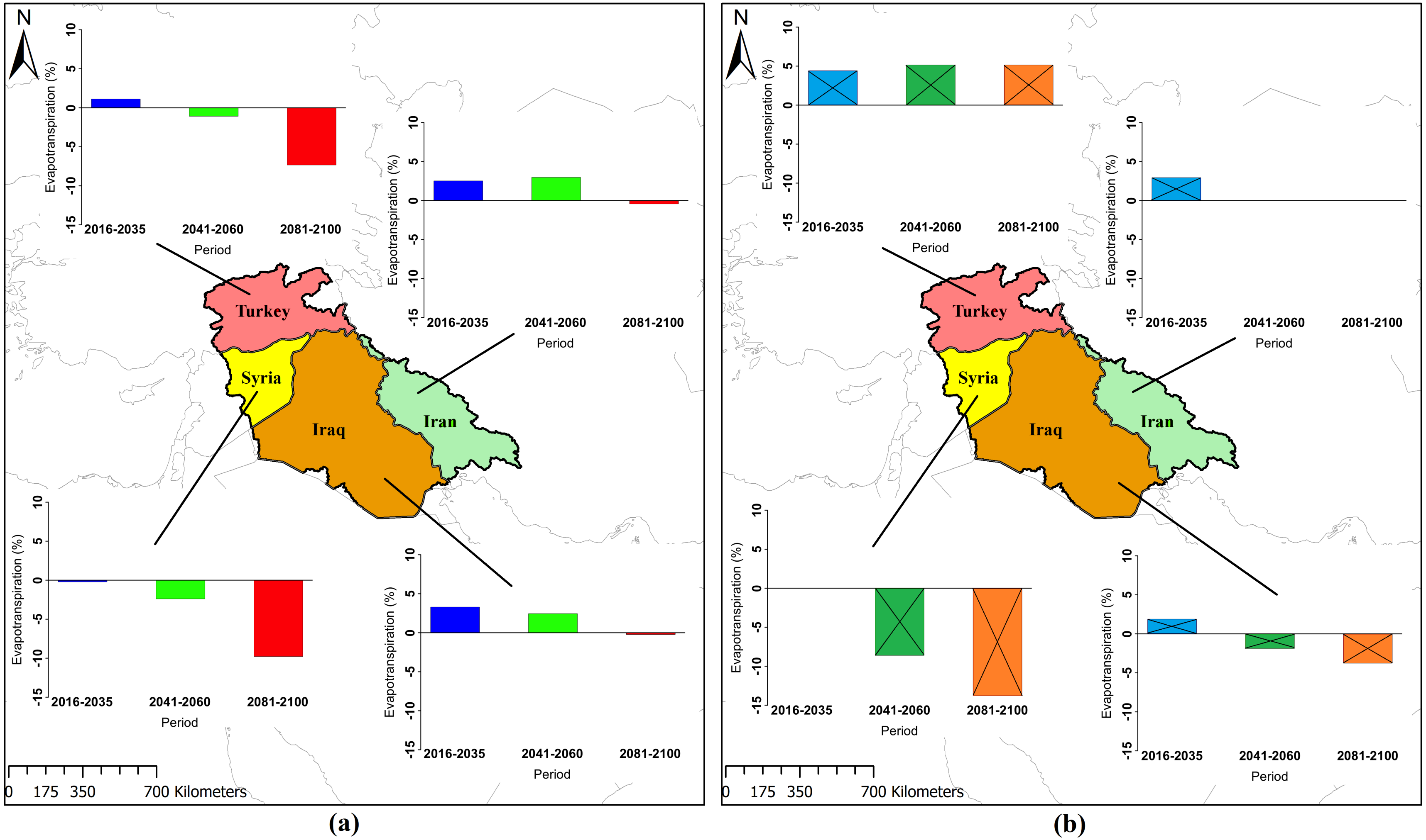

Figure 5.3: Evapotranspiration changes for the riparian countries in the ETB. a) CMIP5. b) CORDEX.

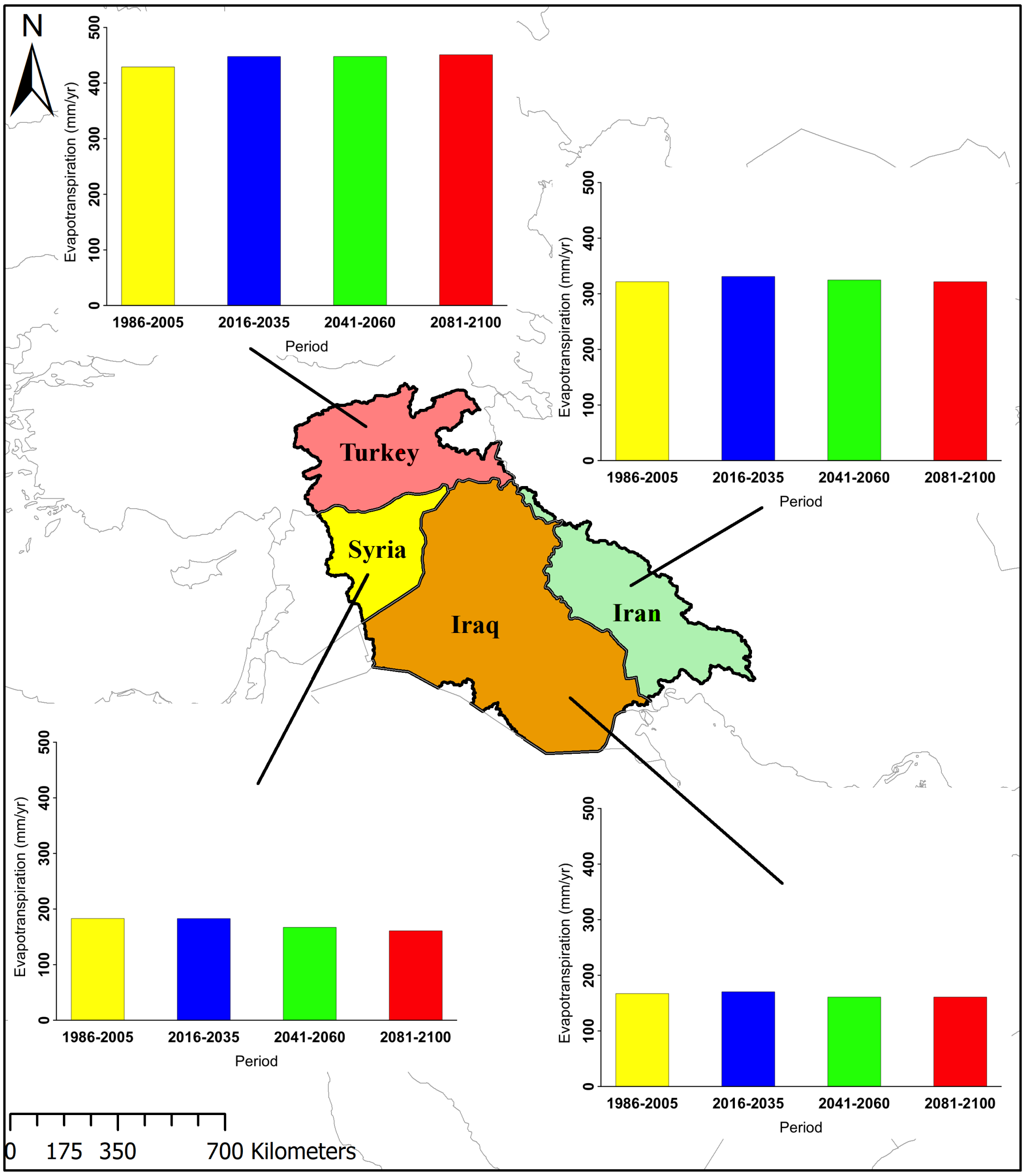

Figure 5. 4: Annual mean evapotranspiration values from CORDEX ensemble for the riparian countries in the ETB.

According to figure 5.4 the annual mean evapotranspiration is higher in Turkey and Iran with about 400 mm and 300 mm recpectively. Syria with 200 mm and Iraq with 150 mm have lower annual mean evapotranspiration rates.

