

**INVESTIGATING THE HYDROCLIMATIC CHANGES
IN THE EUPHRATES-TIGRIS BASIN
UNDER A CHANGING CLIMATE**

Ph.D. THESIS

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Department of Climate and Marine Sciences

Earth System Science Programme

MARCH 2019

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Thesis Advisor: Prof. Dr. Ömer L. ŞEN

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**DEĞİŞEN İKLİM KOŞULLARI ALTINDA
FIRAT-DİCLE HAVZASI'NDAKİ
HİDROİKLİMSEL DEĞİŞİKLİKLERİN İNCELENMESİ**

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To my beloved family,

FOREWORD

There is no doubt that most Ph.D. theses are written and completed after many years of study with sweat, tears, and hesitations. Mine is the same as well. Starting my Ph.D. program with a completely different background than Earth System Science was a challenge to me in the beginning. But, after hopefully "cracking the code", I understand better the importance of the interdisciplinary research. During all these years, I owe many people and institutions a great debt of gratitude.

I'd like to start with my supervisor, Prof. Dr. Ömer L. Şen, for his professional assistance and patient guidance in raising me as a scientist. His suggestions on the research questions aroused my curiosity on the problem about the future water availability due to human-induced climate change. The outline of the thesis is shaped with my supervisor's precious advice and scientific knowledge. My thesis is based on his research project (114Y114) funded by the Scientific and Technological Research Council of Turkey (TUBITAK). Our attempt to answer the research questions of this thesis pave the way for the future analysis on the water-food-energy-climate nexus of our country. Being aware of the urgent necessity of improving the understanding, I feel and hope that we will continue to work on this investigation. Climate change is a major issue in our current era, and mitigating action needs to be taken immediately.

Secondly, I'd like to express my gratitude to Dr. Ufuk U. Turunçoğlu who was available to give useful advice during my whole Ph.D. He accelerated my first efforts on setting up the technical details for the research. I learned a lot from him during his TUBITAK research project (113Y108). I'm grateful to be able to work with a colleague who is an invaluable scientist.

I'm deeply thankful to Dr. David M. Lawrence for inviting and hosting me as a visitor at the National Center for Atmospheric Research (NCAR). Dave is a very positive and intelligent leader who is respected and deeply loved by other scientists. I learned from him not only how to conduct collaborative scientific research, but also how to be a more organized and productive person. All my colleagues in the Terrestrial Sciences Section of NCAR were incredibly welcoming, encouraging, and helpful. I express my special thanks to Dr. Gökhan Danabaşoğlu who initiated my first contact with Dave. Gökhan is a great scientist who currently leads the Community Earth System Model of NCAR. I learned tremendously about model development and the community efforts on global climate studies. This visit was a unique opportunity that undoubtedly made me a better scientist. I feel so lucky to be a part of the NCAR community. The advice of NCAR's Education and Outreach team were very useful for my future career development. I'm thankful to all professional and administrative staff of NCAR for providing such an inclusive and productive working environment for the visitors. I returned from Boulder back to my country with many new ideas, collaborations, friendships, and good memories.

I'd also like to thank to Prof. Dr. Frode Stordal of the University of Oslo. He is a hardworking, productive and encouraging scientist who provided me a working environment in the University of Oslo (UiO) for the times that I was in Norway. He

invited me to give a seminar at the MetOs department of UiO, and to participate a scientific conference in Norway. During those events, I received beneficial feedback that helped me to improve my thesis. Now, towards the end of my Ph.D., I feel the excitement of being accepted as a PostDoc at UiO to work with one of his projects.

Being a part of Eurasia Institute of Earth Sciences (EIES) for a long time, I appreciate the provided research environment and the holistic vision on the scientific problems of our planet. For this, I'm thankful to the all academic and administrative members of our research institute. I'm also thankful to Prof. Dr. Emin Özsoy for his classes on Geophysical Fluid Dynamics at EIES, and his stimulating scientific and personal discussions on various topics. I am deeply grateful to Dr. Yasemin Ezber and Dr. Yasemin Ergüner for their endless support. I'd also like thank Dr. Orkan Özcan for his help.

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Even though, my Ph.D. journey was a bit long and occasionally challenging, I enjoyed the last period with new people, new ideas, and new places. I'd encourage young scientists, who struggles during their journey, to find their passion and stay with the light of science. There is a long way to go for all of us! Remember, as the great Ataturk said, "Our true mentor in life is science."

March 2019

Yeliz YILMAZ

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ABBREVIATIONS

AEI	: Area Equipped for Irrigation
AIC	: Akaike Information Criterion
AMSR-E	: Advanced Microwave Scanning Radiometer for EOS
AMSR2	: Advanced Microwave Scanning Radiometer-2
AR4	: Fourth Assessment Report
AR5	: Fifth Assessment Report
BIC	: Bayesian Information Criterion
CESM	: Community Earth System Model
CLM	: Community Land Model
CMIP5	: Coupled Model Intercomparison Project – Phase 5
CORINE	: Coordination of Information on the Environment
CRU	: Climatic Research Unit of the University of East Anglia
DEM	: Digital Elevation Model
DSI	: Turkish State Hydraulic Works
ECMWF	: European Centre for Medium-Range Weather Forecasts
EEA	: European Environment Agency
ERA5	: ECMWF Reanalysis 5th Generation
ETB	: Euphrates and Tigris Basin
EVT	: Extreme Value Theory
GAP	: Southeastern Anatolia Project
GCM	: General Circulation Model
GEV	: Generalized Extreme Value
GLCC	: Global Land Cover Characteristics
GP	: Generalized Pareto
GRACE	: Gravity Recovery and Climate Experiment
HW	: Headwaters of the ETB
ICBC	: Initial and Boundary Conditions
ICTP	: The Abdus Salam International Centre for Theoretical Physics
IPCC	: Intergovernmental Panel on Climate Change
LULC	: Land Use and Land Cover
MODIS	: Moderate Resolution Imaging Spectroradiometer

NASA	: National Aeronautics and Space Administration
NCAR	: National Center for Atmospheric Research
RCM	: Regional Climate Model
RCP	: Representative Concentration Pathway
SCD	: Snow Cover Duration
SRES	: Special Report on Emissions Scenarios
SRTM	: Shuttle Radar Topography Mission
SWE	: Snow Water Equivalent
TWS	: Terrestrial Water Storage
TWSA	: Terrestrial Water Storage Anomaly

SYMBOLS

P	: Precipitation
E	: Evapotranspiration
R_s	: Surface runoff
R_g	: Groundwater runoff
S	: Water storage
t	: Time
R_n	: Net radiation
λ	: Latent heat of vaporization
SH	: Sensible heat flux
G	: Ground heat flux
H	: Energy storage
Q_a	: Available energy
u	: Threshold value
F_u	: Conditional distribution function
D	: GP cumulative distribution function
μ	: Location parameter
σ	: Scale parameter
ξ	: Shape parameter
x_m	: Return level of m-year return period

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INVESTIGATING THE HYDROCLIMATIC CHANGES IN THE EUPHRATES-TIGRIS BASIN UNDER A CHANGING CLIMATE

SUMMARY

From the beginning of human history, the transboundary waters of the Euphrates and Tigris Basin (ETB) have been the main freshwater resources of the Middle East region. The basin is located on the territories of four major riparian countries (Iraq, Turkey, Iran, and Syria). These waters have been primarily used for irrigation, energy production, domestic use, and livestock. The Euphrates and the Tigris rivers are fed by the snowmelt from the surrounding high mountains. Previous studies showed that the waters of these two rivers are being affected by anthropogenic climate change. However, particularly the modeling studies did not include the effects of the extensive irrigation schemes that have been applied within the scope of the Southeastern Anatolian Project (GAP). GAP is the largest regional development project carried out by Turkey within the headwaters of the basin. GAP includes such investments as irrigation schemes and the construction of major dams. At the current stage of GAP, 22 dams and 19 hydroelectric power plants have been planned, and over the one fourth of the planned irrigation projects are complete. In the future, a total area of approximately 1.8 million hectares will be irrigated. Since the beginning of 90s, the applied irrigation plans have already caused massive land use and land cover (LULC) changes in the region. We estimate that the water resources of the region will be more vulnerable due to the combined effects of greenhouse forcing and LULC changes. In this thesis, we carefully investigate the effects of human-induced changes on the regional climate and water budget of the ETB.

The research questions of the thesis are designed holistically with the previous studies about the basin in mind. For this purpose, we conducted comprehensive research under four main topics. First, several remote sensing products and a meteorological reanalysis data set were analyzed for the Near East region. The relationship between the decline in the water resources and snowpack is investigated. Secondly, the outputs of several General Circulation Models (GCMs) from CMIP5 were compared over the basin in order to find the “best” performing GCM in simulating the climate of the region. The outputs of the selected GCM are used as initial and boundary conditions to force the regional climate model for dynamical downscaling. Thirdly, the hydroclimatic effects of the LULC changes are assessed by comparing the results of three simulations. These simulations are performed under the current climate conditions by using three land use map that show the different irrigation levels. We also analyzed these outputs to conduct an extreme value analysis in order to understand the effects of irrigation on regional maximum temperatures. Lastly, we investigated the combined effect of the changes in the atmospheric composition and LULC. We calculated the water budgets of the headwaters and the GAP region under the changing climate.

Gravimetric satellite data from GRACE is used to investigate the terrestrial water resources of the basin, and to calculate the change in trends. Globally available GRACE data give information on the terrestrial water storage anomalies between 2002 and 2016. We found that the Euphrates and Tigris Basin has a negative water storage anomaly trend of 27.4 mm per year for the areas above 1000 m. Our finding is consistent with the results from previous studies which use the same data set but for a shorter time period. As the reason of the decline in water resources, they pointed out the groundwater use particularly after the long-term drought in 2007. In this study, we claim that there is a significant relationship between the decline in both water resources and the montane snowpack in the headwaters. Owing to the sparse observational network in the Near East region, we employed several remotely sensed satellite products (optical, passive microwave, and gravimetric) and a new meteorological reanalysis data set in order to analyze the snowpack in the ETB. Comparisons between the GRACE and the remote sensing products showed statistically significant correlations for different elevation thresholds. Moreover, high resolution MODIS data indicate a worrying reduction in snow-cover duration. We calculated significant declines up to 4 weeks per decade for the areas above 1000 m, particularly over the Taurus and Zagros mountains known as headwaters of the basin.

In order to select a GCM amongst the CMIP5 models that represents the climate of Turkey and the Euphrates and Tigris Basin, we analyzed several temperature and precipitation outputs between 1971 and 2000. Those outputs were compared with a high resolution ($0.5^{\circ} \times 0.5^{\circ}$) gridded observational data set, namely Climate Research Unit (CRU). Since all models have different spatial resolutions, model outputs were regridded to the spatial resolution of CRU. Then, these models were ranked according to their statistics. We also used the Taylor diagrams to detect the GCM that produces similar values to the observations. Since the focus of the study is on the water budget, the weight is given to the precipitation performance of the models. As a result, the EC-EARTH model was selected to drive the regional climate model for the future scenarios.

A regional climate model, RegCM4, was employed to simulate the individual and combined effects of irrigation induced LULC changes and climate change. Historical simulations were produced by using three different land use maps which reflect the increase of irrigated and dammed areas. These three maps were created by using the data from the European Environmental Agency and the Turkish State Hydraulic Works based on the default land use map of RegCM4. Results of a reanalysis data set (NNRP) were used to force the RegCM4 model in order to produce dynamically downscaled high resolution regional data over the Eastern Mediterranean and Black Sea region in 48 km, and in a nested domain over Turkey in 12 km. By enabling the subgrid feature of the land surface model of RegCM4, land surface variables were computed at a horizontal resolution of 3 km. To evaluate the model results, CRU temperature and precipitation data, and Global Land Data Assimilation System (GLDAS) evapotranspiration data were used. Comparisons between these three simulations revealed that irrigation causes a local cooling over the GAP region (up to 0.8°C) and a slight increase in precipitation (spatially averaged 7%). Simulation results indicate that irrigation projects have significantly altered the regional water budget due to an increase in evapotranspiration of around 51% (partly irrigated) and 114% (fully irrigated) compared to pre-GAP conditions. The dramatically increasing water demand of the semi-arid irrigated region is currently barely compensated by the headwaters of

the ETB. Taking into account the committed water release to the downstream countries shows that there might not be enough water for all the planned irrigation schemes in the GAP region. These concerning results are found by assuming that the current climate conditions are stationary. However, the future projections from the previous studies pointed towards the changing climate conditions due to anthropogenic greenhouse gas emissions. For this purpose, we performed future simulations by forcing the RegCM4 model with the outputs of EC-EARTH and adding the planned irrigation schemes on them.

Future simulations are produced with two scenarios (RCP4.5 and RCP8.5) for the middle (2046-2065) and the end (2081-2100) of the century. To be able to account for the LULC changes, we also used two land use maps that show no irrigation and fully irrigated conditions. In this way, we addressed both individual and integrated effects of LULC change and greenhouse forcing. The results from future simulations for mid-century show an insignificant temperature increase over the GAP region due to irrigation's cooling effect. But, this cooling effect is completely local. Significant temperature increases are projected up to 2.5°C in the rest of Turkey. Moreover, the severe scenario (RCP8.5) estimates that increase in temperature reaches up to 5°C at the end of the century, while this change is around 2°C in the GAP region. The simulations with RCP4.5 scenario produced a slight increase in precipitation for both future periods, a decline in precipitation is projected with RCP8.5 scenario. Lastly, as in the historical simulations, significant increase in evapotranspiration is estimated in the GAP region. So, water loss through evapotranspiration is projected to have higher values. Hence, the future water budget for fully irrigated conditions indicates that water storage in the headwaters is not enough for the water demand of the GAP region. Taking into account the water release to the downstream countries (15.8 billion m³ per year) shows that future irrigation plans are unsustainable. Even if this water will not be released, the water needed for irrigation in the GAP region is projected to be more than the stored water in the headwaters according to the severe scenario at the end of the century.

The results of the thesis paint a bleak picture for future water availability in the ETB in case of continuing on the current water use plans. In the previous studies, it is showed that using different irrigation techniques can help to reduce water loss by increasing the irrigation efficiency. Another adaptation method is to build new deeper dams with a smaller surface area in the colder headwaters. Additionally, the sustainability of the planned irrigation schemes can be reevaluated by considering the results from future projections. The water dispute in the ETB among the riparian countries is a long-standing complex issue of transboundary water sharing. The water loss through the increased evapotranspiration may play a crucial role in shaping the future of water resources management and policies in this water-stressed region.

DEĞİŞEN İKLİM KOŞULLARI ALTINDA FIRAT-DİCLE HAVZASI'NDAKİ HİDROİKLİMSEL DEĞİŞİKLİKLERİN İNCELENMESİ

ÖZET

Fırat ve Dicle Havzası'nın sınıraşan suları tarihten günümüze Orta Doğu'nun ana tatlı su kaynağı olmuştur. Havza başlıca Irak, Türkiye, İran ve Suriye toprakları üzerinde yer almakta ve havzanın suları sulama, enerji üretimi, domestik ve hayvancılık amaçlı olarak kullanılmaktadır. Fırat ve Dicle nehirlerinin kaynağı ise dağlık bölgelerde bulunan karla kaplı alanlardır. Karla beslenen bu iki nehirin sularının da insan kaynaklı iklim değişikliğinden etkilendiği önceki çalışmalarda gözlemler ve modellerle gösterilmiştir. Fakat modelleme çalışmaları, kaynak ülkesi olan Türkiye sınırları içerisinde gerçekleşen Güneydoğu Anadolu Projesi (GAP) kapsamında gerçekleştirilen sulama projelerinin etkisini hesaba katmamıştır. Günümüze kadar GAP kapsamında planlanan sulama projelerinin yaklaşık olarak dörtte biri gerçekleşmiştir. Gelecekte bu planlanan sulama alanlarının tamamının uygulanması sonucunda (arazi örtüsünü değiştirmesi nedeniyle), iklim değişikliğinin de etkisiyle bölgenin halihazırda azalmakta olan su kaynaklarının kırılganlığının artacağı öngörülmektedir. Bu tez çalışmasında, Fırat & Dicle Havzası'ndaki insan kaynaklı faaliyetlerin bölgenin iklimi ve su kaynaklarına etkisi kapsamlı bir şekilde araştırılmaktadır.

Çalışmanın araştırma soruları bölge hakkında daha önce yapılmış araştırmaları tamamlayıcı olarak tasarlanmıştır. Bu amaçla, tez kapsamında dört ana araştırma konusu detaylı bir şekilde incelenmiştir. Öncelikle, havzayı kapsayan Yakın Doğu bölgesi için çeşitli uydu verileri ve yeni bir meteorolojik reanaliz veri seti detaylı bir şekilde analiz edilmiştir. Bölgedeki su kaynaklarındaki azalma ve bu azalmanın kar örtüsündeki değişim ile olan ilişkisi irdelenmiştir. İkinci olarak, bölgenin ikliminin en iyi şekilde benzetimleyen bir Küresel Sirkülasyon Modeli'ni (KSM) tespit edebilmek amacıyla, uluslararası bir çaba olan CMIP5 deneyleri kapsamında kullanılan mevcut küresel iklim modelleri Türkiye ve Fırat & Dicle Havzası için değerlendirilmiştir. Bu seçilen KSM'nin çıktıları kullanılarak bu tez çalışmasının omurgasını oluşturan dinamik olarak ölçek küçültme amaçlı çalıştırılan bölgesel iklim modeli çalıştırılmıştır. Üçüncü olarak, bölgesel iklim modeli sulama projelerinin olmadığı, günümüzdeki ve tamamlanması durumlarını gösteren üç farklı altlık harita ile çalıştırılarak, sulamanın bölgenin hidroiklimine etkisi araştırılmıştır. Hatta bu benzetimlerden bazıları kullanılarak uç değer analizi yapılmış ve sulamanın maksimum sıcaklıklara etkisi de incelenmiştir. Son olarak, sera gazı emisyonlarından kaynaklı iklim değişikliği ve arazi örtüsünün değişmesinin bütünleşik etkisi modelleme çalışması yardımıyla kestirilmiştir. Kaynak bölgesi ve GAP bölgesindeki değişen iklim koşulları altındaki su bütçesi hesaplanmıştır.

Bütün havzanın su kaynaklarındaki azalmayı doğrulamak ve değişim miktarını hesaplamak amacıyla yerçekimsel uydu olarak bilinen GRACE verileri kullanılmıştır. Küresel bir veri seti olan GRACE, 2002-2016 yılları arasındaki depolanan toplam su

miktarındaki anomaliye dair bilgi vermektedir. Fırat & Dicle Havzası'ndaki 1000 metreden yukarıdaki alanlarda depolanan su miktarındaki değişime bakıldığında yılda 27.4 mm'lik bir azalma eğilimi olduğu hesaplanmıştır. Literatürdeki çalışmalarda, daha kısa zaman aralığı için yapılan GRACE analizleri bu bölgede benzer bir trendden bahsetmişlerdir. Su miktarındaki azalmanın ana nedeni olarak ise, özellikle 2007 yılından sonra görülen uzun süreli kuraklı dönemindeki yeraltı sularından yapılan su takviyesi gösterilmiştir. Bu tez çalışmasında, su miktarındaki azalmanın bölgenin asıl su kaynağı olan kar örtüsü ile ihmal edilemeyecek kadar büyük ölçüde bir ilişki olduğu öne sürülmüştür. Geniş bir alana sahip Fırat & Dicle Havzası'ndaki seyrek gözlem ağı yerine, farklı uydu verileri ve meteorolojik reanaliz verisi kullanılarak tüm Yakın Doğu bölgesindeki kar verileri analiz edilmiştir. Farklı zamansal çözünürlüklerine sahip uydu ve reanaliz verileri GRACE verisi ile karşılaştırıldıklarında istatistiksel olarak anlamlı korelasyonlar bulunmuştur. Ayrıca yüksek çözünürlüklü MODIS verisi, kar örtüsünün yerde kalma süresindeki endişe verici azalmayı ortaya çıkarmıştır. Özellikle havzanın kaynak bölgeleri olan Toros ve Zagros dağlarının yüksek kısımlarında (1000 m'den yüksek) on yılda 4 haftaya ulaşan azalmalar hesaplanmıştır.

CMIP5 modelleri arasından Türkiye ve Fırat & Dicle Havzası'nı en iyi temsil eden modeli seçmek amacıyla, 1971 ve 2000 yılları arasındaki benzetimlerin sıcaklık ve yağış çıktıları kullanılarak kapsamlı bir analiz yapılmıştır. Model çıktıları gridlenmiş yüksek çözünürlüklü ($0.5^{\circ} \times 0.5^{\circ}$) gözlem verisi olan CRU ile karşılaştırılmıştır. 45 tane küresel model çıktısının her biri farklı yersel çözünürlüğe sahip olduğu için öncelikle hepsi gözlem verisi olan CRU'nun çözünürlüğüne uyarlanmıştır. Sonrasında model ve gözlem arasındaki temel istatistikler incelenmiş, gözleme göre en az hata verme oranlarına göre performance sıralası yapılmıştır. Ayrıca Taylor diagramları kullanılarak gözleme en yakın modeli bulmak amaçlanmıştır. Tez kapsamında su bütçesi hesapları ön planda olduğu için, performans sıralamalarında modellerin yağışı benzetimleyebilmelerine ağırlık verilmesi sonucu, EC-EARTH isimli küresel modelinin seçilmesine kanaat getirilmiştir. EC-EARTH modelinin çıktıları sonraki aşamalarda çalıştırılacak bölgesel iklim modelinde başlangıç ve sınır değeri olarak kullanılmak üzere hazırlanmıştır.

RegCM4 isimli bölgesel iklim modeli arazi örtüsü ve iklim değişikliğinin etkilerini benzetimlemek için ana araç olarak kullanıldı. Model öncelikle günümüz iklim koşulları altında farklı sulama seviyelerini ve barajları gösteren arazi kullanımı haritaları ile üç farklı benzetim için çalıştırılmıştır. Bu üç harita Avrupa Çevre Ajansı ve Devlet Su İşleri'nden alınan veriler yardımı ile RegCM'in önceden tanımlı altlık haritası da kullanılarak oluşturulmuştur. NNRP reanaliz verisi başlangıç ve sınır koşulu olarak kullanılarak 1991-2010 yılları arasında önce Doğu Akdeniz-Karadeniz bölgesi üzerinde 48 km, sonra da Türkiye üzerinde 12 km çözünürlükte ölçek küçültülmüştür. RegCM4 modelinin kara yüzeyi modelindeki bir özellik de kullanılarak yer yüzeyindeki süreçler 3 km yüksek çözünürlükte modellenmiştir. Bölgesel iklim modelinin performansı sıcaklık ve yağış için CRU, terleme-buharlaşma için GLDAS verisi kullanılarak değerlendirilmiştir. Bu üç benzetimin sonuçlarının kendi aralarında kıyaslanması neticesinde, aynı iklim koşullarında GAP bölgesindeki sulama yapılan alanların artması bölgesel bir soğumaya (0.8°C 'ye varan bir değişim), yağış miktarlarında küçük bir miktarda artışa (en fazla %7), ve en önemlisi terleme-buharlaşma seviyelerinde istatistiksel olarak anlamlı artışa neden olmuştur. Günümüzdeki sulama miktarları (GAP sulama projelerinin %25'i) hiç sulama olmayan koşullara göre %51'lik bir terleme-buharlaşma artışına neden olurken,

sulama projelerinin tamamlanması durumunda %114'lük bir artış modellenmiştir. Bulunan bu değerlerle Fırat ve Dicle Havzası'nın Türkiye'deki kısmının su bütçesi hesaplandığında görüldü ki; kaynak bölgesinde saklanan tüm suyun kullanılması durumunda diğer havza ülkelerine de salınacak su göz önünde bulundurulursa, GAP kapsamında planlanan tüm sulama projeleri için yeterli su miktarı bulunmamaktadır. Bu çarpıcı sonuç, günümüz iklim koşullarının değişmeyeceği kabulü ile elde edilmiştir. Bu sebeple, sera gazı emisyonları kaynaklı bölgede öngörülen iklim değişikliği koşullarını da hesaba katmak ve gelecek dönemlere ait benzetimler için EC-EARTH modeli kullanılarak RegCM4 çalıştırılmıştır.

Gelecek için benzetimler 2046-2065 ve 2081-2100 dönemleri olmak üzere yüzyılın ortası ve sonu için iki farklı senaryo (RCP4.5 ve RCP8.5) kullanılarak gerçekleştirilmiştir. Ayrıca değişimleri hesaplayabilmek için hiç sulama olmayan ve gelecekteki sulamanın tamamlanması koşullarını gösteren iki adet arazi kullanımı haritası da kullanılarak, karşılaştırmalar yapılmıştır. Bu sayede atmosferin kompozisyonundaki değişim ve arazi örtüsü değişikliğinin etkileri hem ayrı ayrı hem de birlikte incelenmiştir. Yüzyılın ortasına ait model çıktıları GAP bölgesinde sulamanın soğutma etkisinden kaynaklı bir sıcaklık değişimi gözlenmemiştir. Fakat bu etki tamamen yerel olup Türkiye'nin geri kalan bölgelerinde 2.5°C'ye varan sıcaklık artışları elde edilmiştir. Yüzyılın sonunda ise kötümser senaryo (RCP8.5) göstermiştir ki, Türkiye'deki sıcaklık projeksiyonları 5°C'ye ulaşırken, GAP bölgesindeki sıcaklık artışı 2°C seviyelerindedir. RCP4.5 senaryosu yüzyılın ortası ve sonu için bu bölge üzerinde küçük miktarda yağış artışı gösterirken, RCP8.5 GAP bölgesinde genelde azalmaya işaret etmektedir. Son olarak, terleme-buharlaşma değerleri aynı günümüz döneminde olduğu gibi gelecekte de GAP bölgesi üzerinde istatistiksel olarak anlamlı bir şekilde artabilir. Bu durumda, buharlaşma ile su kaybı daha yüksek miktarlara ulaşabilir. Nitekim gelecek için su bütçesi hesabı yapıldığında, sulama projelerinin tamamı uygulamaya geçilirse, GAP bölgesinin su ihtiyacını karşılamak için kaynak bölgesinin su rezervi yeterli görünmemektedir. Tabii bu hesaplar Fırat nehrinden diğer havza ülkelerine gönderilecek yıllık 15.8 milyar m³ su üzerinden yapılmıştır. Gelecekte bu suyun paylaşılmaması durumunda dahi, kötümser senaryoya göre yüzyılın sonrasında GAP'ın su ihtiyacı kaynak bölgesinde tutulan su miktarından fazla olabilir.

Çalışma kapsamında yapılan benzetimler mevcut su kullanımı yöntemlerinin gelecekte de devam etmesi durumunda bizlere kötüye giden durumu işaret ediyorlar. Daha önce yapılan çalışmalarda da gösterildiği üzere, daha etkin sulama yöntemleri kullanılarak buharlaşma ile olan su kaybı miktarı azaltılabilir. Başka bir adaptasyon yöntemi ise, barajların daha serin olan kaynak bölgesinde tutulması ve hatta yüzey alanı daha küçük barajların inşa edilmesi göz önünde bulundurulabilir. Ya da GAP kapsamında planlanan sulama projelerinin sürdürülebilirliği konusu baştan dikkatlice gözden geçirilmelidir. Tarihte Fırat ve Dicle'nin sınıraşan sularının havza ülkeleri arasında paylaşımı konusunda nice anlaşmazlıklar olmuştur. Bu çalışma insan kaynaklı iklim değişikliklerinin bölgenin hidroiklimsel koşullarını zorlayacağını ortaya koymuştur. Buharlaşma nedeniyle öngörülen su kaybının artışının gerçekleşmesi, havza ülkeleri arasındaki anlaşmazlığın daha zorlu duruma gelebileceğine işaret etmektedir. Bu sebeple karar alıcılar bölgenin iklim değişikliğine karşı olan kırılganlığını göz önünde bulundurarak, uzun vadeli su kaynakları yönetimi ve politikaları geliştirmelidirler.

1. INTRODUCTION

The Euphrates and Tigris Basin (ETB) is the most important basin of Turkey in terms of water resources. The investments that have been carried out within the scope of the Southeastern Anatolia Project (known by its Turkish initials as GAP) have already caused immense land use and land cover (LULC) changes in the region. It is a known fact that the opening vast fields to irrigated cultivation and dam construction alter the climate through changing the land surface characteristics. Also, this change has been simultaneously happening with the climate change caused by the release of the greenhouse gasses into the atmosphere. There are many studies that investigated the effects of global climate change on the ETB. However, these studies are not complete, as they primarily lack the LULC changes. In this thesis, it is aimed to mitigate this shortcoming, and to study comprehensively the future of the region in terms of both climate and water resources.

Modification of land cover and land use types (i.e. deforestation, desertification, urbanization, and extension of the agricultural fields) are all together called land use and land cover change. The LULC change modulates several terrestrial biogeophysical and biogeochemical processes, particularly the surface energy and water budget [1-4]. When the LULC change reaches a certain threshold it may cause permanent impacts and changes in the local (e.g. [5]), regional (e.g. [6,7]) and global (e.g. [8-11]) climate. Previously, the LULC changes were not considered in the studies that aimed to produce future climate change projections. However, such changes have been increasingly taken into account in recent regional projection studies. The ETB, which is critical for Turkey, is subjected to LULC change at serious extents, especially with the extension of irrigated cultivation. The irrigation projects planned within the scope of GAP have just been over the realization of one fourth. This implies that the extent of the future irrigated fields in the region will be larger than at least three times the extent of the present irrigated fields. The extension of the irrigated fields will affect the water resources of the region by increasing water loss through evapotranspiration, and

cause a change in the climate of the region through transfer of moisture from surface to atmosphere at large quantities. There are not many studies that investigate these possible impacts and changes. On the other hand, many studies have unequivocally revealed that the climate change has been happening globally as a result of the release of greenhouse gasses into the atmosphere. The solution of the multi-dimensional problem (involving energy, agriculture, transboundary waters, etc.) existing for the ETB nowadays could be more difficult in the future due to both global climate change and LULC change related effects. This study, by producing data for the future of this problem, will provide a basis for the decision makers and politicians to develop appropriate solution policies for the future of the problem.

In this study, the main methodology is the regional climate modeling. A regional climate model (RCM), RegCM4, that has been developed by the Abdus Salam International Centre of Theoretical Physics (ICTP) was employed for the simulations. The land surface model of the latest version of the RegCM4, at that time, could resolve the surface features better with the sub-grid feature. Thus, the surface fluxes (sensible heat, latent heat, etc.) could be obtained more accurately by running the land surface model at a higher resolution compared to the atmospheric part. The quality of the input data for the regional climate model is important as well as the model's physical features. This problem is often referred to as "garbage in garbage out" (GIGO) [12]. Therefore, a GCM (General Circulation Model) is selected among the CMIP5 (Coupled Model Intercomparison Project – Phase 5) models in order to drive our future simulations. The future LULC map is generated based on the irrigation projects within the scope of GAP. After setting up the input data sets, several regional climate simulations are performed over our study domain. In the following time, we analyzed the outputs of the RCM runs for calculating the water budget and extreme temperatures of the ETB.

1.1 Literature Review

The outputs of GCMs are indeed useful and relatively easy to access for investigating the future climate change and its impacts through international initiatives such as Intergovernmental Panel on Climate Change (IPCC). Since, the GCMs are designed to solve numerically the global physical processes, they do not provide information

for regional scales in detail. Hence, they are generally insufficient for the studies of regional climate change and hydrology [13]. High-resolution climate data have been obtained by downscaling the GCM outputs to deal with this problem. By this way, we can investigate the climate change impacts at local and regional scales [14]. There are two methods for regional downscaling of GCM outputs: dynamical downscaling and statistical downscaling. Dynamical downscaling is preferred in our study since it simulates the dynamical and physical processes, even though it is computationally expensive. In the dynamical downscaling method, an RCM is driven by the outputs of a GCM as the initial and boundary conditions of the atmosphere and surface. The RCM produces higher resolution climate data. As for statistical downscaling method, statistical transfer functions have been used to create link between GCM outputs and regional climate. The effects of climate change on water (hydrological) cycle and water resources have been investigated by using the high resolution regional climate projections obtained from dynamical downscaling (e.g. [15-18]). Hydrological models are driven by the high-resolution climate data which can be used for basin studies [19]. For this reason, the use of the climate model outputs such as snow water equivalent and runoff has vital importance [19-22]. These variables are calculated by using the atmospheric variables such as precipitation, temperature, wind speed, moisture, shortwave and longwave radiation. Hence, hydrological simulations are important to show the impacts of climate change on hydrological cycle [17, 22]. The outputs of sophisticated atmospheric models provide variations of not only several atmospheric parameters, but also surface energy and water balance. Complex surface-atmosphere models are used for the water balance calculations for each grid cells. These models compute the surface runoff for a specific grid cell by taking into the account the processes such as precipitation, interception, snow accumulation, snow melt, evapotranspiration, infiltration, etc. In this study, we will use the outputs of the employed RCM in order to calculate the regional water and energy balances.

In the Forth Assessment Report (AR4) of IPCC [23], outputs of GCM models for different emission scenarios showed that precipitation rates will decrease dramatically in the Mediterranean Basin towards the end of the 21st century. Thus, this region, defined as one of the climate change hot-spots [13], will become vulnerable to climate change. It is also pointed out that the frequency and intensity of droughts

have been increased in the Mediterranean in the AR5 of IPCC [24]. Simulations performed by different GCMs showed a decrease in precipitation in the Mediterranean Basin. A regional climate modeling study [25] showed that Atlantic storm track shifted northward associated with intensified sub-tropical high pressure cells over Mediterranean region. This change may cause an increase in precipitation of Black Sea Basin, and decrease in precipitation of Mediterranean Basin.

In several downscaling studies [26-28] conducted with regional climate models, a decrease in precipitation is projected for Turkey under several different Special Report on Emissions Scenarios (SRES) of AR4 [29]. In the study of [26], climate change in the Eastern Mediterranean Basin was investigated for the last 30-year period of twenty first century by using the results of A2 scenario simulation that is obtained from the outputs of a global climate model called fvGCM of NASA. As other studies [30, 31], this study showed that the future precipitation of Turkey will decrease in the southeastern region and along the coasts of the Mediterranean and the Aegean Sea. Contrary to this, the coast of the Black Sea (particularly the eastern part) is projected to receive more precipitation. According to the study of [32] almost all models, which were used in an ensemble study, have similar results: decrease (5-25%) in precipitation in the western part of Turkey for the first half of the 21st century. Evans [33] investigated eighteen different GCM results for Middle East region and showed that the biggest decrease (more than 25%) in precipitation expected to be seen in the southwestern part of the Turkey in 2095 due to considerable decrease in storm activities over Eastern Mediterranean region. The annual discharge of the Euphrates River is projected to decrease significantly (29-73%) related to the decrease in precipitation in the Euphrates Basin towards the end of 21st century [34]. The analyses by [18] showed that the adverse hydrometeorological impacts of climate change on Seyhan Basin also involves Çukurova, one of the important plains of Turkey. In this study, bias-corrected dynamically downscaled temperature and precipitation data sets were tested by comparing with observation data sets. Dynamically downscaled model outputs were used as an input to the land surface model, the Simple Biosphere including Urban Canopy (SiBUC). Afterwards, the variables such as surface runoff and reservoir volume were calculated for this basin. The simulations forced with two GCMs (MRI-CGCM2 and CCSR) under the SRES A2 scenario indicated a

considerable decrease in snow water equivalent and surface runoff compared to the present values for Seyhan Basin. Annual streamflow will decrease in the range of 50% - 60% according to analysis of precipitation and evapotranspiration data sets, which were obtained from two different global models. Another study [35] investigated the impacts of sea surface temperature change in the surrounding seas of Turkey on the precipitation of Anatolian peninsula by conducting the sensitivity simulations. It is revealed that warmer summer and autumn sea surface temperatures might enhance the precipitation of the Anatolian peninsula which can trigger the flash floods and torrential rainfall events.

For the future temperature projections, the results of a simulation under a relatively pessimistic scenario (SRES A2) showed an increase in summer temperatures by around 4-5 °C for Turkey towards the end of the century [27]. According to this study, winter runoff increases due to an increase in snow melt over the high mountains after the mid-century. These seasonal changes in surface runoff are crucial particularly in the Eastern Anatolian region which feeds two large rivers namely the Euphrates and the Tigris. For the latest scenarios of IPCC assessments (RCPs [36]), several studies showed a similar temperature increase pattern over Turkey. An RCM study [37] over the Middle-East and North Africa estimated a significant warming with a considerable decrease in precipitation over the whole region at the end of the 21st century. For the same study domain, future projections of another downscaling study [38] indicate higher temperature values between 3-9 °C for the same time period. A study [39] with three GCMs and two RCP (Representative Concentration Pathway [36]) scenarios estimated an increase in the future temperature of Turkey by around 1-6 °C (depending on the scenario and the model). A detailed statistical analysis [40] by using the outputs of future CORDEX simulations [41] showed a significant shift in precipitation seasonality over the Black Sea region and the southeastern Anatolia. All these studies point out the Eastern Anatolia as one of the vulnerable regions in Turkey to climate change. This area is very important in terms of the water resources of Turkey since the headwaters of the ETB is located here. These findings indicate that the water resources of the basin might be under threat in the future.

Historically, prolonged droughts and a lack of water security have been major sources of conflict in this water stressed region [42-45]. Currently, the water resources of

the Near East are reported as highly vulnerable [1, 46] with severe water scarcity throughout the year [47]. Worryingly, the sustainable use of this region's water resources is threatened by the projected climate change related both to greenhouse forcing and land use change [24, 27, 48, 49].

The globally-available satellite retrievals of total terrestrial water storage (TWS) from the Gravity Recovery and Climate Experiment (GRACE) [50] are invaluable for diagnosing the state of water resources in areas such as the Near East where the availability of ground observations are both physically and politically limited. The GRACE TWS retrieval represents the water equivalent thickness which is the aggregate of all the water storage components within a pixel, namely soil moisture, surface water, groundwater, ice and snow [51]. Voss et al. [51] used GRACE data to show the water loss in the Tigris-Euphrates-Western Iran region. They used the outputs of NASA's Global Land Data Assimilation System (GLDAS) to decompose the GRACE TWS signal into its various storage components. Through this approach, they estimated a groundwater depletion of $17.3 \pm 2.1 \text{ mm yr}^{-1}$ for the period between 2003 and 2009. [52] underlined that the groundwater contribution to the GRACE observation can be underestimated by half if the spatial distribution of the reservoirs is not considered in the Euphrates and Tigris Basin (ETB). Another study for this region was conducted by [53] using GRACE TWS data, a land surface model, and well observations. Their model outputs showed that a decrease in groundwater storage is the reason for a negative GRACE TWS trend pattern mainly centered over the northern part of the Iraq-Iran border. After the drought in 2007, the human-induced groundwater loss was recovered in the upper part of the ETB by 2013. The same recovery was not found for the groundwater storage in Iran [53]. In another study, [54] found that total water flux values derived from GRACE and those obtained from two reanalysis datasets (ERA-Interim and MERRA-Land) had high correlations for the mountainous regions of the ETB. They calculated negative water flux trends of around $-2.6 \text{ mm month}^{-1}$ per year. Recently, [55] estimated a decrease in total water storage of around $32.1 \pm 1.5 \text{ Gt yr}^{-1}$ for the northern Middle East region which includes eastern Turkey, Iran, Iraq, and Syria. They claimed that a large negative trend occurred as a result of groundwater depletion and drought which are categorized as a "possible or partial direct human

impact". All these findings point towards a severe depletion of water resources in the region.

Decomposing the total water storage into its components shows a clear signal of groundwater depletion in the Near East region [51-55]. Additionally, surface soil moisture trends show a significant decrease for the Middle East region [56]. Similar results were found over a longer time period by [57]. They also showed a drying tendency in the arid land areas. Among the components of TWS, the mountain snowpack, typically expressed as the volume (or mass) of snow water equivalent (SWE), is an important but less studied part in this equation in the Near East. In this region, the high mountain snowpack acts as a water tower [58]. It is thus important to better understand the role of snow in the TWS signal.

Observations from space play an important role in monitoring the state of the Earth's snow-cover [59]. The accuracy of MODIS snow-cover products (MOD10A1 and MOD10A2) has been evaluated through several studies conducted in the Karasu basin located in the headwaters of the Euphrates River [60-63]. These early studies reveal that these products were reasonably accurate, although clouds were a notable source of error. Ensuing studies in the Karasu basin reduced the cloud problem by making use of the composite 8-day MODIS snow-cover product (MOD10C2) and passive microwave SWE retrievals [64,65]. It was found that a decrease in precipitation and increase in temperature had led to a decrease in peak discharge amounts and an earlier snowmelt timing in both the 2008 and 2009 water years [65]. A strong negative correlation was found between the MODIS snow-covered area and in-situ runoff which is not surprising given that 60-70% of the annual streamflow in the Karasu basin is snowmelt runoff [66]. Snowmelt estimation is thus important in the context of managing the water resources of this region. For this purpose, several studies [66-70] developed different methods for forecasting the daily snow-cover and streamflow.

Both ground observations [71,72] and satellite products [65] show that increasing temperatures have led to earlier spring snowmelt in the mountainous parts of the ETB. Sen et al. [71] investigated the changes in discharge amounts in the ETB and teleconnection patterns, and concluded that earlier snowmelt typically occurs during the negative phase of the North Sea-Caspian pattern. Another study [72] showed that streamflow timing in eastern Anatolia is already occurring over a week earlier

compared to the climatological average for the period 1970-2010. By running regional climate simulations under a high emissions scenario, they projected that by the end of the century this shift would be as large as one month. The end of century projections also showed a considerable decrease in surface runoff for the Aras, Euphrates, and Tigris basins; a lower decline was found for the Coruh basin. In a hydrological modeling study, [73] found similar results, projecting a decrease of 19-58% in annual streamflow in the ETB by the end of the century, corresponding to a temporal shift of streamflow timing of around 3-5 weeks. [74] evaluated the snow water availability in the whole ETB by forcing their model with the outputs of several regional climate simulations. Even though the results (decrease in SWE between 10 to 60 %) show variations due to the different input data, they agreed on a significant decrease in SWE in the lower elevations (under 500m) by the end of the century. A comprehensive analysis of snowmelt projections for different elevation bands was conducted by [27] for the ETB. Their five different regional climate model outputs projected that the seasonal snow-cover would vanish in the lower regions (elevation between 1000 and 1500 m) at the end of the century. Moreover, snow in the middle and higher elevation regions (elevation > 1500 m) were projected to share same destiny for the model outputs forced under various future scenarios. These projections, including business as usual, paint a bleak picture for the future of the water resources of the Near East region.

The extension of the irrigated areas have a potential in affecting the water resources of the region through increased evapotranspiration. The subsequent water loss might enhance the pressure on both production of the energy and the amount of released water to the downstream countries. Finding solution to this multidimensional problem on water resources might be more difficult in the basin due to increasing complexity. The available data are not sufficient to produce reliable solution policies. Recent extreme weather events in the region gave clues about what could happen in the region. For instance, drought over the Mesopotamia region in 2007 caused significant decreases in water resources. Loss in water resources was 144 billion m³ for the region [51]. As a result, the agriculture and livestock were affected, and human migration started. Although Turkey was affected from drought, the water demand of Syria and Iraq increased. A study [44] claim that the chaotic environment after

the most severe recorded drought in Syria between 2007 and 2010 contributed to the Syrian insurrection in 2011. It is obvious that more knowledge about the Euphrates and Tigris Basin is needed to create effective policies for the similar events.

1.2 Purpose of Thesis

The partitioning of the waters of the Euphrates and Tigris rivers between energy production, irrigation, and release for the downstream countries is an ongoing complex issue for the major riparian countries (Iran, Iraq, Syria, and Turkey) in the region. The transboundary water governance has been easily affected from the political situation in the region [75]. At this point, policies must be developed to deal with these problems that may become more complicated over the time. Climate change mitigation plans could be built by the permanent binding clauses on sharing the waters of the Euphrates and Tigris rivers. Therefore, the decision makers need scientifically produced unbiased information in order to make the right decisions. In this thesis, it is aimed to investigate the effects of the irrigation plans on the water resources of the ETB under the current and future climate conditions. By this way, we can contribute to the development of efficient policies for the sake of solving the upcoming issues. The purpose of this study is to produce information for decision makers and politicians to enable them to make the right decisions about the future of the ETB.

Our hypothesis is that human-induced LULC changes enhance the effects of the climate change due to the greenhouse forcing. We estimate that an increase in evapotranspiration due to the extensive irrigation would significantly effect the surface processes. So, the planned future irrigation in the headwaters of the basin would affect severely the water resources of the region along with the projected increasing temperatures and decreasing precipitation. In order to test our hypothesis, we set up our experiments (model simulations) independently such as only LULC change, only greenhouse gas change, and combined change. Then, we carefully analyze the model results in detail.

Research objectives

The objectives of this study are :

1. to investigate the satellite-based observational evidences for snow-related decline in water resources.
2. to find the best performing global climate model over the study area.
3. to reveal the effect of only irrigation projects in GAP on the regional climate and water budget.
4. to determine the impacts of irrigation on temperature extremes in the GAP region.
5. to calculate the current and future water loss through evapotranspiration due to the extension of irrigated cultivation areas.
6. to quantify the potential impacts of combined changes in LULC and greenhouse gasses on the near and distant future climate of the region.
7. to carry out a brief research on the effects of different irrigation techniques on water loss in order to understand the irrigation efficiency in the region.

1.3 Method and Flow

Figure [1.1](#) illustrates the flow of the monograph and the research topics investigated in the thesis. The importance of the research questions and the background were introduced in Chapter 1.

In Chapter 2, we first conducted a comprehensive research for understanding the role of snow in declining water resources in the ETB. For this purpose, several different satellite-based data sets and a meteorological reanalysis were analyzed. The results are given and discussed in Section [2.2](#). Then, the details of the human-induced LULC changes in the headwaters of the ETB were described in Section [2.3](#). Here, we emphasize only the irrigation and dam plans within the scope of the GAP. In this study, the extensive water use plans in the downstream part of the basin are not taken into account.

Dynamical downscaling is the main methodology of the thesis. The regional climate models use their initial and boundary conditions (ICBC) from reanalysis data based

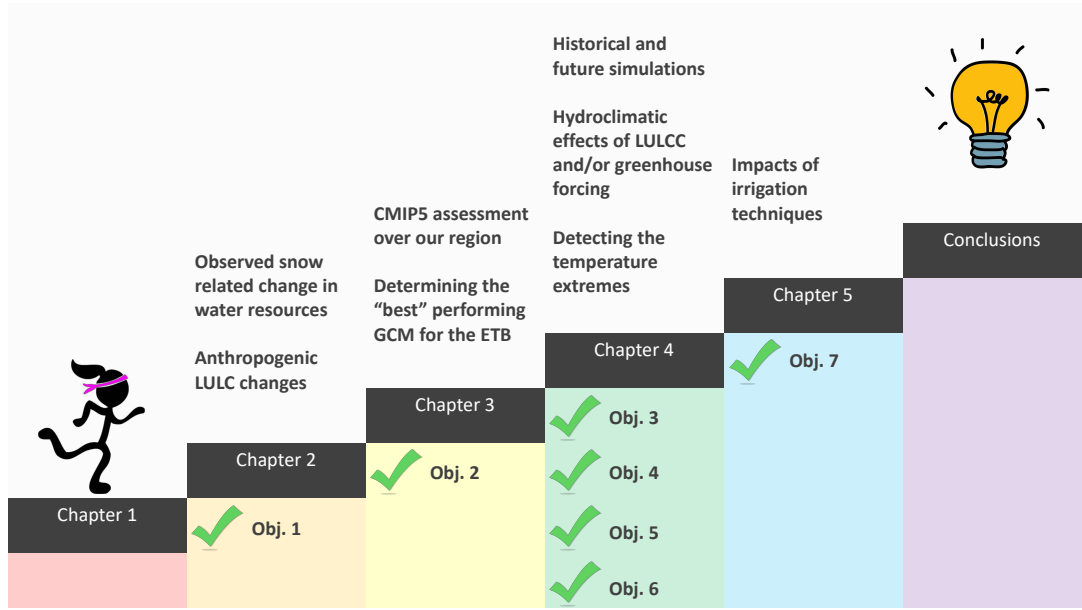


Figure 1.1 : An illustration shows the methodology and flow of the thesis. The items on the steps show the research aims, while the check marks are the achieved objectives in each chapter.

on observations or from simulation outputs from the GCMs. Before performing any simulations by using the regional climate model, we intended to select the "best" possible ICBC for the experiments. As the methodology, we compared the GCM outputs from the CMIP5 to the gridded observation data over our study domains (see Section 4.1.3). For the assessment, the GCMs are ranked according to their descriptive statistics (average, standard deviation, root mean squared error, correlation) in Chapter 3. We also used the Taylor diagrams [76] for both temperature and precipitation data to diagnose the performances of the GCMs for selection.

As mentioned earlier, the backbone of the thesis is the regional climate model simulations with the RegCM4 model developed by ICTP. Chapter 4 pertains to the results of all the historical and future simulations. The reference period simulations are forced with both reanalysis data and the outputs of the selected GCM. We run the historical simulations by using three land use maps which show the different irrigation levels in the GAP region. By comparing these simulations, we expect to assess the hydroclimatic effects of LULC changes in the ETB (see Section 4.2). Additionally, the impacts of irrigation on the regional maximum temperatures are investigated by using an advance statistical method, namely the Extreme Value Theory (EVT) in Section 4.2.4. The future simulations are performed by using two scenarios (RCP 4.5 and RCP 8.5 [36]) with two land use maps which shows non-irrigated and fully irrigated

conditions for a simulation period in the middle of the century (from 2046 to 2065). Lastly, we run two more simulations for the end of the century (between 2081 and 2100) with fully irrigated land use map in order to calculate the water budget under changing climate conditions (see Section 4.3). We expect that the comparison of these simulations (total of ten) will reveal the impacts of climate change as a result of only greenhouse gas emissions or land use change, and both human activities (greenhouse gas release plus LULC change).

Lastly, Chapter 5 includes the results from an attempt to understand the effects of different irrigation techniques. The last version of the Community Land Model, CLM5, of the National Center for Atmospheric Research (NCAR) was employed to simulate the irrigation amounts in the ETB. This sophisticated land surface model allows us to simulate very complicated land surface processes in detail. We wanted to test how CLM5's new irrigation module can capture the amount of water loss which is highly sensitive to the applied irrigation techniques.

2. THE EUPHRATES AND TIGRIS BASIN

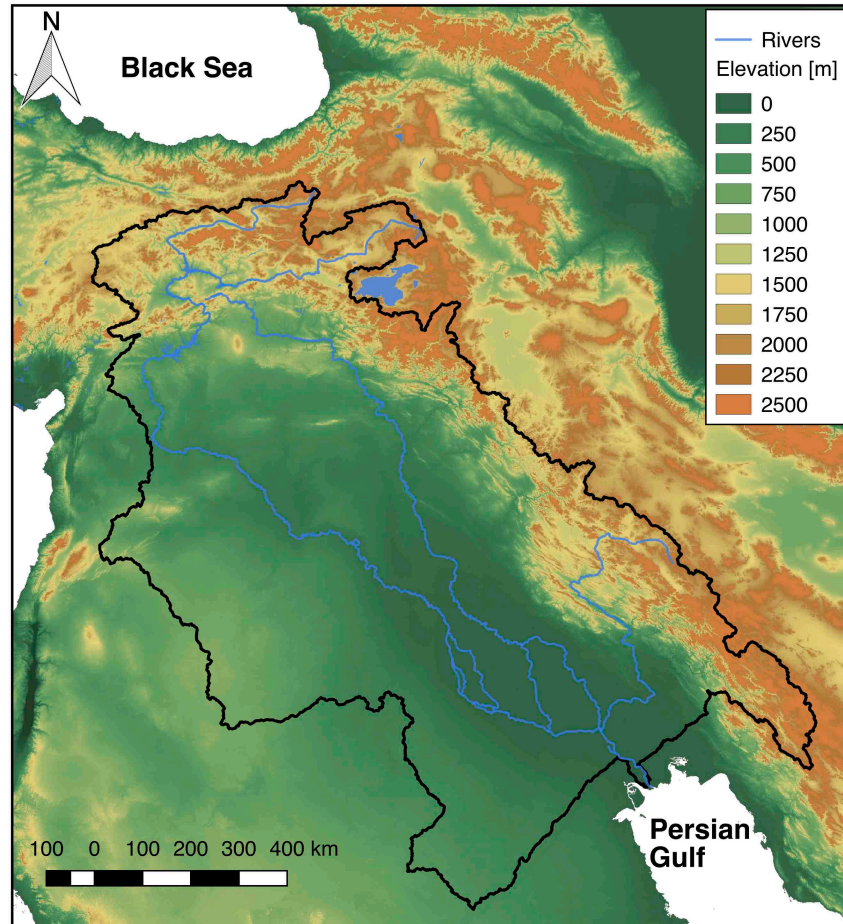


Figure 2.1 : Topography and borders of the Euphrates and Tigris Basin.

2.1 Physical Characteristics and Climate

The ETB is one of the largest transboundary basins in the world, located in the territories of six riparian countries (Turkey, Iraq, Iran, Syria, Saudi Arabia, and Jordan). The waters of this basin is distributed to populations of around 65.5 million [77]. The ETB, with 868,060 km² drainage area, is assumed to be the most important water resources in the Middle East region [31]. The Euphrates and the Tigris rivers have a length of approximately 3000 km and 1850 km, respectively. Both rise at the highlands of eastern Anatolia and flow into the Persian Gulf. The ETB is flanked by high mountains in the north and east. The average elevation of the ETB is 734 m a.s.l. with 26.4%, 8.15%, and 0.4% of the basin situated above 1000, 2000, and 3000 m a.s.l.,

respectively. Notable peaks include Uludoruk (37.48°N,44.00°E) at 4134 m a.s.l. in the Turkish part of the basin, as well as Zard-Kuh (32.64°N, 50.07°E) at 4221 m a.s.l. and Mount Dena (30.95°N,51.43°E) at 4409 m a.s.l. which are both situated in the Iranian Zagros mountains in the southeastern part of the basin.

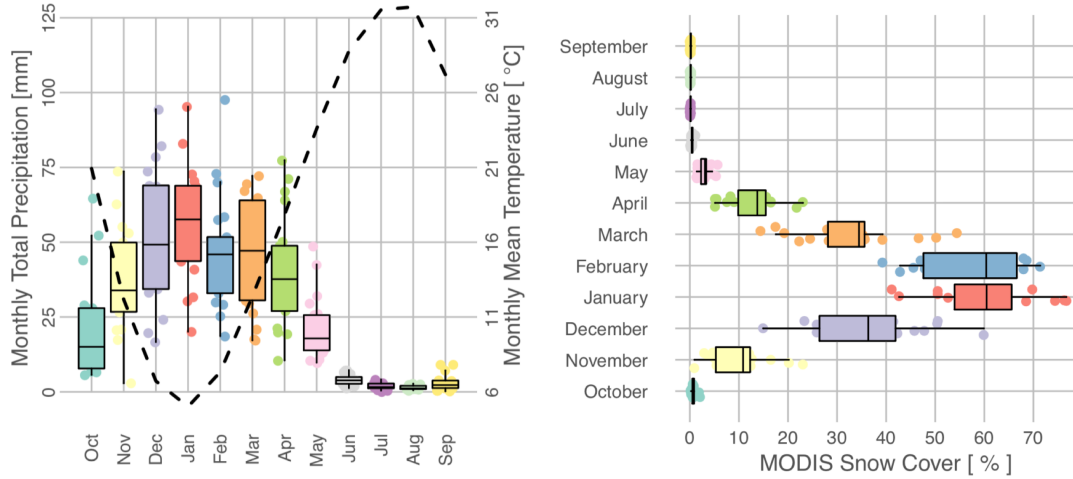


Figure 2.2 : Climatology of the ETB. The boxplots on the left is the precipitation ERA5, while the black dots are the temperature. The boxplots on the right show the MODIS snow cover.

Figure 2.2 shows the basin-averaged precipitation, temperature, and snow cover above 1000 m. According to the MODIS data, ETB has lower median snow cover of 60% in mid-winter with a notably larger inter-annual variability. The climatological (2000-2018) basin averaged 2 m air temperature from ERA5 is 18.7°C [49]. The whole basin receives 357 mm of average annual rainfall [77], while this amount is around 561.3 mm [78] in the northern part of the basin (22 percent of the total area) which is the most important basin for Turkey in terms of water resources. In the total basin area, annual discharge amount is about 147.67 km³/year, while annual runoff is 170.12 mm/year [77]. The Turkish section of the ETB contributes 90% and 51% of the total annual water volume of the Euphrates and Tigris rivers, respectively [79]. This snow-fed river basin is vulnerable to projected climate change [27,31,46].

In this thesis, we first investigated the snow related changes in the whole ETB (Figure 4.5). Then, the upper ETB in Turkey is split into two regions defined as the headwaters (HW) and the GAP region (see the inset of Figure 4.5) for further analyses. The headwaters of the Euphrates and Tigris rivers which are fed by the snowmelt and subsequent runoff in the high eastern Anatolian mountains [31]. On the other hand, the GAP region where irrigation is more dominant is at a relatively lower elevation

compared to the headwaters. The irrigation and energy projects within the scope of the GAP take place in this region. The headwaters region has high vegetation coverage, while the GAP region is mainly characterized by semi-desert land cover conditions. The ETB is located in a transitional climate zone from vegetated lands to arid areas. According to the Köppen-Geiger classification, the headwaters area mainly belongs to the cold snowy forest climate with dry summer (Dsb), while the GAP region has the characteristic of temperate rainy climate with a dry summer, i.e. a Mediterranean climate, (Csa) (Türkeş, 2010). Under climate change conditions, large spatial shifts in ecoregions are projected in the basin [80].

2.2 Observed Snow Induced Changes in the Basin

In the current era, the year 2007 was an important milestone for the Near East region in terms of water resources. Strong observational evidence of a long term drought in the Fertile Crescent was shown for the 2007-2009 period in the study of [81]. The role of large scale climate anomalies, particularly those related to La Niña, in forming droughts in the Middle East was studied by [82]. They underlined the fact that projections point towards a drying and warming of the climate in the Near East, leading to a reduction in peak SWE and earlier snowmelt. It is important to emphasize that other than reducing snowfall, drying has another important effect in that it may lead to an increase in snowpack ablation through sublimation [83]. Changes in peak SWE and snowmelt timing may already be playing an important role in the observed TWS signal over the GRACE observation period (2002-2017). In this chapter, we conduct an exploratory analysis in order to investigate the role of the snowpack in the observed decrease in water storage of the transboundary basin. We analyze several snow-related satellite retrievals (optical, passive microwave and gravimetric) and a new meteorological reanalysis data set for this region (Table 2.1).

2.2.1 Data and approach

In this study, we perform a statistical analysis of the several time varying remotely sensed spatial data related to the snowpack, namely: GRACE TWS, AMSR-E SWE, AMSR2 SWE, and MODIS SCD from both Aqua and Terra. To complement these data sets we also analyzed ERA5 SWE, as well as energy and mass balance fields

that contribute to the SWE. The analyses were conducted for the elevation thresholds mentioned in the previous section based on the aggregated SRTM30 DEM.

Table 2.1 : Description of the satellite retrievals used in this study.

Data set	Variable (unit)	Spatial Resolution	Temporal Coverage
GRACE	Liquid water equivalent thickness anomaly (cm)	1°	2002/04-2017/01
Aqua MODIS	Snow-covered area (%)	0.05°	2002/07-2018/07
Terra MODIS	Snow-covered area (%)	0.05°	2000/03-2018/07
AMSR-E	Snow water equivalent (mm)	25 (km)	2002/06-2011/09
AMSR2	Snow water equivalent Snow depth (mm)	25 (km)	2012/08-2018/07
SRTM30	Elevation (m a.s.l.)	0.0083°	2000/02
ERA5	Snow energy and mass balance	0.25°	2002/01-2018/07

The aforementioned data sets are analyzed both individually and relative to one another. For the individual analyses we look at temporal trends for each basin, both spatially distributed trends and basin averaged trends, for the different elevation thresholds. For each data set we compute trends for the entire currently available sensing period of the data set in question. So for example for AMSR-E, which is no longer sensing but on-board the Aqua satellite, we use the water years 2003-2011, whereas for Aqua MODIS which is still operational we use the water years 2003-2018. By maximizing the temporal extent of each data set we are attempting to let the respective data sets speak for themselves. To diagnose the significance of the temporal trends we employ the Mann-Kendall test which is a non-parametric test that is well suited for hydrological time series [84]. For inter data set comparisons we perform a standard Pearson correlation coefficient analysis. Here the significance of correlations is determined using a two-tailed t-test. Being wary of the error of the transposed conditional (see [85]), we employ statistical significance with some caution. That is to say, the significance tests are merely testing the probability of the data given the null hypothesis (no trend or correlation) and not the reverse. A low probability (p -value)

merely indicates that the data would be unlikely given the null-hypothesis and thus that we are possibly onto something. We define significant as the cases when $p < 0.1$.

2.2.1.1 Satellite retrievals

Gravimetric TWS data

We first explored the monthly time series of GRACE liquid water equivalent thickness anomalies [86, 87]. The GRACE twin satellites measure the change in Earth’s gravity field which is used to produce a global observational data set for tracking the variations in the terrestrial water storage. The main partners of the GRACE mission are the University of Texas Center for Space Research (CSR), the GeoForschungsZentrum (GFZ) Potsdam, and the Jet Propulsion Laboratory (JPL). In this study, we use GRACE TELLUS Level-3 gridded monthly land water mass Release 5.0 (RL05) from all these three data processing centers. We multiplied raw data with the provided scaling grids [50] for each of the $1^\circ \times 1^\circ$ grid cells. GRACE anomaly data were created by using the 2004-2009 time period as a baseline. For our study, we are interested in changes in TWS and so the period used as a baseline in the generation of the anomalies is not important. By inspecting the three GRACE products, we noted that they were all very similar, and we chose to use the CSR product in our analyses.

Optical snow-cover retrievals

Optical sensors measuring reflected insolation can exploit the spectral signature of snow, high reflectance in the visible and near opaqueness in the shortwave-infrared, to retrieve within pixel snow presence/absence and even fractional snow-covered area [88]. In the retrieval process, this signature, which sets snow apart from most other naturally occurring surfaces, is often diagnosed through the use of a normalized difference snow index (NDSI) [88-90]. An example of a sensor with such sensing capabilities is the Moderate Resolution Imaging Spectroradiometer (MODIS) flying on-board both the Terra (2000-present) and Aqua (2002-present). MODIS has a spatial resolution of approximately 500 meters for the spectral bands of interest and a near daily revisit frequency at the equator. The spatio-temporal resolution and length of the MODIS record make it ideal for monitoring changes in the global snow-cover [59].

We employ NASA’s MODIS Collection 6 snow-cover products (MOD10/MYD10) that are hosted by the National Snow and Ice Data Center (NSIDC). These products are

extensively described in [90], [91]. Briefly, these products all build on the use of the NDSI for assigning a confidence on snow presence ('NDSI snow-cover') in a ~ 500 m pixel and subsequently aggregating these in space and time. The ~ 500 m products have been evaluated in various locations with typical errors on the order of 10-20% for collection 6 [92, 93]. In this study, we use the aggregated 8-day [94, 95] and monthly [96, 97] MODIS climate model grid (0.05°) snow-cover products. These products represent the maximum 8-day and mean monthly fractional snow-cover within each 0.05° grid cell.

In a postprocessing step, we use the 8-day product to calculate the snow-cover duration (SCD) for each water year. For each grid cell, any 8-day period where the cloud-cover exceeds 10% is flagged as cloudy and we replaced the value by linearly interpolating the snow-cover values in the adjacent 8-day windows. SCD is then calculated as the number of days (effectively 8 times the number of 8-day windows) that a grid cell is at least 50% snow-covered. The SCD is strongly correlated with peak SWE, since a deep snowpack typically persists longer than a shallow snowpack provided that ablation rates are similar. Hence, the SCD is a useful indirect measure of the SWE storage. It is this relationship between SCD and SWE that is exploited in snow reconstruction [98] and reanalysis techniques [99].

Passive microwave SWE retrievals

SWE is an essential variable for water resources research in cold regions, yet the estimation of SWE storage over large areas remains challenging [98]. The attenuation of microwave radiation emitted by the underlying ground increases as a function of frequency and snow grain size due to volume scattering by the snowpack. Hence, the difference between low and high frequency brightness temperatures in the microwave range tends to increase proportionally with SWE [100]. At the same time, these frequencies are relatively unaffected by cloud cover or insolation [101]. Therefore, we employ SWE retrievals from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E [102]) on board the Aqua satellite and its successor the Advanced Microwave Scanning Radiometer-2 (AMSR2 [103]) on-board the GCOM-W1 satellite, as these cover most of the GRACE data period.

Passive microwave SWE retrievals do have some limitations. At terrestrial temperatures, objects emit microwave radiation at low intensity and so pixels must be considerably larger (0.25°) for passive microwave sensors, than for e.g. optical sensors, to obtain an acceptable signal to noise ratio [98]. Furthermore, the quality of the retrievals is lower in complex terrain [59]. Moreover, the signal tends to saturate for wet and deep snowpacks [101]. Despite these error sources and the resulting uncertainties, we employ passive microwave retrievals as an additional potentially valuable source of information and assume that the signal is stronger than the noise in line with previous studies in the mountains of the Near East (e.g. [64,65,104]).

The AMSR-E instrument, which was operating on board the NASA's Aqua satellite, provided observations for the time period between June 2002 and September 2011 (Table 2.1). We use the monthly level 3 SWE retrievals from AMSR-E which is projected to the 25 km Equal-Area Scalable Earth (EASE) Grids by the NSIDC [102]. As suggested in the data guide [102], SWE values were multiplied by a scaling factor of 2 before any climatological calculation. AMSR2, the successor sensor of AMSR-E, has provided measurements since August 2012 (Table 2.1). AMSR2 is in orbit on-board the JAXA's Global Change Observation Mission-Water 1 (GCOM-W1 "Shizuku") satellite that was launched in May 2012. We used level 3 SWE data from AMSR-2's descending orbit direction at 25 km spatial resolution until July 2018 after multiplying by a scale factor of 0.1 as suggested in their reference manual [103].

2.2.1.2 Meteorological reanalysis data

The European Centre for Medium-Range Weather Forecasts (ECMWF) released their fifth generation of global climate reanalyses, ERA5, at the end of 2017 [105]. During the production phase as a part of the Copernicus Climate Change Service (C3S), massive amounts of in-situ and satellite measurements were used as input into the modeling and data assimilation system. For the modeling, version CY41R2 of ECMWF's integrated forecasting system (IFS) was employed. For the data assimilation, a 4D-variational algorithm was used. ERA5 has higher spatio-temporal resolution than its predecessor ERA-Interim, in addition to improvements in soil moisture representation and in the global balance of precipitation and evaporation. This successor atmospheric reanalysis product is expected to eventually completely

replace the ERA-Interim product. Here, we evaluate the satellite products by using temperature, snowfall, rainfall, sublimation, evaporation, radiation, and SWE from ERA5. All of these variables were obtained from the surface level fields of this reanalysis at 0.25° spatial resolution and hourly temporal resolution. It is worth emphasizing that modern meteorological reanalyses are already constrained by remote sensing through the assimilation of various satellite retrievals. At the same time, none of the satellite retrievals used in this study are assimilated into the ERA5 reanalysis, so ERA5 may be viewed as an independent line of evidence in our analysis.

2.2.1.3 Elevation Based Analysis

We use the SRTM30 digital elevation model (DEM). This is simply the shuttle radar topography mission (SRTM) DEM aggregated from the native 1 arc-second (0.00028° , roughly 30 m) resolution to 30 arc-seconds (0.0083° , roughly 1 km) through spatial averaging. After aggregation any voids in the DEM were filled with the GTOPO30 DEM. Details of the SRTM mission and DEM are provided in [106] and [107]. We used the two tiles E020N40 and E020N90.

For all the data sets listed in Table 2.1 we aggregate the SRTM30 to the resolution and grids of the respective data sets. For all the data sets in regular geographic coordinates, i.e. all but AMSR-E, this is done in a separate two stage process for each data set. First, we apply a 2-D digital filter that averages a neighborhood (corresponding to the data set resolution) around each grid cell on the SRTM30 DEM. Then, we simply find the nearest neighbor smoothed DEM grid cell for each grid cell in the data set. To a very good approximation this yields the aggregated DEM for the grid of the respective data sets. As for AMSR-E, which is projected in the EASE grid with irregular geographic coordinates, for each grid cell we search for all the SRTM30 grid cells that fall within this cell and average these to obtain an aggregated AMSR-E DEM.

Through this process, we obtain coarsened DEMs for the ERA5, GRACE, AMSR-E, AMSR2, and MODIS products. For each basin, we then apply a basin mask using the basin outlines and we only include data set grid cells for the basin analysis if at least 30% of a data set grid cell falls within the basin. We then apply elevation thresholds (500, 1000, 1500 and 2000 m a.s.l) to eliminate irrelevant (snow-free) lower lying points and look at the elevation signal in the temporal trends of the respective products.

2.2.2 GRACE Based Terrestrial Water Storage Changes

The water resources in the ETB has been shrinking due to the extensive irrigation, groundwater pumping, and climate change [51–55]. NASA’s GRACE data show the declining trend of available water in the ETB (Figure 2.3). The first panel displays the increasing negative anomalies, especially after the 2007 drought, which corresponds to the dominating drying conditions for the ETB. The overall terrestrial water storage (TWS) anomalies in the ETB have a steeper trend line after 2007. In order to account for the TWS anomalies at different elevation levels, we applied the elevation masks on the selected GRACE solution (CSR). The trend becomes considerably steeper in the spatially averaged time series for the areas over 1500 m a.s.l. (orange line in Figure 2.3) than for the whole ETB (yellow line in Figure 2.3). While the degradation of annual maximum TWS anomalies with elevation was from higher elevation to lower areas until the drought years (2007-2008), the direction reverses in the last years (2015-2016). The trend for the monthly time series for areas over 1000 m is -2.74 cm per year in the ETB.

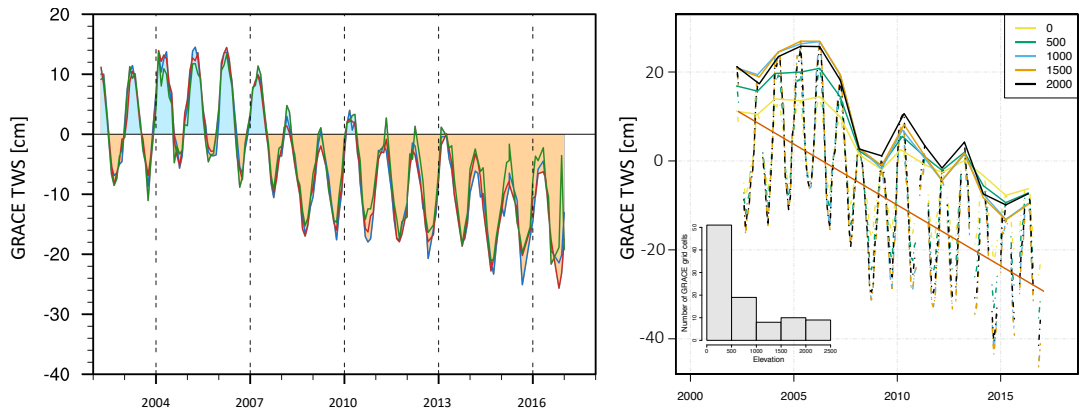


Figure 2.3 : Time series of spatially averaged GRACE TWS anomaly over the whole ETB (left)¹ and for the areas above different elevation thresholds (right)². The histogram show the number of GRACE grid cells in each elevation level over the basins.

2.2.3 Correlations Between Snow Trends and Water Loss

The snow-cover duration (SCD) is calculated for each water year from the MODIS maximum 8-day snow cover from both the Aqua and Terra platforms. Figure 2.4 shows

¹Green, red, and blue lines are the values from different gravity solutions of GRACE from GFZ, CSR, and JPL, respectively. Blue and brown shaded areas show the positive and negative anomalies, respectively.

²The colors in the figure on the right represents different elevation thresholds. The light-red line is the trend line which corresponds to a negative trend of 2.74 cm/year. Dotted lines are monthly, while solid colored lines show the annual maximum values.

the annual SCD trends above 1000 m in the study basins. The SCD trends derived from Terra (Figure 2.4a) indicate a statistically significant ($p < 0.1$) decline up to 4 weeks per decade in the headwaters of the ETB in Turkey and the southern highlands of the ETB in the Zagros mountains of Iran. Significant positive SCD trends of about one week are observed over smaller areas by Mount Ararat and the Greater Caucasus. The SCD trends derived from Aqua (Figure 2.4) show stronger negative trends over a larger extent in the same areas. The high mountain regions in all the basins have significant negative trends of around 4 weeks per decade.

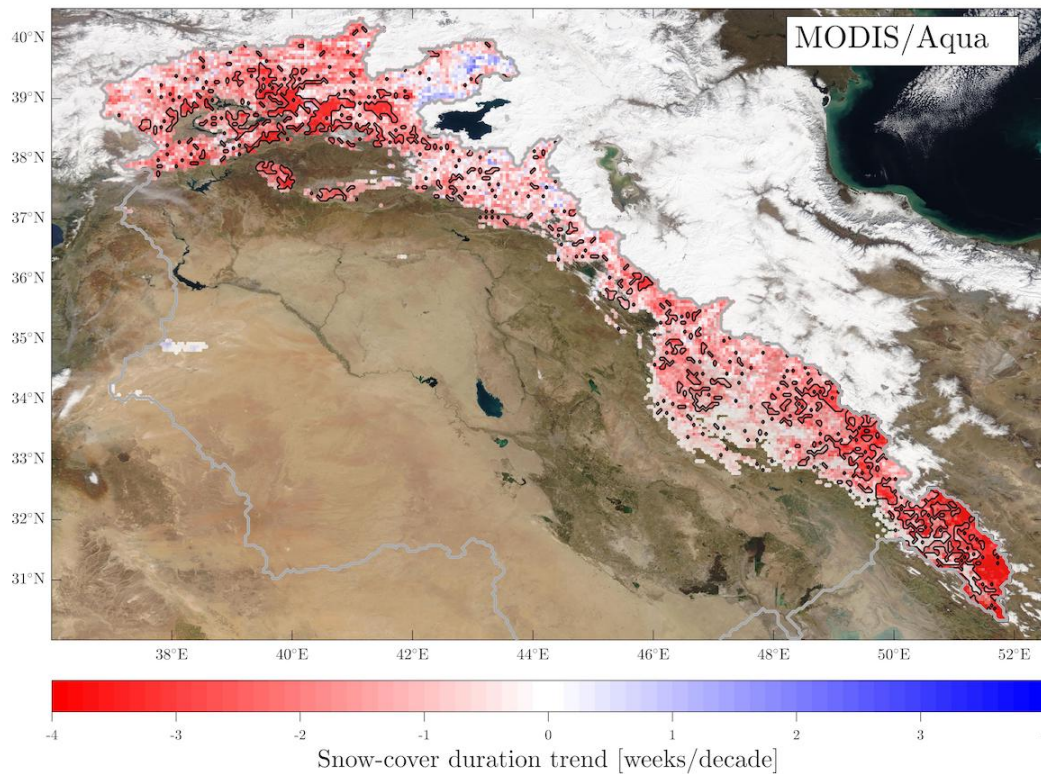


Figure 2.4 : Snow-cover duration (SCD) trend in weeks/decade retrieved from MODIS onboard the Aqua (2003-2018) ³

This evidence of SCD decline can be interpreted as an early warning sign of future projections which show that the seasonal snow-cover may vanish in the regions below 1000 m [31] or between 1000 m and 1500 m a.s.l. elevation [27]. MODIS data is provided from different satellites (Aqua and Terra) for different time periods. It is noted that the SCD trends from Aqua shows stronger and more significant changes for a shorter time period between 2003 and 2018. As such, we compared both data sets for the same time range (2003-2018). This comparison gave almost the same results

³ Areas contoured with black lines show a statistically significant (here $p < 0.1$) trend. Background: Terra MODIS 'true color' (MOD09GA RGB) image of the Near East region taken on 19-Feb-2017 obtained from NASA Worldview.

for Terra as for Aqua. Therefore, we can say that observations from the first two years (2001 and 2002) of Terra gives higher (less negative) temporally averaged SCD trend values over the MODIS grid cells. It is mentioned earlier that SCD and SWE are indirectly yet strongly related (e.g. [92,98,99]): Shorter SCDs indicate either a lower peak SWE, or accelerated ablation, or a combination of the two and vice versa for a longer SCD. We will return to this point in the analysis of the ERA5 outputs.

In Figure 2.5, we compared the spatial pattern of the trends of annual maximum TWSA from GRACE and annual maximum snow water equivalent from ERA5 for the areas above 1000 m. GRACE TWSA trends (between 2002 and 2016) show a statistically significant ($p < 0.1$) decline over the highlands of the Near East region. In the headwaters of the ETB, the negative TWSA trends are up to 2 cm per year, while it can reach up to 4 cm per year in the eastern highlands of the ETB. The declining trends in GRACE TWSA are statistically significant in most of the areas over 1000 m. The significantly declining SWE trends from ERA5 are in the Greater and Lesser Caucasus, Mount Kaçkar, Zagros mountains, Uludoruk, surroundings of Van Lake, and the southeastern Taurus mountains. Here, we clearly see the similarities in the spatial pattern of trends in Figure 2.4 and Figure 2.5.

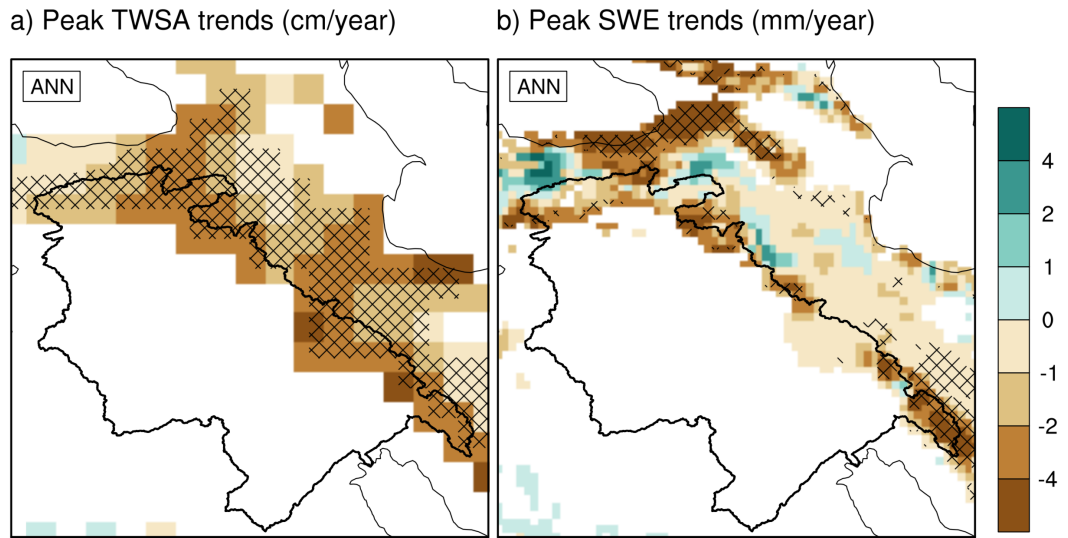


Figure 2.5 : Annual trends in a) peak total water storage anomalies from GRACE and b) peak snow water equivalent values from ERA5 over the all areas higher than 1000m. Hatches show the statistically significant areas at 90% confidence level.

The lower triangular correlation matrices (Figure 2.6) show the strength of the relationship between the time series of spatially averaged TWSA and snow variables

over the areas above different elevation thresholds. The GRACE TWS and ERA5 SWE have a positive significant ($p < 0.1$) correlation for each elevation levels. The significant similarity of the spatial patterns of GRACE TWS and ERA5 SWE has already been shown in Figure 2.5. On the other hand, the SWE retrievals from AMSR-E and AMSR2 satellites have either negative or very small insignificant correlations with GRACE TWS change. The AMSR2 SWE retrievals have a positive and significant correlation with MODIS SCD from both Aqua and Terra. Furthermore, AMSR-E has similar correlation coefficients with both products. ERA5 SWE reanalysis show positive significant correlations with both Aqua and Terra SCD. It is also worth mentioning that the spatially averaged MODIS SCDs from Aqua and Terra platforms show extremely similar (correlation coefficients practically equal to 1) temporal patterns for all the elevations. The interesting part of this analysis is that the GRACE TWS has positive and significant correlations with both Aqua and Terra SCD for the areas over 2000 m, while it was the opposite for lower elevation thresholds.

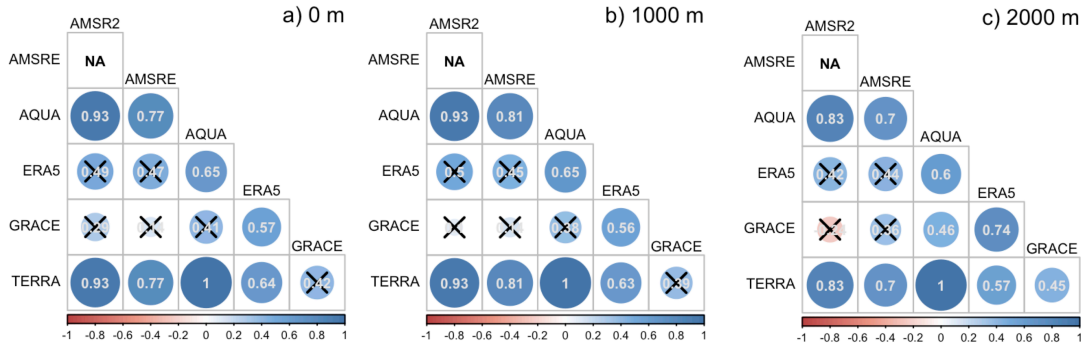


Figure 2.6 : Correlation matrices between annual values⁴ over the areas higher than a) 0, b) 1000, and c) 2000 m for the ETB. Marked (X) correlations are statistically insignificant at a 90% confidence level.

The trends in the annual maximum values of snow-related variables are given in Table 2.2. We calculated these trends for each elevation threshold by fitting a linear model to the annual maximas. The negative TWS anomaly trends calculated from monthly GRACE data are shown for the areas over 1000 m in Figure 2.3. The annual maxima trends similarly show a significant decline in water storage anomalies in the ETB at a confidence level of 99.9%. The magnitude of the negative GRACE trends increases by elevation, as does the magnitude of the trends from the other data sets. In this basin,

⁴The correlations shown here are between the variables of SWE from AMSR-E, AMSR2, and ERA5; MODIS SCD from Aqua and Terra; and lastly TWS from GRACE. The size and the color of the circles show the value of the corresponding correlation coefficients which are also written on the circles.

above 2000 m the average MODIS SCD trends from Aqua and Terra satellites are -2.1 and -1.5 weeks per decade and these are both statistically significant at the 95% confidence level. At the same elevation threshold and significance level, ERA5 SWE show a decreasing trend of around 3 mm per year.

Table 2.2 : Annual trends (unit/year) calculated from the results of a linear model applied to each elevation threshold for the ETB. From top to bottom elevation thresholds are 0, 500, 1000, 1500, and 2000 m, respectively. Significance codes : 0.001 (****), 0.01 (***), 0.05 (**), 0.1 (*).

GRACE TWS (cm)	MODIS Aqua SCD (days)	MODIS Terra SCD (days)	ERA5 SWE (mm)	AMSR-E SWE (mm)	AMSR2 SWE (mm)
-1.58 ****	-0.75 *	-0.50	-0.49	-0.36	-0.76
-2.18 ****	-0.75 *	-0.50	-1.02	-0.65	-1.45
-2.84 ****	-1.15 *	-0.79 *	-1.6	-0.84	-2.56
-2.84 ****	-1.19 *	-0.82 *	-1.65	-0.96	-3.64
-2.53 ****	-1.49 **	-1.06 **	-2.96 **	-1.44	-4.36

The SWE data provided from AMSR-E and AMSR2 passive microwave radiometer systems give negative trends with an increasing magnitude by elevation in the ETB. However, none of these trends are statistically significant. For the upper part of the ETB, [65] showed the decrease in snow depth from the ground measurements while no decrease of SCA amounts from MOD10C2 for a short time period (10 years between 2000 and 2009). Since SCA alone does not give complete information about the volume of the snowpack, we calculated the snow cover duration trends from MODIS snow products in order to understand more about the snowpack. The declining SCD trends in the upper ETB (Figure 2.4) are consistent with the findings of [65] from ground measurements.

2.2.4 Potential Drivers of Snow Depletion

We mentioned the correlations in the spatial patterns of the trends in Figure 2.4 and Figure 2.5. In both figures, the significant changes are observed over the grid cells with the negative TWSA, SCD, and SWE trends. One of the clear indicators of the regional snowpack depletion is the declining SWE trends (Figure 2.5b) which reach above 4 mm per year especially in the Lesser Caucasus and Zagros Mountains. The spatial pattern and the magnitude of ERA5 SWE trends show similarities with the SWE trends from ERA-Interim reanalysis over eastern Anatolia except the Black Sea coasts and the Tigris basin of Turkey [108]. Given the significantly shorter SCD over the

same areas, we continue to investigate the relationship between decreasing TWSA and snowpack depletion by comparing the (basin average) temporal correlations between all data sets in Fig 2.6.

A change in precipitation patterns is the most obvious sign of meteorological or hydrological drought. The drivers of the snowpack depletion might be the anomalies in precipitation alone or a combination with other climate variables such as temperature or radiation. [109] explain the effect of temperature and precipitation on snow persistence decline for the seasonal snow zones in the Northern Hemisphere which includes our domain. They emphasized that temperature is the dominant effect at lower elevations, while the importance of precipitation at higher elevations is greater. In our study, we focus on investigating the snow energy and mass balance variables from the ERA5 reanalysis for the areas over 1000 m elevation. In Figure 2.7a, winter precipitation shows a latitudinal change which increases in the north and decreases in the southern part of the Near East. The statistically significant precipitation decline over the Zagros mountains and surrounding region is concerning in terms of water resources in this arid region. The magnitude of negative change increases towards south. However, for the spring months (MAM), precipitation data shows a significant increase over a smaller area in Zagros mountains (Figure 2.7b), while the decline in spring precipitation over several grid cells is not statistically significant.