5.3 Precipitation

In the ETB, much of the precipitation, which is mostly in the form of snow, falls in the highlands. Flow of air in winter causes movement of moisture from west to east over the Mediterranean toward the ETB, which creates orographic precipitation in the Taurus and Zagros mountain ranges (Evans, 2004). Therefore, any change in the amount of precipitation has a direct effect on the amount of water stored in the form of snow. Figure 5.5a shows the annual mean precipitation changes in the Euphrates-Tigris basin based on riparian country territories for the three period of 2016-2035, 2041-2060, 2081-2100 relative to the reference period of 1986-2005. The bar plots were formed by averaging the output of the GCMs within each countries.

Annual precipitation amount changes for the basin range between %5 and -15%. The analysis indicates decrease in precipitation in Turkey and Syria and increase in Iran and Iraq.

Figure 5.5b shows annual mean precipitation changes in the Euphrates-Tigris basin based on CORDEX dataset for each riparian countries in the three periods of 2016-2035, 2041-2060, 2081-2100 relative to the reference period of 1986-2005.

Precipitation decreases between 0% and 15 % in Turkey and between 0% and 20% in Syria. Annual mean precipitation increases in Iraq and Iran for the 2016-2035 period by about 2% but there is a striking decrease between 5% and 20% beginning from 2041 (Table 5.1).

In general, there is a broad agreement between the GCMs and RCMs simulations, which both indicate increasing precipitation in the southern parts of the basin in contrast to decreasing precipitation in the northern parts and highlands. By the end of the present century, precipitation is projected to decrease between 15% and 20% in the highlands of the ETB and some parts of the lowlands.

Onol and Semazzi (2009) suggest that the increasing precipitation during autumn in the southern parts of the ETB could be as a result of changes in the low-level circulation and enhanced moisture transfer from the regions of Mediterranean Sea, Red Sea and Persian Gulf.

According to Figure 5.6, annual precipitation amount is higher in Turkey and Iran because of high elevation and orographic effect.

Annual precipitation amount for Turkey ranges between 600 mm and 700 mm, while it is around 400 mm for Iran. Iraq and Syria have about 200 mm annual precipitation. The figure illustrate the fact that the highlands of the ETB receive more precipitation than the lowlands.

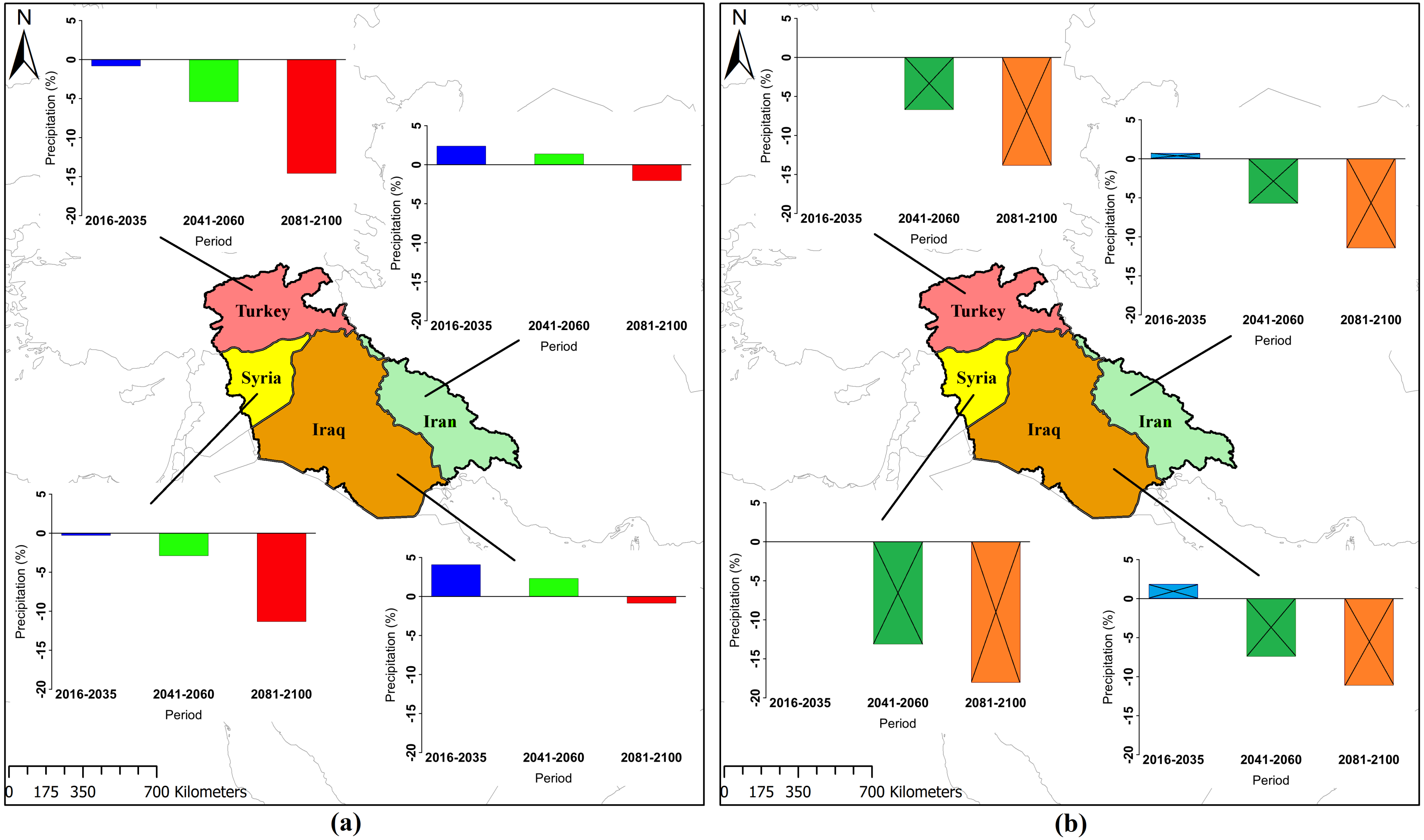

Figure 5.5: Precipitation changes for the riparian countries in the ETB. a) CMIP5. b) CORDEX