In cold regions, precipitation can fall as either rain or snow. Therefore, the ratio between snowfall and rainfall is crucial for understanding the evolution of the snowpack. More rainfall on an existing snowpack can cause faster snowmelt earlier in the year. [110] showed an increase in the frequency of rain-on-snow events for the higher elevations of the Sierra Nevada (U.S.) which is a climatologically similar region to the northern ETB in terms of snow and water resources. Here, we defined the snowfall ratio as follows :

$$\text{snowfall_ratio} = \text{snowfall} / (\text{snowfall} + \text{rainfall})$$

based on the seasonally accumulated snowfall and rainfall. In Figure 2.7c, we see a strong reduction in snowfall ratio in the winter months (DJF). Most of the grid cells above 1000 m have statistically significant negative trends. The decline in snowfall ratio reaches up to 20% per decade in the Iranian part of the ETB and elsewhere in northern Iran. The winter snowfall ratio reduction at a level up to 5 % per decade is

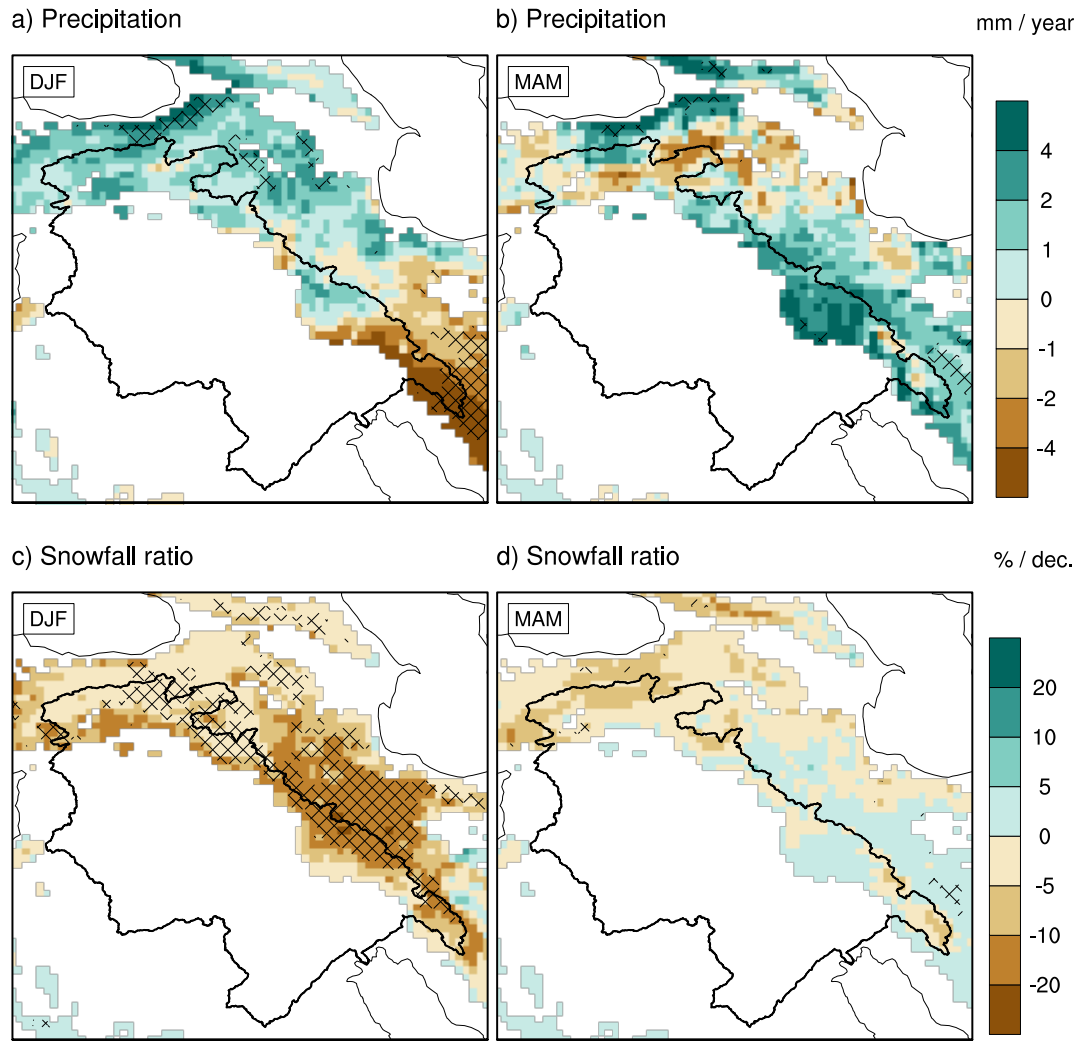


Figure 2.7 : Trends in seasonal (a,b) precipitation and (c,d) snowfall ratio for winter (DJF) and spring (MAM). Hatches show the statistically significant areas at a 90% confidence level.

also significant in the headwaters part of the ETB. In order to understand whether the reduction in snowfall ratio is a signal of temperature change, we analyzed the trends in 2m air temperature and downward radiation (sum of surface downwards solar and thermal radiation) from the ERA5 reanalysis (Figure 2.8).

In Figure 2.8, the winter temperature increases (up to 3°C per decade) over the whole study domain, but significant changes overlap with precipitation and snowfall ratio change only over the Zagros mountains. This change could explain the significant precipitation and snowfall ratio decline in winter months over this mountainous region. As for radiation, ERA5 does not show a significant change in DJF over the whole domain. Here, it is noted that seasonal temperature climatology does not show directly how temperature changes during the rainfall or snowfall events, instead it is only an

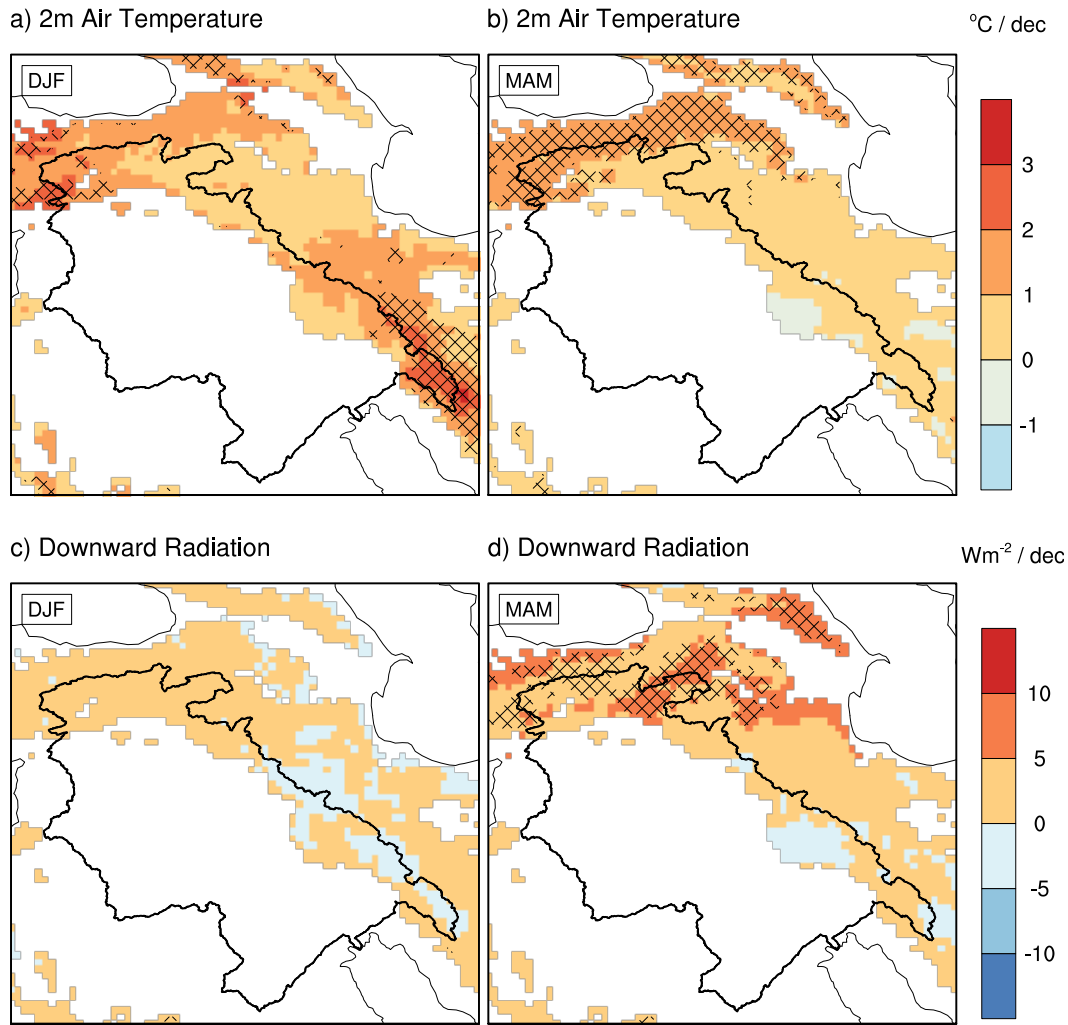


Figure 2.8 : Decadal trends in seasonal (a,b) 2 m air temperature and (c,d) downward radiation for winter (DJF) and spring (MAM). Hatches show the statistically significant areas at a 90% confidence level.

indicator of how temperature changes overall during the season. For the spring months, the magnitude of change in snowfall ratio is not as strong as the winter months (Figure 2.7d). The snowfall ratio reduces in the northern Near East, while it increases at most by 5 % per decade in the south. These changes are mostly not significant. However, the grid cells which show the snowfall ratio decline coincide with the increase in downward radiation in MAM which are between 5 and 10 Wm⁻² per decade and also significant (see Figure 2.8d). Despite being in the same region, the snowpacks in Mediterranean mountains can show different responses to warming conditions [111].

Snow ablation consists of snow sublimation, snowmelt, blowing snow, and avalanche processes. Here, we examine the loss of snow from the point of sublimation and snowmelt amounts. Our results show that one of the most interesting phenomena

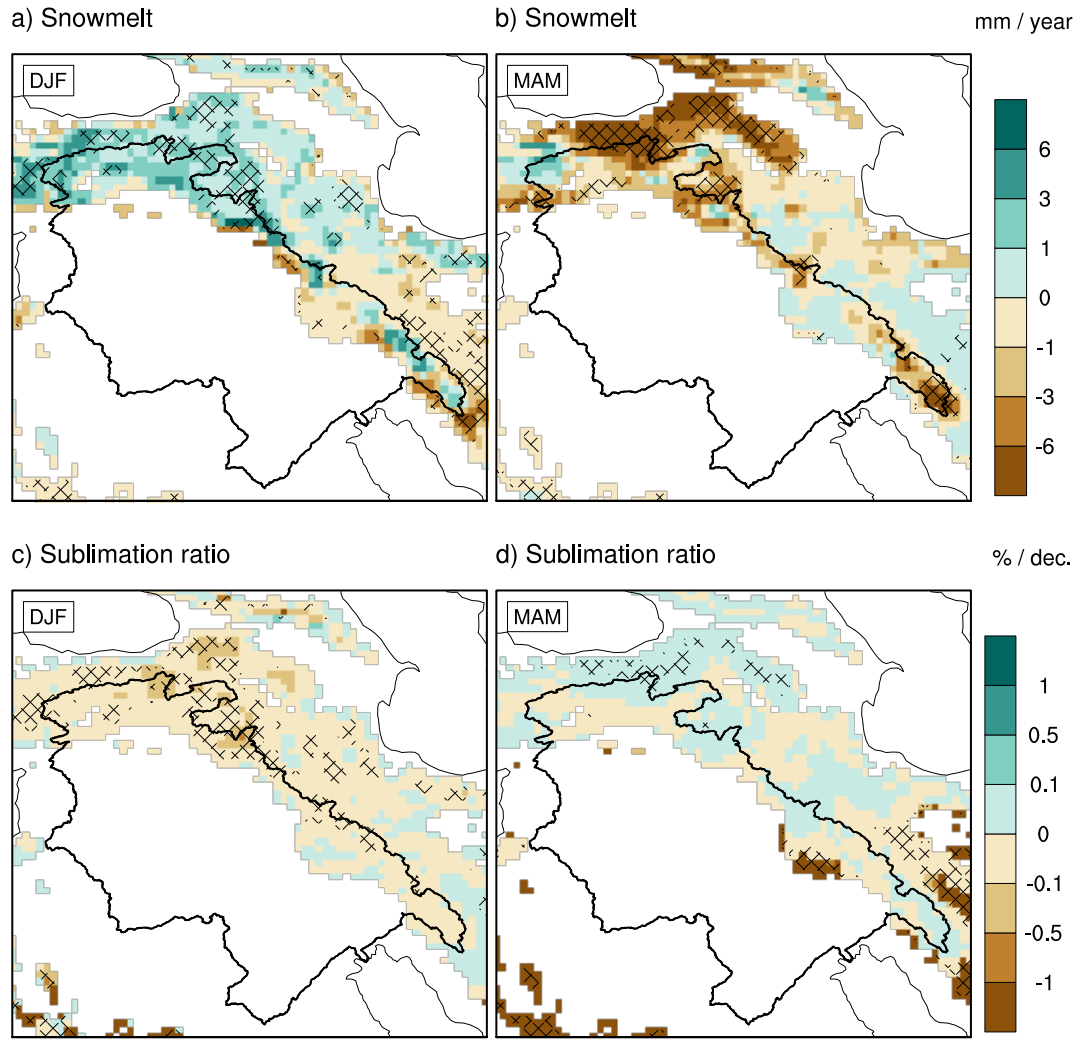


Figure 2.9 : Same as Figure 2.7, but for (a,b) snowmelt and (c,d) sublimation ratio

concerns the obvious change in snowmelt patterns (Figure 2.9a-b). Snowmelt trends significantly increase in winter, and decrease in spring over all the basins. The change pattern is usually opposite and often significant in both seasons, which means that the increasing snowmelt regions in DJF reduces in MAM. This feature is a clear sign of earlier snowmelt that is in line with the studies of [71], [112], and [72]. All these studies concluded that the earlier snowmelt occurs due to the increasing temperatures in recent years. ERA5 2m air temperature data also show consistent results with their findings (see Figure 2.8a-b). Earlier snowmelt can be driven by the many factors that affect the forcing in the surface energy balance. Here, we investigated the temperature which drives the sensible heat flux exchanges. The significant temperature increase could explain the spring snowmelt decline up to 10 mm per year over the Greater and Lesser Caucasus, and the headwaters of the ETB (Figure 2.9b). As a result of warming conditions and drying conditions, we may also expect to see a strong signal

in sublimation ratio which is defined as :

$$\text{sublimation_ratio} = \text{sublimation} / (\text{sublimation} + \text{snowmelt})$$

In the winter months, sublimation ratio trends decrease significantly over the areas where snowmelt increases (Figure 2.9c). Conversely, sublimation ratio raises significantly around 0.1% per year in the Lesser Caucasus. These numbers are surprisingly smaller than the findings of [83] where they estimate that 24-33% of the annual snow ablation is due to evaporsublimation over the Sierra Nevada mountains (Spain) in the Mediterranean region. We may surmise that the ERA5 reanalysis data may have limitations to simulate the finer scale snow processes over the complex terrain of the Near East. Still, given that snowmelt significantly decreases in spring months (Figure 2.9b), and MODIS SCD trends decline over the same areas (see Figure 2.4b), there is supposed to be less snow in the beginning of the season. Lastly, condensation processes (opposite of evaporation), namely rain-on-snow, could be an important source of snowmelt, since it leads to a strong latent heat flux from the atmosphere towards the surface. [110] clearly explain in their study how earlier snowmelt affects snowmelt runoff and water security. The combination of increasing rainfall (Figure 2.7) and snowmelt (Figure 2.9) may increase the chance of winter time flooding especially in the eastern Black sea coast.

2.3 Anthropogenic Land Use Changes in the Basin

The waters of the Euphrates and Tigris rivers have been used for large-scale irrigation since the beginning of the ancient Mesopotamian civilizations [31]. Since then not much has changed in terms of the water use in the region. The riparian countries still intensively use the waters of these two rivers for the purposes of agriculture, domestic use, and energy production. The total area equipped for irrigation (AEI) in the whole Euphrates and Tigris Basin is around 6.5-7 million ha [79]. According to a global inventory of [113], the AEI with surface water is larger compared to the AEI with groundwater in the whole basin. By the year 2003, groundwater abstraction for irrigation reported in EUROSTAT for Turkey was 18.4% of total water abstraction for irrigation, while the area actually irrigated with groundwater was estimated to be around 49% of the total area actually irrigated which is approximately the same as that reported number by the Turkish State Hydraulic Works (DSI) (Supplement-S1

of [113]). [77] reported that the total irrigation water withdrawal in the basin was around 99000 km³ (which is 88% of the total water withdrawal) of which Iraq accounts for approximately 44%, Iran for 25%, Turkey for 18% and Syria for 13%.

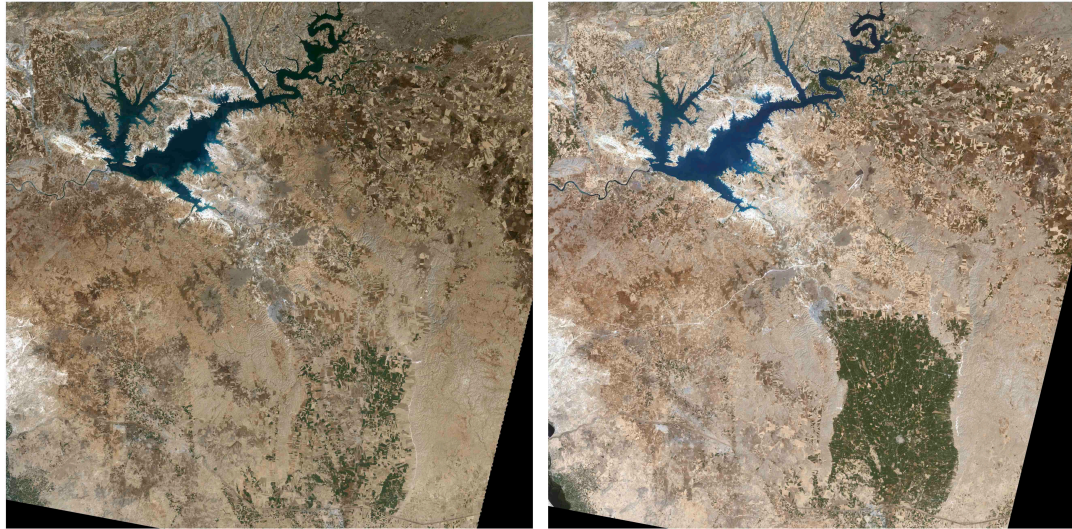


Figure 2.10 : Extension of the irrigated areas in the Harran Plains. Before (left), in 1993, and after (right), in 2002, the irrigation from the Ataturk Dam was started. (image credit : NASA)

Since the early 1990s, starting with the irrigation of the Harran Plains, such irrigation schemes carried out within the scope of the abovementioned GAP have substantially altered the land use of the upper ETB. In Figure 2.10, the satellite images [114] show the extension of the irrigated areas in the Harran Plains after the arrival of water from the Ataturk Dam reservoir. Here, the first image is acquired from the Landsat 5 on 23 August 1993, and the second image is obtained from Landsat 7 ETM+ instrument on 24 August 2002. By the end of 2017 (see Figure 2.11), 30.4% (~0.55 million ha) of the planned irrigation projects were in operation [115]. According to the master plan of GAP, an immense area of 1.8 million hectares will be irrigated upon the completion of the ongoing irrigation investments.

The waters of the Euphrates and the Tigris rivers will not only be used for irrigation, but also for energy production. As reported in [79], the capacity of the large dams in the Euphrates and Tigris river basin is around 99 million m³ for Turkey, 11 million m³ for Syria, 110 million m³ for Iraq, 15 million m³ for Iran. These dams are in use of irrigation, hydropower, water supply, and flood protection purposes. The construction of 22 dams and 19 hydropower plants is planned within the scope of the GAP [115]. By the end of 2017, 78% of the planned hydropower capacity had been installed which

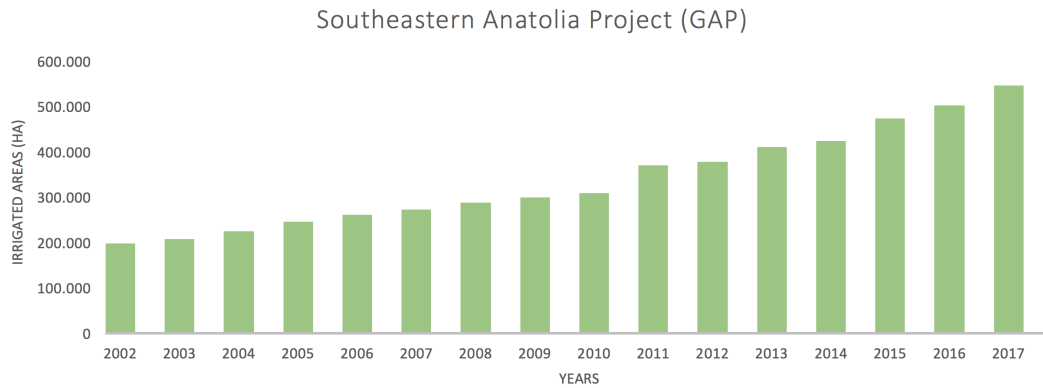


Figure 2.11 : Areal coverage of the extending irrigated areas in the GAP.

corresponds to a total production of 443.8 billion kWh [115]. Approximately one fourth of the hydroelectric production in Turkey is provided by the hydropower plants of GAP [115]. Since the date that the Atatürk Dam became operational as a part of the GAP, irrigated agricultural activities have increased in the region. This large dam is of central importance in the GAP for irrigation and hydropower. In order to highlight the significance of this date, which is a milestone for the land use change in the region, all dates prior to this will be considered as “pre-GAP”. The exact date of the start of the GAP project is not important here, but the pre-GAP period corresponds the time before the irrigated agricultural areas had started to expand rapidly around the years of 1993 and 1994. Due to the basin’s location, the use of transboundary water resources is one of the main reasons for geopolitical problems in the Middle East region. Overexploitation of the Euphrates and Tigris rivers as a result of human activities for irrigation and hydropower can significantly affect the amount of water flow to the downstream countries.

3. GENERAL CIRCULATION MODEL (GCM) SELECTION

The abbreviation GCM stands for either general circulation model, or global climate model. The GCMs, including the Earth System Models (ESMs), are powerful tools for simulating the global physical processes [24]. The outputs of these numerical models are used to represent the interactions between the Earth system components (atmosphere, land surface, ocean, etc.). Since the computational cost of running a GCM is expensive, the GCMs are developed by the climate research centers or modeling groups.

The evaluation of and comparison between different GCMs is coordinated under the international frameworks such as the Coupled Model Intercomparison Project (CMIP). The latest completed experiment is the fifth phase of the Coupled Model Intercomparison Project (CMIP5) organized by the World Climate Research Programme (WCRP) between 2010 and 2014 [116]. CMIP5 is a comprehensive experiment that aims to produce the global scale simulations by using the several climate models from different climate modeling centers for certain emission scenarios, and to compare those simulations. Outputs of those models provide the initial and boundary conditions required by the regional climate model. Various GCM outputs produced by different modeling groups in the CMIP5 experiment were used in the 5th Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC).

It is widely known that the performance of the regional climate models mostly depends on the performance of the (global) model whose outputs are used as initial and boundary conditions [117, 118]. Using the outputs of only one GCM increases the uncertainty in the simulations [41]. Ensemble simulations are used to reduce the uncertainty by initializing the regional climate model with a larger number of GCMs. In this type of studies, higher amount of computational source is required. Thus, using insufficient number of GCMs are common in the regional climate modeling studies. There are several studies about GCM driven regional climate models for Turkey (e.g., [26, 27, 48]). In those studies, the accessibility of data was the selection

criteria for the GCM used to run their simulations. In this thesis, it is extremely difficult to perform ensemble simulations due to the expensive computational costs. Thus, only one suitable GCM will be selected instead of using a random one after analyzing the outputs of 45 different GCM simulations (see Table A) for the larger domain over a region that covers the Eastern Mediterranean- Black Sea- Middle East- Eastern Europe- Balkans. The performance-based selected GCM among CMIP5 models will be used for the scenario simulations. The aim of this evaluation process is to reduce the uncertainty in the regional climate simulations caused by the initial and boundary conditions. Therefore, it is aimed to force our regional climate model, RegCM4, with the GCM outputs which simulates the study region fairly well. So, we first need to determine the ‘best’ performed GCM over the study domain before starting the simulations.

3.1 Analysis data

3.1.1 CMIP5 simulations

Table A shows the list of CMIP5 models [116] that were used in this chapter. The GCM number 46 (MME - Multi Model Ensemble) shows the average of the 45 GCMs, and this data can not be used to run the regional climate model. All these GCMs have different model components, and include different biogeophysical and biogeochemical processes. Also, their spatial resolutions vary notably between a wide range, still coarse to understand regional dynamics.

Here, we evaluate the ability of 45 different CMIP5 GCM outputs to simulate historical total precipitation and mean 2 m air temperature for the period between 1971 and 2000. This time period is determined for climatological (30 years) analysis due to the differences in the end date of CMIP5 reference period simulations between 2000 and 2005. All data sets were analyzed over the EMBS (whole domain), Turkey, the ETB, the ETB of Turkey, and the rest of the ETB (the basin area outside of Turkey) for each season and annually.

As for methodology, we first calculated the descriptive statistics (mean, bias, root mean squared error (RMSE), correlation coefficient) from all data sets. Gridded observation data set mentioned in Section 3.1.2 is used to evaluate the performance of GCMs. As

shown in Table A, each GCM has different horizontal resolution. Therefore, first, all GCM grids were interpolated to the spatial resolution ($0.5^\circ \times 0.5^\circ$) of the observation data [117]. Then, the statistics from the interpolated data sets were compared with the observation.

3.1.2 Gridded Observation Data : CRU

High-resolution gridded data set from Climatic Research Unit of the University of East Anglia (CRU) is used as observation data for monthly mean temperature and total precipitation. The spatial resolution of this global data set is $0.5^\circ \times 0.5^\circ$ degree, and the temporal coverage is from 1901 to present time (Harris et al., 2014). For the analysis with the CMIP5 data, we used the TS3.21 version of the CRU data set, while the TS4.01 version is used for the further analysis for model performance evaluation (see Section 4.1.3).

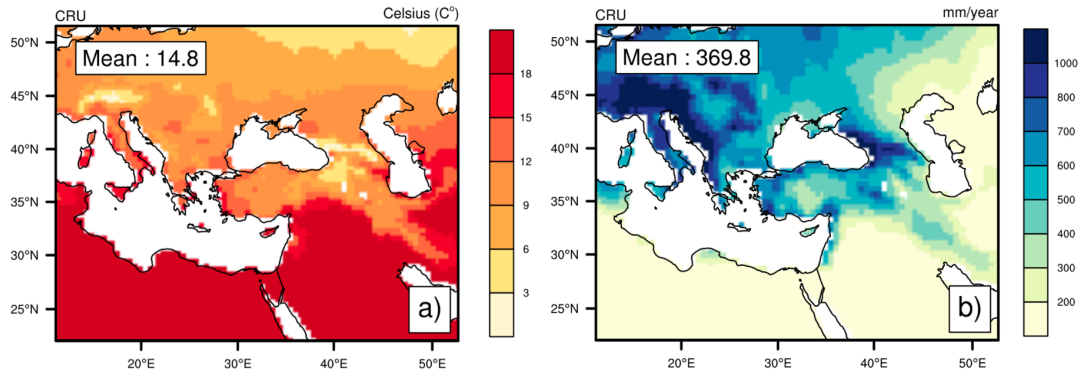


Figure 3.1 : CRU annual a) mean 2m air temperature and b) total precipitation climatology for 20-year (1991-2010) over the EMBS domain.

Figure 3.1 shows the temperature and precipitation climatology over the whole domain. The annual mean temperature pattern demonstrates a clear meridional gradient being higher in the south of the domain. The mean temperature is 14.8°C over the EMBS, while it is 10.5°C over the ETB of Turkey. The highest total precipitation values are observed over the mountainous areas such as the Caucasus and European Alps. The total annual precipitation is around 370 mm over the EMBS, while it is 616 mm over the Turkish part of the ETB. The headwaters of the ETB receives more precipitation. It is noted that the total precipitation over the whole ETB basin is 326 mm per year [49]. The spatially-averaged time series of Turkey for both annual mean temperature and total precipitation data are given in Figure 3.2. The mean values (blue lines) are fitted

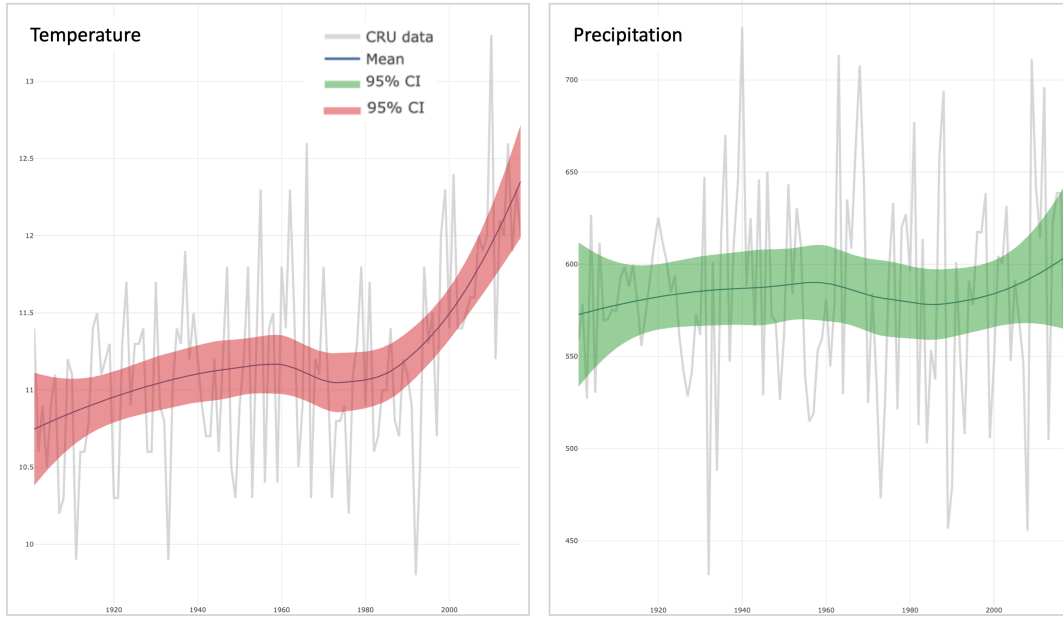


Figure 3.2 : Annual mean 2m air temperature (left) and total precipitation (right) time series for all CRU TS4.02 observational period (1901-2017) over Turkey. Blue lines show the fitted mean values, while the shaded areas are the 95% confidence interval.

by using the LOESS (Locally Estimated Scatterplot Smoother) method. LOESS is a non-parametric regression method for fitting a smooth curve between two variables. Long-term average temperature and precipitation over Turkey are 11.2 °C and 584 mm per year, respectively. The annual temperature values increase in the recent years, especially after experiencing the lowest annual temperature (9.8 °C) in 1992. The latest (in 2017) annual CRU observation is 12 °C, while its maximum reached 13.3 °C in 2010. The precipitation of Turkey has a high temporal variability. The maximum precipitation values that exceeds 700 mm per year were observed in 1940, 1963, 1968, and 2009. According to the CRU data, the latest (in 2017) observed annual total precipitation is 529 mm which is below average.

3.2 Evaluation of CMIP5 Simulations

In Figure [3.3](#), we see that all GCMs give very different biases for each subdomain. Ranking the models according to their biases from the gridded observation data for both surface temperature and precipitation does not give us a clear answer for determining the "best" GCM over our study domain. For example, NCAR's CESM1-BGC precipitation output gives the lowest annual bias over the whole domain, while temperature bias is the lowest from the GFDL's ESM2G run. For the Turkish

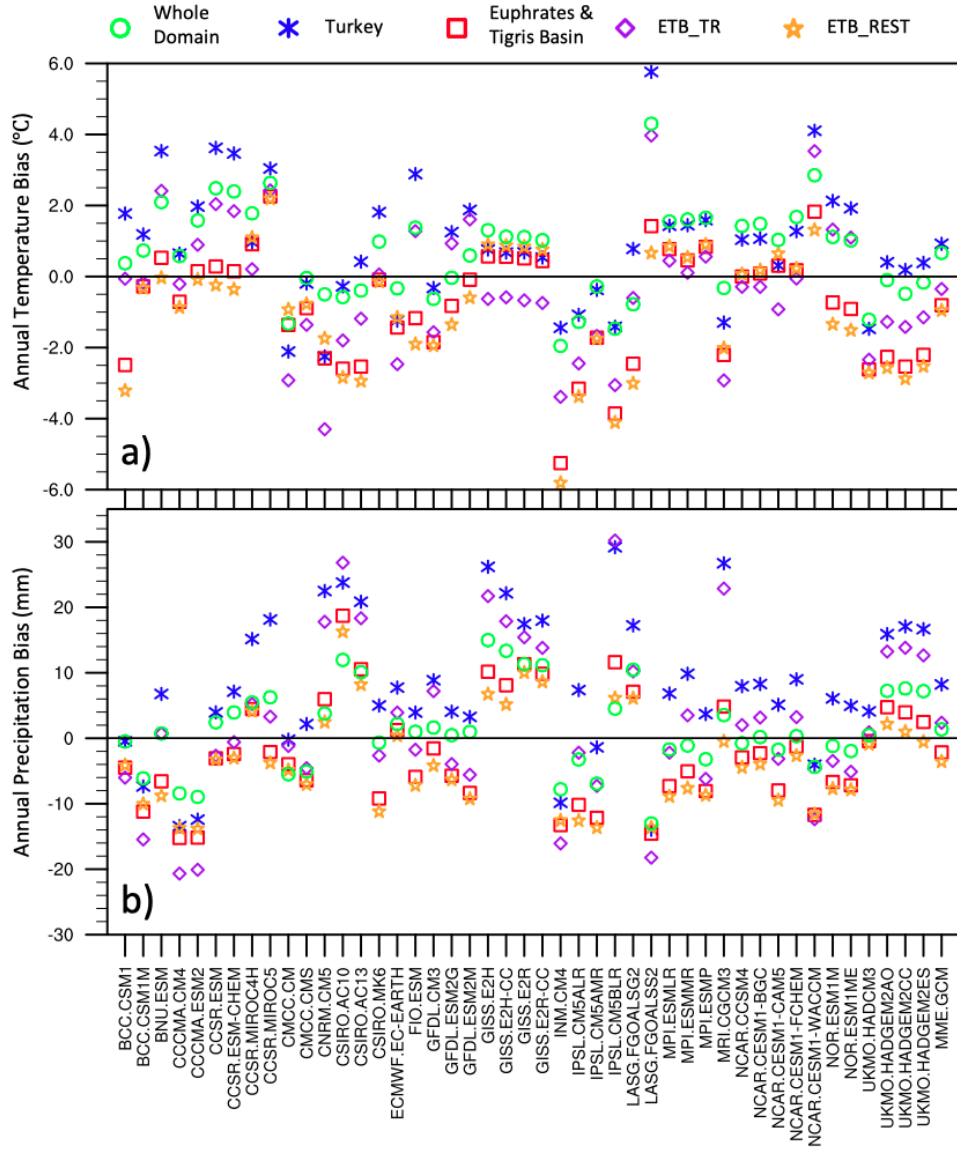


Figure 3.3 : Annual a) temperature and b) precipitation bias for each GCM outputs. Green, blue, red, purple, and orange symbols are the statistics spatially averaged over the the EMBS (whole domain), Turkey, the ETB, the Turkish part of the ETB (ETB_TR), and the rest of the ETB (ETB_REST), respectively.

part of the ETB where we will calculate the water budget by using the outputs from regional climate model, NCAR's CESM1-FCHEM is the "best" for temperature, while the CCSR's ESM-CHEM simulation has the lowest bias for precipitation.

Taylor diagrams [76] enable the evaluation of different statistical measures such as correlation, normalized standard deviation and RMSE all together. Here, Taylor diagrams for both temperature and precipitation were drawn for comparison (Figure 3.4) over the whole domain. Each point in the diagram (different colors show different

GCMs) represents the similarity between observed and modeled precipitation and temperature. The closest point to the observation data (the point called OBS in the diagrams) shows the superior performance among all GCM outputs. First five values that were statistically significant in both Taylor diagrams were given in the Table 3.1. Lapse rate correction in the temperature interpolation is needed because of the elevation differences due to the resolution difference between model and observation data. For this purpose, gridded elevation values of both model and observation are required. Unfortunately, it was not possible to provide this information for all GCMs. In the Table 3.1 the uncorrected (no lapse rate correction) results are given. Absence of the lapse rate corrected values may render temperature parameter less reliable for the selection of GCM. This leaves the precipitation parameter as the more reliable selection criteria. Therefore, it is decided to select the GCM among the models which produce better results for precipitation. Also, the precipitation performance of the input data is important for the water budget calculation in the GCM-driven simulations.

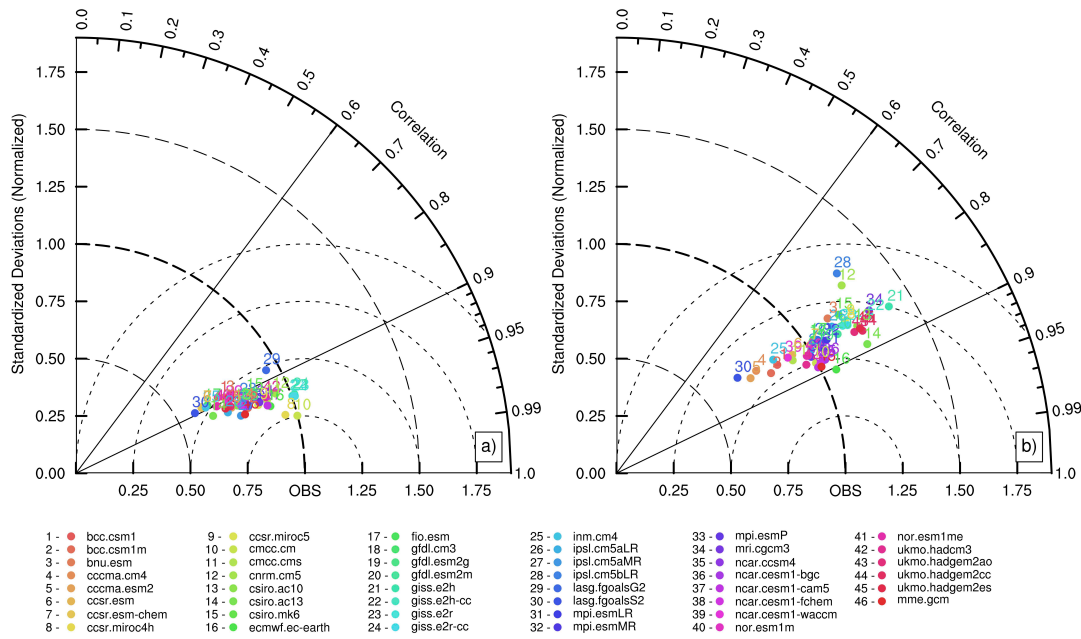


Figure 3.4 : Taylor diagrams show the GCM performances over the whole domain for a) temperature and b) precipitation. ¹

EC-EARTH model has the best results for two statistic measures (Correlation and RMSE in Table 3.1). Normalized standard deviation value (1.061) of the EC-EARTH model is not different from the observation data even though it is not among the first

¹The arcs in the diagrams represent the correlation between model and observation, y-axis shows normalized standard deviation values (meaning of 1-value is that standard deviations of both data sets (observation and model) are equal), and x-axis shows average error (the distance from OBS point).

Table 3.1 : The first five statistically significant GCMs from the Taylor diagrams

Temperature		Precipitation	
Correlation	RMSE	Correlation	RMSE
CMCC.CM (0.968)	EC-EARTH (2.040)	EC-EARTH (0.904)	EC-EARTH (0.337)
CCSR.MIROC4H (0.963)	CESM1-CAM5 (2.074)	CSIRO.AC13 (0.889)	CESM1-CAM5 (0.345)
EC-EARTH (0.945)	CCSR.MIROC4H (2.095)	CESM1-CAM5 (0.885)	NCAR.CCSM4 (0.356)
IPSL.CM5AMR (0.944)	CMCC.CMS (2.114)	CESM1-FCHEM (0.880)	CESM1-FCHEM (0.0357)
CESM1-CAM5 (0.943)	GISS.E2RCC (2.135)	NCAR.CCSM4 (0.879)	UKMO.HADCM3 (0.362)

five GCMs in the ranking. Another reason to select the EC-EARTH model is that RegCM4 only supports EC-EARTH model outputs among the first five statistically significant GCMs. As a result of evaluations, EC-EARTH model was selected for the scenario simulations.

3.3 Strengths and Limitations of the Selected GCM

Among these 45 simulation outputs (Table A), we had to select only one GCM for downscaling due to our limited computational sources. Otherwise, ensemble simulations are the common way to reduce the uncertainty caused by the initial and boundary conditions [41]. The future model projections suffer from the lack of a validation option and are heavily dependent on the underlying scenario story lines. Therefore, we evaluated the GCM performances by investigating their ability in reproducing the historical temperature and precipitation patterns. Also, download and storage of all CMIP5 outputs are a limitation. After the selection process of "EC-EARTH" model for our scenario simulations, we wanted to see where the selected GCM stands among the CMIP5 for the future simulations.

In Figure 3.5, we compared the spatially averaged temperature and precipitation change over Turkey. The spatially averaged time series are provided from the Climate Explorer of the Royal Netherlands Meteorological Institute (KNMI) [119]. The boxplots show the differences between the historical runs and middle (2046-2065) and end (2081-2100) of the century simulations for different scenarios. In the middle of

the century, the median (mean) increase in temperature values are 1.83 (1.91) °C for the RCP4.5 scenario, while they are estimated as 2.85 (2.82) °C for the most severe scenario compared to the reference period. At the end of the century, these median numbers reach up to 2.38 and 4.76 °C for both scenarios, respectively. The outputs from EC-EARTH show lower temperature values compared to the other CMIP5 simulations for all cases. For precipitation, most of the CMIP5 models indicate a decline (negative values of boxplots) for the both scenario and simulation period (mid- and end of the century). However, the EC-EARTH model estimates more precipitation than the other models with an exception for the middle of the century with RCP8.5 scenario. For this period, mean EC-EARTH precipitation matches with both the mean and median of all CMIP5 models.

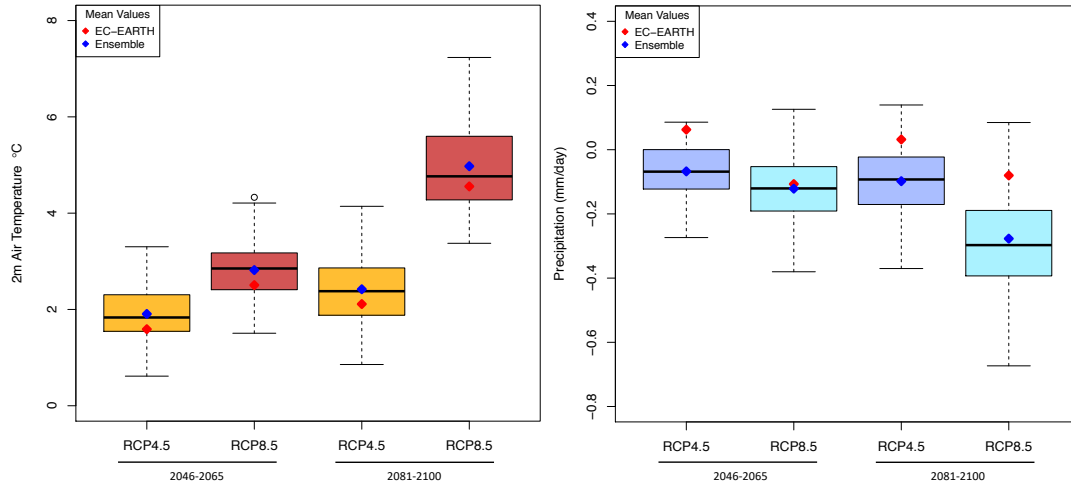


Figure 3.5 : The spatially averaged temperature (left) and precipitation (right) change (blue and red) between future and reference simulations of CMIP5 models over Turkey. ²

The difference of the temporal pattern of the EC-EARTH's precipitation compared to other models can be a limitation. But, at the same time, future is uncertain. The precipitation performance of the EC-EARTH was found as the "best" over our study domain compared to the historical observations. In addition to it's better statistics over the region and being supported by RegCM4 model, another advantage of this model is its high horizontal resolution ($1.1^{\circ} \times 1.1^{\circ}$). We expect an improvement in the ICBCs of the model due to the high spatial resolution of the input data.

²The boxplots show the 25th and 75th percentiles range, while the dotted lines show the 5th and 95th percentiles of CMIP5 simulations. The yellow and purple boxes are for the RCP4.5 scenario, while red and blue boxes are for the RCP8.5 scenario simulations. The thick lines show the median of the CMIP5 ensemble.

4. REGIONAL CLIMATE SIMULATIONS

Dynamical downscaling can be basically defined as increasing the both spatial and temporal resolutions of global model outputs or global reanalysis data by using regional climate model over the selected domain. The land processes may not be defined in an adequate precision in the global models. By this way, representations of the regional topographic properties, surface types and surface effect can be realistically reflected on the high-resolution model results [120]. In order to increase the resolution of the outputs of the global circulation models and to produce several projections from these results, it is needed to perform regional climate change simulations by using dynamically downscaling method (e.g. [12, 13, 25, 121]). This chapter includes the methods and the results for achieving the research objectives [3-6] listed above.

4.1 Model Setup and Data Collection

For running regional climate models, several input data are needed such as ICBCs and surface information (topography and land use maps). As mentioned before, the accuracy of the input data directly affects the RCM outputs [12]. Here, we created land use maps considering the LULC changes (agricultural irrigation and dam constructions), after selecting the 'best' GCM as an input (see the previous section). In this section, we introduce the details of the preparation of the input data and model set up, and then we perform the RCM simulations.

4.1.1 Land Use and Land Cover Maps

The accuracy of the LULC classification has an important role on climate simulations [122]. One of the contributions of our study is the generation of the current and future land use maps over the GAP region by considering real data rather than using hypothetical scenarios, and prescribing these to regional climate simulations. For this purpose, both of the implemented and planned irrigation schemes, as well as the filled dams were added to the prescribed land use map.