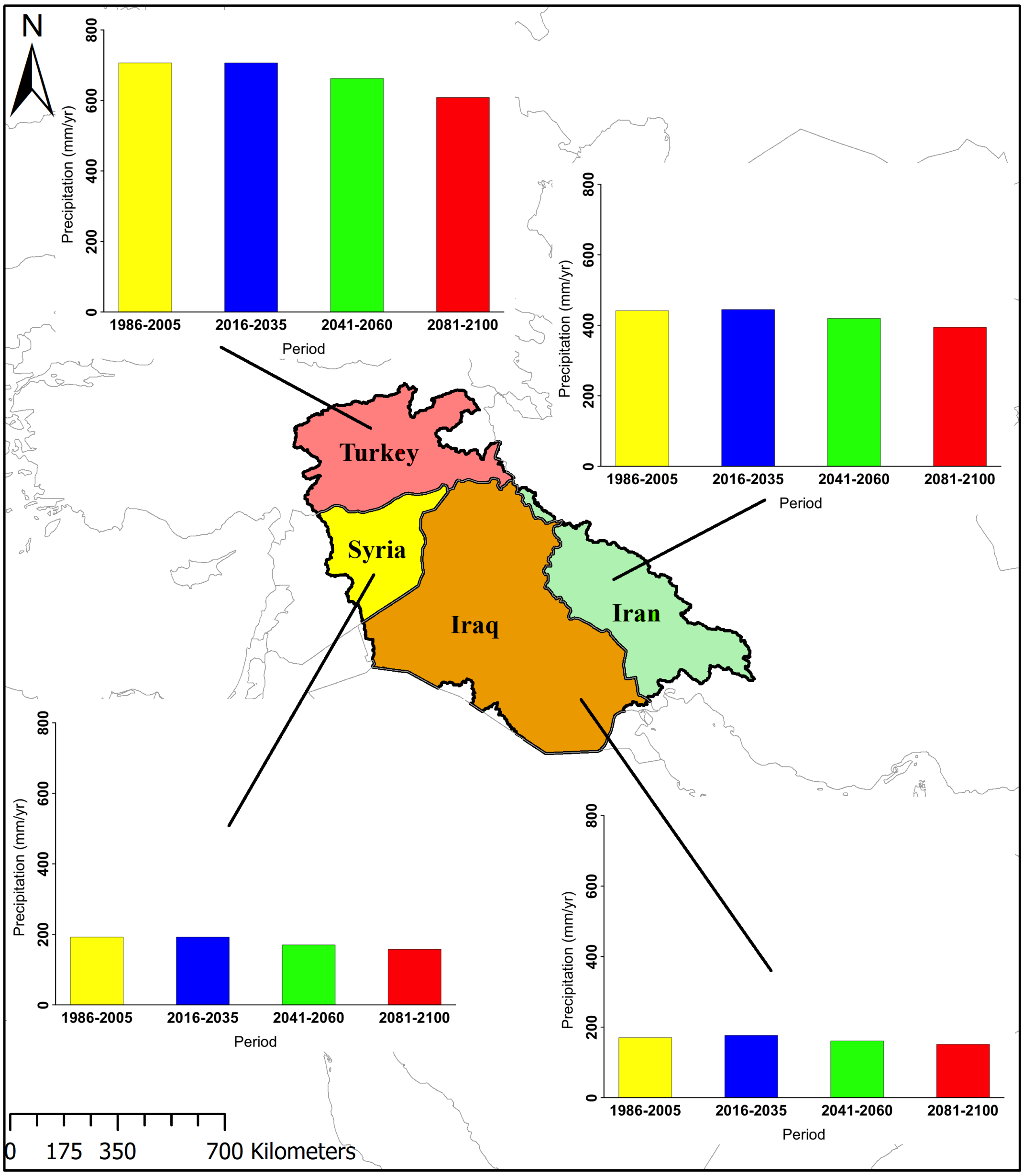

Figure 5.6: Annual mean precipitation values from CORDEX ensemble for the riparian countries in the ETB.

5.4 Runoff (P – E)

Figure 5.7a shows annual mean runoff (P – E) changes in the Euphrates-Tigris basin based on CMIP5 dataset for the three periods of 2016-2035, 2041-2060, 2081-2100 relative to the reference period of 1986-2005. Barplots indicate decrease in runoff for all four riparian countries and the changes in this variable ranges between -5 % and -1% with maximum decrease in Turkey (about 5%). Syria follows Turkey with about 3% decrease.

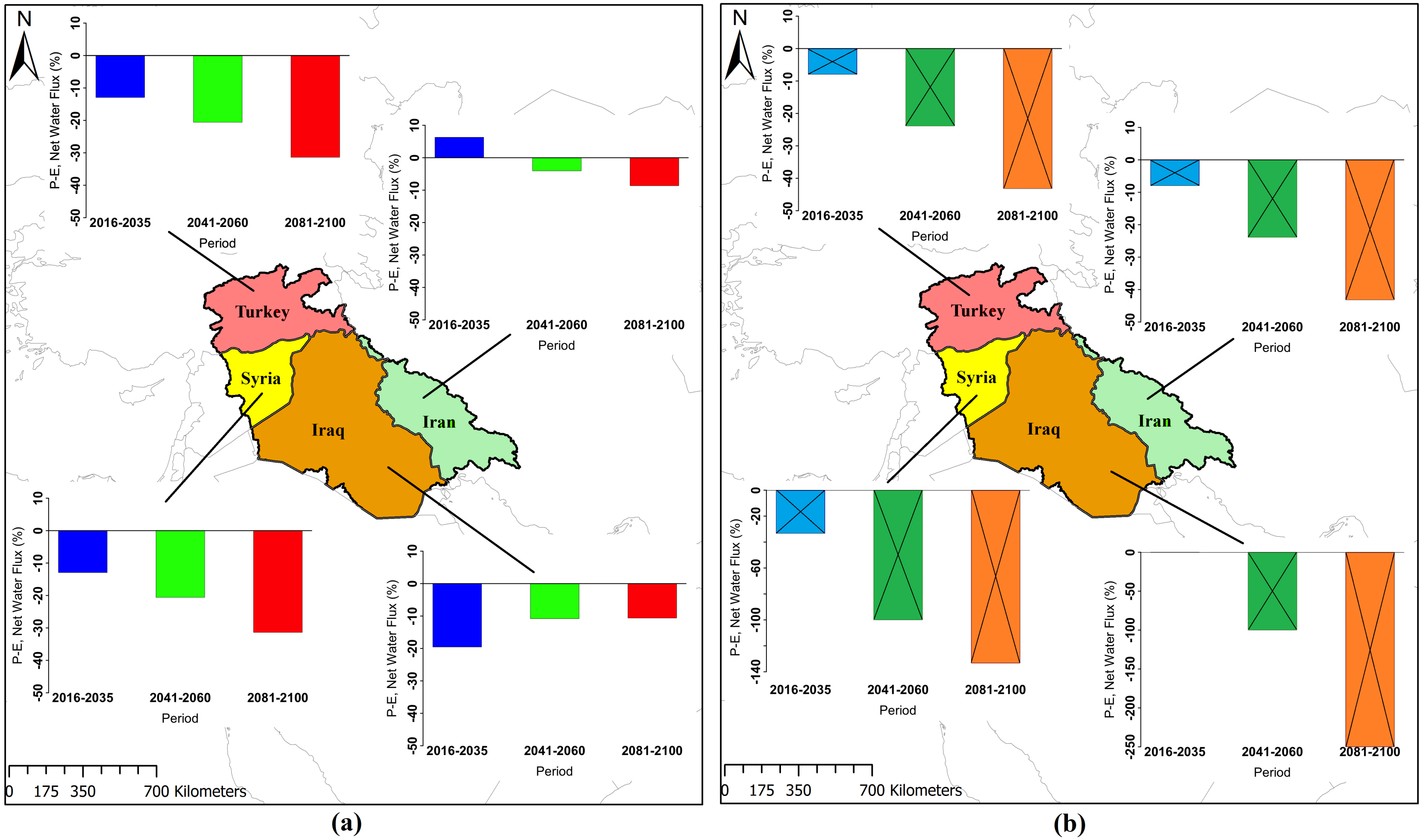

Figure 5.7: P-E, Net Water Flux changes for the riparian countries in the ETB. a) CMIP5. b) CORDEX.

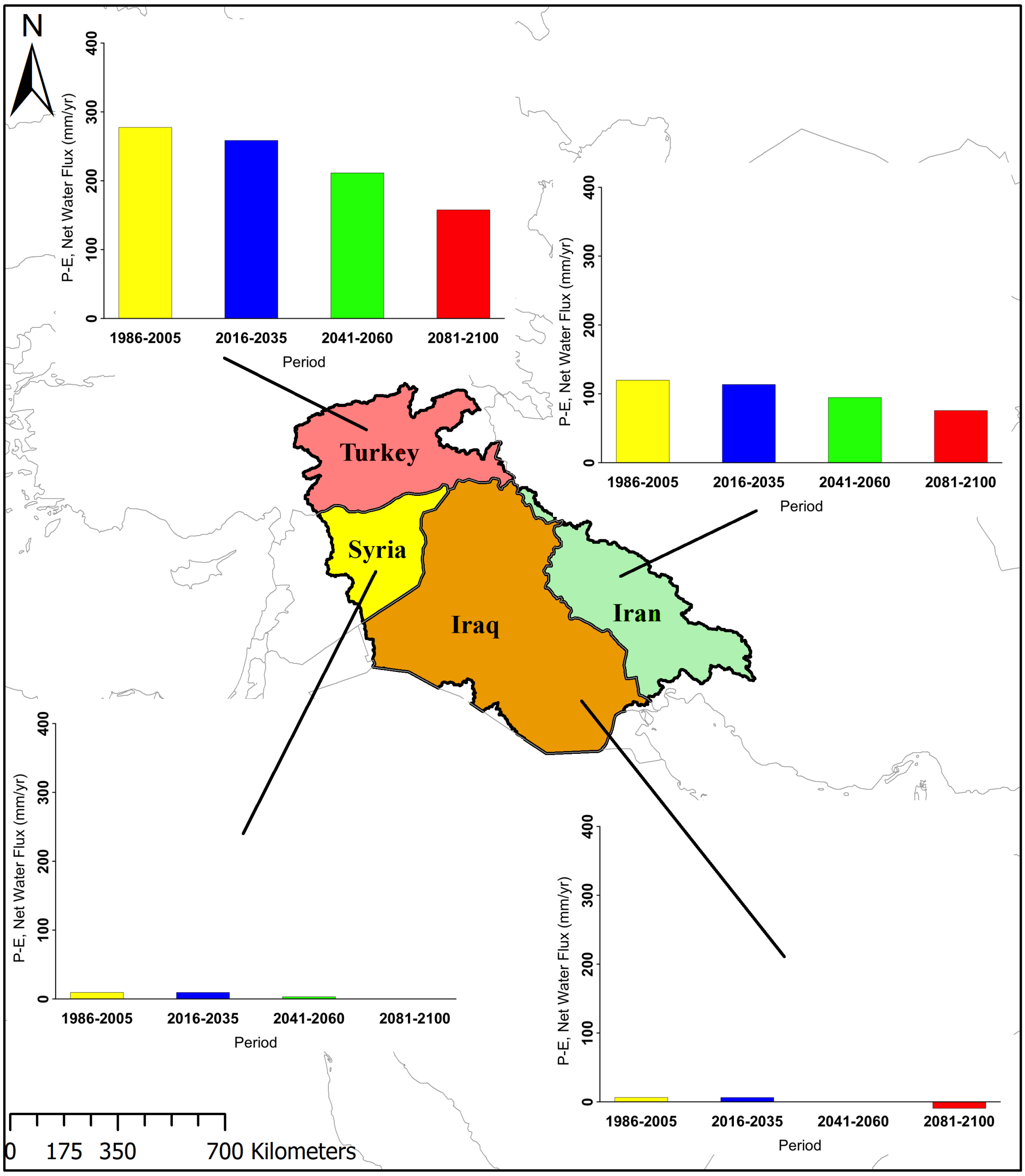

Figure 5.8: Annual mean P-E, Net Water Flux values from CORDEX ensemble for the riparian countries in the ETB.

Decrease in runoff is projected to be about 2% and 1% for Iraq and Iran respectively (Table 5.1). Figure 5.7b indicates the projected changes of runoff for Turkey, Iran, Iraq and Syria from CORDEX dataset for 2016-2035, 2041-2060 and 2081-2100 period relative to the 1986-2005 reference period. One of the remarkable results of this study is that runoff is projected to decrease substantially in all riparian countries. Runoff decreases in Syria and Iraq about 140% and 250% respectively; while the reduction is about 50% in Turkey and Iran (Table 5.1). It is clear from the figure 5.8 that the territory of Turkey with 300 mm/y runoff for the reference period is the main source of water in the basin and the annual runoff in this territory decreases for the projection periods. In contrast to Turkey, the annual surface runoff in Syria and Iraq remains unchanged. For Iranian territory, the annual surface runoff decreases for the projection periods, especially for 2081-2100.Table 5.2 shows the average annual runoff values in the ETB from 1986 to 2100 for Turkey, Syria, Iraq and Iran based on CORDEX ensemble means. This table indicates significant decrease in runoff values in the riparian countries of the ETB in the future. The mean annual streamflow for the 1986-2005 period in Turkey is 51 BCM. Turkey has the maximum flow level among the riparian countries. This value will decrease to 29 BCM in the 2081-2100 period. The lowest annual flow in the basin equals to 1 BCM, which belongs to Syria. It is projected to decrease to about -0.4 BCM by the end of the century. The 3 BCM of water produced in Iraq presently will become negative, indicating water deficit, which likely occurs as a result of irrigation crop fields in the country. The model extracts water from the runoff term to maintain the irrigated crop fields, and when there isn't sufficient water in the runoff term, it becomes negative, meaning that the vegetation should be supported by transfering water from somewhere else. In the case of Iran, the runoff is projected to drop from 20 BCM to 12 BCM by the end of the century.

Table 5.2: Annual Net Water Flux values (BCM) from CORDEX dataset in the riparian countries of the ETB

Period	Turkey	Syria	Iraq	Iran
1986-2005	51	1	3	20
2016-2035	47	0.7	3	18
2041-2060	39	0	0	15
2081-2100	29	-0.4	-4	12

5.5 Climate Change Indices

It is noted that the climate indices have potential to help analyze the changes in the climate characteristics of different regions around the world. For this reason, in this study ten climate indices based on daily air temperature and precipitation were analyzed. Table 5.3 summarizes the projected changes in ten climate indices in the ETB.

Table 5.3: Modeled annual values of reference period (1986-2005) and percentage or amount changes for future periods (2016-2035, 2041-2060 and 2081-2100) for the climate indices from CMIP5 experiment in the ETB based on riparian country (Turkey, Syria, Iraq and Iran) territories. The table mainly indicates the changes in the indices except " TN90p" and "TX90p" that shows the future state of these parameters.

Parameter	Turkey				Syria				Iraq				Iran			
	1986-2005	2016-2035	2041-2060	2081-2100	1986-2005	2016-2035	2041-2060	2081-2100	1986-2005	2016-2035	2041-2060	2081-2100	1986-2005	2016-2035	2041-2060	2081-2100
	Actual value	Percentage /Amount change	Percentage /Amount change	Percentage /Amount change	Actual value	Percentage /Amount change	Percentage /Amount change	Percentage /Amount change	Actual value	Percentage /Amount change	Percentage /Amount change	Percentage /Amount change	Actual value	Percentage /Amount change	Percentage /Amount change	Percentage /Amount change
CDD (day)	82.178	2.477	7.79	17.058	159.709	-1.219	4.338	11.107	163.91	0.013	1.931	9.806	128.629	0.57	3.236	8.001
CWD (day)	9.438	-0.073	-0.607	-1.365	3.547	0.005	-0.123	-0.298	4.091	0.032	-0.023	-0.277	5.723	0.078	-0.013	-0.349
DTR(celsius)	11.618	0.127	0.36	0.804	13.318	0.053	0.148	0.303	13.945	0.013	0.089	0.249	14.001	0.151	0.244	0.545
TR (day)	35.799	10.693	24.248	53.69	103.821	16.22	31.858	59.565	115.799	14.532	30.039	59.165	48.582	12.962	29.447	64.222
GSL (day)	270.36	12.807	26.899	50.888	347.952	6.132	10.079	14.831	343.629	5.805	10.361	16.32	288.277	13.785	27.877	27.877
R99pTOT(mm/yr)	27.172	4.977	10.079	16.678	5.942	2.15	2.303	4.528	11.333	2.351	4.249	8.662	21.429	4.471	8.917	17.407
Rx5day(mm/5day)	53.076	1.05	2.308	2.244	23.441	1.128	1.156	1.634	35.51	1.577	2.582	3.655	54.43	2.932	5.167	7.83
SDII (mm/day)	5.096	0.125	0.284	0.453	3.929	0.07	0.164	0.356	5.112	0.21	0.378	0.68	6.074	0.24	0.556	0.959
TN90p (%)	15.09	28.045	45.085	70.124	15.016	28.435	46.587	73.723	14.996	29.01	47.952	75.501	14.585	27.358	46.082	73.91
TX90p (%)	14.798	26.493	42.918	69.728	14.265	25.058	40.832	68.084	14.952	27.878	45.289	72.431	15.374	29.435	47.37	74.606

5.5.1 Maximum length of dry spell (CDD)

This index, which represents maximum number of consecutive days with precipitation less than 1 mm, is estimated by CMIP5 ensemble as about 82, 129, 160 and 164 days for 1986-2005 period for Turkey, Iran, Syria and Iraq respectively (Figure 5.9). Although it does not change much in near future, this index is expected to increase significantly for the middle and end of the century. RCP8.5 scenario simulations predict that the maximum length of dry spell will rise to 90, 132, 164 and 166 days in the middle of the century and 99, 137, 171 and 174 days to the end of the century for Turkey, Iran, Syria and Iraq respectively.