4.1.1.1 Base maps

In the default settings, the LULC map of the employed RCM, RegCM4 (see Section 4.1.2), uses the satellite images from 1992 and 1993 in order to describe the LULC classification. However, this input data is lack of the recent dam and irrigated crop areas. Therefore, we updated the default LULC map by using different base maps in order to show the current and the future situation of the LULC classification over the GAP region. Here, we first give the information about default base map and then two data sets we used for the update.

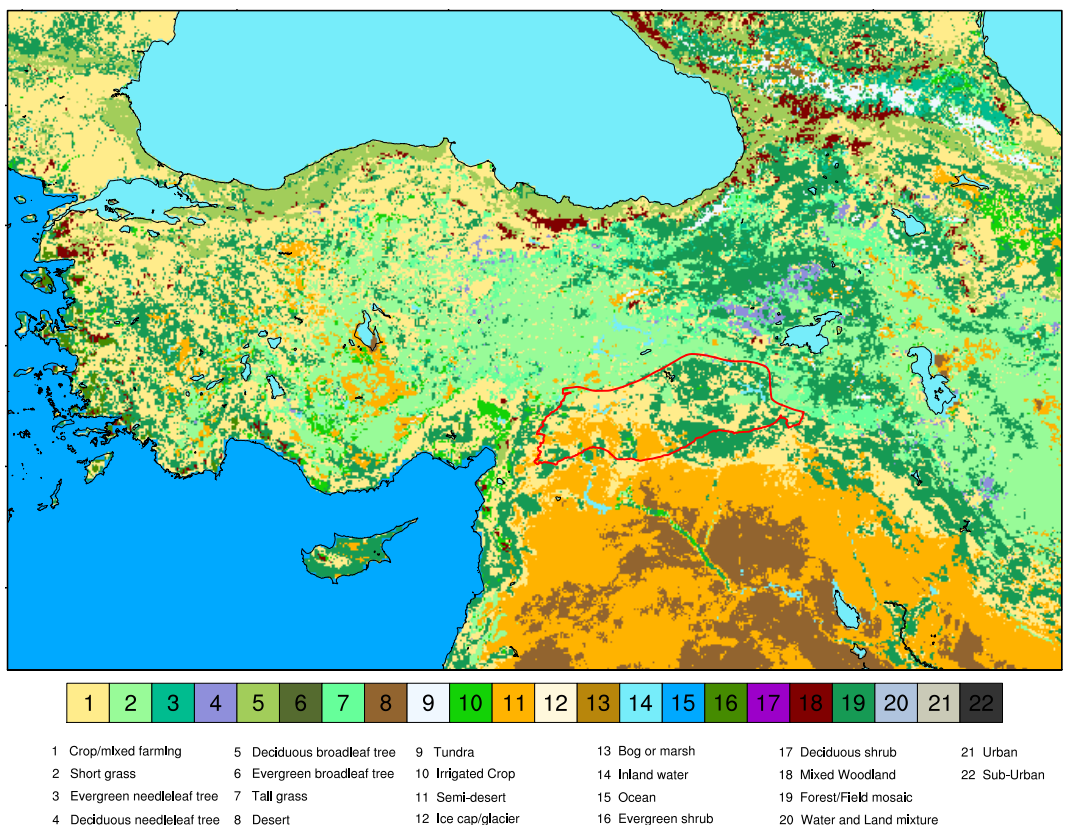


Figure 4.1 : GLCC based LULC map in 3 km resolution over Turkey¹.

Global land cover characteristics data

RegCM4 model uses the Global Land Cover Characteristics (GLCC) global data set [123] as its default LULC map. The GLCC data set was produced from Advanced Very High Resolution Radiometer (AVHRR) satellite retrievals between the dates of April 1992 and March 1993 at 1km horizontal resolution. This land use map represents the natural conditions before the LULC change in the GAP region. Hence, it becomes possible to apply the aforementioned LULC changes on the prescribed LULC map,

¹The red line indicating the borders of the GAP area subject to LULC change.

which did not include recent dam constructions and irrigated crop area. Therefore, a number of modifications (see Section 4.1.1.2) on the default LULC map, hereafter pre-GAP, of the RegCM4 model was required to gauge the impact of LULC change on the hydroclimate of the upper ETB.

The default LULC map (Figure 4.1) was used as an input for the regional climate model which is created by using the terrain program of RegCM4 which uses a static surface dataset of GLCC. This default LULC map has 22 land cover classes for the use of the land surface model BATS (Biosphere-Atmosphere Transfer Scheme). The other maps are also generated for same classes.

The 2006 CORINE land cover data

The GLCC data in Figure 4.1 shows the land use characteristic of the region, especially before the Ataturk Dam has become operational (before GAP). By the end of 2014, the area of the irrigated crop in the GAP region was 424710 ha, this being corresponding to %24.6 of the irrigation projects of the GAP [124]. A comparison between the GLCC data and the up-to-date LULC map given in Figure 4.2 clearly shows the expansion in irrigated crop and inland water areas. Thus, a new ‘current’ LULC map is created by updating the default LULC map based on the Coordination of Information on the Environment (CORINE) data [125].



Figure 4.2 : CORINE 2006 LULC map at 250 m spatial resolution.

CORINE Land Cover (CLC) 2006 dataset is a computerized inventory consisting of land cover information of 38 countries (most of the European Union member, and Middle and East European countries). These data are gathered under the CORINE programme by the European Environment Agency (EEA) [125]. The origin of data

is based on the CORINE 2000 data obtained from I&CLC2000 (IMAGE2000 and CLC2000) satellite display project. CORINE land cover projects are considered necessary by the European Parliament member countries and Europe's environmental institutes. These projects still continue due to the need of realistic and quality land use information. At the time of generation of the current map in the present study, the CORINE 2012 project had been launched. However, the validation of this data set for Turkey was not accomplished. Therefore, the CORINE 2006 data (Figure 4.2) was used as a base map for creating the current LULC map.

Turkish state hydraulic works data

The future LULC map corresponds to the accomplishment of the 100% of the irrigation projects. So, we obtained the master plan of the irrigation areas in the ETB from the Turkish State Hydraulic Works (DSİ). The DSI map given in the Figure 4.3 does not have the land cover information of the region, but shows the layout plan of the irrigation projects within the GAP program. The status of the irrigation projects is given in five different categories : prior examination, planning, project, construction, and operation. Future LULC map was generated by assuming the extension of irrigated areas upon the completion of the irrigation schemes in these all categories over the GAP region. When we use this land use map, it means that all five categories are fully irrigated.

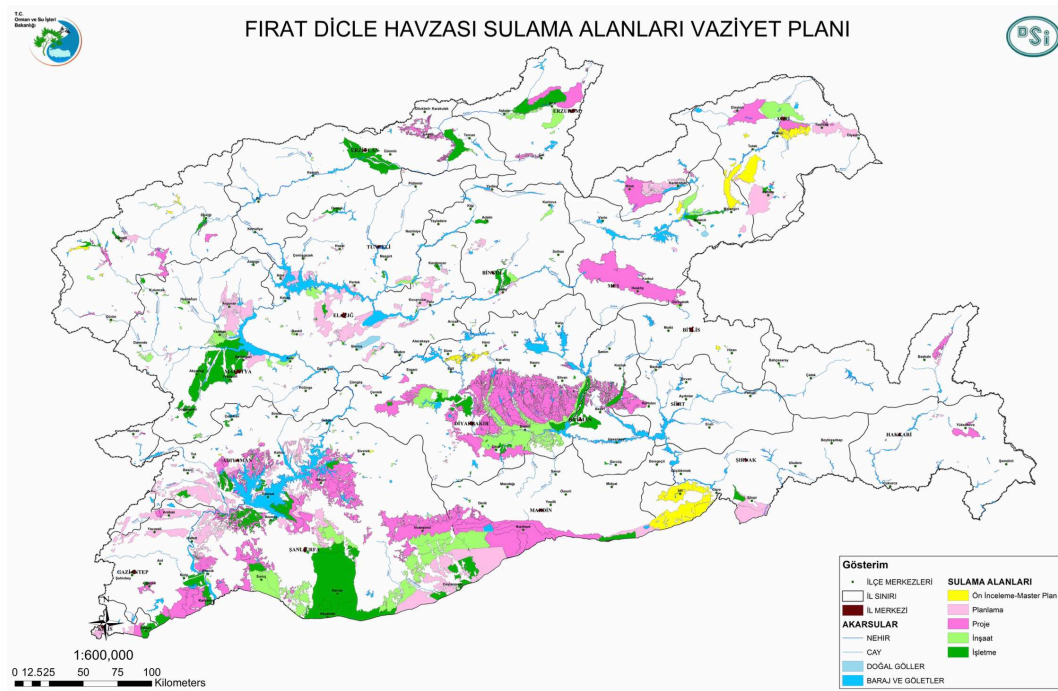


Figure 4.3 : The situation and the plans of the irrigation projects in the ETB by 2015.

4.1.1.2 LULC map generation method

In order to create the current and future land use maps as an input for the RegCM4 simulations, the pre-GAP map was processed via QGIS 2.8 and NCL (NCAR Command Language). Since the projection of three maps are different from each other, the projections of all maps were transformed to the Lambert Conformal Conic projection which is the default projection of the model outputs. Similarly, datum information which includes the coordinate systems of the maps was transformed to WGS 84 to pave the way for working on three different maps (see Appendix C).

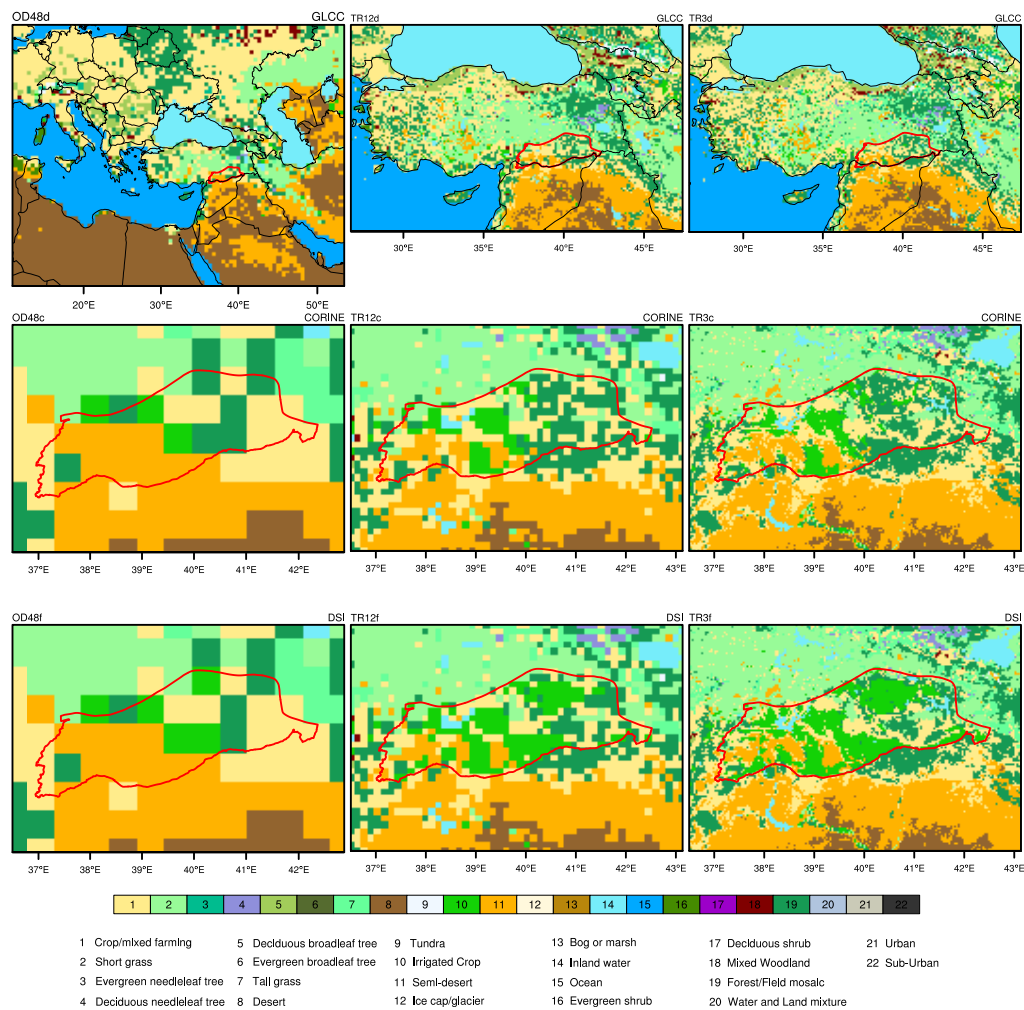


Figure 4.4 : Pre-GAP, current, and future LULC maps. ²

While producing the new land use maps, only LULC changes in the GAP region were taken into account. The extension of irrigated crop and inland water areas was applied on the newly derived land use maps. The pre-GAP, current, and future LULC maps

²Maps in the rows show the ones created from GLCC (pre-GAP), CORINE (current) and DSI (future) data sets. Columns show the maps in different model resolutions for 48, 12, and 3 km, respectively. For simplicity, the area enframed with red lines show the GAP region.

used in this study are shown in Figure 4.4. These maps describe the non-irrigated, partially, and fully irrigated areas in the GAP region, respectively.

Table 4.1 shows how the fractional areal coverage of each LULC type changes according to the land use map. In the pre-GAP land use map, only 0.7 % of the GAP region is irrigated, but this increases to 17.4 % and 38 % for the current and future land use maps, respectively. After filling-up the reservoirs of the constructed dams, the inland water fractional coverage similarly increases from 1.7 % to 2.6 % and 3.0 %.

Table 4.1 : Fractional areal coverage (in %) of each LULC type in GAP region for the three land use maps.

LULC type	Pre-GAP	Current	Future
 1 - Crop/mixed farming	41.3 %	32.2 %	24.4 %
 2 - Short grass	8.2 %	7.8 %	7.8 %
 3 - Evergreen needleleaf tree	0.1 %	0.1 %	0.1 %
 4 - Deciduous needleleaf tree	0.1 %	0.0 %	0.0 %
 7 - Tall grass	0.6 %	0.5 %	0.5 %
 10 - Irrigated Crop	0.7 %	17.4 %	38.0 %
 11 - Semi-desert	14.6 %	12.5 %	10.5 %
 14 - Inland water	1.7 %	2.6 %	3.0 %
 19 - Forest/Field mosaic	32.5 %	26.8 %	15.7 %

4.1.2 Regional Climate Model : RegCM4

A regional climate model, in the form of the revision-4283 of RegCM4, is the main tool used for this study. RegCM4 is a hydrostatic, compressible, sigma-p vertical coordinate, and community model [126] developed by the International Centre of Theoretical Physics (ICTP). Compared to its previous versions, RegCM4 includes several improvements in radiative transfer and boundary layer schemes. The default land surface model of RegCM4, derived from BATS1e (Biosphere-Atmosphere Transfer Scheme [127]), is enabled due to its subgrid approach which enables solving for the surface variables in high resolution (3 km in our case).

4.1.2.1 Forcing data sets

The initial and lateral boundary conditions to the model were provided by the NCEP/NCAR Reanalysis Product version 1 (NNRP1) global reanalysis [128]. NNRP1 data have 6-hourly temporal (1948-present) and $2.5^\circ \times 2.5^\circ$ spatial coverage, and

17 pressure levels. The NOAA Optimum Interpolation weekly mean of sea surface temperature (OISST) V2 with a spatial resolution of $1^\circ \times 1^\circ$ global grid was also employed [129]. For all the experiments mentioned in Section 4.1.2.3, the simulations were performed first over the OD48 (red lines in Figure 4.5) domain by using the NNRP1 and OISST data as initial and boundary conditions, then the outputs of the 48 km simulations were used to drive the nested 12 km simulation over the TR12 (blue lines in Figure 4.5) domain.

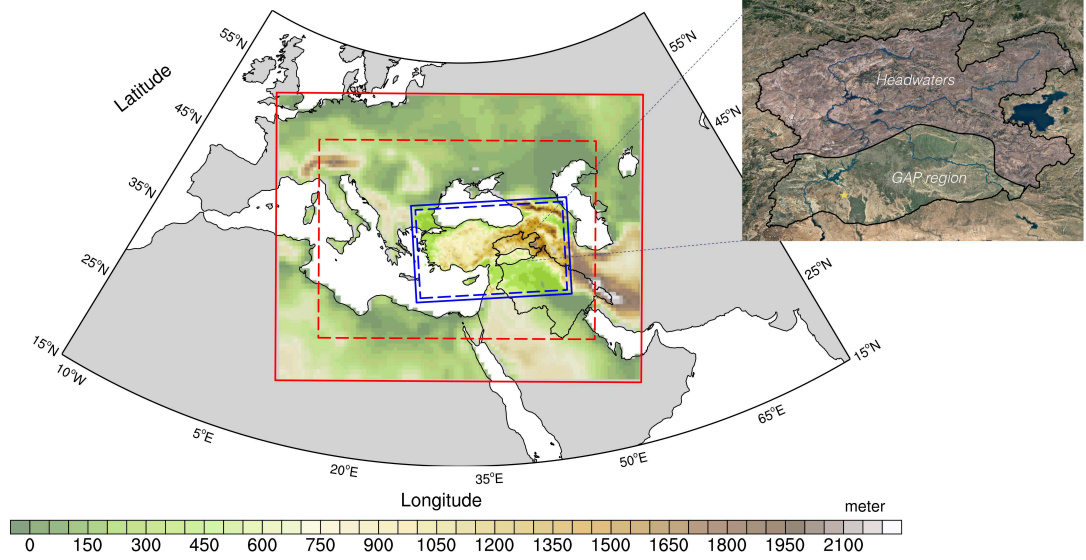


Figure 4.5 : Study domains and topography. ³

4.1.2.2 Model domain and model parameters

Model domain

The Eastern Mediterranean and Black Sea region (EMBS; red lines in Figure 4.5) forms the geographic link between Europe and Asia. Turkey, as the largest country fully contained within this region, has several climatic zones [130] due to its complex topography and landscape. It is located (blue lines in Figure 4.5) in one of the hotspots that is highly vulnerable to climate change [13]. In addition to greenhouse gas emissions, human activities such as irrigation and recently constructed dams in the country's largest basin, the ETB, have the potential to enhance the anticipated effects of climate change at local and regional scales.

³The red rectangle encompasses the domain with the model topography at 48 km resolution; the blue rectangle is for TR12 domain with the topography data at 3 km resolution. The dashed lines show the nudging zones of the domains. The black lines show the borders of the Euphrates and Tigris Basin. Inset: Satellite image of the upper ETB split into the headwaters and GAP region. The yellow star shows the location of the Harran Plain and Atatürk Dam.

Model parameters

Before performing the designed experiments (see Section 4.1.2.3), we first evaluated the model's physical parameters by comparing the observation data, CRU. For this purpose, we run several simulations particularly to find the best performing cumulus convection scheme and moisture scheme over the OD48 domain. After several sensitivity experiments (results not shown here) over the model domains, the following model physics parameterizations were chosen: the Grell cumulus convection scheme [131] for both over land and ocean with the [132] closure assumption, the Subgrid Explicit moisture scheme (SUBEX [133]), the boundary layer scheme of [134], the radiation scheme of NCAR CCM3 [135], and the ocean flux scheme of Zeng et al. [136] (See Table 4.2).

Table 4.2 : Physics options and parameters that are used in the RegCM4 simulations.

	OD48 (48 km)	TR12 (12 km)
Grid number (y,x), Vertical resolution	(75,95), 18 level	(100,160), 23 level
Center (latitude, longitude)	(40,32)	(38.7,37)
ICBC (atmosphere, sst)	(NNRP or EC-EARTH, OISST)	
Boundary condition grid number	(12,12)	(18,18)
Boundary layer model	Holtslag PBL [134]	
Cumulus convection scheme	Grell [131]	
Cumulus closure scheme	Fritsch & Chappell [132]	
Moisture scheme	SUBEX [133]	
Ocean flux scheme	Zeng [136]	
Radiation mode	CCSM [135]	

As mentioned previously, 12 km horizontal resolution (3 km for surface processes) has been used in the simulations for TR12 domain. Thereby, the turbulent fluxes of latent and sensible heat released into atmosphere especially from agricultural lands can be precisely obtained by running a land surface sub-model in higher resolution than the main climate model. In addition, simulations have been conducted for 23 vertical sigma levels by increasing the default (18 levels) model layer number (Table 4.2). Increasing the vertical resolution is important to simulate the land-atmosphere processes due to the complex topography of Turkey. Effectiveness of the boundary conditions in the simulations was extended by increasing the grid numbers from 12 to 18, which are used for the nudging regions. If the number of the grids of the whole domain is increased, grid number of the nudging regions should be increased too.

4.1.2.3 Experimental design

RegCM4 model was used to simulate the regional climate corresponding with the three generated land use maps (see Figure 4.4) of the GAP region, namely:

non-irrigated : pre-GAP period (natural conditions),

partly irrigated : current LULC change (25% completion level of irrigation projects in GAP),

fully irrigated : future LULC conditions (completion of the irrigation plans).

As mentioned earlier, we will use the NNRP data set for the model for the reference period simulations. Also, one reference period simulation is performed with the selected GCM, EC-EARTH, for comparison both with historical and future simulations. As given in Table 4.3, we performed 10 simulations with different forcing data, land use maps, and future scenarios.

Table 4.3 : List of the experiments. The simulations with green, red, and blue background are historical, middle and end of the century, respectively.

No	Forcing Data (scenario)	Land Use Map	Simulation Period
1	NCEP/NCAR Reanalysis	Non-irrigated	1991-2010
2	NCEP/NCAR Reanalysis	Partly irrigated	1991-2010
3	NCEP/NCAR Reanalysis	Fully irrigated	1991-2010
4	EC-EARTH	Non-irrigated	1986-2008
5	EC-EARTH (RCP 4.5)	Non-irrigated	2046-2065
6	EC-EARTH (RCP 8.5)	Non-irrigated	2046-2065
7	EC-EARTH (RCP 4.5)	Fully irrigated	2046-2065
8	EC-EARTH (RCP 8.5)	Fully irrigated	2046-2065
9	EC-EARTH (RCP 4.5)	Fully irrigated	2081-2100
10	EC-EARTH (RCP 8.5)	Fully irrigated	2081-2100

The model simulations with the default and two reconstructed land use maps were conducted, first, over a domain at a horizontal resolution of 48 km over the Balkans and EMBS region (OD48 experiments), and later on nested domain at 12 km resolution over Turkey (TR12 experiments). The BATS scheme of RegCM4 was run with a 3 km subgrid set-up. This configuration resolves the land surface variables at higher resolution over Turkey. By using the subgrid parameterization modification of BATS, we aim towards an improvement of the representation of the surface processes particularly in mountainous regions [137].

Naming convention for the simulations

In the next sections, we named the simulations with a format of

'domain name'+'initial of land use map'+'_forcing data'+'_simulation period'

with following options :

domain name : OD48 or TR12

land use map : d (for default), c (for current), and f (for future LULC map)

forcing data : NNRP, GCM (for EC-EARTH), RCP45 and RCP85 (for EC-EARTH with RCP 4.5 and 8.5 scenarios)

simulation period : ref (for reference period), mid (middle of the century) and end (end of the century)

For instance, the simulation called OD48c_NNRP_ref stands for the experiment No.2 in the Table 4.3 over the larger domain in 48 km, while the TR12f_RCP45_mid is the simulation No.7 in the Table 4.3 over Turkey.

4.1.3 RegCM4 Performance Analysis

The performance of the regional climate model was evaluated by comparing the simulation outputs against observational products (see Section 3.1.2) for the period between 1991 and 2010 with the default (non-irrigated) land use map. The evaluation was focused on the 20-year mean values of downscaled climate fields such as surface air temperature, precipitation, and evapotranspiration. The temperature values over the headwaters region are essential due to its role in snow accumulation and the timing of snowmelt [71]. Precipitation and evapotranspiration are the main components of the terrestrial water budget. Therefore, the performance of the model in simulating these three variables is critical to diagnose the consequences of the LULC changes on the regional climate and hydrological cycle.

Figure 4.6 shows the comparison between downscaled model results driven by the NNRP data and observations over the EMBS region at a grid spacing of 48 km. The first map (Figure 4.6a) shows spatial pattern of the observed surface temperature within the OD48 domain. The annual mean temperature shows a clear meridional gradient being higher in the south of the domain similar to the temperature pattern of the ETB (see Figure D.1). Over the bigger domain, the lowest mean temperature values are observed over the mountainous areas such as the Caucasus and European Alps. The model has a warm bias (Figure 4.6d) over the OD48 domain by about 0.5°C. However,

model outputs for average near surface air temperature give a cold bias in the ETB of around -1.7°C (Figure D.1d).

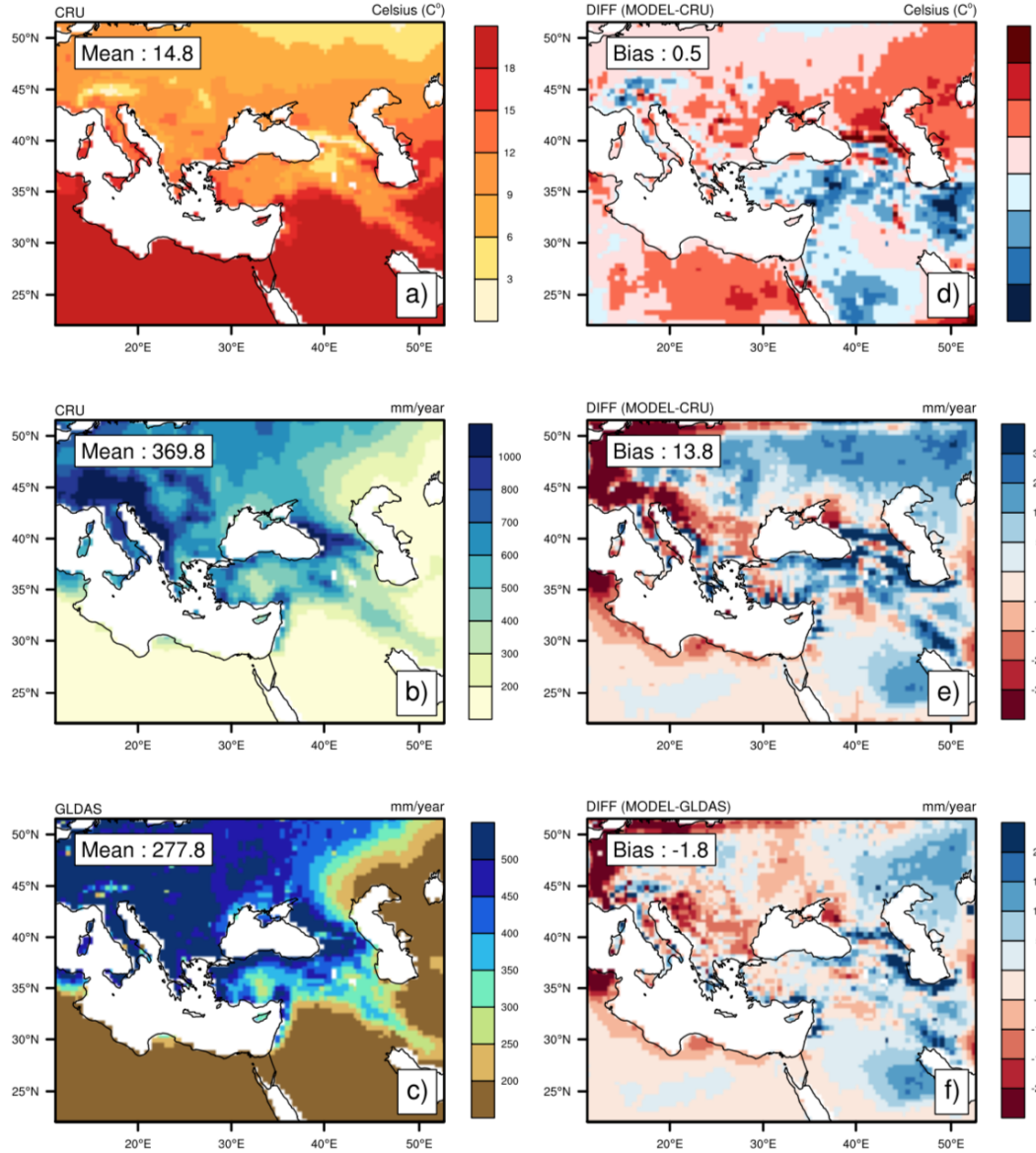


Figure 4.6 : Evaluation of the modeled temperature, precipitation and evapotranspiration against the observations for the whole domain (OD48) between 1991 and 2010. ⁴

Figure 4.6b clearly demonstrates that for the 20-year average annual precipitation the model has a wet bias in the higher elevations and the coastal regions. Even though, the bias over these areas are high, averaged bias (13.8 mm per year, Figure 4.6e) corresponds to a relative bias less than 4%. Also, the positive bias is simulated in the headwaters of the ETB and a dry bias in the lower elevation downstream GAP

⁴Rows show temperature, precipitation and evapotranspiration, respectively. The first column (a-c) shows the observations, the second (d-f) the difference of the modeled outputs from the observations.

region (Figure D.1b). Still, the overall bias for the ETB is around 52.7 mm per year (Figure D.1e) which amounts to a relative bias of just 10%.

The performance of the model in terms of estimating evapotranspiration is quite important, since the simulation outputs will be used in a water budget calculation. Both the absolute and relative biases for the 20-year average annual evapotranspiration are lower compared to those of the precipitation when spatially averaged over both the EMBS (Figure 4.6f) and the ETB (Figure D.1f). Although the bias is small (-1.8 mm per year) for the larger domain, the regional climate model has a low temporal R-squared statistic (0.37) which shows that the model struggles to capture the correct temporal evapotranspiration distribution (Figure 4.6c) over the larger domain. However, the RCM shows an opposite performance over the ETB (Figure D.1c). The spatial R-squared statistic is very low around 0.22, while the temporal correlation is relatively high of 0.76 (see Table D.1).

The scatter plot (Figure 4.7a) of observed and modeled temperature shows that the regional climate model is able to simulate the spatial distribution of the near surface temperature field, with high square of cross-correlations (Pearson, R^2) of around 0.98 and 0.99 for the ETB and OD48 (see Table D.1), respectively. The large temperature biases could also be due to the scarcity of observation stations over the highlands. The overall performance of the model in terms of reproducing the observed temperature field has a slight overestimation over the OD48 domain, and a tendency of underestimation over the ETB (Figure 4.7d). Furthermore, despite the slight wet and dry bias patterns that were previously mentioned, the model is able to capture the overall spatial pattern (Figure 4.7b) of the 20-year average annual precipitation in the ETB with a relatively high R-squared statistic (0.77, Table D.1) as well as the temporal pattern of the spatially averaged precipitation values (Figure 4.7e). In their study, Bozkurt and Sen [35] were able to produce a similar precipitation pattern distribution (Figure D.1b) over the ETB by using a similar model physics configuration but with RegCM3. The overall RMSE over the ETB is slightly higher, at around 117.6 mm per year (Table D.1), but this only amounts to a relative RMSE of 21%. As a whole the performance of RegCM4 in terms of simulating evapotranspiration is satisfying over the entire 20-year simulation period as the model is able to capture the main tendencies in the interannual variability (Figure 4.7f).

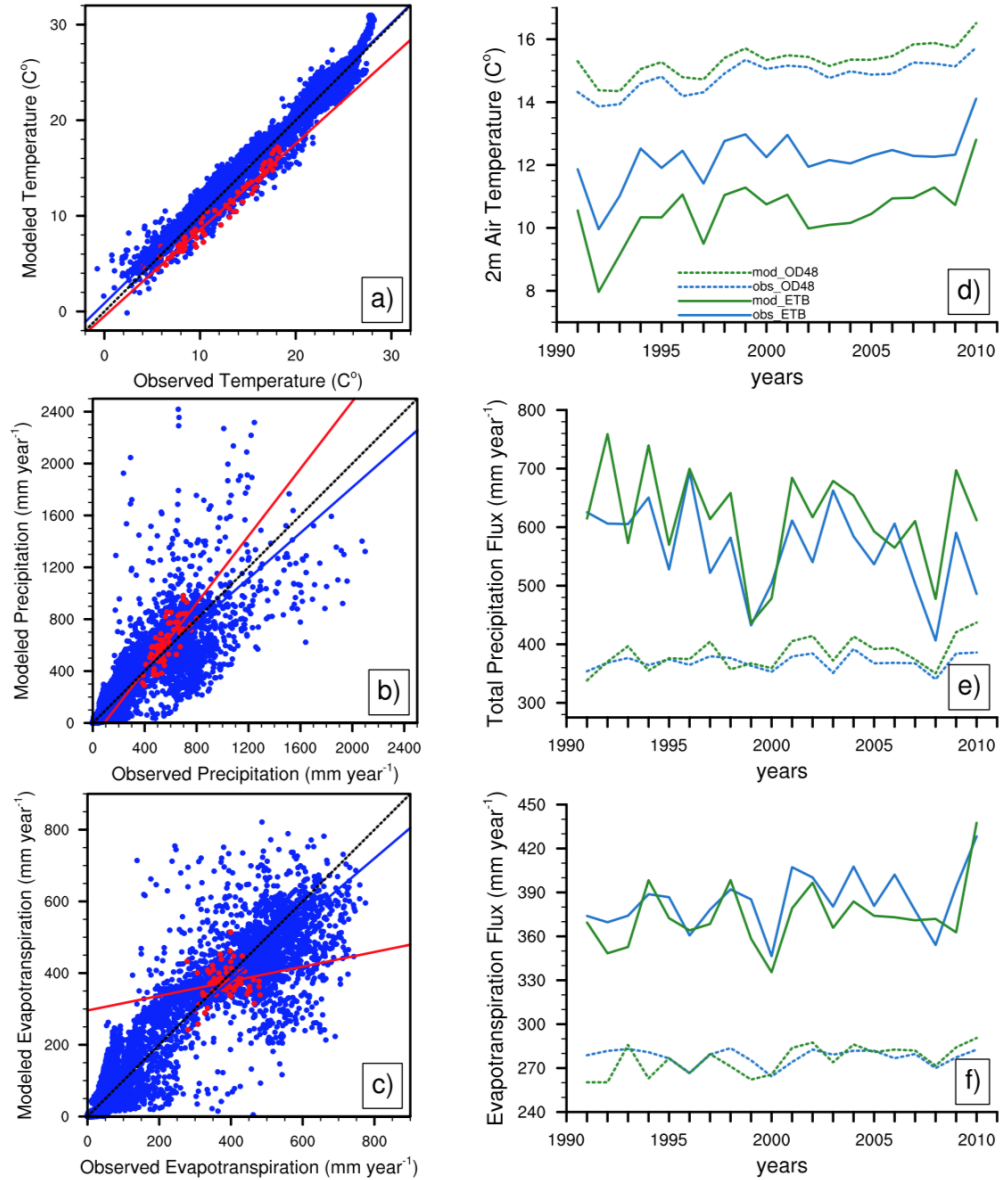


Figure 4.7 : Comparison of temporally and spatially averaged observations and model results. ⁵

Comparison against observations over the ETB region showed that the model is able to reproduce the temperature, precipitation and evapotranspiration fields fairly well. The biases could be caused by deficiencies both in the model and in the observation data. Reducing the uncertainty caused by the observation data is still a challenging issue regardless of the source of the products, including the gauge-based (i.e. CRU) precipitation estimates [138].

⁵(a-c) shows scatter plots of the 20-year averaged modeled and observed values for the whole domain (blue dots) and the ETB (red dots), while the last column (d-f) shows the time series spatially averaged over the whole domain (solid lines) and the ETB (dotted lines) for the model simulations (green) and observations (blue).

4.2 Simulating the Hydroclimatic Effects of LULC Changes

As mentioned above, changing the land surface characteristics (in our case irrigation and extension of the dam areas) has a direct effect on the regional water and energy balance. The water and energy budgets are directly linked through evapotranspiration (see Section 4.2.1). Here, we simulate only the hydroclimatic effects of these LULC changes under the same climate conditions for the period between 1991 and 2010. For this purpose, we analyzed the outputs of first three simulations (No.1-3 in Table 4.3) over the ETB in 12 km resolution. Recall that surface processes are modeled in 3 km with subgrid feature. So, the variables investigated below are averaged over 12 km grid cells from the outputs originally calculated in 3 km spatial resolution.

4.2.1 Water and energy budget calculation at the land surface

The water budget for the surface layer can be expressed as:

$$\frac{dS}{dt} = P - E - R_s - R_g \quad (4.1)$$

where $\frac{dS}{dt}$ is the change in water storage, P is the precipitation, E is the evapotranspiration, R_s is the surface runoff, and R_g is the groundwater runoff. Under the natural conditions (e.g. no reservoir constructions), it is assumed that there is no change in long-term water storage ($\frac{dS}{dt} = 0$). Consequently, the sum of runoff rates ($R_s + R_g$) is equal to the long-term average of the precipitation minus evapotranspiration ($P - E$) values. In the land surface model (BATS) of RegCM4, the required irrigation water for plants is supplied from an artificial runoff flux in order to avoid the water stress in irrigated crop grid cells. In the ETB, the irrigation water for the GAP region is transferred from the reservoirs of the dams storing the water of the headwaters region. Hence, the $P-E$ values were used in order to calculate the water storage in this study. The land surface energy balance is generally formulated as follows

$$\frac{dH}{dt} = R_n - \lambda E - SH - G \quad (4.2)$$

Here, the first term is the change in energy storage, R_n is net radiation, λE is the latent heat flux (λ is the latent heat of vaporization and E is the evapotranspiration flux), SH is the sensible heat flux, and G is the ground heat flux. Here, the net radiation is defined as positive towards the surface while the remaining fluxes are defined as positive when

directed away from the surface. Often one assumes that the change in energy storage is zero, so that the surface energy balance can be reformulated as

$$Q_a = R_n - G = \lambda E + SH \quad (4.3)$$

where Q_a is the energy available for transfer from the surface to the atmosphere by turbulent fluxes (λE , SH). By using the outputs of the simulations, a residual term is calculated by subtracting the latent and sensible heat fluxes from the net radiation (summation of net shortwave and net longwave radiation). This calculated residual term corresponds to the sum of change in energy storage and ground heat flux. As in equation 4.2, if we assume that there is no change in energy storage, then the residual term equals to the ground heat flux. From the Equations 4.1 and 4.2, it is clear that the surface energy and water balances are coupled through evapotranspiration term (E).

4.2.2 Effects of irrigation on surface processes

In this section, we mainly show the results of the high resolution (TR12) simulations. These simulations have 12 km spatial resolution and are run with the three land use maps which show the different levels of irrigation and dam constructions in the GAP region. The change in annual means of several surface variables are given in Table 4.4 for both the GAP region and headwaters area of the ETB.

To determine whether the changes in the simulations are statistically significant, the Student's t-test was applied to the model results. This tests if the null hypothesis (in our case "H0: the time averages of two different simulation results are the same") is correct or not. According to the test, rejection of the H0 occurs when the calculated probability of t-values is less than a certain threshold (5% in our case). A change in the time average of a model result due to a change in irrigation is deemed statistically significant when the null hypothesis is rejected at the 95% confidence level.

Over the 20-year simulation period, the model results indicate that the irrigation schemes have a moderate cooling effect over the irrigated grid cells (Figure 4.8a and 4.8e). The annual mean 2 m air temperature and ground temperature decreased by as much as 0.8°C and 2.1°C (see Table 4.4), respectively, in the GAP region due to irrigation. Still, the absolute changes in temperature values due to irrigation were not statistically significant according to the t-test results.

Table 4.4 : LULC change effect on land surface variables for the two sub-regions: the Southeastern Anatolia Project (GAP) region, and the headwaters area (HW). The numbers in the parentheses show the magnitude of absolute (°C) or relative (%) changes. Marked (*) numbers indicate a change that is statistically significant at the 95% confidence level.

Variables (unit)	GAP			HW		
	Non-irrigated	Partly Irrigated	Fully Irrigated	Non-irrigated	Partly Irrigated	Fully Irrigated
2m Air Temperature (°C)	15.67	15.31 (-0.36 °C)	14.84 (-0.83 °C)	7.48	7.43 (-0.05 °C)	7.35 (-0.13 °C)
Skin Temperature (°C)	15.64	14.68 (-0.96 °C)	13.55 (-2.09 °C)	5.96	5.89 (-0.07 °C)	5.81 (-0.15 °C)
Precipitation (mm)	506.1	522.5 (+3.2%)	538.8 (+6.5%)	924.7	935.6 (+1.2%)	952.1 (+3.0%)
Evapotranspiration (mm)	415.7	628.8 (+51.3%)*	886.1 (+113.2%)*	526.2	532.4 (+1.2%)	541.5 (+2.9%)
Sensible Heat Flux (Wm^{-2})	51.07	39.80 (-22.1%)*	25.64 (-49.8%)*	29.42	29.21 (-0.7%)	28.98 (-1.5%)
Latent Heat Flux (Wm^{-2})	33.67	50.87 (+51.1%)*	71.64 (+112.8%)*	43.83	44.33 (+1.1%)	45.07 (+2.8%)
Soil Moisture-10cm (mm)	233.83	261.1 (+11.7%)*	294.0 (+25.7%)*	283.8	285.2 (+0.5%)	287.2 (+1.2%)
Specific Humidity (g/kg)	5.32	5.73 (+7.7%)*	6.23 (+17.3%)*	3.69	3.72 (+0.9%)	3.76 (+2.0%)
Convective Precipitation (mm)	137.5	149.1 (+8.4%)	162.1 (+17.9%)	181.3	188.2 (+3.8%)	198.4 (+9.4%)
Snow Water Equivalent (mm)	43.77	45.58 (+4.1%)	45.21 (+3.3%)	314.09	316.87 (+0.9%)	317.00 (+0.9%)
Net Radiation (Wm^{-2})	83.9	90.1 (+7.3%)	96.7 (+15.2%)	77.3	77.6 (+0.4%)	78.2 (+1.1%)
Wind Speed (ms^{-1})	1.775	1.807 (+1.8%)*	1.815 (+2.3%)*	1.685	1.675 (-0.6%)	1.657 (-1.7%)
Boundary Layer Height (m)	1009.9	921.6 (-8.7%)*	796.1 (-21.2%)*	824.0	818.5 (-0.7%)	809.9 (-1.7%)
Bowen Ratio (-)	3.29	2.17 (-34%)*	0.94 (-71.4%)*	0.91	0.88 (-3.8%)	0.57 (-37.6%)

Additionally, annual mean ground and 2 m air temperatures did not change significantly in the headwaters area or in the rest of the domain. Particularly in summer months, the cooling effect of irrigation greatly reduces the temperature in the GAP region by around 1.5°C at near the surface, and 4.2°C at the ground surface for the fully irrigated simulation.

The sensible heat flux decreases compared to the control run by around 22% and 50% for partly and fully irrigated conditions, respectively, as opposed to the increase of 51% and 113% in latent heat flux values (Table 4.4). While the effect of irrigation on the sensible heat flux was confined only to the irrigated grid cells, it spreads to the neighboring grid cells for the latent heat flux. In connection with this, the alteration of the surface energy partitioning due to the increased water availability also changes the Bowen ratio throughout the year. Statistically significant changes in the Bowen ratio occurred in the GAP region decreasing to 2.17 and 0.94 on average for the current (TR12c_NNRP_ref) and future (TR12f_NNRP_ref) land use map simulations, respectively (Table 4.4). In the latter case, the annual Bowen ratio also declined from 0.91 to 0.57 on average in the HW area of the basin. For the GAP region, these typical values correspond to a shift in type of surface from semi-arid landscapes to irrigated crop. The moisture content of soil increases over the semi-arid areas for both the surface and rooting layers in the GAP region due to the irrigation (Table 4.4). In the case of the completion of all irrigation plans (TR12f_NNRP_ref), the model results show that total soil moisture of the GAP region increases by around 25.7% in the upper soil layer (10 cm).

The most striking modeled impact of the wet soil generated by irrigation is the dramatic increase in evapotranspiration amounts (Figure 4.8c and 4.8g). The spatially averaged change in evapotranspiration for the GAP region is around 51% for the current irrigation status (TR12c_NNRP_ref) and 113% for the completion of the all irrigation plans (TR12f_NNRP_ref). However, the increased evapotranspiration in the headwaters region is insignificant compared to the lower part of the basin (Table 4.4). In summer months, the magnitude of evapotranspiration in the GAP region is doubled for the partly, and tripled for the fully irrigated simulations.

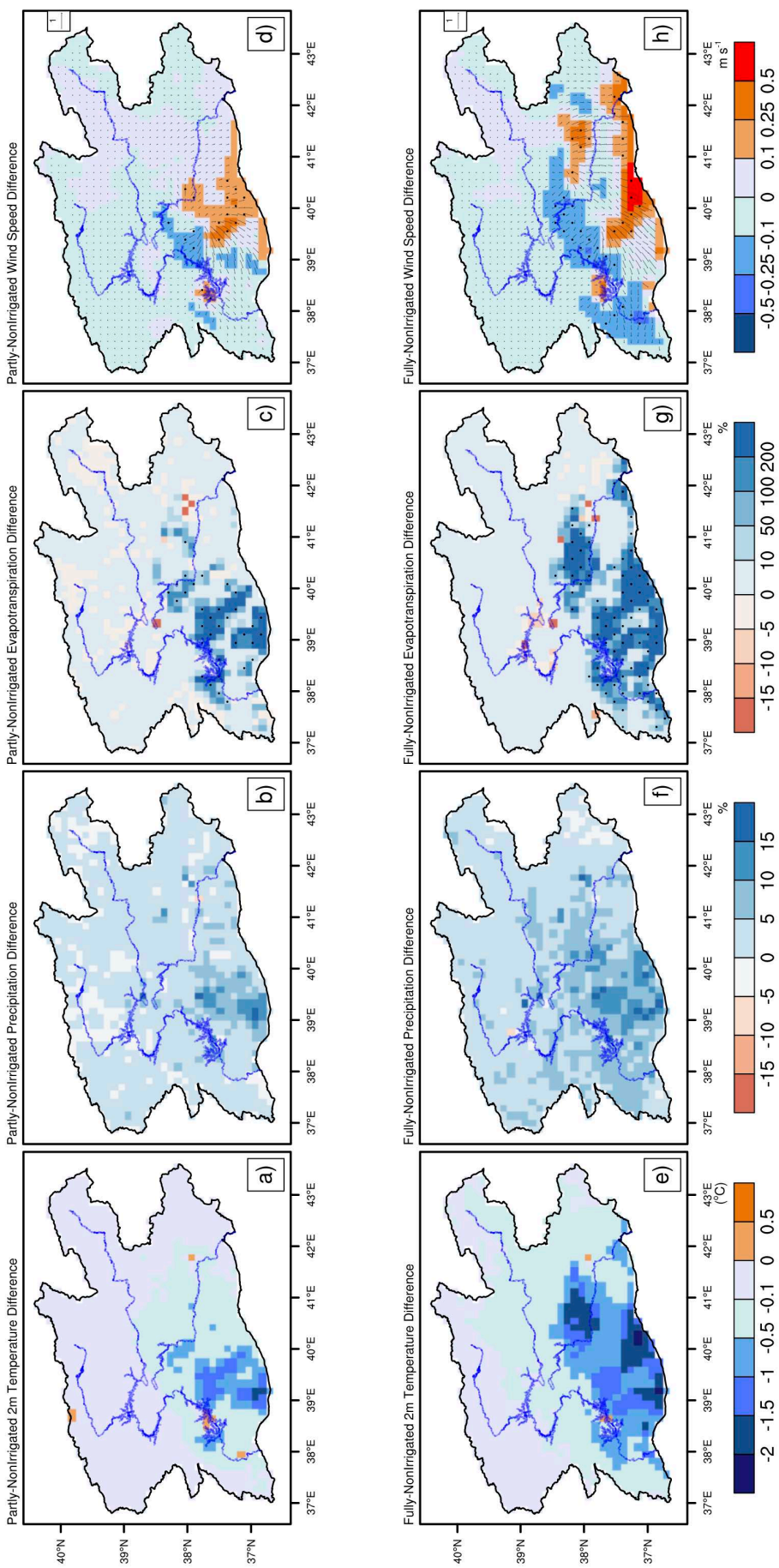


Figure 4.8 : Differences of partly and fully irrigated simulations from non-irrigated simulation over the ETB for 1991–2010 for (a, e) annual mean 2m air temperature, (b, f) precipitation, (c, g) evapotranspiration, and (d, h) wind speed, respectively. Dotted areas show the statistically significant changes.

Specific humidity is the mass of water vapor per unit mass of moist air. As a direct result of the influx of water vapor supplied to the boundary layer through enhanced evapotranspiration, annual specific humidity increases over the irrigated grid cells. During the summer months, when the irrigation applications peak, the increase in specific humidity compared to the control run is even higher: 13.1% and 29.3% for the partly and fully irrigated simulations. For the headwaters part of the basin, insignificant changes of around 2% occur for specific humidity in the TR12f_NNRP_ref simulation (Table 4.4). Enhanced water vapor leads to an increase in convective precipitation as a result of the increased convective cloud formation. For the fully irrigated conditions (Table 4.4), the convective precipitation increases by around 18% and 9.4% for the GAP and headwaters regions, respectively. However, statistically significant increases only occur in small areas over the GAP region. Unlike the convective precipitation, the change in total precipitation (snow + rainfall) amounts due to the increased irrigation applications were not significant anywhere (Figure 4.8b and 4.8f). For the fully irrigated conditions, annual precipitation increased by around 6.5% and 3.0% for the GAP region and the headwaters area, respectively. In the GAP region, we also see a statistically significant decrease in averaged atmospheric boundary layer height of around 88 meters and 214 meters for the partly and the fully irrigated simulations, respectively (Table 4.4). In addition to the water budget components, the snow related outputs of the model do not show significant changes according to the t-test results. The SWE over the GAP region show an increase annually of 4.1% and 3.3% for the partly and fully irrigated simulations, respectively (Table 4.4). Lastly, wind speed increases mostly over the lowland areas of the GAP region while it tends to decrease over the highlands of the GAP region (Figure 4.8d and 4.8h). Overall, it significantly increases over the GAP region for both current and future simulations (Table 4.4). An increase in wind speed increases the turbulent flux exchange, and vice versa for decrease.

4.2.2.1 Soil-moisture precipitation feedback

We show, as in other modeling studies [11, 139–141], that the irrigation practices cause a cooling effect (i.e., the oasis effect) over the heavily irrigated areas due to the increased evapotranspiration and associated latent heat flux. On the other hand, this influence may vary for different regions as shown in the study of Lobell et al. [9], depending on the ability of the employed models in simulating the soil moisture. Even

though one of their analyzed regions is Turkey, the borders of their domain does not include the ETB. We find that the irrigation-induced decrease in both skin and near surface temperatures occurs throughout the day with a peak around noon where the energy available from radiation for turbulent exchange reaches its maximum.

The most dramatic impact of irrigation and dam constructions is the steep increase in evapotranspiration. The land surface model of RegCM4, i.e. BATS, suppresses the water stress on crops by using the irrigation water to moisten the root zone (irrigation water is extracted from the surface runoff even if it becomes negative, meaning that there must be water transfer from somewhere else to meet the water demand of the irrigation practices). Thus, there is more water available for evapotranspiration. This leads to a transition in the evapotranspiration regime from a water limited to energy limited as a result of the enhanced irrigation (see Figure 4.9 adopted from [3, 142, 143]). Thus, energy partitioned to the latent heat flux increases, which increases the evapotranspiration from the surface. The magnitude of the turbulent heat fluxes is also inversely proportional to the aerodynamic resistance which is itself dependent on the wind speed, atmospheric stability, and surface roughness length [3]. The conversion of the land cover to the irrigated crop (c.f. Table 4.1) leads to a decrease in roughness length [127], albeit not much, and consequently an increase in aerodynamic resistance which we would expect to decrease both turbulent heat fluxes. The significant decrease in the sensible heat flux (c.f. Table 4.4) could also be explained by the local temperature inversion (i.e., the difference between the skin and near surface air temperatures is negative) over the irrigated grid cells (results not shown here). And, the significant latent heat flux increase could also be explained by the typical stomatal resistance decreases [127] in the conversion to irrigated crop areas which, in turn, lowers the bulk surface resistance for the latent heat flux. Furthermore, the wind speed increases over the irrigated areas, while it decreases in the rest of the GAP region. A possible reason of this duality is formation of inland sea breeze phenomenon [144] due to the temperature difference over the irrigated and dry areas. As a result of temperature differences, the wind flows towards the dry and warmer regions from the cool and wet land areas. Due to the higher wind speeds over the irrigated grid cells, which lowers the aerodynamic resistance, the evapotranspiration is further enhanced.

The increase in the latent heat flux also causes an increase in water vapor concentration in the shallower boundary layer, and consequently enhances the convective cloud formation. The net climate feedback of clouds is not well understood in the literature [145-147]. Still, it is known that the increase in high-altitude clouds (e.g. cirrus) trap more heat, while low level clouds (e.g. stratocumulus) cause cooling by reflecting more sunlight. Convective clouds are generally optically thick low level clouds. Thus, we might expect a decrease in net surface radiation due to the enhanced convection. However, the irrigation simulations resulted in an increase of net radiation at the surface. This occurs for several reasons. Firstly, the surface albedo decreases and so the subsequent absorptance of shortwave radiation (i.e., the ratio of absorbed to incoming shortwave radiation) at the surface increases. Secondly, irrigation causes a statistically significant decrease in outgoing net longwave radiation due to the evaporative cooling of the skin temperature leading to a decrease in upward longwave radiation at the surface (as suggested by the Stefan-Boltzmann law).

The driver of the changes in temperature is the change in the partitioning of the available energy between latent and sensible heat fluxes due to LULC change in GAP region. The starting point is the increase in soil moisture due to irrigation. This, in turn, may lead to the direct soil moisture-precipitation feedback mechanism which is discussed in several studies [143, 148-151]. This direct positive feedback mechanism is simply the recycling effect between increased soil moisture and increased precipitation through increased evapotranspiration [152]. This feedback exemplifies the important role of surface turbulent fluxes in controlling precipitation by their modulation of the available moisture in the boundary layer. In addition, there is another indirect feedback of soil moisture-precipitation via boundary layer dynamics [134, 142]. Through this mechanism an increase in soil moisture leads to a decrease in the sensible heat due to a repartitioning of the available energy. This, in turn, leads to a shallower boundary layer. We can see this response in our simulations, too (Table 4.4). At the same time, as discussed, darker and cooler soil enhances net surface radiation by absorbing more solar radiation and reducing longwave emissions. The combination of the higher water vapor concentration and the shallower boundary layer leads to an increase in moist static energy, which accelerates the development of convective processes [142]. This indirect feedback mechanism can explain the

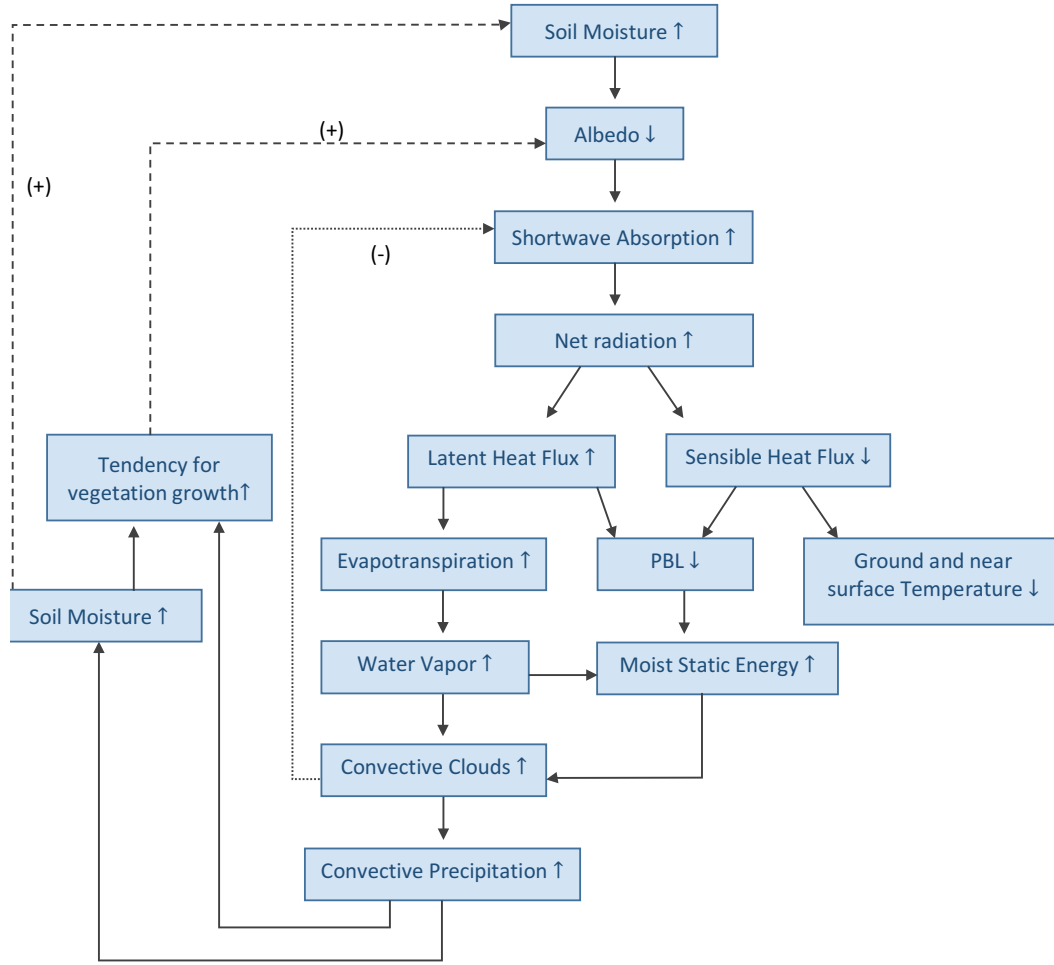


Figure 4.9 : Conceptual diagram of the land-atmosphere interactions due to a change in soil moisture. The dashed lines show a positive feedback, while the dotted line represents a negative feedback.

increase in convective precipitation that we find in our simulations. The importance of soil moisture for enhanced precipitation in semi-arid has been shown in many other modeling studies [76, 151, 153]. The indirect soil moisture-precipitation mechanism may be a positive (amplifying) or negative (damping) feedback depending on the analysis region or the employed model. Our findings in their current form suggest a positive soil moisture-precipitation feedback mechanism in the ETB. More studies are needed to understand the control of the vertical resolution on land surface-boundary layer interactions [154]. Recently, Tuttle and Salvucci [155] showed that three factors (long-timescale variability, precipitation persistence, and endogeneity between soil moisture and precipitation) must be accounted for in order to determine the sign and strength of the soil moisture-precipitation feedback.

4.2.3 Change in water and energy balance

It is stated above that the water and energy budgets are directly linked through evapotranspiration. Here, we first investigate the change in energy balance components, and then the water budget.

4.2.3.1 Irrigation effect on energy balance components

Figure 4.10 summarizes the overall effects of LULC change on the annual mean 2m air temperature and energy balance components. The significant changes due to the irrigation activities usually occur over the irrigated grid cells in the GAP region. Consequently, the spatially averaged values of surface variables were also affected over the upper ETB, even though the changes in the headwaters area were insignificant. Owing to the extensive irrigation, increase in soil moisture (Table 4.4) leads to a significant change in the partitioning of the available energy from radiation between the latent and sensible heat fluxes. The latent heat flux increases with more irrigation, while it is opposite for the sensible heat flux of the GAP region (Figure 4.10). Our irrigation simulations resulted in an increase of net radiation at the surface due to an increase in the absorption of shortwave irradiance.

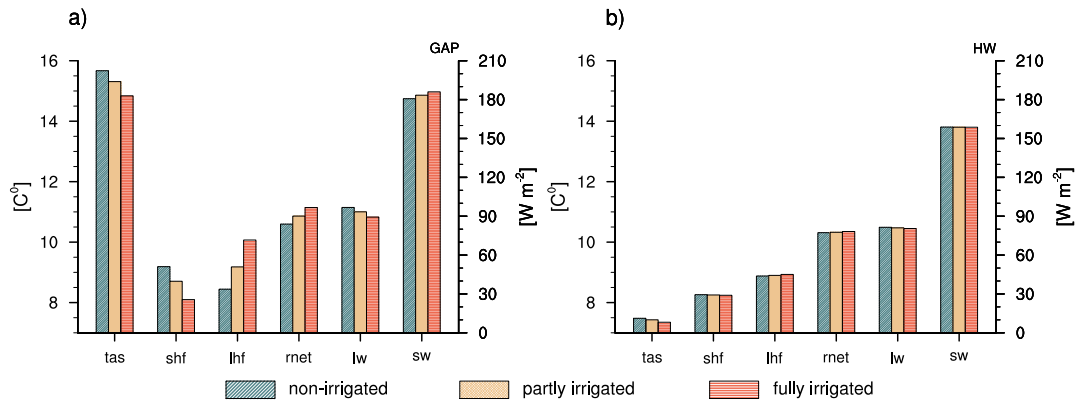


Figure 4.10 : Annual mean 2m air temperature (tas), sensible heat flux (shf), latent heat flux (lhs), net radiation (rnet), net upward longwave (lw) and net downward shortwave (sw) radiation fluxes averaged over (a) the GAP and (b) HW regions for three different simulations.

Figure 4.11 shows the changes in the diurnal cycles of climatic variables over the GAP region for the different simulations. The diurnal cycle of the net radiation does not change so much, with only a slight increase between 9:00 and 12:00 local time for the more irrigated conditions (Figure 4.11a). Figure 4.11b and c illustrates that the change in the partitioning of the available surface energy between sensible and latent

heat fluxes due to irrigation becomes apparent especially during mid-day (local time between 9:00 and 15:00) with a decrease in the sensible flux and an increase in the latent heat flux. The latent heat flux for the fully irrigated conditions is about three times as high as that for the non-irrigation situation at noon time (12:00). Owing to the irrigation's cooling effect, the magnitude of the decrease in skin temperature (Figure 4.11d) is higher than that in the near surface air temperature (Figure 4.11e). Still, both temperatures peak at noon time. While the specific humidity is nearly constant during the day for non-irrigation condition, irrigation amplifies the magnitude of change in specific humidity during the daylight times (Figure 4.11f). The thickness of the boundary layer also decreases most around the noon time (Figure 4.11g). Irrigation also increases total precipitation flux (Figure 4.11h) during mid-day (local time between 9:00 and 15:00). There is a slight increase in total precipitation flux during the night time (local time between 00:00 and 06:00) for both of the irrigation simulations.

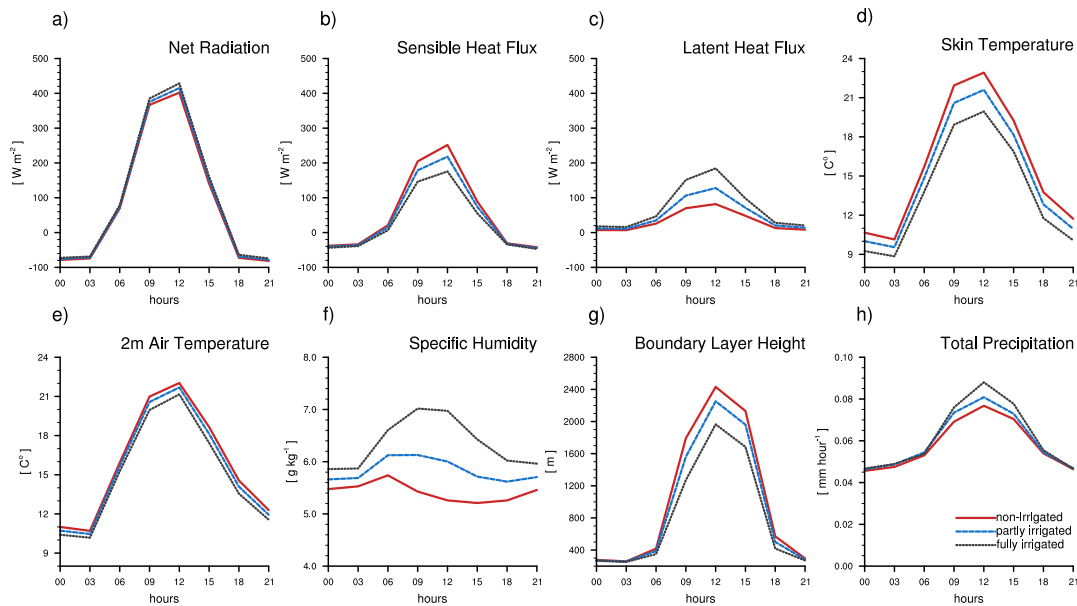


Figure 4.11 : Diurnal cycles of a) net radiation, b) sensible and c) latent heat flux, d) skin temperature, e) surface air temperature, f) specific humidity, g) atmospheric boundary layer thickness, and h) precipitation shown for GAP region for the three different TR12 simulations.

4.2.3.2 Water loss through evapotranspiration

The dramatic increase in evapotranspiration due to the irrigation has a compelling impact on the water budget. The impact of irrigation on the seasonal cycle of the water budget components is shown in Figure 4.12. Similar to the change in annual mean

values of the land surface variables (Table 4.4), the irrigation projects affect mostly the irrigated GAP region (Figure 4.12a) as opposed to the headwaters areas (Figure 4.12b). The increased evapotranspiration can be seen throughout the year with an exception of the winter (DJF) months. As shown in detail in Figure 4.12a, the evapotranspiration amounts increase in parallel to the timing of the irrigation activities in the GAP region, and reach its maximum in summer months (JJA). The irrigation effect on convective precipitation and total precipitation mostly occurs in spring (MAM) months for both the GAP region and headwaters areas. According to the fully irrigated simulation, the relative increase in spring convective precipitation (18.7%) over the GAP region is higher than in the headwaters area (7%). In the GAP region, the increase in evapotranspiration is markedly higher than the change in total precipitation. As such, the precipitation minus evapotranspiration ($P - E$) values rapidly decrease for the partly and fully irrigated simulations in the GAP region, because precipitation increase is less than the evapotranspiration increase. The simulated magnitude of water deficit over the GAP region in summer months is 212 mm and 348 mm for the partly and fully irrigated model runs, respectively.

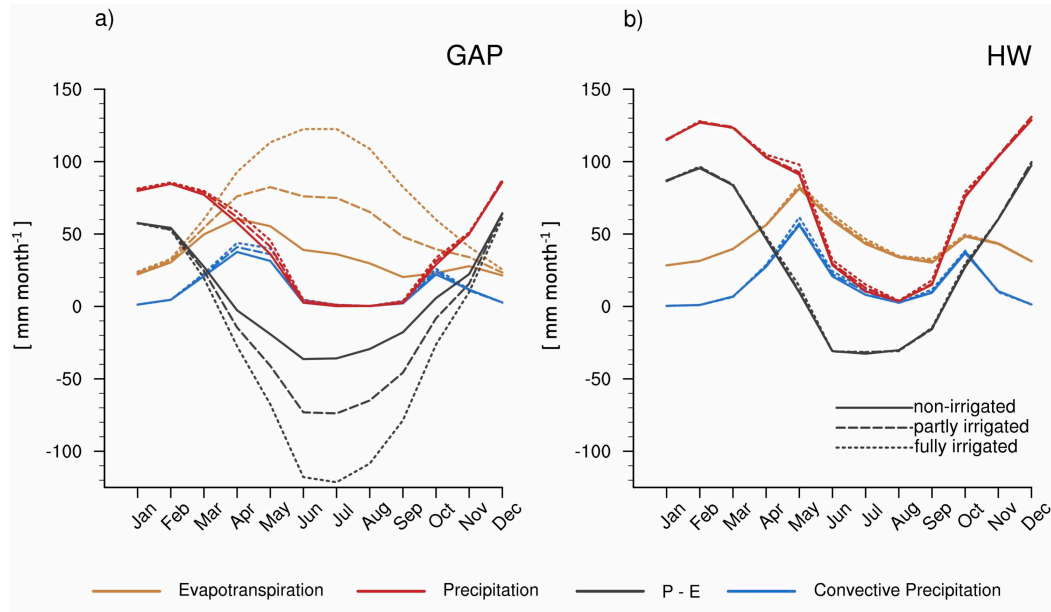


Figure 4.12 : Seasonal cycle of the water budget components for (a) the GAP region, and (b) the headwaters region.

The significant changes due to the irrigation activities usually occur over the irrigated grid cells in the GAP region. According to the model results, the impact of irrigation on the water budget is mainly due to the increase in evapotranspiration and decrease in runoff ($P - E$) flux. In order to better understand the impact of the changes in the

water budget, we calculated the $P - E$ values for the sub-regions of the Euphrates and Tigris basins obtained by separating their basins in the HW and GAP region as shown in Figure 4.13.

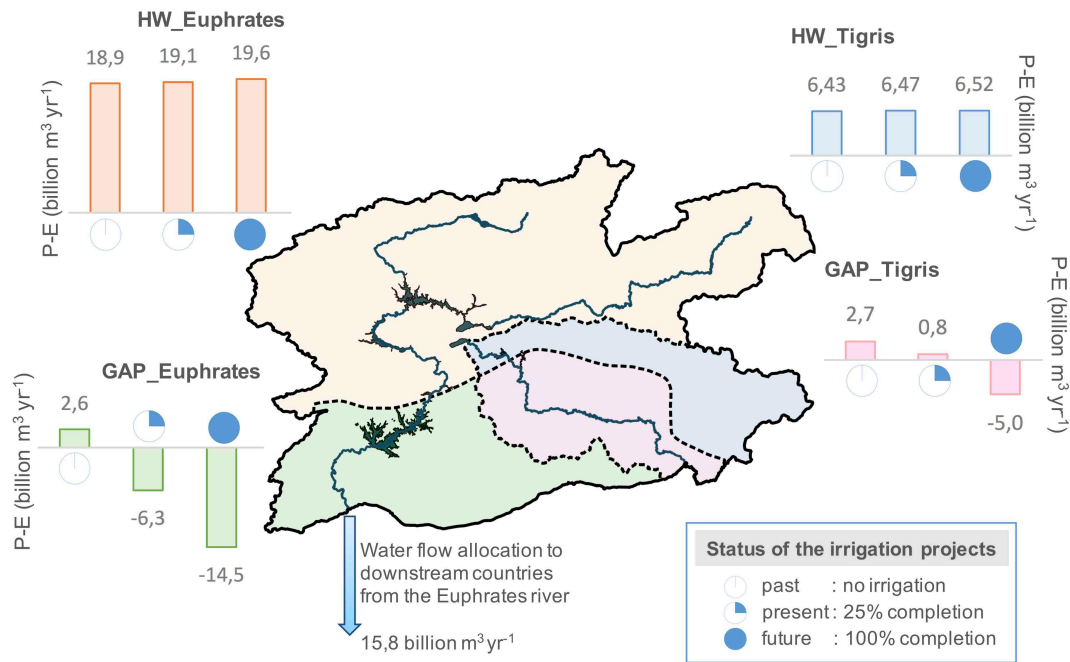


Figure 4.13 : Conceptual diagram of the water budget components for three different TR12 simulations over the headwaters and the GAP region. The subregions are shown on the map as headwaters regions of the Euphrates (orange) and the Tigris (blue) rivers, and the GAP regions of the Euphrates (green) and the Tigris (pink) rivers.

Under the natural conditions (no irrigation), positive $P - E$ values indicate water storage potential both in the headwaters and GAP regions. Due to the slight increase in precipitation amounts in the headwaters area, $P - E$ values slightly increase in both sub-regions (orange and blue areas in Figure 4.13) of the headwaters for partly and fully irrigated conditions. However, after the start of the irrigation projects reflected by the current land use map (partly irrigated), we see that the $P - E$ value over the Euphrates part of the GAP region (green region in Figure 4.13) becomes negative, representing local water deficit by around 6.3 billion m³ per year. For the simulation with the future land use map, reflecting fully irrigated conditions, the simulated $P - E$ values for the GAP region indicate an even stronger water deficit. These values are calculated as 14.5 and 5 billion m³ per year in the Euphrates and the Tigris parts of the GAP region, respectively. In the overall situation, the water need for irrigation in the GAP region could be compensated by the water surplus of the headwaters area. However, we need to take the water commitment to the downstream countries into

account for a holistic evaluation of the water budget for the upper ETB. Whether this deficit could be met by transferring water from the headwaters region will be discussed later in the discussion section.

The increasing water demand of the irrigated region, GAP, is currently compensated by the headwaters of the Euphrates and Tigris basin. Moreover, our simulations show that the water need of GAP region may not be met from the water storage of the headwaters area in the case of the application of all the planned irrigation schemes. Our simulations use the same climate forcing as boundary and initial conditions, so that the water loss rates calculated under the current climate conditions. However, climate change induced by anthropogenic emissions of greenhouse gasses has been projected to have adverse effects on the ETB (e.g. [27, 31, 33, 48]). This brings up another important question that these three simulations has not addressed: what will be the combined effects of irrigation induced LULC changes and the greenhouse gas emissions on the hydroclimate of the ETB. Before investigating the future simulations, we first analyzed the effect of irrigation on the temperature extremes in the next section.

4.2.4 Effects of irrigation on extreme temperatures

Irrigation, commonly applied in crop production, forms an important link between land use and water resources [143]. One of the main biogeophysical impacts of irrigation is its local cooling effect on the near-surface air temperature [141] which is caused by an increase in evapotranspiration over the irrigated areas. We showed in Section 4.2.2 that the irrigation causes the oasis effect in the GAP region. In addition to its local cooling effect, irrigation also affects the extreme climate conditions. Observational [156] and modeling [157] studies showed the importance of irrigation for hot extremes.

The waters of the ETB are used extensively both for energy and food production and thus constitute a vital water resource for the region. Annually, the six riparian countries use around 88% (100.000 km³) of the total water withdrawal for irrigation [77]. As shown in the previous section, these irrigation plans have biogeophysical impacts on the regional climate and water budget of the basin.

Here, outputs from our regional climate model with LULC change simulations are assessed in order to extract information about the cooling effects of irrigation from the point of climate extremes instead of climatic averages. We use high-resolution

gridded daily maximum temperature outputs of the simulations No.1 and No.3, namely TR12d_NNRP_ref and TR12f_NNRP_ref respectively (Figure 4.14). As methodology, the EVT is applied to these model outputs over the ETB.

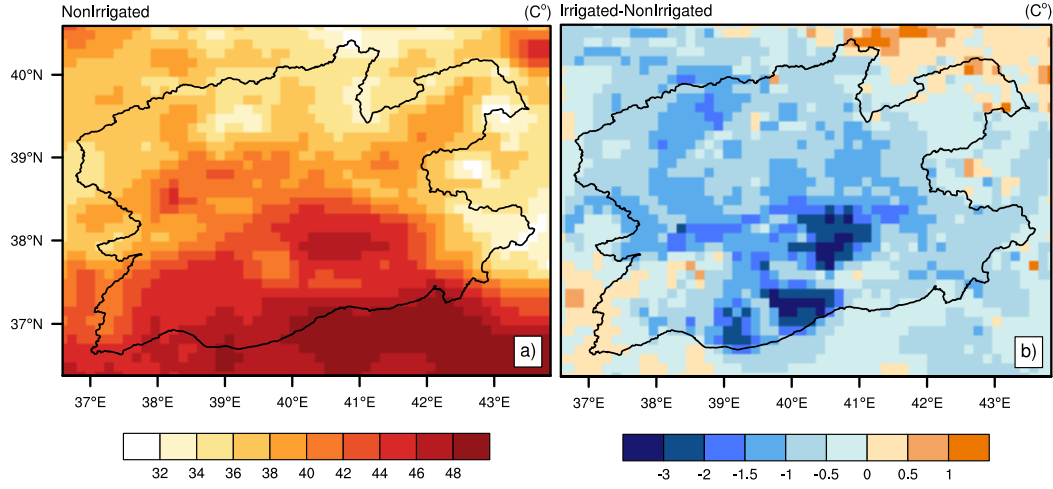


Figure 4.14 : Simulated maximum temperatures over the upper ETB a) for non irrigated conditions and b) difference between the fully irrigated and non irrigated results.

4.2.4.1 Extreme value theory

EVT is a powerful statistical methodology used to characterize the stochastic behavior of rare events. As such, EVT is concerned with describing the tail of a probability distribution. The two most commonly used techniques in EVT are the Generalized Extreme Value (GEV) and the Generalized Pareto (GP) method. GEV focuses on the distribution of block maxima whereas GP looks at the distribution of values which exceed a certain threshold. To maximize our sample size, we employed the GP method, as opposed to GEV, to model temperature extremes.

Let $X = (X_1, \dots, X_n)$ be a random sample with an unknown underlying distribution F . In addition, let u denote the threshold value and define the conditional distribution function F_u :

$$F_u(x) = F[X > u + x | X > u] = \frac{1 - F(u + x)}{1 - F(u)}, x \geq 0.$$

The GP cumulative distribution function is defined as:

$$D_{(\xi, \mu, \sigma)}(x) = \begin{cases} 1 - \left(1 + \frac{\xi(x - \mu)}{\sigma}\right)^{-1/\xi}, & \text{for } \xi \neq 0, \\ 1 - \exp\left(-\frac{x - \mu}{\sigma}\right), & \text{for } \xi = 0, \end{cases} \quad (4.4)$$

where μ, σ, ξ are location, scale and shape parameters, respectively. The Pickands-Balkema-de Haan theorem, the second theorem in EVT, states that $\lim_{u \rightarrow \infty} F(u) \sim D(\xi, \mu, \sigma)$, i.e. that the exceedances of the threshold (u) will be distributed as the GP distribution.

In order to interpret the results of the GP model, here we use the “return level” terminology. The value x_m that is expected to be exceeded every m -years is defined as

$$x_m = \begin{cases} u + \frac{\sigma_u}{\xi} \left[(m\zeta_u)^\xi - 1 \right], & \text{for } \xi \neq 0, \\ u + \sigma_u \ln(m\zeta_u), & \text{for } \xi = 0, \end{cases} \quad (4.5)$$

where ζ_u is the probability of exceeding the threshold, and the scale parameter σ_u is a function of the threshold. In this study, using the GP distribution, we determined the temperature extremes with a 100 year return period.

4.2.4.2 Threshold selection

As mentioned, the GP method allows for a higher sample size than GEV. Still, the threshold selection requires the choice in balancing bias (too low threshold) and variance (too high threshold) [158]. Two methods are available to determine the threshold value. The first technique uses the mean residual life plot to look for the lowest threshold where the mean excess is a linear function of the threshold. The second approach is to evaluate the stability of the GP distribution parameter estimates by fitting the model at a range of thresholds.

For the threshold selection procedure, we first used the mean residual life plots (see Figure E.2) for two simulation outputs (Figure E.1). However, the interpretation of these plots was not simple, as the linearity was observed for all potential threshold values. Instead, we fit the GP model to a range of different thresholds. The uncertainty in the estimated scale and shape parameters was evaluated by observing the point where the confidence interval bars become large (see Figure E.3), which occurred around 41.5 °C. Figure 4.15 shows that number of exceedances over this determined constant threshold is 820 points. The same figure also demonstrates the seasonal trend for the temperature values. The Mann-Kendall test also showed statistically significant results ($p - \text{value} < 0.05$) for the seasonal trend. Therefore, we chose to specify a non-stationary threshold by defining the threshold as a time-depended function. Accordingly, we defined the threshold as a sine function (red), as the 90th percentile

for each day (green), and as a harmonic function (i.e. a sum of sines and cosines) fit to the 90th percentiles (blue). The number of exceedances over these time-dependent thresholds are 316, 244, and 297, respectively.

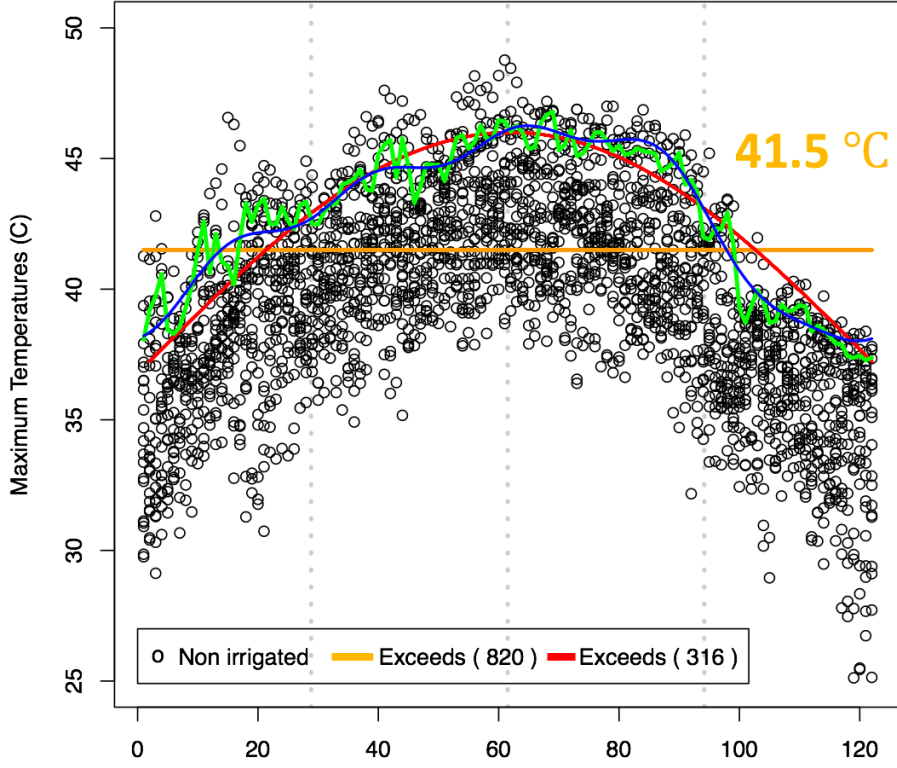


Figure 4.15 : Daily maximum temperatures for the non-irrigated simulation over the 122-day period in the JJAS season. ⁶

4.2.4.3 Parameter Estimation Methods

Once the threshold is specified, the shape and scale parameters should be estimated. There are several methods for parameter estimation of the GEV and GP distribution functions. In this study, we employed maximum likelihood estimation (MLE), Bayesian estimation, and L-moments estimation methods in order to estimate the parameters of the GP distribution. These are all provided by version 2.0 of the extRemes package [159].

4.2.4.4 Regional Extremes

After selecting the thresholds, we fit the GP model to these four different subsets of exceedances from the control simulation. Table 4.5 shows the model results by

⁶The orange line represents the threshold of 41.5 °C, the red line is a sine function for the seasonal trend, the green line represents the threshold values calculated based on 90th percentile values, and the blue line is the fitted harmonic equation.

using MLE parameter estimating method. Negative log-likelihood (NLL) values are conditional probability densities (see also Figure E.4). The lowest NLL value is calculated as 223.85 from the 90th percentile for each day. In all cases, the negative shape parameters correspond to distributions with finite tails. The lowest standard errors for scale and shape are received from 90th percentile and harmonic fitted thresholds (results are not shown here). Finally, we evaluated the Akaike information criterion (AIC) and Bayesian information criterion (BIC) values in order to measure the quality of the GP model. The lowest values are obtained from the model fit to exceedances over the 90th percentile. Therefore, we calculated the return levels from the GP model results with the non-stationary threshold for 90th percentile.

Table 4.5 : The results of the GP distribution model fit to given data.

	Constant	Sine	90 th percentile	Harmonic
NLL	1392.87	367.08	223.85	278.49
Scale	3.018	1.310	0.951	1.080
Shape	-0.406	-0.109	-0.032	-0.139
AIC	2789.744	738.169	451.700	560.991
BIC	2799.163	745.681	458.694	568.379

Return levels for several return periods with different parameter estimation methods are given in Figure 4.16. For both cases, Bayesian method calculates higher return levels compared to MLE and L-moment methods for all selected return periods. Due to the cooling effect of irrigation, smaller return levels are observed with the irrigated simulation outputs. The GP distribution with the Bayesian method predicts that the maximum temperatures will exceed the threshold by 6 °C and 7.4 °C for 20-year and 100-year return period for non irrigated conditions in the upper ETB, while these numbers are 5.2 °C and 5.9 °C for irrigated case for the same climate conditions, respectively.

4.2.4.5 Strength and limitations

In EVT, the samples are assumed to be independent and identically distributed (iid). In our case, the samples were generated by spatially averaging the simulation outputs to look at the basin-wide response. Still, to apply EVT at the pixel level and look at spatial patterns, we would have to quantify spatial dependence of the extremes using the statistical models such as max-stable processes or copulas. Additionally,

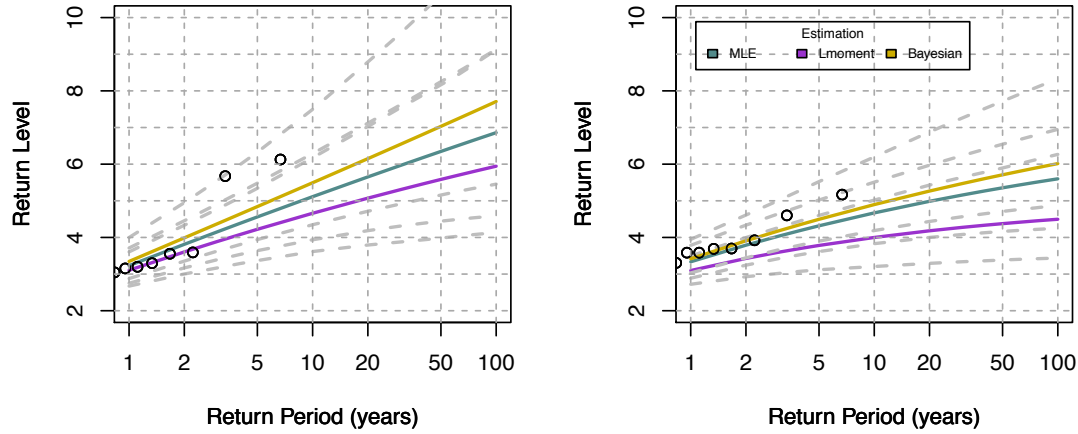


Figure 4.16 : Sampled (circles) and fitted (lines) return levels ($^{\circ}\text{C}$) of exceedances for the control (left) and irrigated (right) simulations.

we are attempting to minimize the time dependence by using the non-stationary 90th percentile threshold. Still, temporal dependence should be further analyzed.

Here, we assessed the effects of irrigation on regional temperature extremes over the upper ETB for the period between 1991 and 2010. The GP distribution with varying threshold values was fit to the RCM outputs. Different parameter estimation methods for the exceedances over the 90th percentiles all agreed that irrigation reduces the maximum temperatures under the present day climatic conditions. Although, we did not address the spatial dependence of the extremes, EVT results indicate that irrigation has the potential to reduce the magnitude of the extreme temperatures under the present climate conditions.

4.3 Future Climate Projections for the Region

As mentioned earlier, we use the GCM outputs for simulating the future simulations. In Chapter 3, we selected the best performing GCM over our domain among the CMIP5 models. In order to calculate the future changes compared to the reference period, we first run a simulation (No.4 in Table 4.3) for the period between 1986 and 2008. The time window of this historical simulation is different than the previous NNRP-driven runs (No.1-3) due to an earlier ending in selected GCM. We wanted to conduct at least 20-year simulations for the climatology. The performance of the GCM-driven model simulation compared to the observation is presented in Section 4.3.1. Afterwards, the results of the greenhouse forcing are given in Section 4.3.2 for the mid-century with RCP 4.5 and RCP 8.5 scenarios. We also discuss our results in comparison to the other

future simulations over our study domain. Finally, the integrated effect of the changes in both LULC and greenhouse emissions are described in Section 4.3.3 for both middle and end of the century. We analyzed the effects of these changes on the regional water budget in detail.

4.3.1 Performance of the GCM driven simulations

Comparing the original GCM outputs with model results which was run by using GCM outputs is important to answer whether the regional model can reveal the general pattern or not. Therefore, original outputs of the global model were compared to outputs of regional climate model for the larger domain. The results for 2m surface temperature and precipitation variables are shown for the period between 1986 and 2008 in Figure 4.17. Horizontal resolution of global model is $1.1^{\circ} \times 1.1^{\circ}$ (~ 120 km), and the resolution of the simulations conducted with RegCM4 is 48 km for the bigger domain. For that reason, difference maps of two model outputs are not given. Generally, spatial patterns on the maps seem to be matching each other for two variables (temperature and precipitation). For example, temperature decreases from coasts to inland areas at the same rates in both of the maps. Likewise, precipitation distribution of global model over the whole domain is simulated similarly by the regional model. This match can be expressed this way: regional climate model (RegCM4) can simulate similarly the patterns of the original outputs of global model (EC-EARTH) at a higher resolution. Nonetheless, particularly precipitation simulations show that the regional climate model generates more precipitation than the global model.