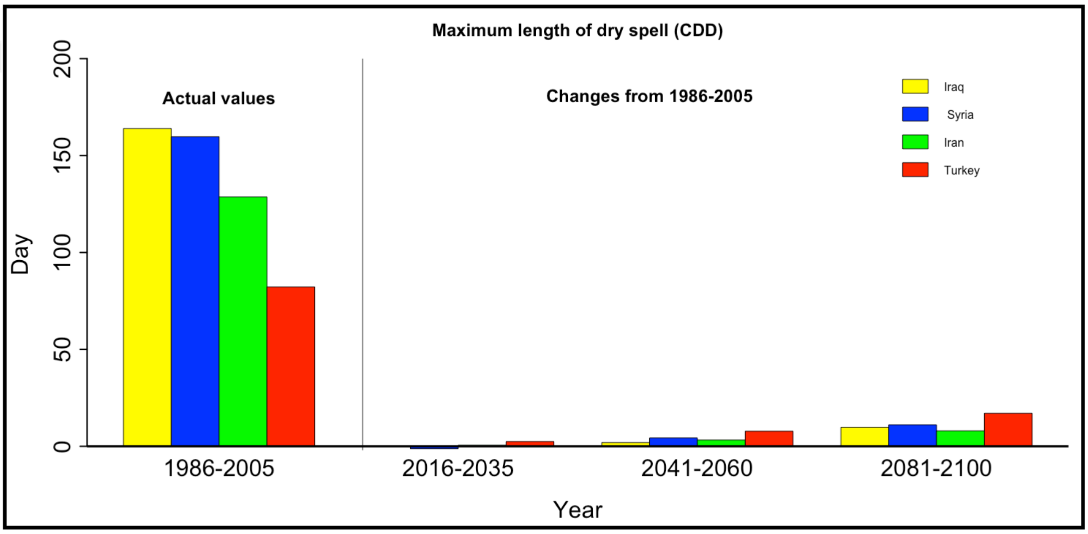

Figure 5.9: Maximum length of dry spell for the 1986-2005 period and its future changes for the riparian countries in the ETB.

5.5.2 Maximum length of wet spell (CWD)

This index, which is the longest period with a daily precipitation of 1 mm and above, is estimated by CMIP5 ensemble as 9, 6, 4 and 4 days for 1986-2005 period for Turkey, Iran, Syria and Iraq respectively (Figure 5.10).

RCP8.5 scenario simulations do not forecast a significant change for the first period. The only major change in the second period is the half-day (0.6) decline of this index for Turkey, while changes in the other three countries are negligible. For the end of the century the reduction of CWD is 1.5 days for Turkey and about 0.5 day for other riparians.

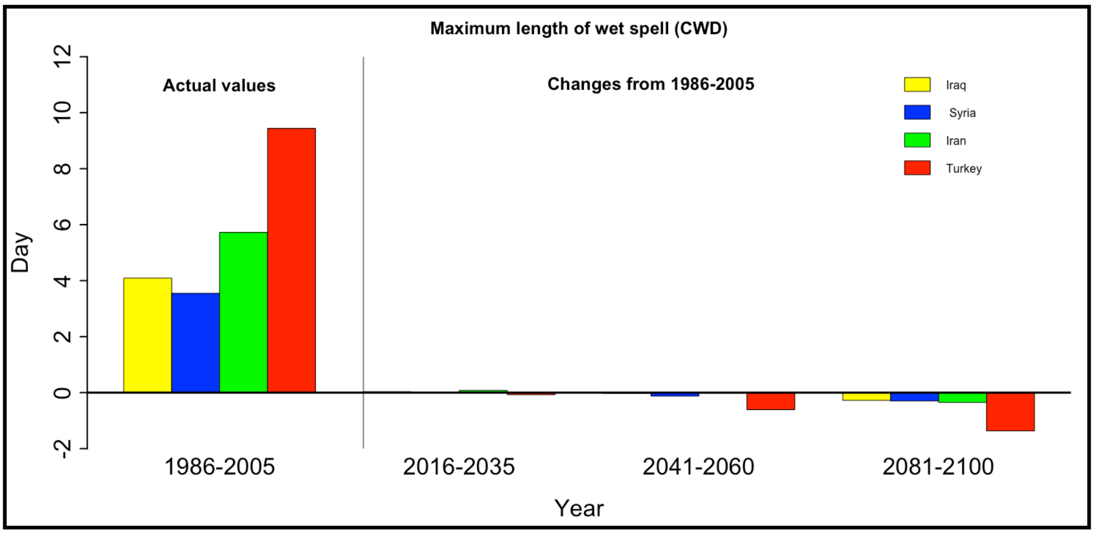

Figure 5.10: Maximum length of wet spell for the 1986-2005 period and its future changes for the riparian countries in the ETB.

5.5.3 Daily temperature range (DTR)

The daily temperature range index is a measure of the difference between maximum and minimum temperatures on annual basis. Especially in temperate climates where the sea effect is high, DTR has low values and in the continental parts the index values are high. Global model simulations give the values of this index for Turkey, Iran, Syria and Iraq at around 12 °C, 14 °C, 13 °C and 14 °C respectively (Figure 5.11).

RCP8.5 scenario simulations predict that there will be small increases in this index in the future. The highest increase at the end of the century is related to Turkey, which will not be greater than 0.8 °C.

Therefore, a significant change in daily temperature range will not occur in the ETB due to global warming. The reason is that temperature increases will affect both the minimum and maximum temperatures used in the calculation of this index in the same direction (up).

5.5.4 Number of tropical nights (TR)

This index, which gives the annual count of days at which the daily minimum temperature is above 20 °C, is calculated by the global models for the 1986-2005 period and is around 36, 49, 104 and 116 days for Turkey, Iran, Syria and Iraq respectively (Figure 5.12).

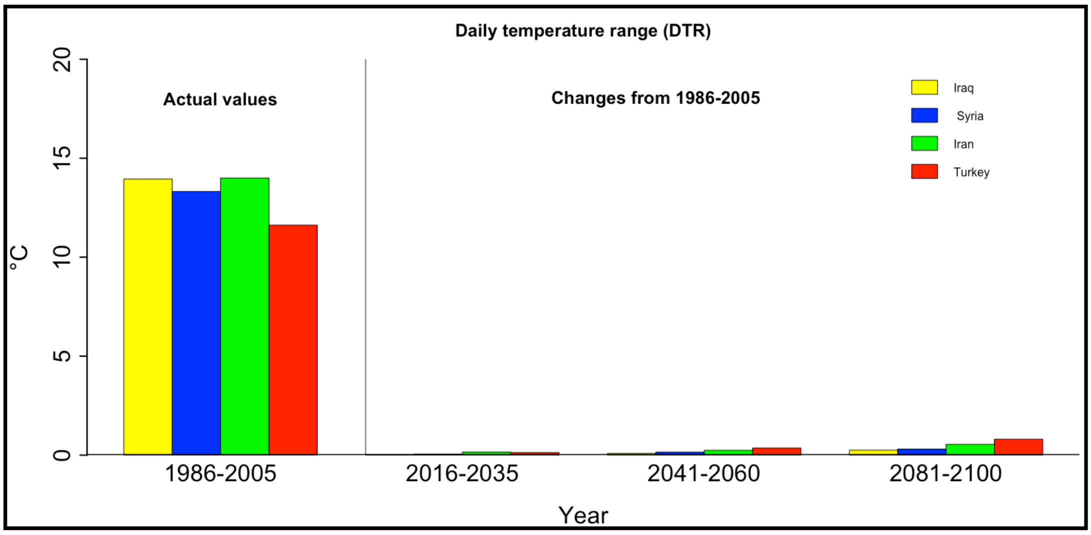

Figure 5.11: Daily temperature range index values for the 1986-2005 period and its future changes for the riparian countries in the ETB.

This index will also increase significantly in the future. The increase for the 2016-2035 period is estimated to be around 11, 13, 16, 15 days, for the 2041-2060 period around 24, 29, 32, 30 days and for the 2081-2100 period around 54, 64, 60 and 60 days for Turkey, Iran, Syria and Iraq respectively.

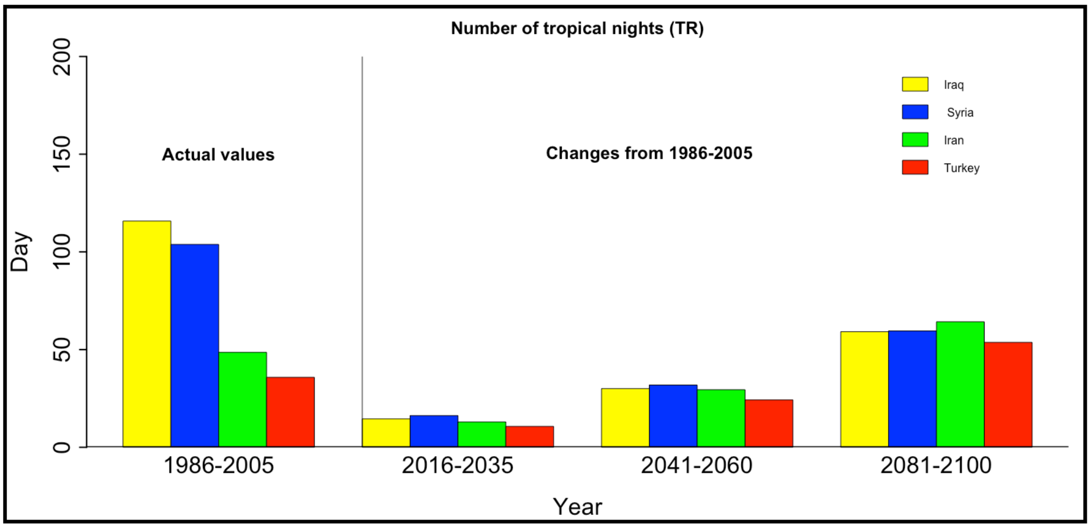

Figure 5.12: Number of tropical nights for the 1986-2005 period and its future changes for the riparian countries in the ETB.