Downscaled 2m surface temperature, precipitation and evapotranspiration outputs of reference period simulation (1991- 2008) were also compared to high resolution ($0.5^{\circ} \times 0.5^{\circ}$) gridded observation data (CRU and GLDAS). Since the observation data set (CRU) has values only over land, the areas over sea were masked in the difference maps in last column of the Figure 4.18. As seen in the maps, the model gives a cold bias by -0.8°C . Both seasonal and annual comparisons show that the model underestimates the temperature slightly lower than the observations. Biases from observations can surpass -3°C in the seasons of spring and autumn over Turkey. For other seasons, biases are smaller. This evaluation is also valid for the Southern parts of

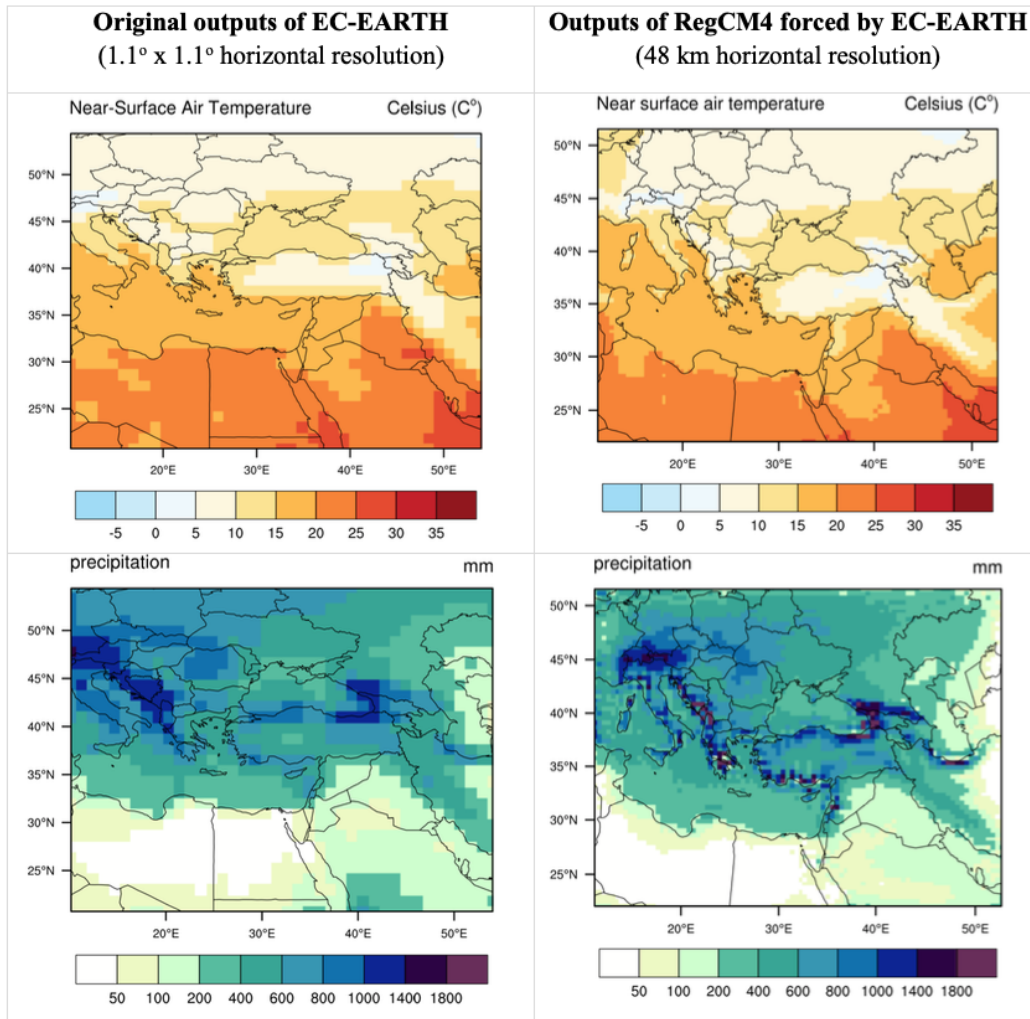


Figure 4.17 : Comparison of the regional climate model outputs (right column) forced with GCM (EC-EARTH) and the outputs of the EC-EARTH global model (left column).

Anatolia region. For this region, annual temperature difference is over -2°C . Modelled precipitation distribution is generally matching with the observed precipitation (Figure 4.18). But the model tends to overestimate the precipitation, except for summer. In summer season, in the Balkans and Caucasia, model generates lower precipitation values. In Turkey, the general tendency is in the same way but the biases are lower. In the Southeastern Anatolia region, annual biases are quite lower than other regions. Annual precipitation bias is around 1.5 mm which is much lower than the simulations with NNRP (see Figure 4.6). Lastly, for the evapotranspiration, GCM driven simulation over the OD48 domain has higher bias compared to NNRP driven simulation. As mentioned, the ETB is located in a transitional climate zone. The south of the basin is very dry (evapotranspiration is less than 200 mm per year), while the northern part is wetter. The regional model can capture the spatial distribution of

evapotranspiration fairly well, while it is not the same for temporal patterns (see Table [D.2](#)). Still, the difference between observation and our simulation is quite smaller over the GAP region.

Observation data sets may not represent the precipitation and evapotranspiration values fairly due to several reasons (e.g. number of stations, interpolation technique, employed model for reanalysis). This can cause important differences between model based and observed distributions over mountainous areas.

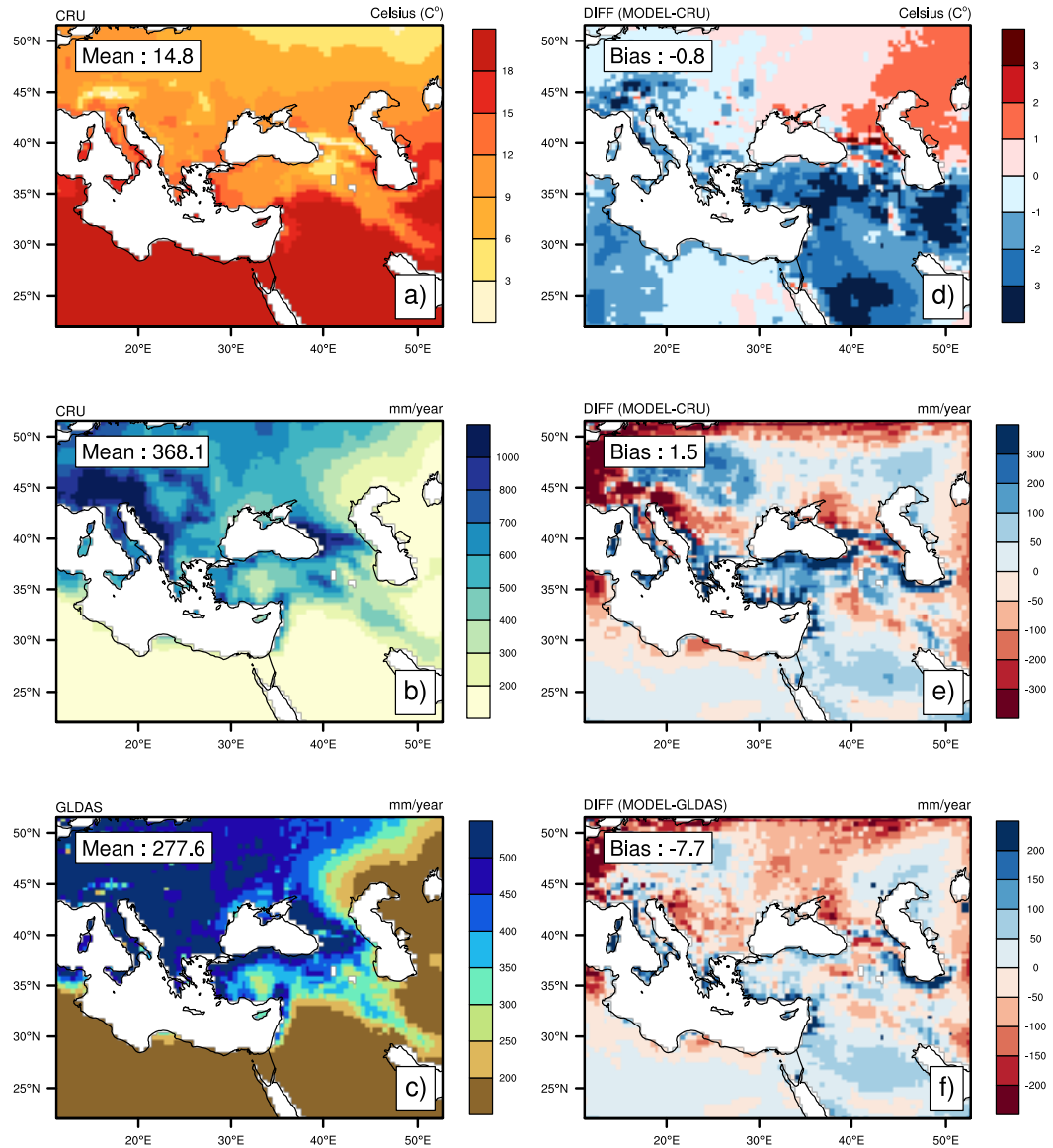


Figure 4.18 : Same as Figure [4.6](#), but the model is forced with GCM for the period between 1991 and 2008.

Reanalysis data is mostly accepted as gridded observation data. Therefore, it is assumed that a regional model which is run with reanalysis data will have better simulations (better lateral boundary conditions – better simulation). On the other hand,

GCMs conduct climate simulations based only on their own abilities. To run the same model with GCM outputs and also with reanalysis data and to compare results are important to understand the performance of the GCM on the climate simulations.

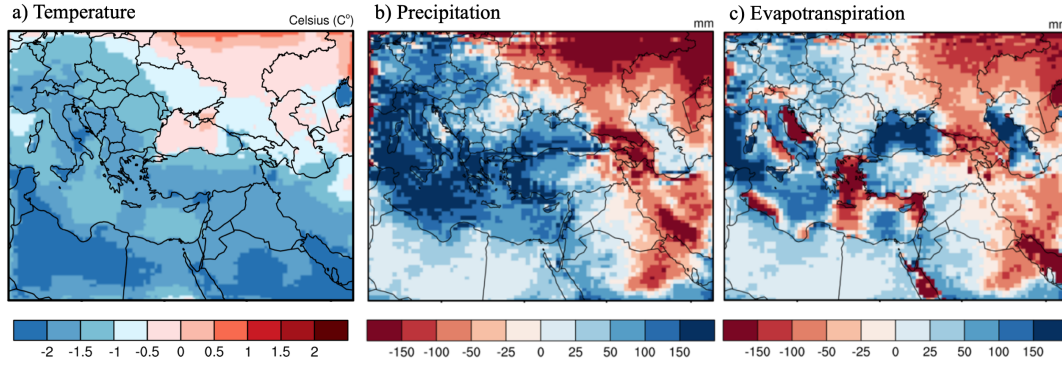


Figure 4.19 : Differences (GCM-NNRP) between model outputs forced with GCM and NNRP for a) 2m air temperature, b) precipitation, and c) evapotranspiration, respectively.

Figure 4.19 shows the differences between the simulations forced with GCM and NNRP data over the OD48 domain. The outputs of 2m surface temperature, precipitation and evapotranspiration are averaged over a period between 1991 and 2008. Patterns given for the 48 km domain indicate that GCM's simulations are colder than reanalysis forced simulations. Temperature biases are less than 2°C over Turkey and ETB. For precipitation, the biases are larger over the seas and higher elevations. This fact might be a signal of the problem from the ocean model used by GCM over the seas. Errors in the simulated sea surface temperature can also affect the precipitation and temperature (reanalysis simulation uses observed sea surface temperature). Considering the evapotranspiration, the biases between two simulations seem to be lower over the land areas. Hence, the possible error source might be mainly the sea surface temperature. Still, both simulations produce similar patterns for precipitation and evapotranspiration over the whole ETB and GAP region.

4.3.2 Results of scenario experiments

Here, we analyze the climate change projections due to only the greenhouse forcing. The downscaled future outputs over larger (OD48) and smaller (TR12) domains are performed with RCP 4.5 and RCP 8.5 scenarios. The changes are expressed in term of the differences from the reference period (i.e. difference between the period of 2046-2065 from the period of 1986-2008).

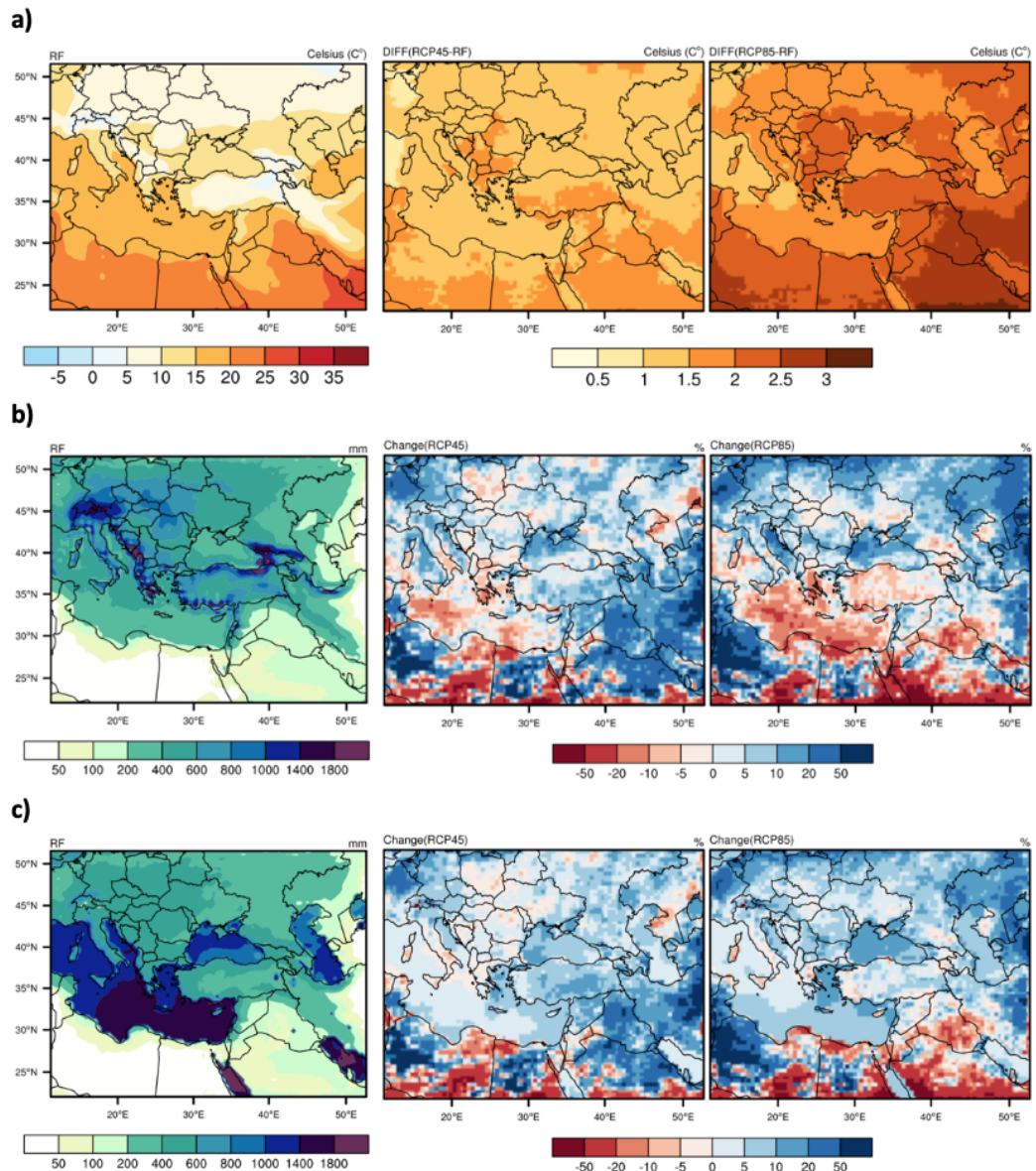


Figure 4.20 : Climate change projections for the mid-century over the OD48 domain. The maps in the first column show the reference period simulations (1986-2008) for the climate variables of a) 2m air temperature, b) precipitation, and c) evapotranspiration, respectively. Second and third columns show the relative differences from reference for RCP 4.5 and RCP 8.5, respectively.

Figure 4.20 shows the annual temperature, precipitation, and evapotranspiration values for both reference and future simulations over the larger domain. Temperature projections indicate an absolute increase up to 3°C over the whole domain for the mid-century. The temperature increase is around 2°C over the ETB with the RCP4.5 scenario, while this increase would be 2.5°C for the most severe scenario (Figure 4.20a). For precipitation, RCP4.5 shows an increase over most of the domain, while RCP8.5 points the increase in the northern half of the domain and a decrease

in the southern half (Figure 4.20b). In particular, Eastern Mediterranean, Greece and Turkey are the main areas which are subjected to the precipitation decrease. For evapotranspiration, mostly precipitation related changes are estimated (Figure 4.20c). According to the both RCP scenarios, an increase in evapotranspiration is projected over Turkey and ETB. Changes in precipitation and evapotranspiration are negligible over the southern part of the domain (arid and semi-arid areas). Although the percentages are high, these dry areas receives very low amount of precipitation. So, even a slight change in precipitation and evapotranspiration corresponds to a large relative change.

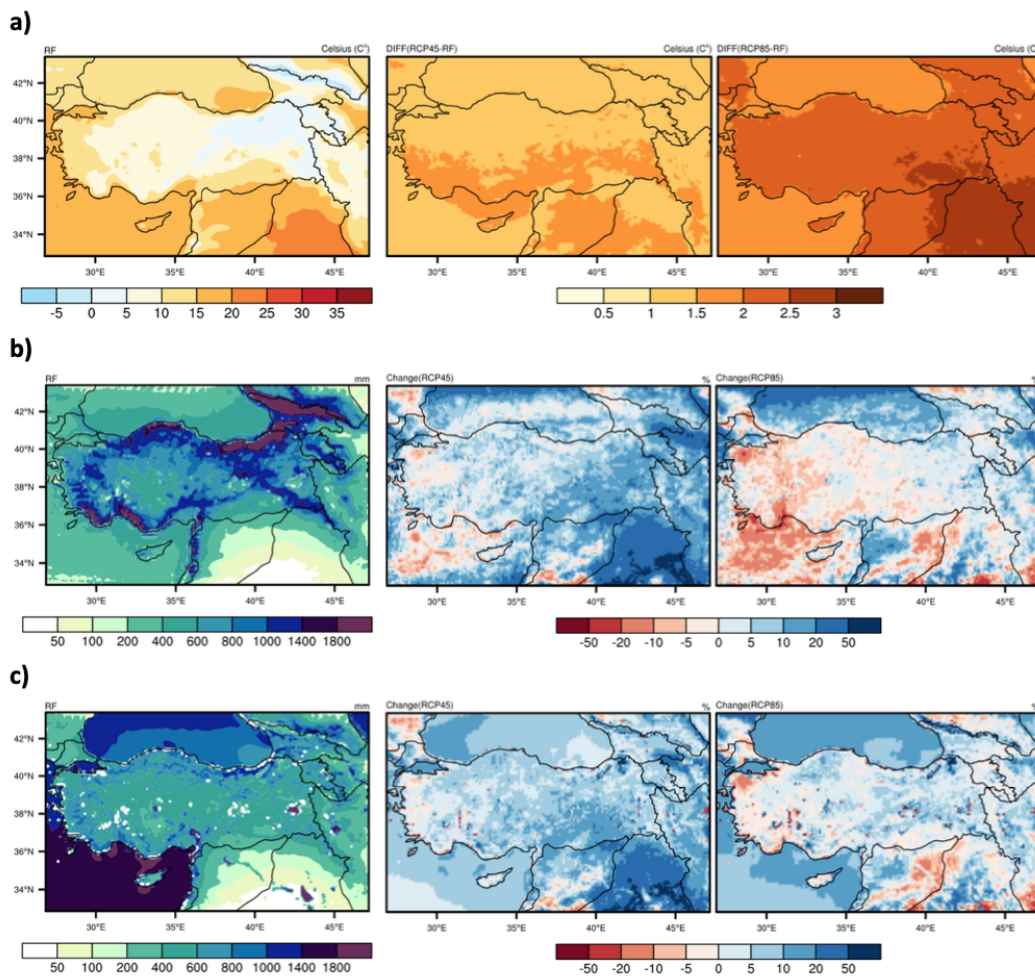


Figure 4.21 : Same as 4.20, but for high-resolution simulations over TR12 domain.

For the nested domain (TR12), the high-resolution simulation outputs a similar spatial pattern for temperature and evapotranspiration for the reference period (see the first column in Figure 4.21). RegCM4 gives high precipitation values over the mountainous areas. Still, annual future projections have a similar change pattern with coarser simulations (48 km) for both scenarios. According to the RCP4.5 scenario,

temperature over southern part of Turkey increase up to 2°C, while the rest of the domain will be around 1.5°C. For the most severe scenario (RCP 8.5), temperature increase will be around 2.5°C, except southeastern region which will have an increase up to 3°C. For the annual total precipitation, decrease levels are estimated up to %20 (e.g. around Antalya) especially for the western part of the domain. As for the RCP 8.5 scenario, there is a dipole precipitation change tendency for the eastern and the western parts of Turkey. The same scenario simulation also shows slight evapotranspiration change for the GAP region. For the seasons, the RCP4.5 scenario shows that temperature increases mostly in winter and summer seasons especially in southwest part of the domain. These changes rise up to 2.5°C. According to the RCP8.5 scenario, the highest temperature increase would be over 3°C in autumn for the southeastern parts. Also, with RCP4.5 scenario, autumn and summer precipitation tends to decrease as opposed to the spring and winter seasons. For the RCP8.5 scenario, except for winter, precipitation shows no tendency to decrease.

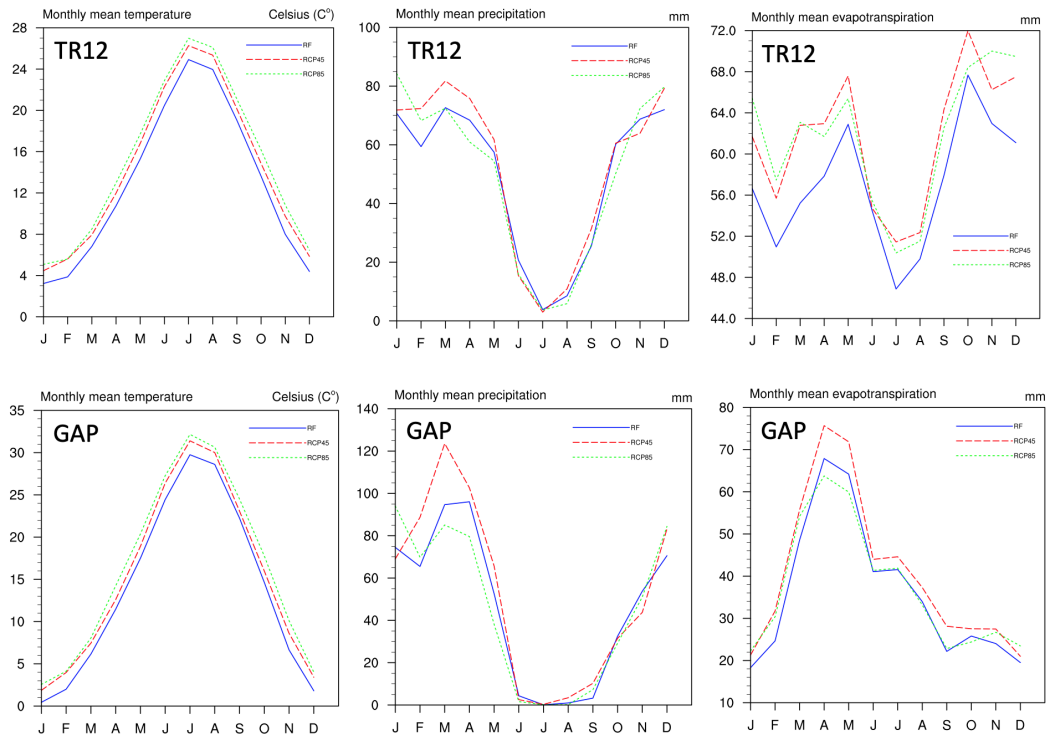


Figure 4.22 : Seasonal cycles for the whole TR12 domain (upper panel) and only GAP region (bottom panel) for the 2m air temperature, precipitation, and evapotranspiration.

To understand the seasonality of the changes, the monthly distribution of spatially averaged values are analyzed for the whole TR12 domain and GAP region. Figure 4.22 shows the seasonal distributions of temperature, precipitation and evapotranspiration

variables for reference period (1986-2008) and future period (2046-2065). For Turkey and GAP, both of the scenarios show a significant temperature increase throughout the year. Precipitation change occurs mostly in spring and winter seasons for both region. The RCP4.5 scenario result tends to increase in both winter and spring while the RCP8.5 tends to increase in winter but decrease in spring. Evapotranspiration values show an increase compared to the reference for both scenarios. However, monthly outputs from RCP8.5 scenario have higher values only in winter months (NDJF) compared to RCP4.5 scenarios for TR12 domain. However, the change pattern over the GAP region is a slightly different for RCP8.5 scenario. The spring months (MAMJ) with the most severe scenarios has lower evapotranspiration values than the reference run.

4.3.3 Combined impacts of the changes in both LULC and atmospheric composition

After investigating the individual effects of LULC change (see Section 4.2.2) and greenhouse gas emissions (see Section 4.3.2), we performed the simulations No.[7-10] (Table 4.3) in order to understand the combined effect of those two. As shown in Figure 4.4, irrigated areas cover only a few grid cells in 48km base map. So, the LULC changes occur only in a couple of grids since the GAP region covers relatively a small area. Hence, the coarser simulation results with fully irrigated land use map are mostly dominated by the changes in the composition of the atmosphere (RCP scenarios). For this reason, the outputs from the high resolution (12 km) simulations with fully irrigated land use map will be presented herein.

Figure 4.23 demonstrates a comprehensive comparison between the reference and the future period simulations (No.7-10) with fully irrigated conditions over the inner domain, TR12. These maps shows the effect of the LULC change under changing climate conditions for three climate variables, namely temperature, precipitation, and evapotranspiration. Downscaled results in this figure cover three different time period such as reference (1986-2008), future for middle of the century (2046-2065), and future for end of the century (2081-2100). All of the future period simulations are conducted for both RCP 4.5 and RCP 8.5 scenarios.

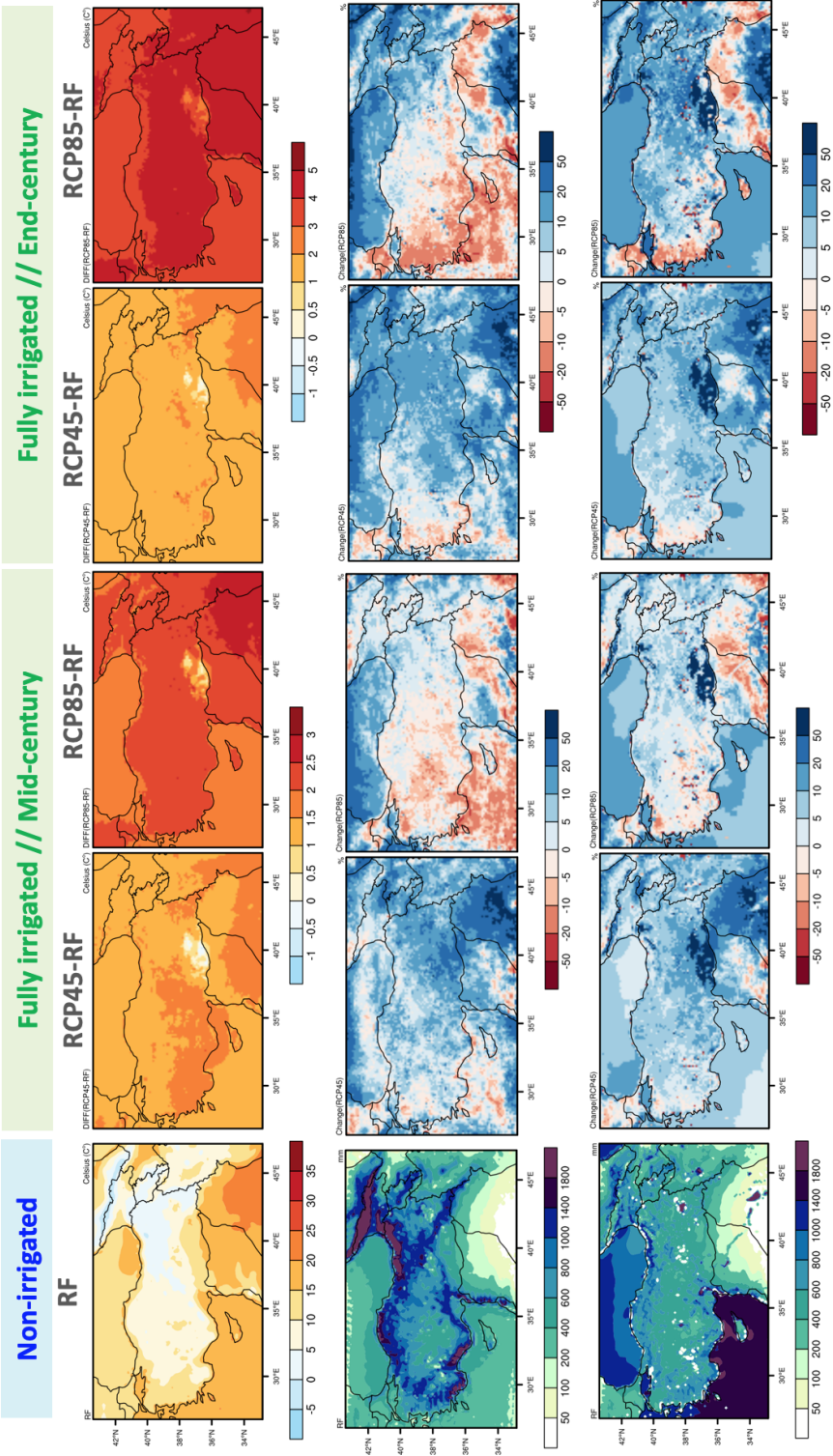


Figure 4.23 : Comparison of reference simulation to the fully irrigated condition for mid- and end of the century. Rows are temperature, precipitation, and evapotranspiration, respectively. First column is reference simulation (No.4) results, while the rest is the difference of the future simulations (No.7-10) from the control run.

The temperature increase levels for both future periods are consistent with the findings of the previous downscaling studies [27,48] for the region. For the mid-century, the temperature in Turkey rises up to 1-1.5°C for RCP 4.5 and around 2-2.5°C for RCP 8.5 scenario except the GAP region. Due to the cooling effect of irrigation, lower temperature change over the GAP area is projected. It means that the level of the temperature increase caused by the greenhouse gas emissions is at the same order with the temperature decrease amount due to the human-induced LULC changes in the GAP region. Therefore, we can obviously say that LULC changes are estimated to offset the greenhouse effect on the temperature field over the GAP region. On the other hand, this limitation effect in the GAP region gradually disappears at the end of the century. For the most severe scenario (RCP 8.5), the temperature of GAP region reaches up to 3-4°C, while the temperature of the whole domain is estimated around 5°C except the Black Sea coasts. According to RCP 4.5 scenario, annual mean temperature of Turkey is projected to be around 2°C for the last 20 years of the century.

In terms of precipitation change, the spatial distribution of the relative change compared to the reference simulations are given in the second row of Figure 4.23. For RCP 8.5 scenario, precipitation tends to decrease over Turkey, however, an increase by 2% is simulated in GAP region for the mid-century. By the end of the century, the change in precipitation amount follows a dipole pattern in the eastern and the western part of Turkey. RCP 8.5 scenario estimates an increase up to 20% in the western Turkey, whereas the decrease is at the same level for the eastern part. It is also possible to see this dipole pattern in the lower part of the Euphrates and Tigris Basin. This pattern is also observed in the outputs of the simulations for the end of the century compared to the earlier years. The simulations with RCP 4.5 scenario estimate precipitation increase over almost the whole domain for the mid- and end of the century.

Annual total evapotranspiration values show that LULC changes in addition to the climate change have a remarkable local impact over the GAP region. The RCP simulations with default land use map for the middle of the century demonstrated that the effects of the future scenarios in the GAP region were around 10% and 1% increase, for RCP 4.5 and RCP 8.5 scenarios respectively (see Figure 4.21). However, in all the future simulations for fully irrigated conditions, more than 50% evapotranspiration

increase are estimated when the LULC changes are taken into the account (Figure 4.23). The exact increase rates of evapotranspiration in the GAP region are 113% and 112% with RCP 4.5 and RCP 8.5 scenarios respectively for the mid-century, and similarly 112% and 121% with RCP 4.5 and RCP 8.5 scenarios respectively by the end of the century.

4.3.4 Future of the water budget

In order to compare the future water budget with the reference period water budget, the spatially averaged changes for precipitation, evapotranspiration and $P - E$ are given in Figure 4.24 and 4.25. In the headwaters, both of the precipitation and evapotranspiration values slightly increase for both of the future RCP scenarios (Figure 4.24). Still, the stored water in the headwaters ($P - E$) decreases for the RCP 8.5 simulations, whereas it increases for the RCP 4.5 scenario simulations. The response of the model to the irrigation depends on the scenario. The change in water budget in the headwaters is mostly affected by the increased greenhouse gases in the atmosphere, not from the irrigation. In the previous simulations (see Section 4.2.2), we showed that the irrigation's cooling effect does not affect the headwaters significantly. Therefore, the increase in temperature by the end of the century is projected to be around 1.9°C and 4.3°C for RCP 4.5 and RCP 8.5 simulations, respectively (Figure 4.24).

Headwaters	Reference	RCP 4.5		RCP 8.5	
	1986-2008	2046-2065	2081-2100	2046-2065	2081-2100
Precipitation (mm)	911.9	1031.3 (%13↑)	1028.8 (%13↑)	919.8 (%1↑)	941.4 (%3↑)
Evapotranspiration (mm)	514.0	575.9 (%12↑)	570.4 (%11↑)	547.8 (%7↑)	603.0 (%17↑)
P-E (mm)	397.9	455.4	458.4	372	338.4
2m Air Temperature (°C)	6.00	7.42 (1.4 C° ↑)	7.86 (1.9 C° ↑)	8.28 (2.3 C° ↑)	10.29 (4.3 C° ↑)

Figure 4.24 : The spatially averaged changes in the water budget components and temperature for reference, mid- and end of the century simulations with different RCP scenarios over the headwaters of the ETB. The colored numbers are the relative changes of future simulations compared to the reference period. $P - E$ (precipitation minus evapotranspiration) amounts correspond to the stored water in the headwaters.

In the GAP region, the increase in precipitation for RCP 4.5 is around 19% and 13% for mid- and end of the century, respectively (Figure 4.25). On the other hand, the RCP 8.5 simulation shows a slight increase, 1%, for the mid-century as opposed to

the decrease, 2%, in the end of the century. As stated previously, irrigation causes a dramatic increase in evapotranspiration. Table in Figure 4.25 shows the integrated effects of irrigation and climate change on the evapotranspiration amounts. For both scenarios, evapotranspiration is projected to double by the mid- and end of the century. The magnitude of the increase in evapotranspiration is much higher than the change in precipitation in the GAP region. Hence, the water budget is significantly affected from the irrigation in the future, similarly to the reference period. Even though irrigation has a cooling effect in the GAP region, temperature will increase due to the increase in greenhouse gas forcing. Under natural conditions (i.e. no irrigation), the GAP region is warmer than the headwaters area. The simulated results show that the magnitude of the increase in temperature in the GAP region will be lower than the headwaters due to the irrigation under the future emission scenarios.

GAP region	Reference	RCP 4.5		RCP 8.5	
	1986-2008	2046-2065	2081-2100	2046-2065	2081-2100
Precipitation (mm)	544.6	646.7 (%19↑)	615.5 (%13↑)	549.4 (%1↑)	534.3 (%2↓)
Evapotranspiration (mm)	435.6	929.7 (%113↑)	925.7 (%112↑)	922.3 (%112↑)	962.7 (%121↑)
P-E (mm)	109	-283	-310.2	-372.9	-428.4
2m Air Temperature (°C)	13.84	14.6 (0.8 C° ↑)	15.03 (1.2 C° ↑)	15.47 (1.6 C° ↑)	17.48 (3.6 C° ↑)

Figure 4.25 : As Figure 4.24, but for the GAP region.

It should be noted that overestimation of the precipitation field in the simulations has been previously shown in the ETB. Therefore, the precipitation, and consequently the evapotranspiration amounts given in Figure 4.24 and 4.25 can be higher compared to the observation values for the reference period. For example, according to the CRU data set, the total annual precipitation values are 592.6 and 514.4 mm for the headwaters and the GAP region, respectively. Tables in the Figure 4.24 and 4.25 can be corrected by using these numbers. Still, the relative changes will be the same after the bias correction. Therefore, after bias correction, we calculated the $P - E$ values in another unit (billion m³ per year) which we can compare with the committed water release amount to the downstream countries.

Figure 4.26 show the projected water storage amounts under climate change conditions with an assumption of not changing the LULC (no irrigation). The simulation results gives positive $P - E$ values for both headwaters and the GAP region. Compared to the

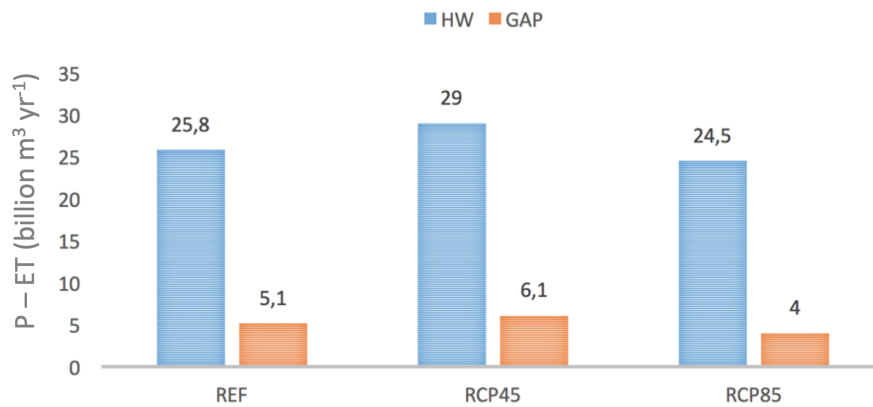


Figure 4.26 : Water storage ($P - E$) for non-irrigated conditions in the mid-century.

reference simulations, RCP4.5 scenario results even show an increase in stored water due to an increase in precipitation values in the middle of the century. Still, the most severe scenario projected less water storage potential for the ETB.

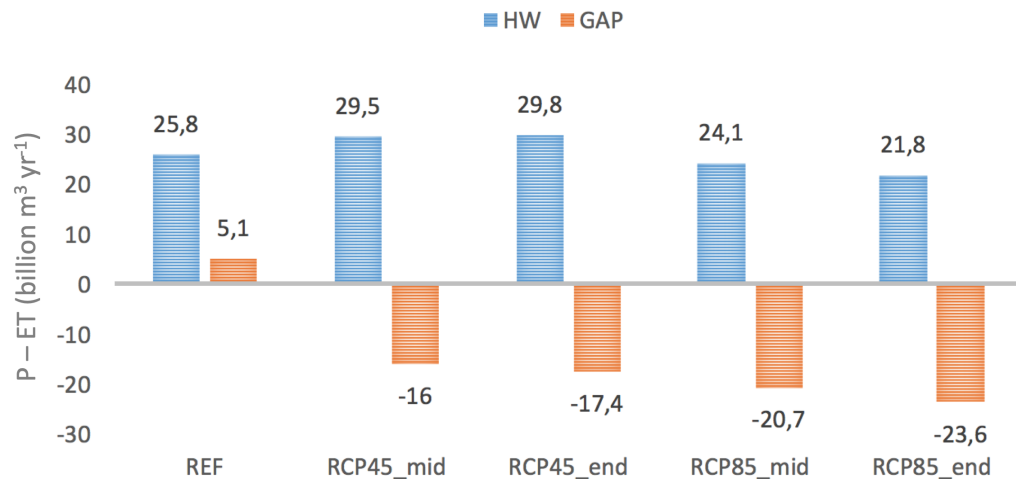


Figure 4.27 : Future water storage ($P - E$) from fully irrigated simulations.

The substantial increase of evapotranspiration due to irrigation has a striking effect on the regional water budget. Figure 4.27 illustrates the water storage ($P - E$) from the future simulations assuming that all irrigation schemes are completed. Since, the irrigation has a local effect on evapotranspiration, the headwaters region has positive $P - E$ values for both RCP scenarios. However, we see the negative values (corresponding to water loss) for the GAP region due to high evapotranspiration. According to the regional climate model, the stored water in the headwaters is not enough to compensate the irrigation demand from GAP and water release to the downstream countries (15.8 billion m³ per year) in the middle of the century. Moreover, there might not be enough water to irrigate the GAP region at the end of century.

5. IMPACTS OF IRRIGATION TECHNIQUES ON WATER BUDGET

There is no doubt anthropogenic climate change has global and regional effects. As a response to the human-induced climate change, actions are need to be taken considering mitigation, adaptation, and resilience strategies. A long-term sustainable water management is extremely important in order to build resilience in the Middle East and North Africa region [160]. In particular, for the ETB, implementing more efficient irrigation systems could be the first step as an adaptation action [161,162]. In this chapter, we aimed to investigate the effects of different irrigation techniques (flood, sprinkler, and drip) on the water balance of the ETB.

Increasing the use of high-efficiency irrigation systems such as drip and sprinklers leads to a decrease in water loss through evapotranspiration. Depending on the choice of irrigation methods, the water use amount changes. It is also known that the selection of the irrigation techniques changes the estimated water budget, in particular the calculation of the evapotranspiration, soil moisture, and surface runoff fluxes.



Figure 5.1 : Commonly used irrigation techniques.

DSI, as the executive institution for the irrigation schemes, has plans for irrigation modernization in order to reduce the use of inefficient surface irrigation methods in five selected sites in Turkey [163]. Only one of the irrigation schemes, Kartalkaya, is located in the GAP region. The planned irrigation network will be a closed system (pressurized pipe). According to the DSI [164], the irrigation ratio and irrigation efficiency for Turkey as a whole are presently 65% and 45%, respectively. By using the sprinkler and drip irrigation methods the efficiency increases by around 60% and 80-90%, respectively.

As mentioned earlier, the land model of RegCM4 that we used in the previous chapters does handle the irrigated crop areas by supplying unlimited irrigation water to the root zone in order to avoid the plant wilting [127]. So, this irrigation scheme corresponds to the flood irrigation which is also the primary irrigation technique widely used in the GAP region. This method causes excessive water losses due to the leakage and evapotranspiration. Our model simulations use the flood irrigation settings as default since there is no representation of the different irrigation techniques. Therefore, there exists a great need to assess the impacts of the irrigation techniques on the water budget in order to produce realistic results which can help the decision makers to evaluate the future water losses in the ETB.

In this chapter, we present the results from the simulations which were performed during a research visit to NCAR where the employed model, CLM5, is being developed.

5.1 Modeling the Irrigation Effects

Irrigation techniques play a crucial role in changing the evapotranspiration amounts, and subsequently water balance [165–169]. However, the representation of the different irrigation techniques is not available in most of the land surface models. Even so it is, there is no standard for definition for the different irrigation methods. For instance, irrigation's amount, timing, and applied location may differ in several studies. Therefore, discrepancy in the implementation of the irrigation modules cause differences in modeled irrigation efficiency percentages.

Evans and Zaitchik [165] evaluated the water balance in the Khabur watershed, the borders of which partly covers the GAP region. In their modeling study, they implemented two parameterizations for different irrigation techniques (flood and drip) in a regional model (MM5). They showed that flood irrigation is very water inefficient, while it is the opposite for drip irrigation. Using the drip irrigation method decreases the evapotranspiration by around 30% in the irrigation season compared to flood irrigation. Moreover, drip irrigation simulations demand 60% less water overall relative to flood irrigation simulations. They pointed out that the planned Syrian irrigation expansion are only feasible with modernization of the irrigation systems.