5.5.5 Growing season length (GSL)

This index, which represents the annual count between the first span of at least 6 days with daily mean temperature >5 °C and the first span after July 1st of 6 days with daily mean temperature <5 °C, is estimated to be around 270, 288, 348 and 344 days for Turkey, Iran, Syria and Iraq respectively for the period of 1986-2005

(Figure 5.13). In the future, the index values are expected to increase slightly. The predicted increase amounts are between 6-14 days for the first period, 10-28 days for the second period and 15-51 days for the third period. In this case, for the end of the century, the growth season length of Turkish territory will be 321 days. These values are about 316, 363 and 360 for Iran, Syria and Iraq respectively. According to the RCP8.5 scenario, almost all of the year will be suitable for agriculture in Syria and Iraq in terms of temperature.

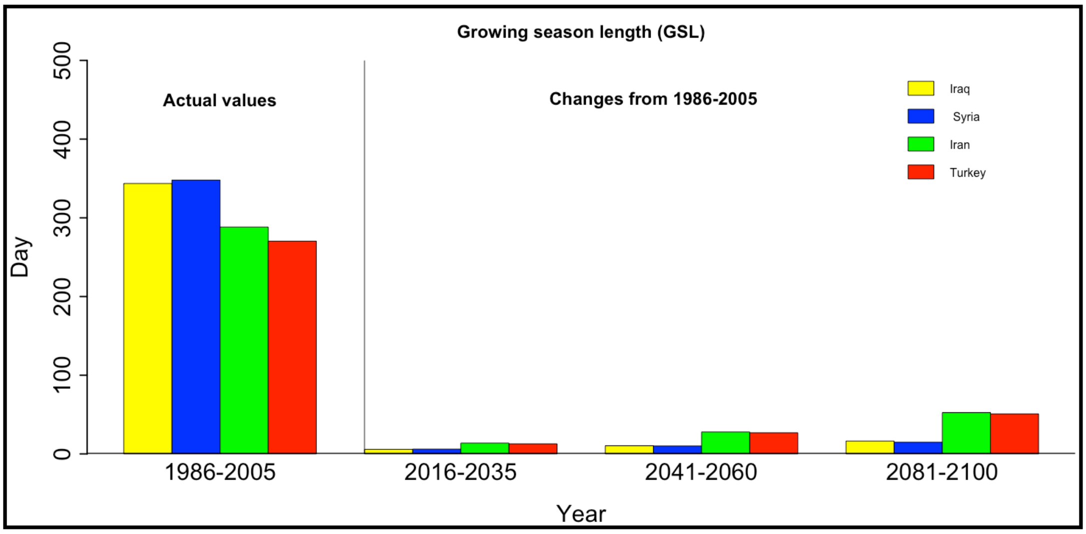

Figure 5.13: Growing season length index values for the 1986-2005 period and its future changes for the riparian countries in the ETB.

5.5.6 Annual total precipitation when daily precipitation >99th percentile (R99pTOT)

This index represents the annual total precipitation when the daily precipitation amount on a wet day (mean daily precipitation ≥ 1.0mm) > 99 percentile of precipitation on wet days in the 1961-1990 period. According to the CMIP5 ensemble, the reference period value of this index is 27, 21, 6 and 11 mm/yr for Turkey, Iran, Syria and Iraq respectively (Figure 5.14). RCP8.5 projections show that the rates of this index will increase in the future. This increase will be between 2-5 mm/yr in the first period, 2-10 mm/yr in the second period and 5-17 mm/yr for the last period.

In this case, it can be said that the amount of precipitation of heavy rainy days in the ETB especially in the territories of Turkey and Iran will increase significantly in the future.

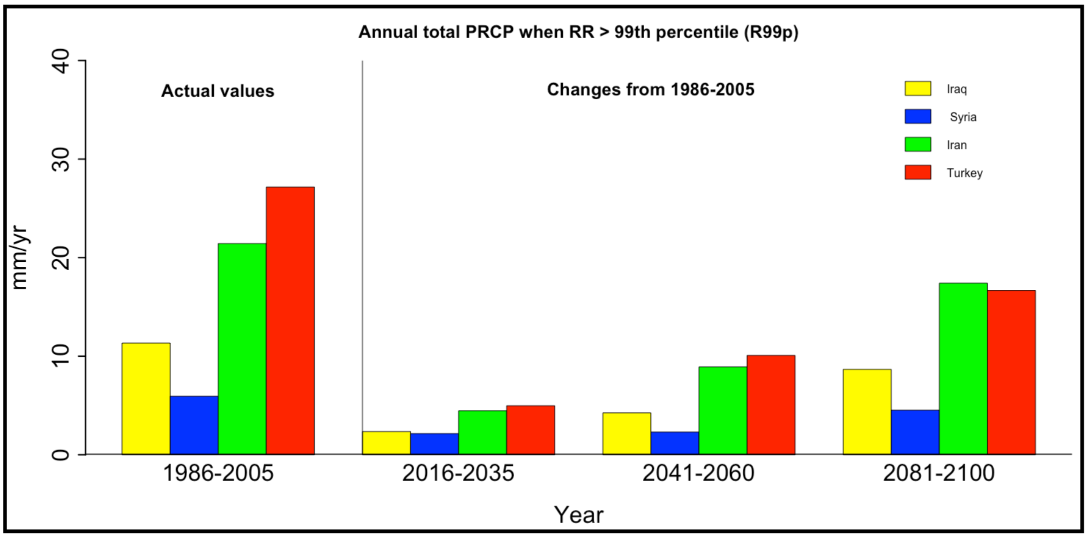

Figure 5.14: Extreme rainy days precipitation values for the 1986-2005 period and its future changes for the riparian countries in the ETB.

5.5.7 Maximum consecutive 5-day precipitation (Rx5day)

This index, which expresses maximum amount of precipitation for consecutive 5 days, is calculated by the models for the reference period as about 53, 54, 23, 36 mm/5days for Turkey, Iran, Syria and Iraq respectively (Figure 5.15). RCP8.5 scenario simulations predict that this amount will increase slightly in the future. However, the increase amounts are not significant. The highest increase rate is 8mm/5days for Iran in the last period.

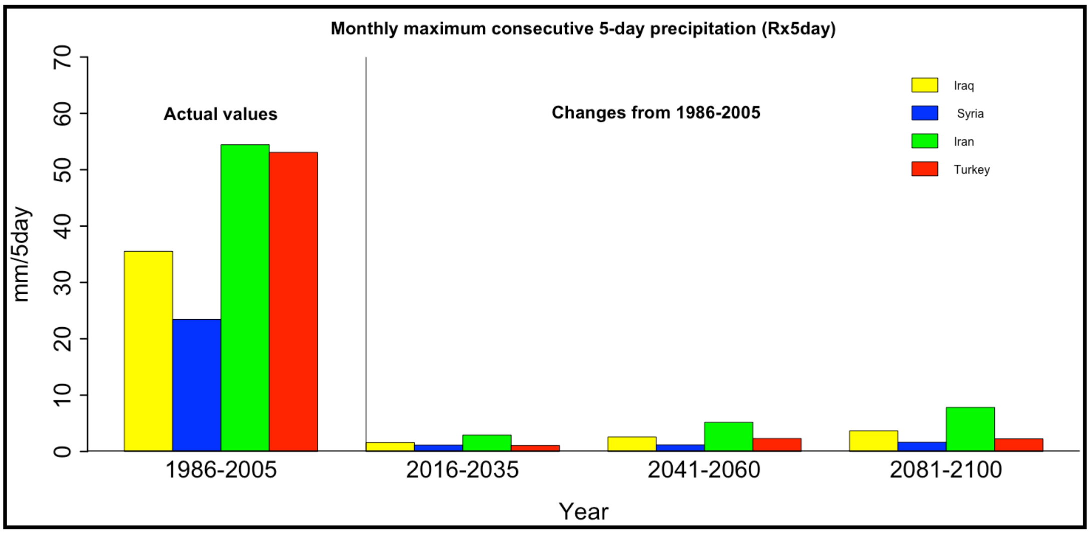

Figure 5.15: Maximum consecutive 5-day precipitation index values for the 1986-2005 period and its future changes for the riparian countries in the ETB.

5.5.8 Simple precipitation intensity index (SDII)

Simple precipitation intensity index is obtained by dividing the daily precipitation amount on wet days (mean daily precipitation ≥ 1.0mm) by the number of wet days. For Turkey SDII is 5 mm/dy for the reference period (Figure 5.16). The index values for Iran, Syria and Iraq are 6, 4 and 5 mm/dy respectively for the 1986-2005 period. RCP8.5 scenario simulations show that these values will increase in the future but the increases will not be substantial.

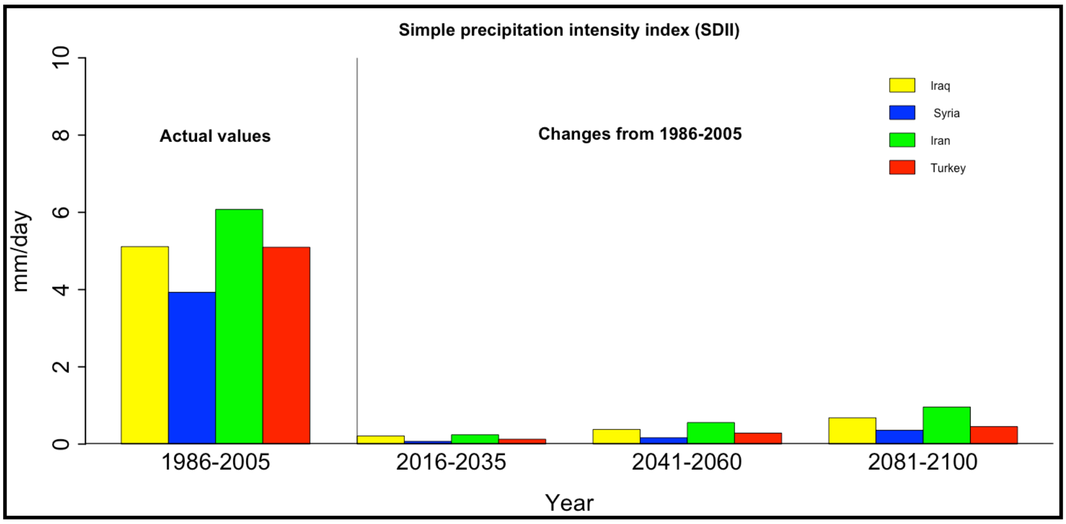

Figure 5.16: Simple precipitation intensity index values for the 1986-2005 period and its future changes for the riparian countries in the ETB.

5.5.9 Percentage of days when TN > 90th percentile (TN90p)

This index (warm nights index) shows the percentage of days when daily minimum temperature (TN) > 90th percentile of days for the base period 1961-1990. Global models estimate around 15% warm nights index for all riparian countries for the period 1986-2005 (Figure 5.17).

RCP8.5 scenario simulations predict that this value will increase to 28%, 27%, 28% and 29% for Turkey, Iran, Syria and Iraq respectively in the 2016-2035 period. It is estimated that the increase in TN90p index will continue up to 70 % for all of the countries by the end of the century.

In this case, according to the norms of 1961-1990, the warm nights will cover 70% of the whole year in the ETB for the end of the century.

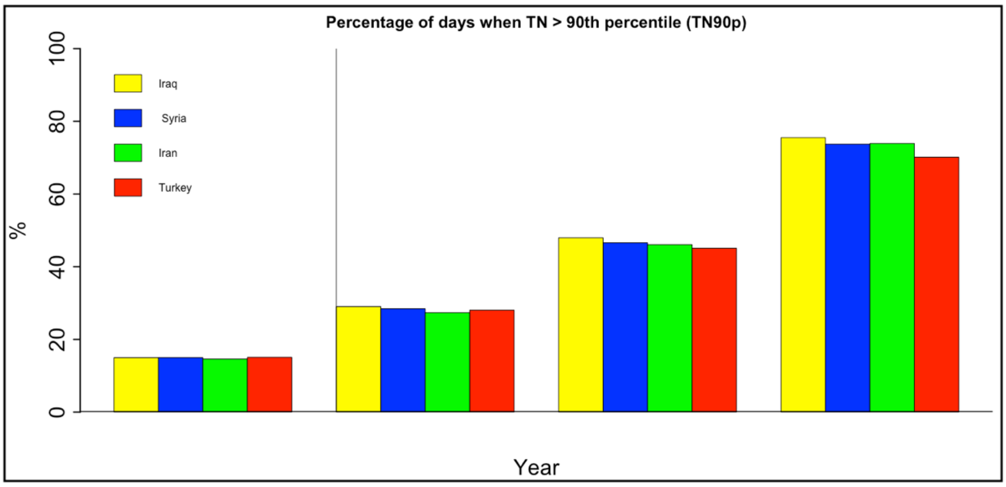

Figure 5.17: Percentage of warm nights for the 1986-2005 period and its future state for the riparian countries in the ETB.

5.5.10 Percentage of days when TX > 90th percentile (TX90p)

This index (warm days index) shows the percentage of days when daily maximum temperature (TX) > 90th percentile of days for the base period 1961-1990. Global models calculate around 15% warm days index for all riparian countries for the period 1986-2005 (Figure 5.18). RCP8.5 scenario simulations predict that this value will increase to 26%, 29%, 25% and 28% for Turkey, Iran, Syria and Iraq respectively in the 2016-2035 period.

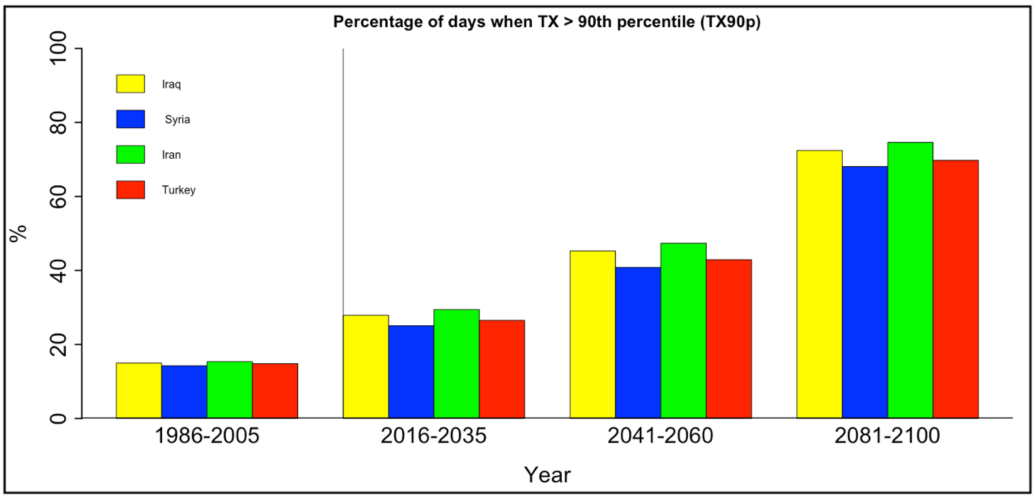

Figure 5.18: Percentage of warm days for the 1986-2005 period and its future state for the riparian countries in the ETB.

It is estimated that the increase in Tx90p index will continue up to 70 % for all of the countries by the end of the century. In this case, according to the norms of 1961-1990, the warm days will cover 70% of the whole year in the ETB for the end of the century.