Their method to represent the irrigation techniques in land surface and hydrological models has been used in several studies (e.g. [167,170]).

A novel method for irrigation representation in a land surface model was developed by deriving the irrigation information from satellite data [166]. They showed that the irrigated areas over the continental United States heavily affects the water and energy balances due to the change in partitioning of available energy at the land surface. As for the irrigation scheme, they used an algorithm to represent the sprinkler technique. They concluded that the amount, location, and timing of water application is important for simulating irrigation.

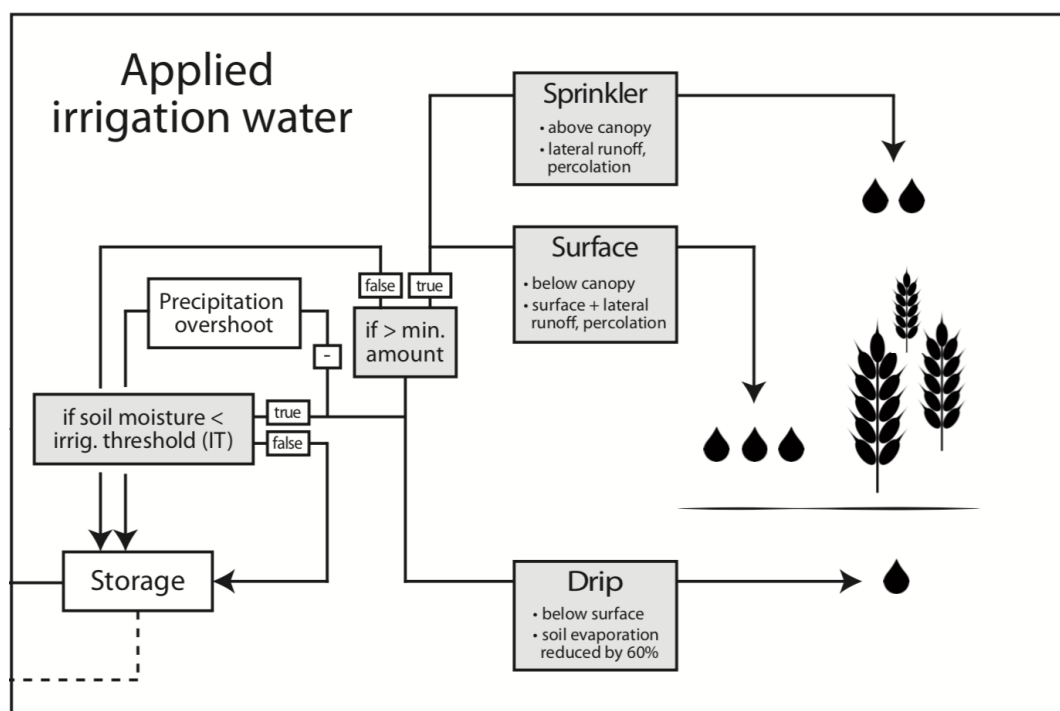


Figure 5.2 : Irrigation in LPJmL (adapted from Jägermeyr et al. (2015)).

Another modeling study that includes the parameterization of irrigation systems is the LPJmL model [168]. They developed a plant-specific irrigation requirement approach in their model simulations as shown in the schematic diagram (c.f. Figure 5.2). In the case of accounting for the downstream effects at the basin level, the transition to sprinkler or drip systems from flood irrigation reduces the non-beneficially consumed water by around 54-76%. They underlined that improvements in irrigation systems are important for a sustainable food security. In their recent study, they also showed that irrigation efficiency improvements might halve the water withdrawal in many river basins [171].

Lawston et al. [167] evaluated the irrigation methods with the outputs of high-resolution simulations over the central Great Plains of the USA during a dry (2006) and a wet (2008) regime. They similarly showed the irrigation impacts depend on the timing and spatial distribution as well as the employed irrigation method. Crucially, including more detailed irrigation parameterization into models has the potential of improving both forecasts and projections. At the same time, irrigation induced changes on the surface are mostly localized. The timing and frequency of irrigation cause differences in response of the regional simulations [172].

Another global modeling study of irrigation parameterization was conducted for the ACME Land Model which was originally derived from CLM 4.5 [169]. In their study, it is showed that drip irrigation is the most efficiently used water amongst the sprinkler, flood, and drip irrigation from both surface water and groundwater. They emphasize that irrigation water use efficiency is sensitive to the choice of water source and irrigation technique.

Fader et al. [173] assessed the climate change impacts on irrigation requirements in the Mediterranean region. They concluded that 35% of water could be saved by implementing more efficient irrigation systems. In Syria, Egypt, and Turkey, these saving potentials are higher than other Mediterranean countries. In the case of no improvements in irrigation systems, an increase in gross irrigation requirements is projected to be between 4 and 18% by the end of the century. They suggested that some region-wide decisions and adaptation measures could be taken for reducing the net irrigation requirements in the future.

5.2 Methodology

After the literature search, we decided to employ the Community Land Model (CLM) as the tool for understanding the effects of irrigation techniques. The latest release of CLM model, CLM5, has a newly developed irrigation scheme. In order to start any implementation of irrigation techniques, we needed to conduct several sensitivity simulations at a high spatial resolution ($0.125^\circ \times 0.125^\circ$) over the whole ETB. As the initial approach, we will draw on a similar methodology as in the previous studies for drip irrigation [167,170] and sprinkler irrigation [166].

5.2.1 Land Surface Model : CLM5

CLM is the land surface model of the Community Earth System Model (CESM), both developed by NCAR scientists. This state-of-the-art land surface model has a comprehensive representation of the land-atmosphere interactions [5.3]. The last version of the land model is CLM5.0 [174] which was released on the 5th of February 2018 (<https://github.com/ESCOMP/ctsm/>). The main developments in CLM5.0 include notable updates of the components of CLM4.5 in soil and plant hydrology, snow density, river modeling, carbon and nitrogen cycling and coupling, and crop modeling [174]. Many of the developments in CLM5.0 focused on land use and land cover change. Human land management in CLM5.0 is represented more realistically. In the crop model, rice, sugarcane, tropical corn and soybean are added to the existing crop types. Representation of the fertilization rates and irrigation areas is updated by using an input data set. Another update is also about the irrigation trigger. These developments will undoubtedly be useful for our study, but they are yet to be tested through sensitivity analyses over the ETB.

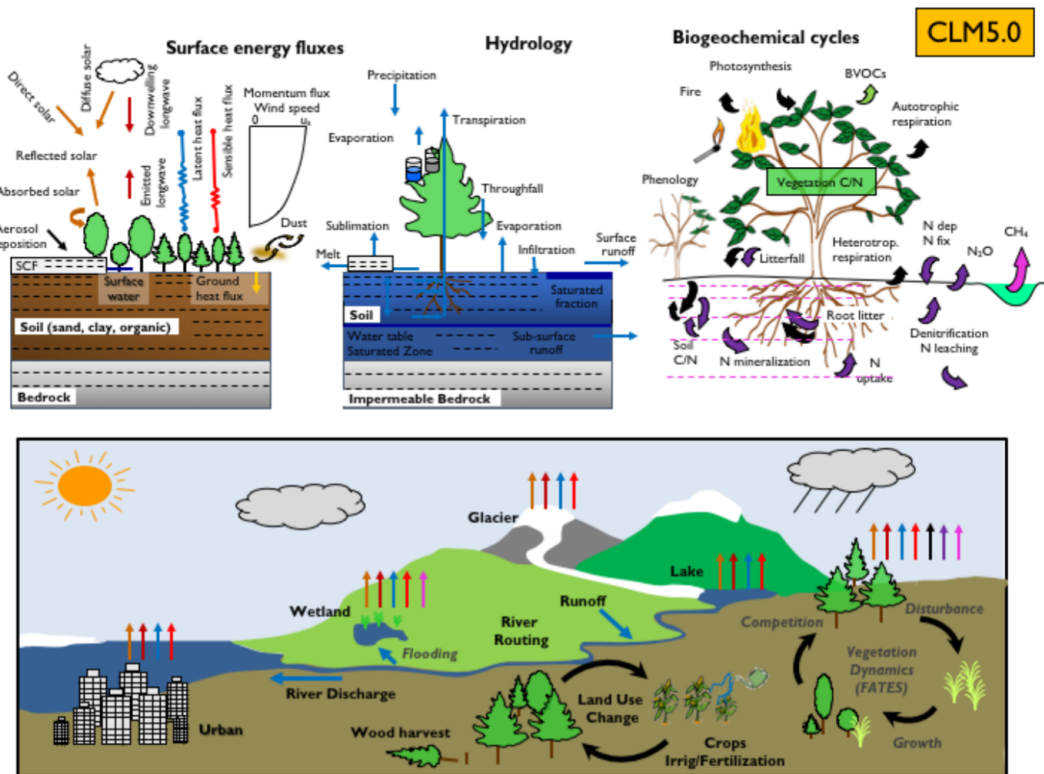


Figure 5.3 : Schematic diagram of the comprehensive representation of the biogeophysical, biogeochemical, and land surface processes in CLM5 (Image credit : Lawrence et al. (2018)).

5.2.2 Irrigation in CLM5

CLM5 has an irrigation algorithm depending on the soil moisture conditions [174]. The model irrigates only the grid cells with irrigated crop areas [175] that is based on the area equipped for irrigation data [176]. According to the control algorithm that becomes active every day after 6 AM, the irrigation water is applied to the ground surface if the leaf area index (LAI) is higher than 0, and available soil water is lower than a specific threshold (see Figure 5.4). The irrigation water (D_{irrig} ; the difference between irrigation moisture threshold and available moisture) is applied evenly every time step during the irrigation period (T_{irrig}). At the end, the irrigation water amount is subtracted from the river water storage for conservation of mass.

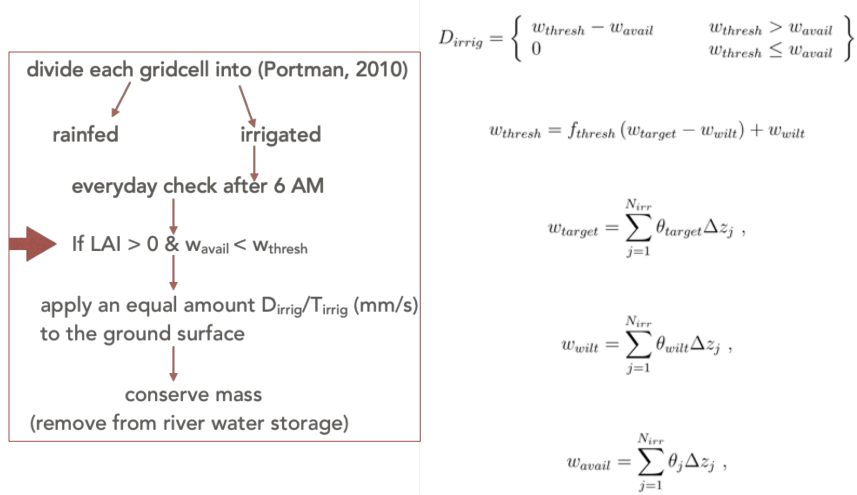


Figure 5.4 : Schematic diagram of the irrigation representation in CLM5.

The irrigation moisture threshold (w_{thresh}) is calculated with the formulas given in Figure 5.4. All process and the formulas are parameterized at a specific setting (see Figure 5.5) that corresponds to the drip irrigation. In order to understand the CLM5's response to the different irrigation settings, we performed several sensitivity simulations by perturbing the default parameters.

Parameter	value	Parameter	value
Threshold fraction	1.0	Irrigation length (s)	14400 (4 hours)
Irrigation depth (m)	0.6	Irrigation start time (s)	21600 (6 AM)
Target soil matric potential (mm)	-3400	Min LAI	0.0
Wilting point <u>smp</u> (mm)	-150000		

Figure 5.5 : Default irrigation parameters in CLM5.

5.2.3 Modeling Steps

Our experimental design, other than the initial parameter sensitivity analysis, consists of three different simulations for the historical period between 1991 and 2010 over the ETB. As a forcing data set, the Global Soil Wetness Project Phase 3 (GSWP3) data will be used. Under the same climate conditions, three simulations will be carried out by using different irrigation techniques such as flood, drip, and sprinkler. A comparison of these simulations will reveal the impacts of irrigation techniques on the regional water budget and climate. Accordingly, we will be able to produce alternative irrigation scenarios in order to reduce the water loss through evapotranspiration. In this way, new information about the ETB will be generated for the future water management strategies within the scope of climate change adaptation.

In order to further develop the irrigation technique parameterizations in CLM5.0, we will follow the steps listed below:

1. Comparing the input data of CLM5, which represents the irrigation equipped area, with the land use maps used in our previous simulations.
2. Specifying the regional domain for the simulations, and setting up the model configuration.
3. Sensitivity tests of the default irrigation parameters.
4. Implementing the code for irrigation techniques in the irrigation module of CLM5.
5. Conducting the final simulations for the ETB, and analyzing the outputs.

If we explain the listed items in detail :

Step 1: The irrigation model of CLM5.0 uses a base data set of areas equipped for irrigation [176] and MIRCA2000 data [175] to categorize the irrigated crop areas. First, the accuracy of the map for irrigated areas is investigated by comparing with the previously used land use maps in our simulations. Our simulations were conducted by using three different land use maps which reflect the increasing status of irrigation and dams (see Section 4.1.1). If the difference is large between the areas equipped

for irrigation and current land use map, an update in the CLM's input data may be required.

Step 2: The areal coverage of the model domain and the spatial resolution are determined for planned simulations. The technical details of the model configurations is decided with the assistance of David M. Lawrence and Sean Swanson from NCAR who has experience with the water storage in the ETB [51].

Step 3: CLM's irrigation model has several irrigation parameters (Figure 5.4). If irrigation is needed in a specific grid cell, the amount of irrigation water is calculated as a function of the soil moisture deficit which depends, in part, on the aforementioned parameters. Therefore, these parameters and their associated uncertainty need to be estimated through a set of sensitivity experiments.

Step 4: We intended to add the parameterization for three irrigation techniques into the CLM5's source code. The default settings are only able to simulate drip irrigation (Sean Swenson, personal communication). The sprinkler scheme used a study [167] (based on the study of Ozdogan et al. [166]) considers the water application amounts of the farmers. In their algorithm, irrigation is applied equally by around 5 mm/h if the available root-zone moisture is 10% above the stress point. The water application stops when available root-zone moisture is 80% of the maximum soil moisture. The drip scheme used in another study [165] applies the water just enough to allow for transpiration without putting any stress on the plant. The parameterization computes the evapotranspiration and the canopy resistance both for the current soil moisture and assuming no soil moisture stress. The difference of these two values is used as the irrigation amount. In our plan, we want to consider these algorithms.

Step 5: After completing the previous steps, the last simulations will be performed.

As we explain in the next section, the steps 4 and 5 are not completed due to limited time and sources.

5.3 Results

As the first step, CLM5's input data was compared with the current land use map that we used in our regional climate model simulations. Figure 5.6 shows the percentages of the areas equipped for irrigation that CLM5 uses as input data. The inset in this

figure shows the land use map of GAP that we produced for our previous simulations (see Figure 4.4). When we compared these two information, we saw the difference over the GAP region. It means that CLM5's input data does not include the recently irrigated areas in the upper ETB. Therefore, this map needs an update before any implementation.

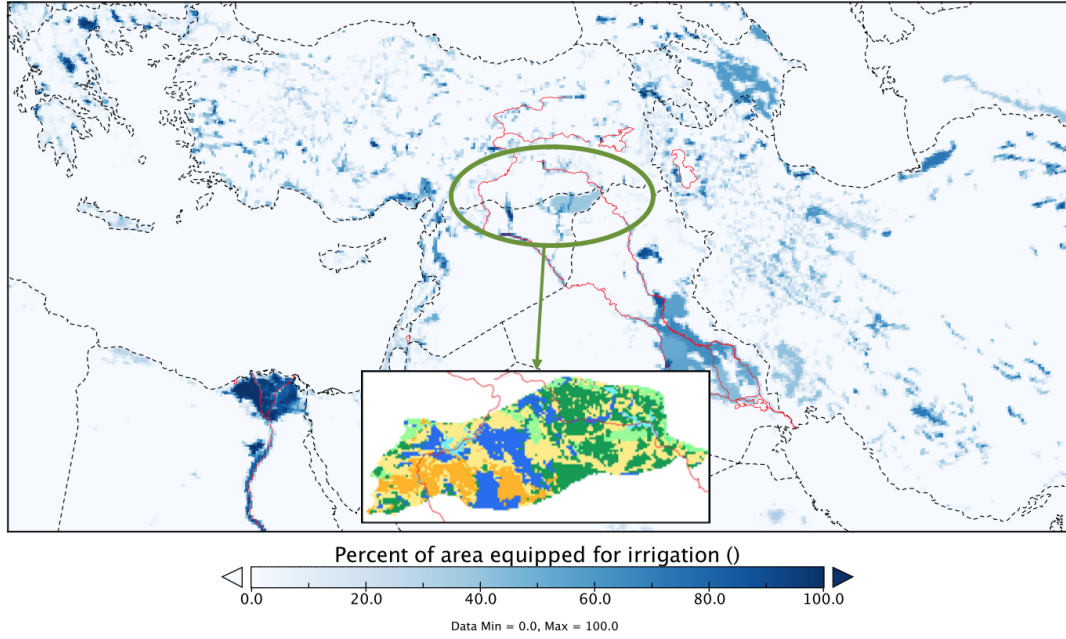


Figure 5.6 : Percent of area equipped for irrigation over Turkey and the surrounding region. Inset: Current land use map of GAP region where blue grid cells show the irrigated crop areas in GAP region.

As the up-to-date irrigated crop areas, a new data set [177] based on NDVI that shows the global irrigated areas can be used. Figure 5.7 shows the irrigated areas in high resolution over the ETB. When this map compared with the Figure 5.6, it is obvious that new map has the currently irrigated areas in the GAP region, particularly the Harran Plain and surroundings.

Moving to the second step includes setting up the model for our study region. We, first, created a study domain for the whole ETB by masking out the grid cells outside of the basin borders. Afterwards, a control simulation was run at a high ($0.125^\circ \times 0.125^\circ$) spatial resolution by using the I2000Cln50BgcCropGs compset of CLM5 for the 10 years between 1991 and 2000. The results (Figure 5.8) of the control run with default parameters are consistent with general spatial patterns of temperature, precipitation, and evapotranspiration over the ETB. However, mean evapotranspiration is underestimated particularly over the GAP region due to the lack of irrigated areas

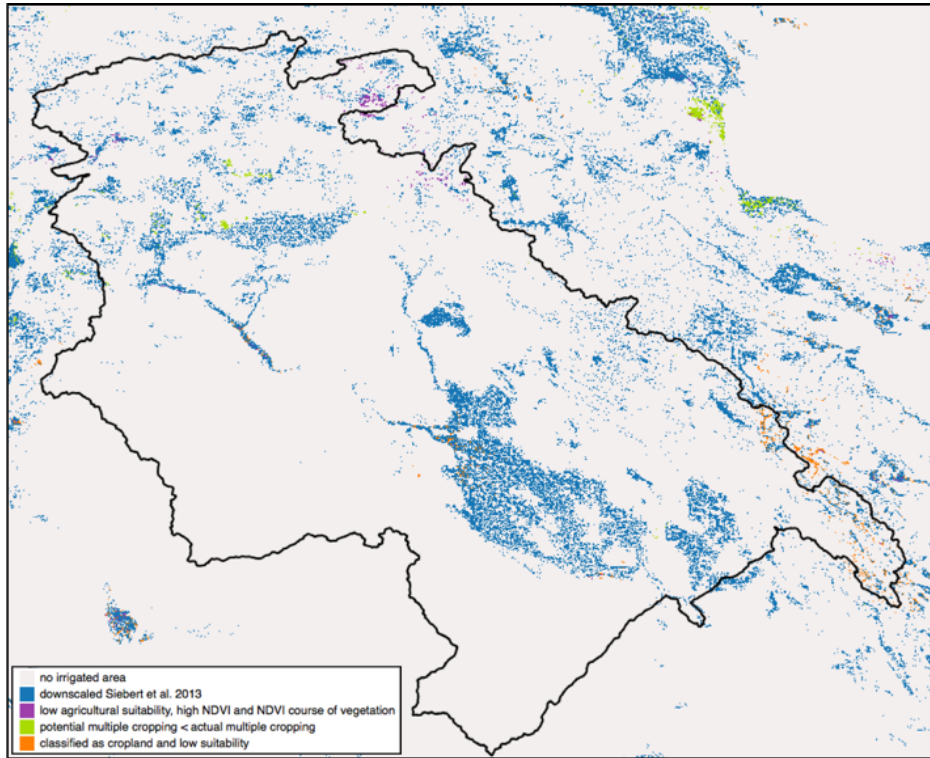


Figure 5.7 : Up-to-date irrigated areas (in blue) over the ETB.

in the input map. Also, the annual sum of irrigation amounts for the whole ETB was calculated as being about 126723 km³ per year. However, this value was given as 99365 km³/year in UNEP's report [77] which is the only reference for irrigation water in the ETB. This statistics may be an average for a different time period. We need to find more information on irrigation amounts for the whole basin in order to evaluate the performance of CLM5 in simulating irrigation.

As step three, we conducted several sensitivity simulations for the same time period and resolution as the control run. Figure 5.5 shows the default parameters that CLM5 uses for the irrigation scheme. Here, irrigation depth, threshold fraction, irrigation length, and irrigation start time were selected as key parameters for the irrigation techniques sensitivity. Then, we performed 8 different simulations over the ETB by perturbing selected parameters:

- Sim. 1 : Control run (with default parameters)
- Sim. 2-3 : Irrigation depth = 0.5 and 0.9
- Sim. 4-5 : Threshold fraction = 0.8 and 0.9
- Sim. 6 : Irrigation length = 3 hours

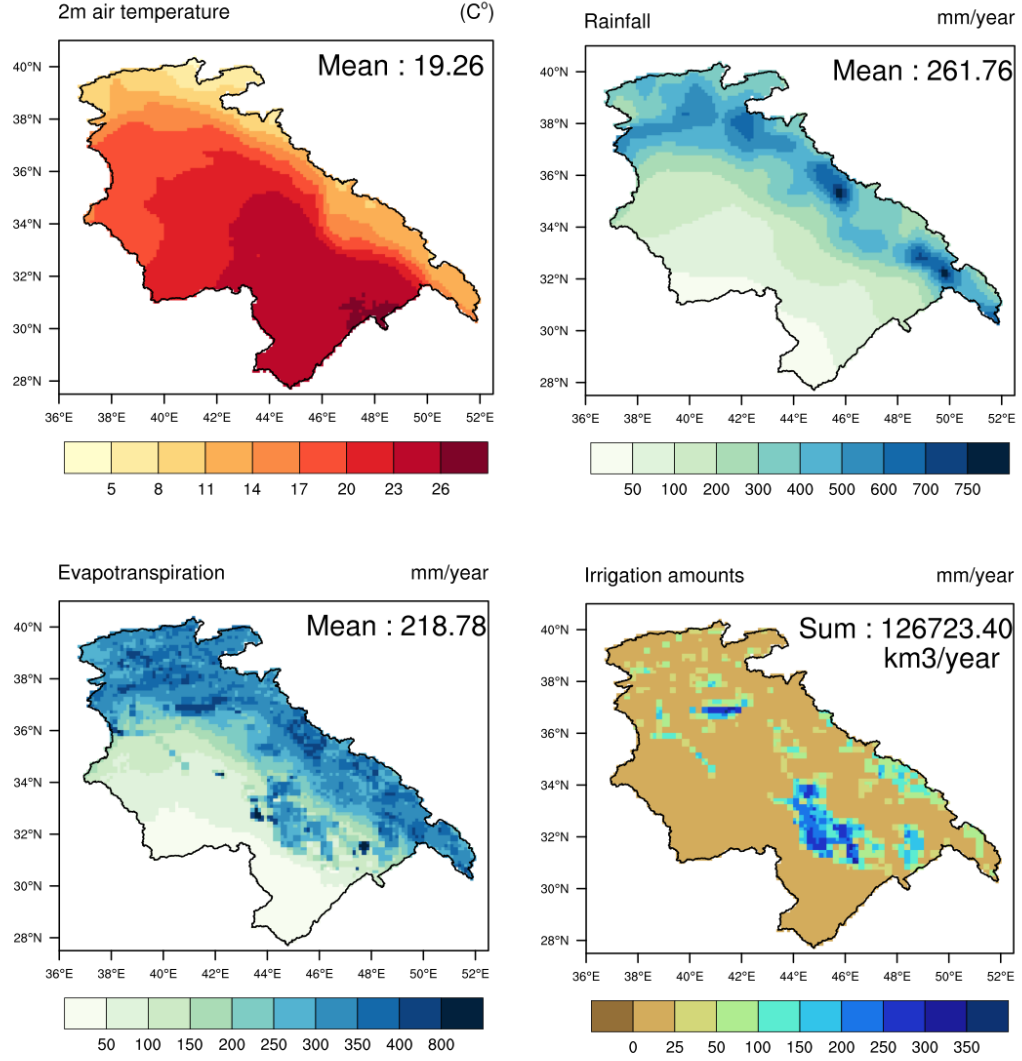


Figure 5.8 : Temporally averaged CLM5 results for temperature, precipitation, evapotranspiration and irrigation amounts over the ETB for the period between 1991 and 2000.

- Sim. 7 : Irrigation start time = 5AM
- Sim. 8 : Irrigation length = 3 hours and irrigation start time = 5AM

For the next step, we briefly analyzed the monthly outputs of CLM5. In Figure 5.9, time series of annual maximum irrigation amounts over the ETB show that using the deepest soil layer for irrigation (depth_0.9) requires a higher irrigation amount. Changing the irrigation depth from 0.5 to 0.9 increases total irrigation amount required by around 7000 km³ per year (Figure 5.10). The control run (depth_0.6) gives a number in between those two. If we decrease the threshold fraction, we observe that the irrigation amount decreases. This value defines the limit of applicable water amount. The default value (1.0) corresponds to unlimited available water if irrigation is needed.

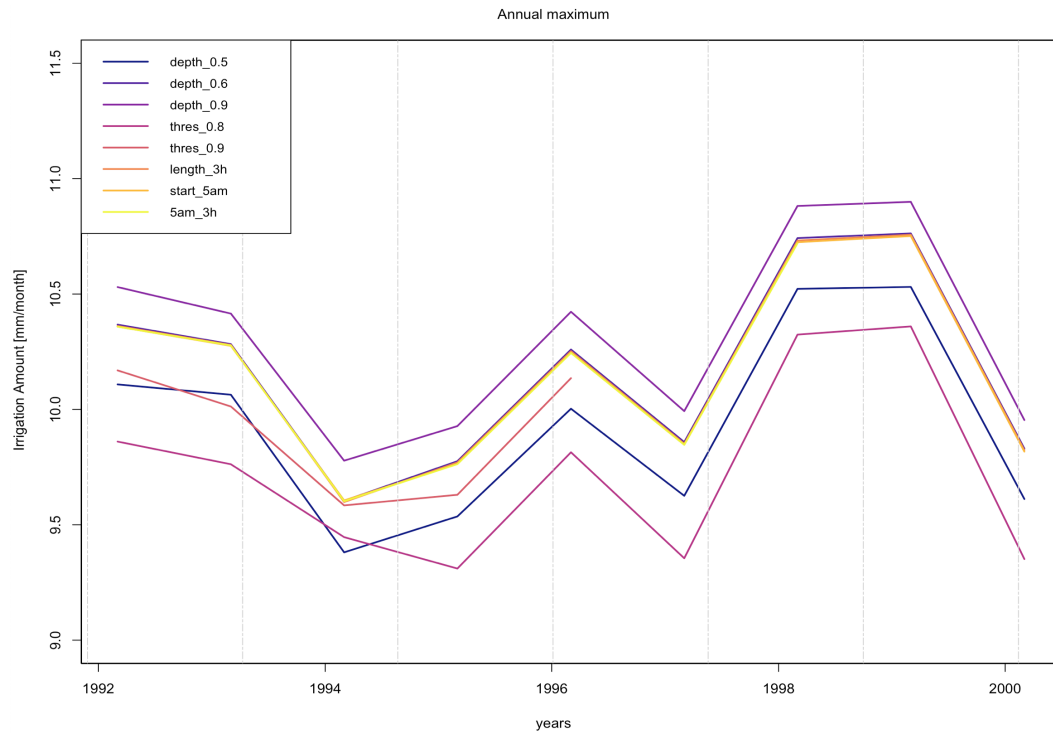


Figure 5.9 : Time series of annual maximum irrigation amounts for the period between 1992 and 2000.

Changing the irrigation start time and length does not affect the annual maximum irrigation amounts compared to control run (depth_0.6). However, a combination of starting irrigation earlier (5AM) and a shorter irrigation time (3h) decreases the total irrigation amount required (simulation 5AM_3h).

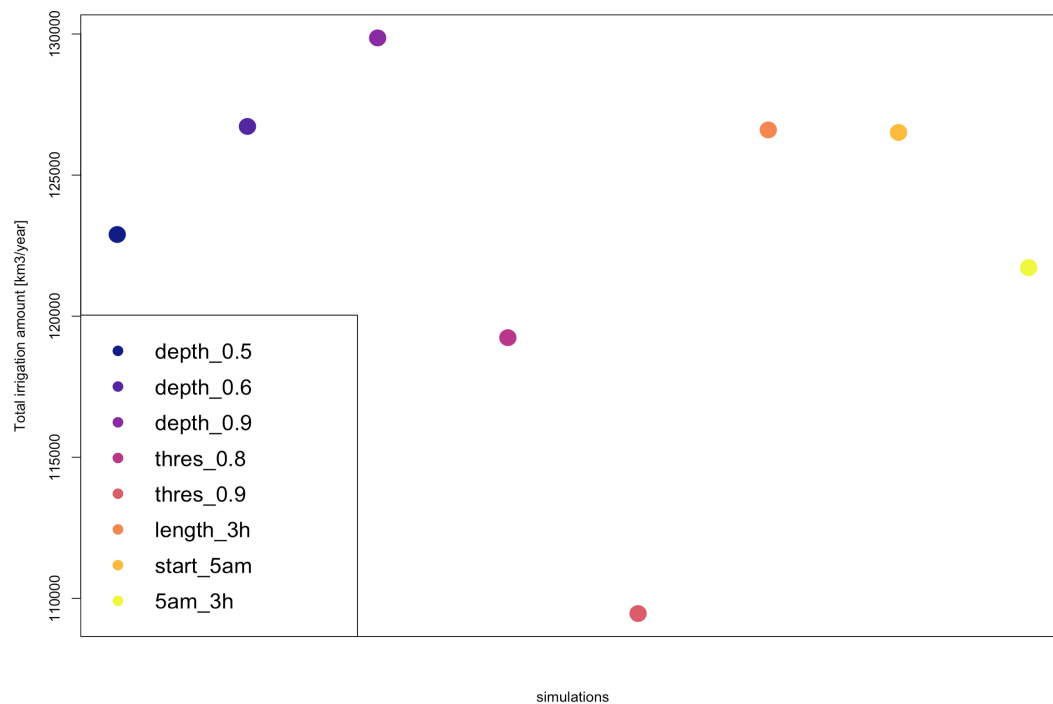


Figure 5.10 : Total irrigation amounts for each simulations.

5.4 Future Work

After the third step, it is understood that implementing irrigation techniques in CLM5 requires a longer research period and more computational resources. So, the completion of this chapter stays as a future work. According to our results, we first need to update the base irrigation map over our study domain. Also, sensitivity experiments can be conducted for a point simulation instead of the whole basin in order to use less computational source. For the whole basin, we need more data on irrigation amounts. This data can be obtained from DSI's pressurized irrigation systems [163]. Also, simulations with CLM5 model will be offline. One could evaluate the irrigation efficiency by using the coupled climate simulations.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

Here, we summarize our findings from this thesis study under three title. First, we underline the observed changes in water resources and snowpack from remote sensing products. Secondly, the hydroclimatic effects of irrigation at the surface are emphasized. Lastly, we briefly give the results of future simulations with no irrigation and fully irrigation conditions.

Remotely sensed changes in montane snowpack

The effects of climate change on water resources is already a major concern in the Near East which is a semi-arid region (e.g. [27, 31, 34, 48, 80, 178, 179]). Over exploiting the water resources by irrigation and dams has already affected the regional water budget [49]. The declining water storage in this water scarce region has been pointed out in several studies [51, 53-55]. The projected streamflow amounts [72-74, 180] show an important shift in the hydrological cycle due to earlier snowmelt. In this study, we analyzed data from some of the available remote sensing products over this understudied region in order to understand the contribution of the mountain snowpack in the negative trends of water storage anomalies. The main findings are as follows :

- Previous studies focused on the changes in water storage mostly in the ETB for a shorter time period. The analyses for the whole GRACE observational period (2002-2017) showed that three GRACE solutions (GFZ, CSR, and JPL) agree on strong negative trends in GRACE TWSA for four basins in the Near East region. Our analyses demonstrate that the decrease in TWS continues with an accelerated trend even after the drought years (2007-2009) in a larger domain, not only in the ETB. Elevation-based analysis indicates that the statistically significant negative GRACE monthly TWS trends are 2.74, 1.4, 2.22, and 1.85 cm per year for the areas over 1000 m in the ETB, KAB, COB, and VAN, respectively.

- The most striking result is a major significant shift in snow-cover duration in the headwaters and southern highlands of the ETB, and the high mountains of the KAB. The often significant negative MODIS SCD trend that reaches up to 4 weeks per decade is a clear indicator of snowpack decline in the Near East. If this negative trend continues, the seasonal snowpack which currently starts to form in the late autumn months (October, November) and peaks in the late winter months (January, February) may disappear in a few decades over these areas.
- The ERA5 SWE trends are also another line of evidence for snowpack depletion over the mountains of the Near East. For the areas above 2000 m a.s.l., the magnitude of the significant negative SWE trends are 2.96, 2.41, and 4.51 mm per year for the ETB, KAB, and COB, respectively. For VAN, the SWE decline is 1.61 mm per year according to the ERA5 reanalysis, but not significant. The results from ERA5 are an important independent line of evidence since it is a new higher resolution reanalysis data set that is constrained by remote sensing products (but not those used in this study).
- Another line of evidence is the great similarity in spatial patterns between the negative trends in GRACE TWS, ERA5 SWE, and MODIS SCDs. The strong decrease signal from all these data sets is coincident over the headwaters of the ETB, the Lesser Caucasus, and the Zagros mountains.
- Passive microwave sensors provide precious information for the remote areas such as the mountains of the Near East. However, their retrievals struggle to capture the SWE amounts without bias correction over complex terrain. Here, through weak correlations with many of the other products examined, we show the poor performance of the SWE values retrieved from the AMSR-E and AMSR2 passive microwave radiometer systems over the mountains of the Near East.
- Lastly, we analyzed the snow energy and mass balance variables from the ERA5 reanalysis in order to investigate the potential drivers of snowpack decline. For the snowfall ratio, we found significantly negative trends up to 20% per decade over the Lesser Caucasus, VAN, COB and the Zagros mountains in the winter months. Total precipitation increased significantly by around 4 mm per year in both DJF and MAM especially over the COB and the Black Sea coasts. Additionally, results

from ERA5 clearly show earlier snowmelt in line with significantly increasing temperatures up to 2°C per decade.

Effects of LULC changes on the regional climate and water

Hydroclimatic effects of the human-induced LULC changes in the Euphrates and Tigris Basin (ETB) were analyzed over a period of 20 years between 1991 and 2010. In our study, the human induced LULC change is characterized by increased irrigation and dam construction in the GAP region. After a promising evaluation of the performance of the employed regional climate model, RegCM4, with a focus on the reproduction of the temperature, precipitation, and evapotranspiration fields, we show the impacts of LULC changes on the hydroclimate of the ETB. The main conclusions of this part of the study are given below:

- Compared to the results from the control run, the model with irrigation maps indicate that the 2m surface air temperature values over the irrigated grids decrease by about 0.4-0.8°C, while the cooling in skin temperature was around 0.9-2.1°C for partly and fully irrigated conditions, respectively. Our findings are consistent with various studies that have demonstrated the cooling effect of irrigation.
- Irrigation reduces the maximum temperatures under the present day climatic conditions.
- Irrigation in the GAP region locally alters the surface energy balance through a statistically significant increase in the Bowen ratio. Evapotranspiration has a statistically significant increase of 51% and 113% relative to the control simulation for the partly and fully irrigated simulations, respectively. The expansion of the irrigated fields will affect the water resources of the GAP region by enhancing water loss through evapotranspiration.
- The strong positive feedback mechanism between soil moisture and precipitation is also observed in our study. The combined effect of a lower boundary layer and cooler soil leads to increased convective precipitation, mostly in spring which coincides with the irrigation period, over the ETB.
- The conversion of a land use class can alter climate due to its effect on surface fluxes. Here, it is shown that the applied irrigation in the GAP region perturbs

both the surface water and energy balances in the ETB via significantly increasing the evapotranspiration. These results indicate that future modeling studies should include irrigation for a more realistic representation of the climate responses.

- According to the diurnal cycle analysis, the effects of irrigation are visible especially during the daytime. The largest changes in climatic variables coincide with the irrigation months (April through September).
- Finally, increased water loss will put pressure on both the production of the electrical energy and the water commitments to the downstream countries. The solution of this multidimensional problem of water resources in the basin will become more difficult. A sustainable water practice might be achieved in the region through a modernization of the implemented and planned irrigation systems.

Future of the GAP region

The effects of human-induced changes in LULC and greenhouse were analyzed for the future by using two scenarios (RCP4.5 and RCP8.5) for 2046-2065 and 2081-2100.

The main conclusions of the future simulations are given below:

- Compared to the results from the control run, the future simulations for the end of the century indicate that the magnitude of the increase in surface temperatures in the GAP region will be lower than the headwaters due to irrigation's cooling effect.
- Temperature decrease caused by increased evapotranspiration will be at the same order of the increase in temperature due to RCP forcing. Hence, the temperature of the irrigated region will not be changed significantly in the middle of the century. However, simulations show the warming of the region at the end of the century.
- For both RCP 4.5 and RCP 8.5 scenarios, the annual evapotranspiration is projected to increase in the whole ETB by the end of the century. The magnitude of evapotranspiration in the GAP region is doubled for both of the scenarios compared to the reference run.
- According to the model results, the impact of irrigation on the water budget is mainly due to the increase in evapotranspiration and the consequent decrease in water storage (P-E). By the end of the century, the water loss amounts in the GAP region will be higher under the RCP 8.5 scenario compared to the RCP 4.5 scenario.

6.2 Recommendations

In our study, we showed that the water storage of the ETB has a declining trend. According to the remote sensing products, decreasing snowpack in the higher elevations has a positive correlation with this negative trend. Moreover, land use and land cover changes will heavily affect the surface energy and water balance of the northern Euphrates and Tigris Basin, and by extension the downstream countries, too. A study [181] showed using a coupled regional hydroclimate model [182] that the water demands from the downstream countries can be compensated by different water release scenarios from the upstream sector of the ETB. They suggested that storing water in the headwater part of the basin is an effective water storage strategy in order to reduce considerable amounts of the evaporation from the reservoirs in the arid lower part of the basin, since the reservoirs located in the upstream region have the cooler climate and small surface area. Efficient dam building by narrowing the surface area could be a solution to reduce the water loss through evapotranspiration. Moreover, modernization of the irrigation systems is the most important measure that could be implemented for the all GAP irrigation scheme. As shown by Evans and Zaitchik [165], irrigation efficiency is the key for reducing the evapotranspiration from this semi arid region. The water-related tension is already a challenging issue in the region. Some adaptation measures can be implemented according to the calculated water loss. Tackling the significant water loss through evapotranspiration has a potential for shaping the future water resources management and policies in the region. The importance of the water-energy-food nexus in the implementation of an integrated approach for transboundary water resources management in the ETB has already emerged at the national and international levels [183]. Our study encourages the environmental scientists and policy makers to address the issue of water loss via evapotranspiration. As a corollary, our study points out the potential future consequences of the combination of the ‘tragedy of the commons’ [184] dilemma and the changing climate of the Euphrates and Tigris Basin.

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APPENDICES

APPENDIX A.1 : The list of the CMIP5 GCMs

APPENDIX B.1 : ERA5 reanalysis maps

APPENDIX C.1 : LULC map generation method

APPENDIX C.2 : Mapping the LULC changes

APPENDIX D.1 : Model performance analysis

APPENDIX E.1 : Extreme value analysis

APPENDIX A.1

Table A.1 : The list of the compared GCM simulations from CMIP5.

GCM	Model Name	Modeling Center (or group)	Spatial Resolution (lat $\times$ lon in degree)
1	BCC CSM1	Beijing Climate Center, Meteorological Administration China	2.8×2.8
2	BCC CSM 1M		1.1×1.1
3	BNU ESM	Beijing Normal University	2.8×2.8
4	CCCMA CM4	Canadian Centre for Climate Modelling and Analysis	2.8×2.8
5	CCCMA ESM2		2.8×2.8
6	CCSR ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8×2.8
7	CCSR ESM CHEM		2.8×2.8
8	CCSR MIROC4H		0.56×0.56
9	CCSR MIROC5		1.4×1.4
10	CMCC CM	Centro Euro-Mediterraneo sui Cambiamenti Climatici	0.75×0.75
11	CMCC CMS		1.8×1.8
12	CNRM CM5	Centre Nat. de Recherches Météorologiques	1.4×1.4
13	CSIRO AC10	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	1.25×1.8
14	CSIRO AC13		1.25×1.8
15	CSIRO MK6		1.8×1.8
16	EC-EARTH	EC-EARTH consortium	1.1×1.1
17	FIO ESM	First Institute of Oceanography, SOA, China	2.8×2.8
18	GFDL CM3	NOAA Geophysical Fluid Dynamics Laboratory	2×2.5
19	GFDL ESM2G		2×2.5
20	GFDL ESM2M		2×2.5
21	GISS E2H	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies	2×2.5
22	GISS E2H-CC		2×2.5
23	GISS E2R		2×2.5
24	GISS E2R-CC		2×2.5
25	INM CM4	Institute for Numerical Mathematics	1.5×2
26	IPSL CM5ALR	Institut Pierre-Simon Laplace	1.9×3.75
27	IPSL CM5AMR		1.25×2.5
28	IPSL CM5BLR		1.9×3.75
29	LASG FGOALSG2	Ins. of Atmos. Physics, CAS and CESS	2.8×2.8
30	LASG FGOALSS2	Ins. of Atmos. Physics, CAS	1.6×2.8
31	MPI ESMLR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	1.9×1.9
32	MPI ESMR		1.9×1.9
33	MPI ESMP		1.9×1.9
34	MRI CGCM3	Meteorological Research Institute	1.1×1.1
35	NCAR CCSM4	National Center for Atmospheric Research	0.9×1.25
36	CESM1-BGC	Community Earth System Model Contributors	0.9×1.25
37	CESM1-CAM5		0.9×1.25
38	CESM1-FCHEM		0.9×1.25
39	CESM1-WACCM		1.9×2.5

Table A.1 (Continued): The list of the compared GCM simulations from CMIP5.