6. CONCLUSION AND DISCUSSION

The results obtained from the analysis of temperature, precipitation, net water flux, evapotranspiration and climate change indices in the ETB basin can be summarized as follows:

According to global and regional RCP8.5 scenario simulations, temperature in the whole Euphrates-Tigris basin will increase throughout the 21st century. Simulations indicate 1 °C increase in surface air temperature for the 2016-2035 period whereas it is about 3 °C and 6 °C for the 2041-2060 and 2081-2100 periods respectively. The consequence of this increase in temperature in the regional hydrological cycle is the reduction in snow cover and temporal shifts to earlier days in melting of snow in the highlands.

In terms of precipitation, there is a wide agreement amongst the simulations, which show decreases up to 15% in Turkey and Syria for the 21st century. Precipitation in Iraq and Iran is projected to increase by 5% for the 2016-2035 and 2041-2060 periods, whereas simulations produce a decrease by 15% for the 2081-2100 period.

Projected changes in the evapotranspiration indicate generally increases in the basin for the early period in response to the increasing temperatures, however it decreases by the end of the century because of decreasing precipitation, especially in the headwaters region. Neither CMIP5 nor CORDEX simulations consider the areal expansion of irrigated agriculture, so evapotranspiration changes from the basin does not include landscape change induced water losses in the future. The study of Yilmaz et al. (2019) shows that irrigation induced evapotranspiration in the future could amount to very high values that adversely affect the water budget of the upper Mesopotamia, which could have important implications not only for Turkey but also for the downstream countries.

Based on different model experiments, the surface runoff is found to decrease about 10-50% in the basin by the end of the 21st century. Surface runoff in Syria, Iraq and Iran also projected to decrease between 10-250%.

Investigation of climate change in the ETB based on the riparian country territories indicates that Turkey will undergo the largest changes as it possesses most of the headwaters region of the basin. The changes in the surface runoff is projected to be by 20 - 50% reduction in Turkey by the end of the present century. But downstream countries, especially Iraq and Syria which are dependent on the water released by Turkey, will experience more stress in the future.

Investigation of climate indices in the ETB indicates that climate extremes will become more intense in the future. Temperature extremes of TN90p (warm nights index) and TX90p (warm days index) will increase up to 70% by the end of century. SDII and Rx5day precipitation indices will increase in the future but these increases will not be substantial. In the case of R99pTOT, it can be concluded that the amount of precipitation of heavy rainy days in the ETB, especially in the territories of Turkey and Iran, will increase significantly in the future. There is a slight increase in CDD and GSL and a slight decrease in CWD by the end of century. TR index will also increase significantly in the future. A significant change in daily temperature range will not occur in the ETB.

The ecosystems in the basin and the developments of the riparian countries in the ETB can be affected by the variations of the hydro-climatic parameters. Decreasing water availability in the coming years could be known as the most adverse impact of climate change in the basin. Combined with climate change, human activities will further stress the water resources in Iraq and Syria. Although dams have negative impacts on the water sustainability and ecosystems especially in the downstream countries, reduction of hydropower and irrigation water potential due to decreasing water availability may lead to building more dams in the ETB. Ilisu dam on the Tigris river is the best example to illustrate the negative impacts of human activities in the basin. This dam has impacted the heritage of Hasankeyf, which hosts a unique habitat in the ETB.

The climate change in the ETB may lead to other natural hazards such as salinization and desertification. The ETB has faced with severe droughts in the past years. For instance, the severe drought in the winter of 2007 - 2008 had a big effect on the agricultural production in the region. The initiation of development projects by the riparian countries since 1960s which are uncoordinated with water availability in the ETB and crisis in water demand management and inefficient water policies of the riparian countries within the national framework are the main causes of water mismatch between supply and demand in the ETB. On top of these, changes in hydroclimatic parameters can result in and exacerbate water disputes in the region due to increased water demand and supply imbalance. These problems could be solved by coordinated regional actions and assessment of the factors for water allocation.

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APPENDICES

APPENDIX A: Tables

APPENDIX A

Table A.1: Information about the CMIP5 global models. 39 models were run for RCP8.5 scenario.

Institution	Global Model	Spatial Resolution (ºlat x ºlon)
Beijing Climate Center, China Meteorological Administration	BCC CSM1	2.8x2.8
	BCCSM 1M	1.1x1.1
College of Global Change and Earth System Science, Beijing Normal University	BNU ESM	2.8x2.8
Canadian Centre for Climate Modelling and Analysis	CCCMA CM4	2.8x2.8
	CCCMA ESM2	2.8x2.8
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	CCSR ESM	2.8x2.8
	CCSR ESM CHEM	2.8x2.8
	CCSR MIROC4H	0.56x0.56
	CCSR MIROC5	1.4x1.4
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC CM	0.75x0.75
	CMCC CMS	1.8x1.8
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancéeen Calcul Scientifique	CNRM CM5	1.4x1.4
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO AC10	1.25x1.8
	CSIRO AC13	1.25x1.8
	CSIRO MK6	1.8x1.8
EC-EARTH consortium	ECMWF EC EARTH	1.1x1.1
The First Institute of Oceanography, SOA, China	FIO ESM	2.8x2.8
NOAA Geophysical Fluid Dynamics Laboratory	GFDL CM3	2x2.5
	GFDL ESM2G	2x2.5
	GFDL ESM2M	2x2.5
NASA Goddard Institute for Space Studies	GISS E2H	2x2.5
	GISS E2H-CC	2x2.5
	GISS E2R	2x2.5
	GISS E2R-CC	2x2.5
Institute for Numerical Mathematics	INM CM4	1.5x2
Institut Pierre-Simon Laplace	IPSL CM5ALR	1.9 x3.75
	IPSL CM5AMR	1.25x2.5
	IPSL CM5BLR	1.9x3.75
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua	LASG FGOALSG2	2.8x2.8
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG FGOALSS2	1.6x2.8
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI ESMLR	1.9x1.9
	MPI ESMMR	1.9x1.9
	MPI ESMP	1.9x1.9
Meteorological Research Institute	MRI CGCM3	1.1x1.1
National Center for Atmospheric Research	NCAR CCSM4	0.9x1.25
Community Earth System Model Contributors	NCAR CESM1-BGC	0.9x1.25
	NCAR CESM1-CAM5	0.9x1.25
	NCAR CESM1-FCHEM	0.9x1.25
	NCAR CESM1-WACCM	1.9x2.5
Norwegian Climate Centre	NOR ESM1M	1.9x2.5
	NOR ESM1ME	1.9x2.5
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	UKMO HADCM3	2.5x3.75
	UKMO HADGEM2AO	1.25x1.875
	UKMO HADGEM2CC	1.25x1.875
	UKMO HADGEM2ES	1.25x1.875
Multi Model Ensemble	MME GCM	0.5x0.5

Table A.2: Information about the models of Cordex framework used in this study.

Institution of the Regional Climate Model	Regional Climate Model	Forcing Global model
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	CCCma-CanESM2
Climate Limited area Modelling Community (CLM-Community), Germany	CLMcom-CCLM4-8-17	CNRM-CERFACS -CNRM-CM5
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	CNRM-CERFACS -CNRM-CM5
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	CSIRO-QCCCE-CSIRO-Mk3-6-0
Royal Netherlands Meteorological Institute (KNMI), Netherlands	KNMI-RACMO22T	ICHEC-EC-EARTH
Climate Service Center (GERICS), Germany	GERICS-REMO2009	IPSL-IPSL-CM5A-LR
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	IPSL-IPSL-CM5A-MR
Climate Service Center (GERICS), Germany	GERICS-REMO2009	MIROC-MIROC5
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	MIROC-MIROC5
Climate Limited area Modelling Community (CLM-Community), Germany	CLMcom-CCLM4-8-17	MOHC-HadGEM2-ES
Climate Service Center (GERICS), Germany	GERICS-REMO2009	MOHC-HadGEM2-ES
Royal Netherlands Meteorological Institute (KNMI), Netherlands	KNMI-RACMO22T	MOHC-HadGEM2-ES
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	MOHC-HadGEM2-ES
Climate Limited area Modelling Community (CLM-Community), Germany	CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR
Climate Service Center, Max Planck Institute for Meteorology (MPI-CSC), Germany	MPI-CSC-REMO2009	MPI-M-MPI-ESM-LR
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	MPI-M-MPI-ESM-LR
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	NCC-NorESM1-M
Swedish Meteorological and Hydrological Institute (SMHI), Sweden	SMHI-RCA4	NOAA-GFDL-GFDL-ESM2M

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