40	NOR ESM1M	Norwegian Climate Centre	1.9×2.5
41	NOR ESM1ME		1.9×2.5
42	HADCM3	Met Office Hadley Centre (additional	2.5×3.75
43	HADGEM2AO	HadGEM2-ES realizations contributed by	1.25×1.875
44	HADGEM2CC	Instituto Nacional de Pesquisas Espaciais)	1.25×1.875
45	HADGEM2ES		1.25×1.875
46	MME GCM	Multi Model Ensemble	0.5×0.5

APPENDIX B.1

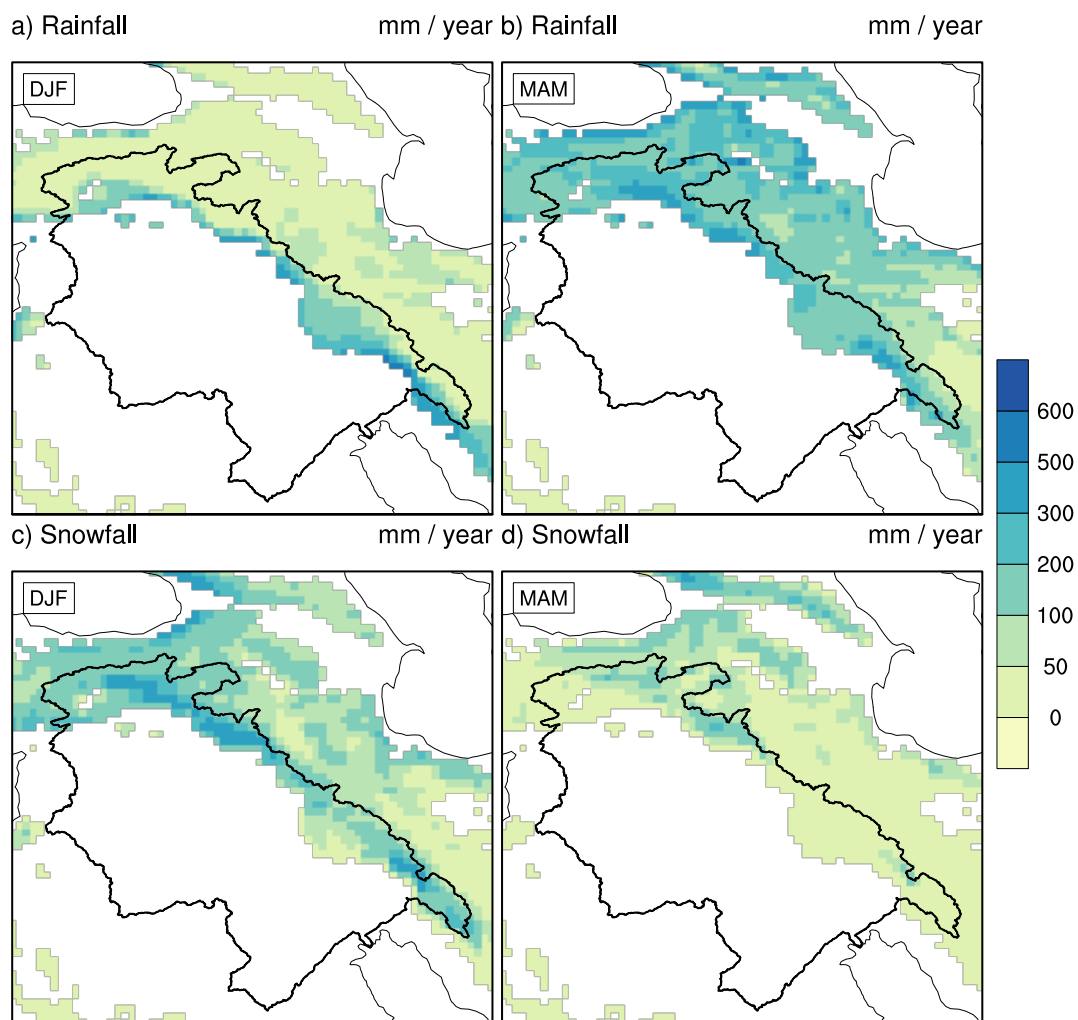


Figure B.1 : Seasonal climatology of (a,b) rainfall and (c,d) snowfall for winter (DJF) and spring (MAM) months.

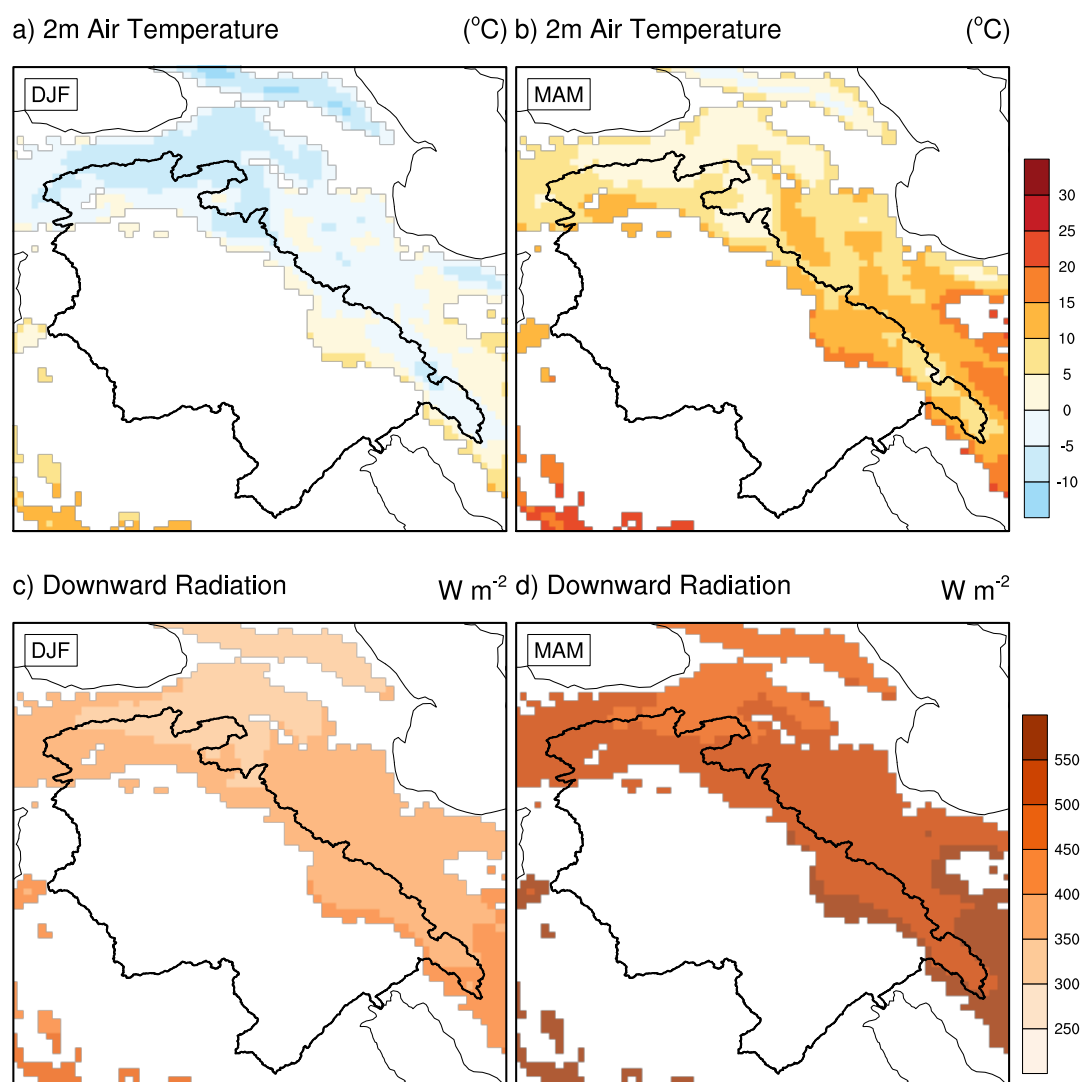


Figure B.2 : Same as Figure **B.1** but for (a,b) temperature and (c,d) downward radiation.

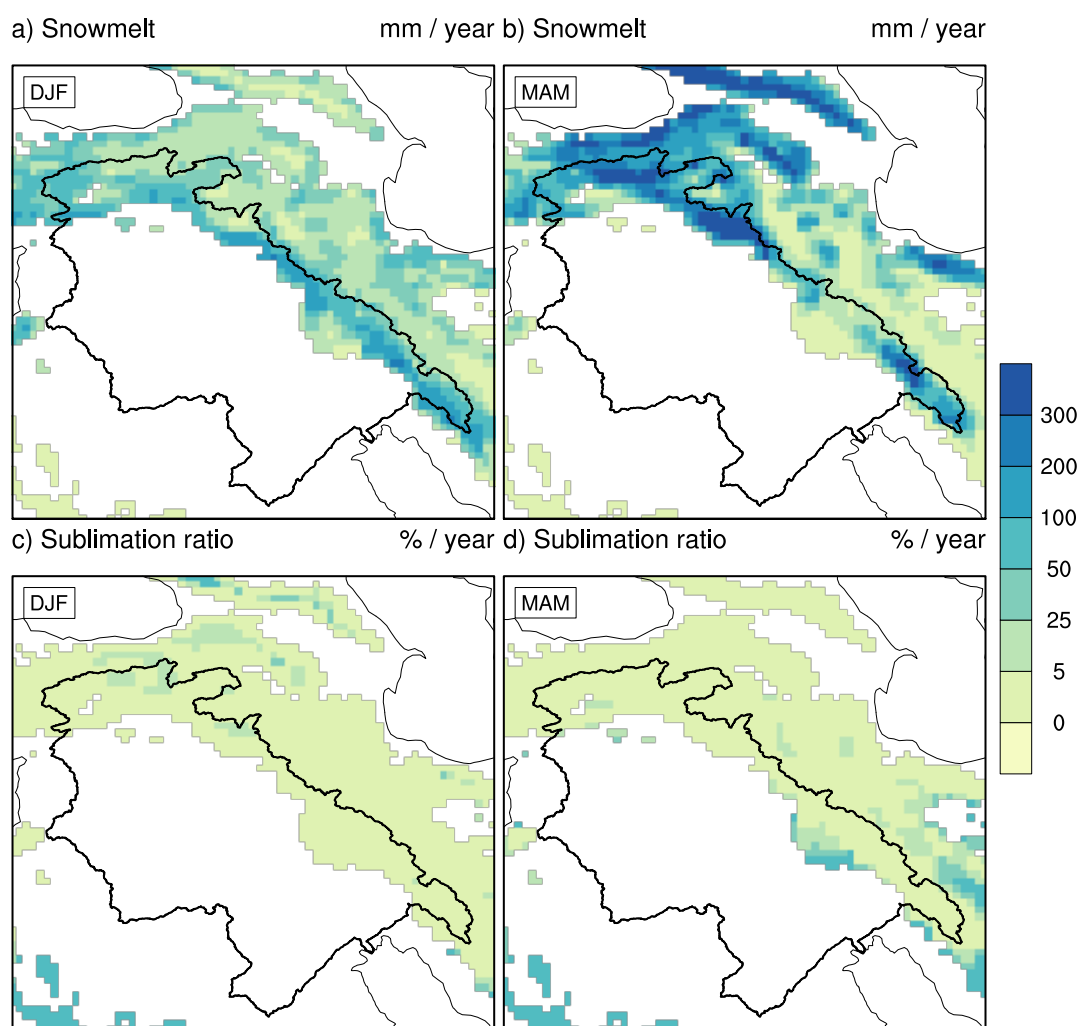


Figure B.3 : Same as Figure **B.1**, but for (a,b) snowmelt and (c,d) sublimation ratio.

APPENDIX C.1

The methodology used for generating the current and future LULC map, and following post-process steps are described in detail:

Editing the projection information

The default LULC map has a conical (Lambert Conformal Conic) map projection. However, CORINE 2006 data has azimuthal (Lambert Azimuthal Equal Area) map projection, and also DSI map has the regular lat/lon grid. Since the projection of all base maps are different from each other, firstly, the projections are transformed to the conical projection which is the default for the model outputs. Secondly, datum information which includes the coordinate systems of the maps is transformed to the WGS 84 to pave the way for working on three different maps.

Projection transformation process is done by using the functions of an open source tool called the Geospatial Data Abstraction Library (GDAL). Also, the file format of CORINE data (GeoTIFF) is transformed to the NetCDF file by using the same tool. The ArcGIS software is used for reformatting the DSI map (from TIFF to NetCDF).

Overlaying the maps

After obtaining there reformatted base maps, we verified their correct positions by using an open source software called QGIS (Quantum Geographic Information System). QGIS is also used to display the updated maps, to obtain the metadata, and to verify the applied changes.

Matching the different land use types

Land use information in the default (pre-GAP) LULC map is represented with 22 different BATS land categories (see Figure 4.1). However, the CORINE land use map has a totally different classes in 46 types (see Figure 4.2). For this reason, matching those different categories is required in order to create the new LULC maps.

Table C.1 : Matched categories in the GLCC and CORINE base maps

Data set	Code - Definition of irrigation (color)	Code - Definition of dams (color)
GLCC	10 - Irrigated crop (grass green)	14 - Inland water (light blue)
CORINE	212 - Permanently irrigated land (citrine)	512 - Water bodies (blue)

In the Table C.1, the codes show the land use category number in the given data sets, while the colors are the land use types in the maps (Figure 4.1 and Figure 4.2)

Updating the LULC information

Most time-consuming part of generating the current and future land use maps is to integrate the all information explained above. In order to create new files, a program

is written in NCAR Command Language (NCL). New maps including the land use change information are created in the NetCDF file since it is the required format in our regional climate model, RegCM4. Additionally, these maps are generated for different resolutions in 48, 12 and 3 km, respectively (see Figure 4.4).

APPENDIX C.2

Grid numbers for each map in different resolutions are also given in the Table 1.2. In general, land cover land use changes within the scope of GAP due to irrigation projects are mainly changed the “irrigated crop” and “inland water” categories. It can be seen from the Table 1.2 that, increased grid numbers in those categories are mostly transformed from the categories of “crop/mixed farming”, “semi-desert” and “forest/field mosaic”. Percentages of the changes in the land use types for three LCLU maps are also shown in the Figure 1.6. Percentage of “irrigated crop” areas is increased from 1% to 17% and 38% for current and future LCLU maps, respectively.

Table C.2 : Model grid numbers for different LULC maps in different resolutions. Numbers in the parentheses give the changes compare to pre-GAP period (while red numbers show the increase, blue gives the amount of decrease).

48 km [Grid Number: 7125, GAP: 24]					12 km [Grid Number: 16000, GAP: 383]					3km [Grid Number: 256000, GAP: 6237]				
No	Land Use Type	Pre-GAP	Current	Future	Pre-GAP	Current	Future	Pre-GAP	Current	Future	Pre-GAP	Current	Future	
1	Crop/mixed farming	1529	1527 (-2)	1527 (-2)	2989	2952 (-37)	2927 (-62)	46007	45436 (-571)	44946 (-1061)				
2	Short grass	481	481 (0)	481 (0)	1817	1817 (0)	1817 (0)	28237	28212 (-25)	28207 (-30)				
3	Evergreen needleleaf tree	30	30	30	107	107	107	1888	1882	1882				
4	Deciduous needleleaf tree	4	4	4	72	72	72	1233	1233	1233				
5	Deciduous broadleaf tree	208	208	208	690	690	690	10969	10969	10969				
6	Evergreen broadleaf tree	0	0	0	0	0	0	2	2	2				
7	Tall grass	21	21 (0)	21 (0)	335	335 (0)	335 (0)	6072	6066 (-6)	6066 (-6)				
8	Desert	1857	1857	1857	588	588	588	9655	9655	9655				
9	Tundra	12	12	12	106	106	106	1638	1638	1638				
10	Irrigated Crop	28	31 (+3)	33 (+5)	151	215 (+64)	290 (+139)	2892	3932 (+1040)	5220 (+2328)				
11	Semi-desert	668	668 (0)	668 (0)	1699	1690 (-9)	1684 (-15)	26903	26776 (-127)	26651 (-252)				
12	Ice cap/glacier	3	3	3	0	0	0	0	0	0				
13	Bog or marsh	1	1	1	2	2	2	27	27	27				
14	Inland water	386	386 (0)	386 (0)	2501	2505 (+4)	2505 (+4)	40359	40413 (+54)	40440 (+81)				
15	Ocean	1209	1209	1209	2518	2518	2518	41218	41218	41218				

APPENDIX D.1

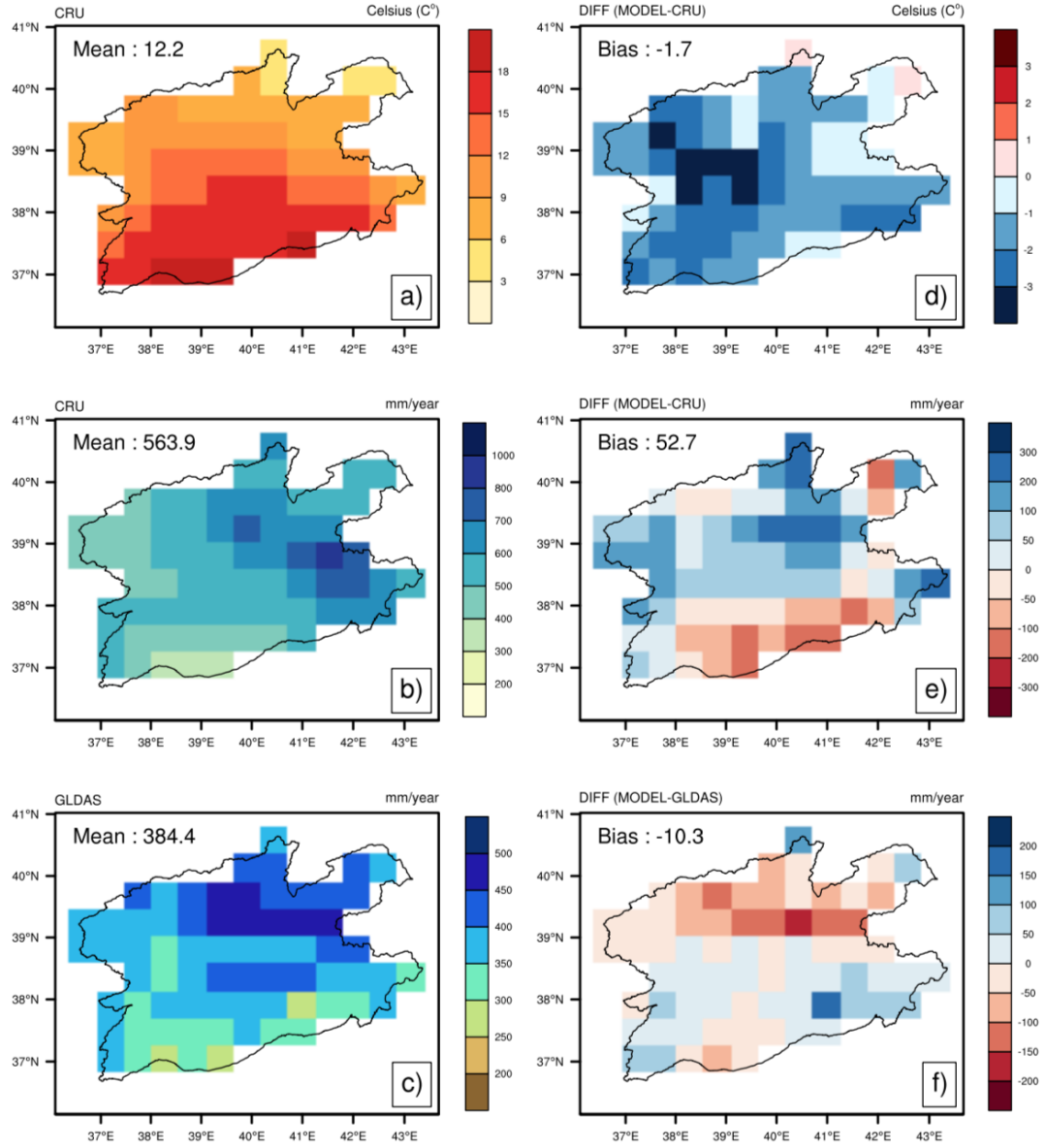


Figure D.1 : Same as Figure 4.6, but for ETB.

Table D.1 : Statistics of performance evaluation for temperature (TEMP), precipitation (PREC), and evapotranspiration (EVAP) over the OD48 domain and the ETB basin for 1991-2010 period.

		Mean_{obs}	Bias	RMSE_{temp}	RMSE_{spat}	Corr_{temp}	Corr_{spat}
OD48	TEMP :	14.8	0.5	0.5	1.3	0.95	0.99
	PREC :	369.8	13.8	22	193.8	0.81	0.83
	EVAP :	277.8	-1.8	9.4	127.8	0.37	0.82
ETB	TEMP :	12.2	-1.7	1.7	1.9	0.95	0.98
	PREC :	563.9	52.7	75.5	117.6	0.77	0.77
	EVAP :	384.4	-10.3	17.5	58.9	0.76	0.22

Table D.2 : Same as Table D.1, but the model is forced with GCM for the period between 1991 and 2008.

		Mean_{obs}	Bias	RMSE_{temp}	RMSE_{spat}	Corr_{temp}	Corr_{spat}
OD48	TEMP :	13.9	-0.8	0.9	1.7	0.54	0.98
	PREC :	369.5	1.5	30.1	185.8	0.36	0.84
	EVAP :	269.7	-7.9	16.4	126.1	0.11	0.83
ETB	TEMP :	8.7	-3.3	3.4	3.5	0.25	0.98
	PREC :	614.1	47.4	156.6	102.1	-0.05	0.75
	EVAP :	372.7	-8.7	32.4	63.7	-0.01	-0.1

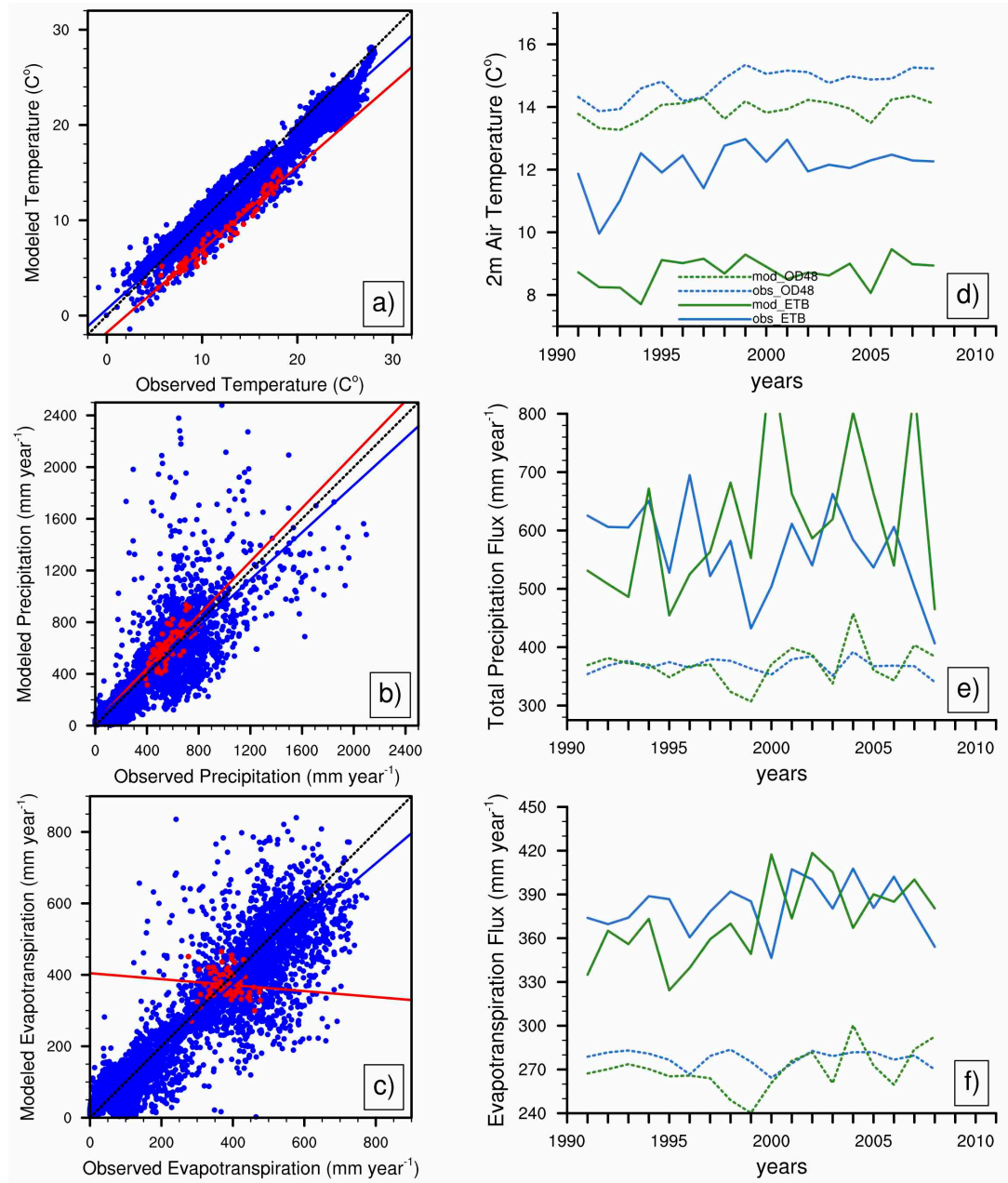


Figure D.2 : Comparison of temporally and spatially averaged observations and model results that forced with the GCM for the period between 1991 and 2008. (a-c) shows scatter plots of the 18-year averaged modeled and observed values for the whole domain (blue dots) and the ETB (red dots), while the last column (d-f) shows the time series spatially averaged over the whole domain (solid lines) and the ETB (dotted lines) for the model simulations (green) and observations (blue).

APPENDIX D.2

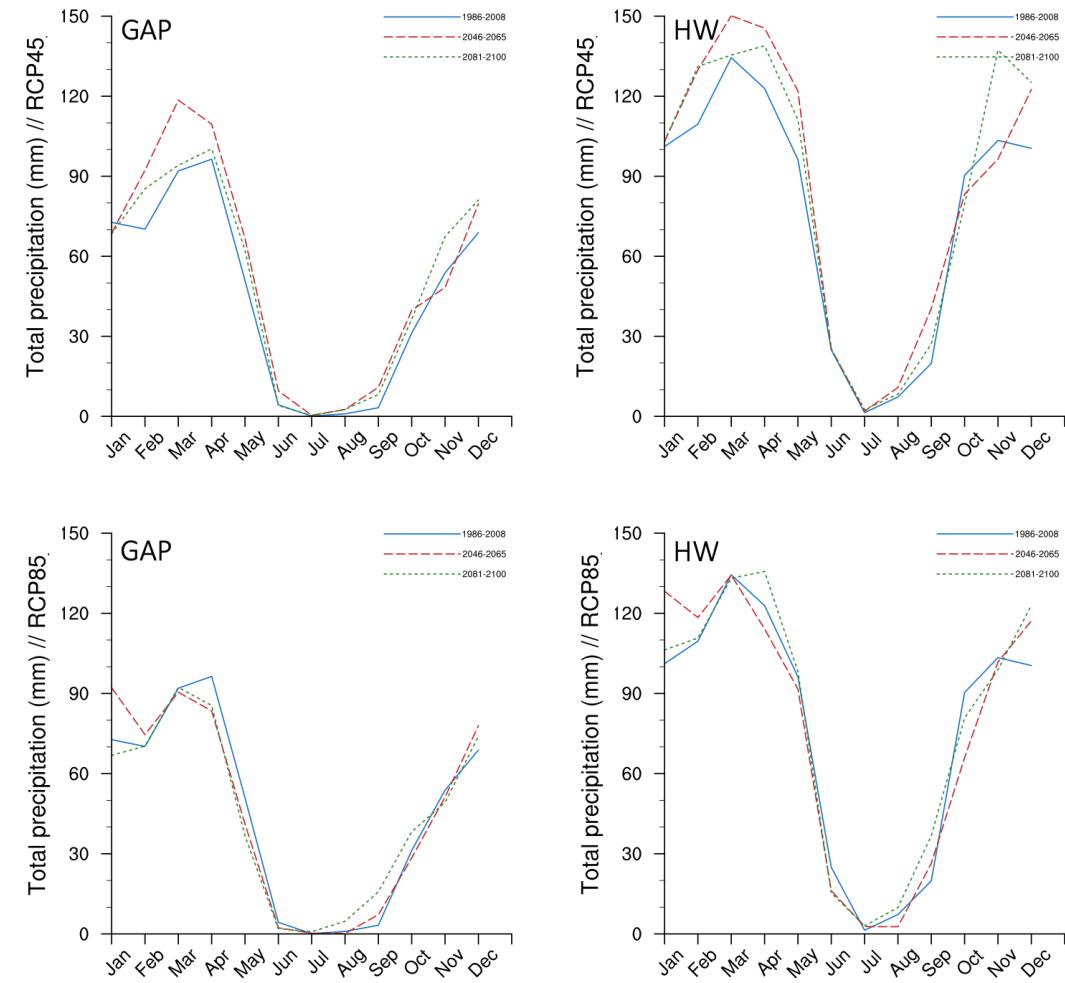


Figure D.3 : Seasonal cycle of precipitation for future simulations with no irrigation.

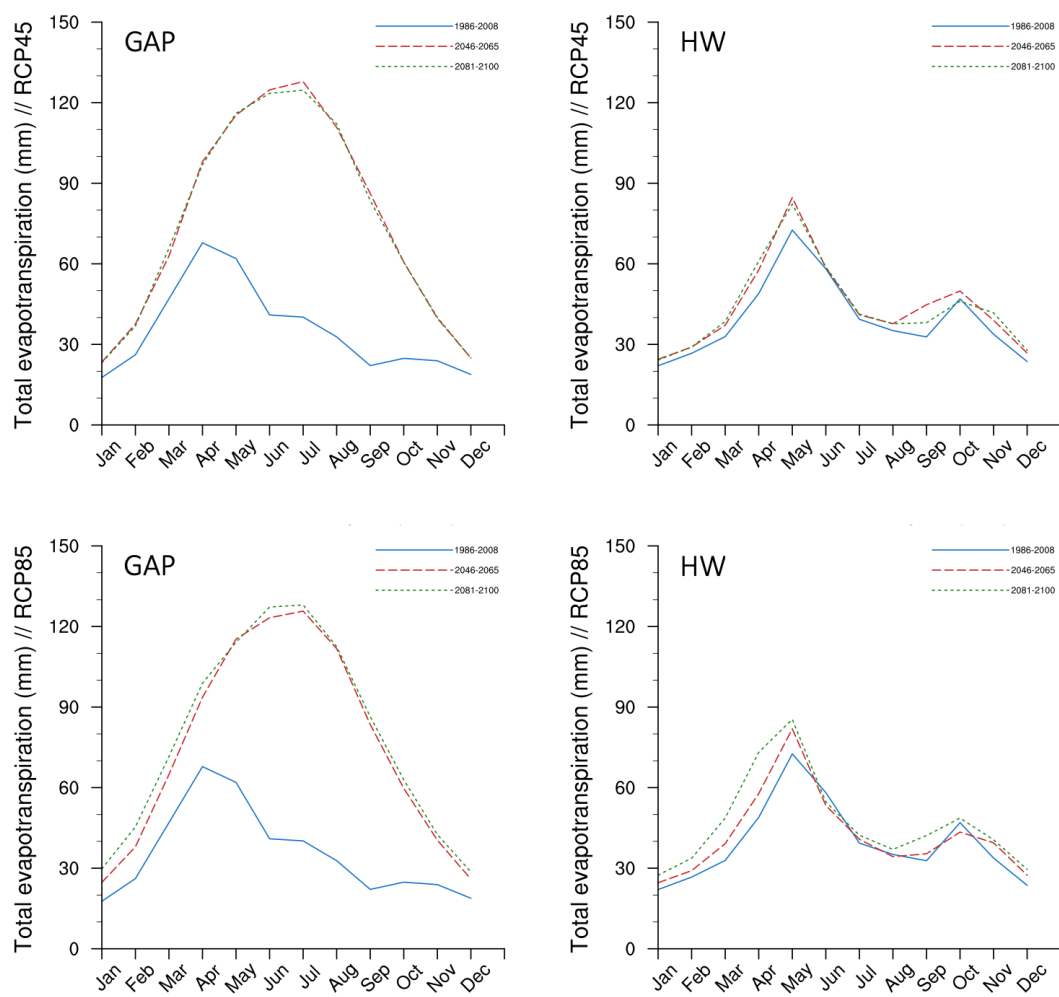


Figure D.4 : Seasonal cycle of evapotranspiration for future simulations with no irrigation.

APPENDIX E.1

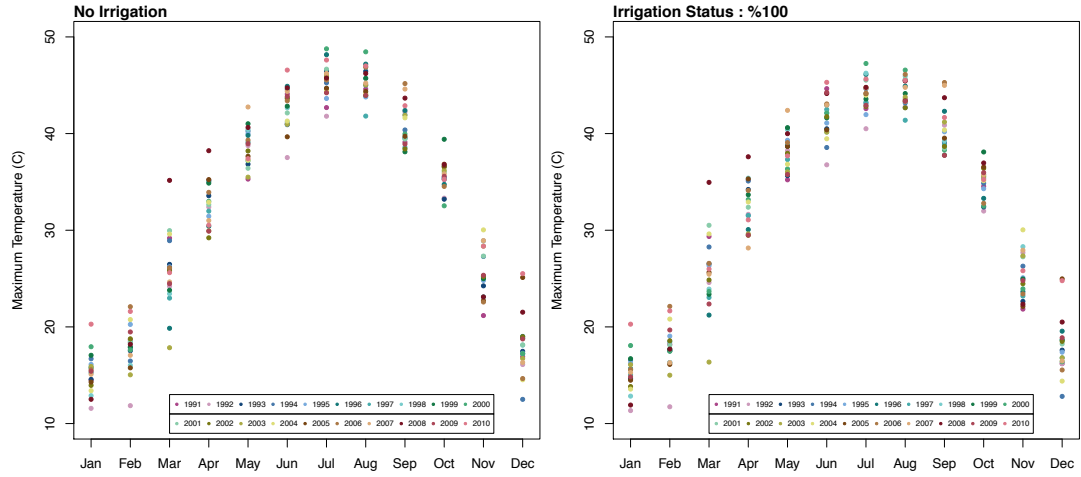


Figure E.1 : Monthly distribution of the maximum temperatures for each year from the non-irrigated (left) and fully irrigated (right) reference period simulations.

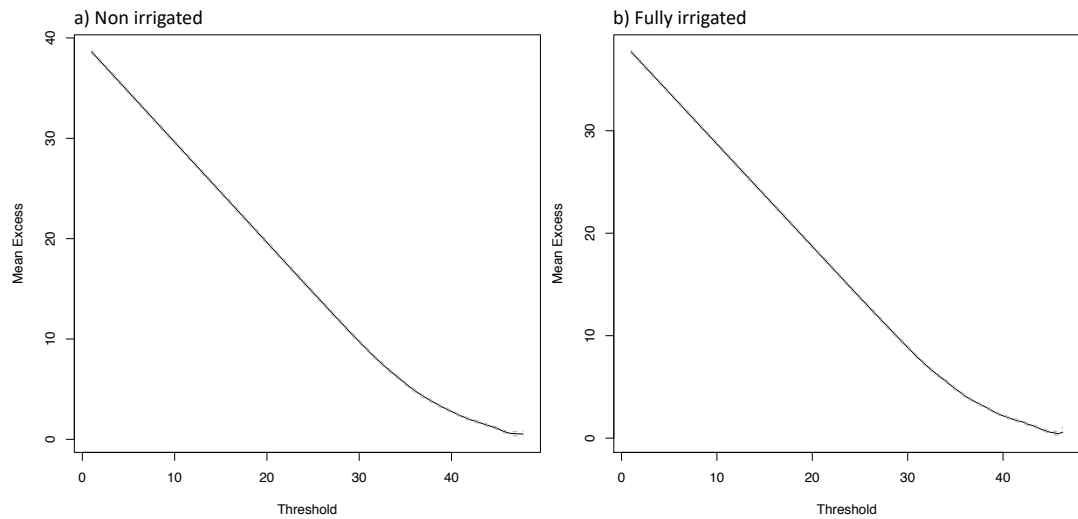


Figure E.2 : Mean residual life plots for a) non irrigated and b) fully irrigated simulations. Dashed gray lines indicate the 95% confidence intervals for the mean excesses.

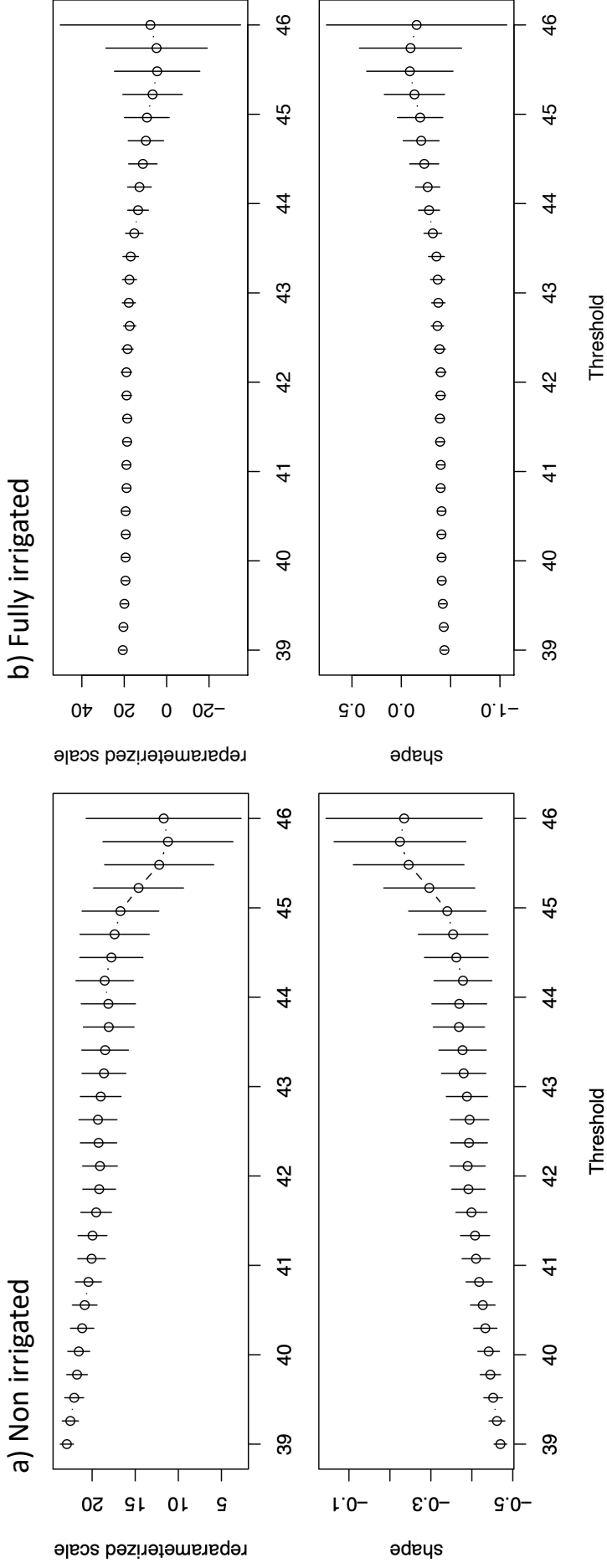


Figure E.3 : Threshold selection diagnostic plots for the maximum temperatures from the a) non irrigated and b) fully irrigated simulations.

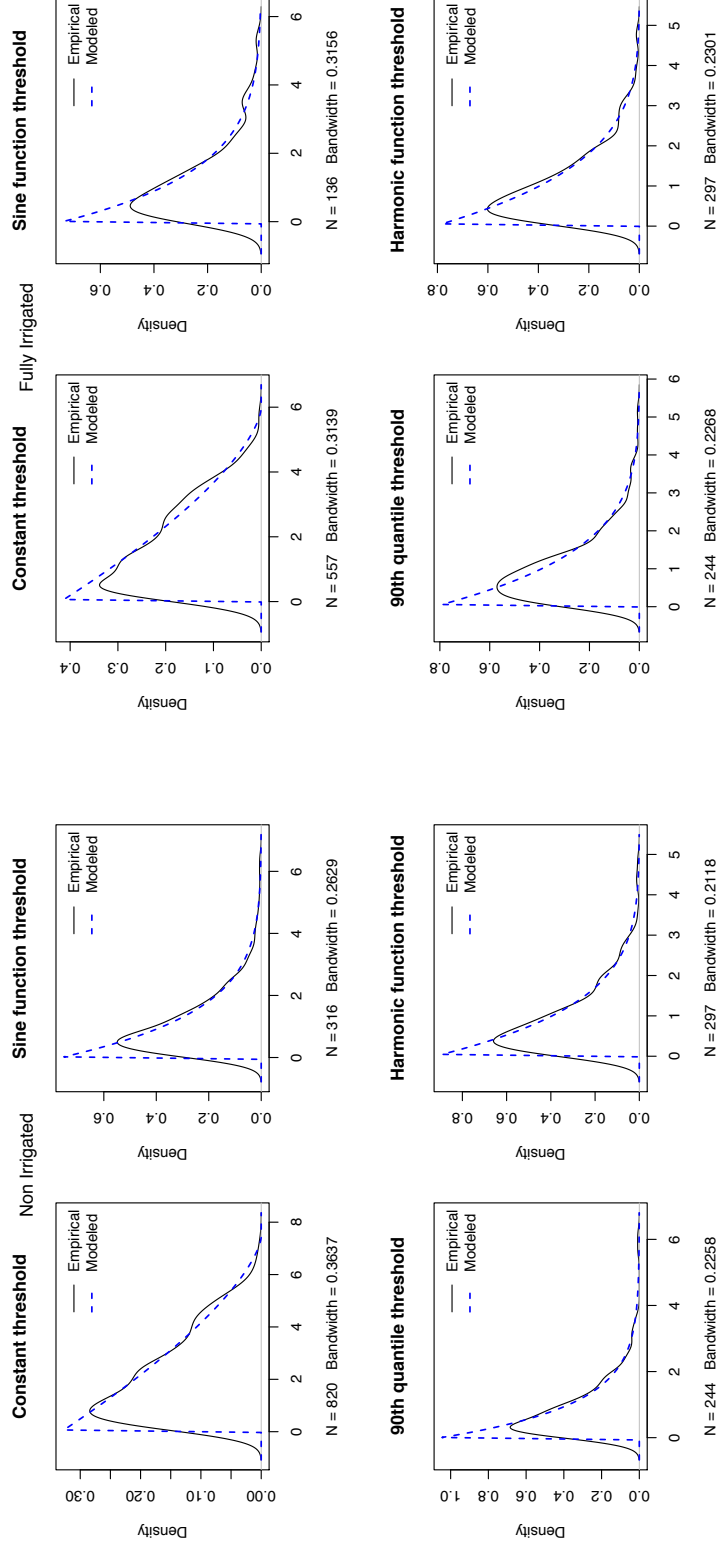


Figure E.4 : Diagnostic plots of fitting the GP model to the exceedances of the constant, sine, 90th quantile, and harmonic thresholds from the non irrigated (left) and fully irrigated (right) simulations.

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

Peer-reviewed journal articles :

- **Yılmaz Y.A.**, Aalstad, K. and Sen, O.L., 2019, *Multiple Remotely Sensed Lines of Evidence for a Depleting Seasonal Snowpack in the Near East*, Remote Sens., 11, 483, [DOI:10.3390/rs11050483](https://doi.org/10.3390/rs11050483).
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Seminars :

- İnsan Kaynaklı İklim değişikliğinin Su Kaynaklarına Etkisi: Fırat-Dicle Havzası Örneği (07.03.2019), Meteorological Engineering Department Seminar, Istanbul Technical University, Istanbul, Turkey.
- Modeling the Hydroclimatic Effects of Land Use and Land Cover Changes Under a Changing Climate (24.10.2018), AYBE Seminar, Istanbul Technical University, Istanbul, Turkey.
- Modeling the Hydroclimatic Effects of Land Use and Land Cover Changes in the Upper Euphrates and Tigris Basin Under a Changing Climate (10.07.2018), CISL Seminar, NCAR Mesa Lab, Boulder, CO, USA.
- Modeling the Hydro-Climatic Effects of Land Cover / Land Use Changes in the Euphrates and Tigris Basin Under a Changing Climate (16.05.2017), MetOs Seminar, Department of Geosciences, University of Oslo, Oslo, Norway.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

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- Langendijk G.S., Aubry-Wake C., Osman M., Gulizia C., Attig-Bahar F., Behrens E., Bertoincini A., Hart N., Indasi V.S., Innocenti S., van der Linden E.C., Mamnun N., Rasouli K., Reed K.A., Ridder N., Rivera J., Ruscica R., Ukazu B.U., Walawender J.P., Walker D.P., Woodhams B.J., **Yılmaz Y.A.**, Three Ways Forward to Improve Regional Information for Extreme Events: An Early Career Perspective, *Frontiers in Environmental Science*, 7, 2019, [DOI:10.3389/fenvs.2019.00006](https://doi.org/10.3389/fenvs.2019.00006)

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- **Yılmaz Y.** and H.N. Dalfes, Extreme Value Statistics of Downscaled Climate Projections for Turkey and Its Region, *Geophysical Research Abstracts*, Vol. 14, [EGU 2012-4627](https://ui.adsabs.harvard.edu/abs/2012EGU...14.4627Y), 2012 (Poster)