

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**ASSESSING THE IMPACT OF CLIMATE CHANGE ON EUPHRATES AND
TIGRIS DISCHARGE USING DISTRIBUTED HYDROLOGIC MODEL**



M.Sc. THESIS

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Department of Climate Science and Meteorological Engineering

Atmospheric Sciences Program

JULY 2024

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**İKLİM DEĞİŞİKLİĞİNİN FIRAT VE DİCLE NEHİR AKIMLARI
ÜZERİNDEKİ ETKİSİNİN DAĞILI HİDROLOJİK
MODELLE DEĞERLENDİRİLMESİ**

YÜKSEK LİSANS TEZİ

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In loving memory of my grandfather,



FOREWORD

After some point in the early 2000s, human society chose to be influenced by the idea of influence itself, but not by the underlying messages, not wondering if the messages carried even made sense. This situation got so out of hand that technology created a state of limbo for us, as we all gave up questioning and searching for meaning. Today's world economy does not offer any hope for individuals my age (and younger) to make long term plans. The social contract, as we know it, is overdue. Our humane ways are exploited, just as all the natural resources.

Three years ago, I began to question my purpose on Earth. Being keen on hydropolitics, I always knew my yearning for leaving something good behind was going to land me in this field and, Dr. Özlem Baydaroğlu revoked my qualms and convinced me to return to academia for higher education, where my energy fits the best. It was the time when my mentor, Professor Yurdanur Unal made me remember her belief in me as she allowed me to research this topic on day one and created a teacher out of me on the way, which gave my life more meaning than ever before. As she introduced me to Professor Mehmet Cüneyd Demirel, a life changing academic, I started learning hydrologic modeling. The more I followed my intuition, the more life has gifted me with its abundance. Without my comrade Aslı İlhan, I would not be able to even dream of what I am delivering today on this very project. Last but not least, thanks to my precious mom, my dear cat Kettle, and my dear fellow Tamer Yanık, for standing by me in each and every darkest hour when my mind was out of service and when I needed that push to go the extra mile. Thanks to my very dear sister from another mother Eda Arıman for having my back in every single situation along the road.

Ultimately, I am hoping my research intention and the know-how I acquired throughout the whole process will multiply the opportunities for further research for the good of my beloved country and surely for any of those in need. I owe my gratitude to Mustafa Kemal Atatürk for gifting us with an invincible republic that raised me and that will eternally stand strong.

May 2024

Emre SALKIM
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ABBREVIATIONS

BGR	: Federal Institute for Geosciences and Natural Resources
CDF	: Cumulative Distribution Function
CDO	: Climate Data Operators
CMIP	: Coupled Model Intercomparison Project
CORDEX	: Coordinated Regional Climate Downscaling Experiment
DEM	: Digital Elevation Model
DJF	: December, January, February
DSI	: State Hydraulic Works (Devlet Su İşleri)
ECMWF	: European Centre for Medium-Range Weather Forecasts
EMBS	: Eastern Mediterranean and Black Sea
ER	: Euphrates River
ERA5	: ECMWF Reanalysis Version 5
ERQM	: Empirical Robust Quantile Mapping
ESCWA	: Economic and Social Commission for Western Asia
ESM	: Earth Surface Model
ETB	: The Euphrates-Tigris Basin
GTOPO30	: Global 30 Arc-Second Elevation
HS	: Hargreaves-Samani Method
HYPE	: Hydrological Predictions for the Environment
IPCC	: Intergovernmental Panel on Climate Change
JJA	: June, July, August
KGE	: Kling-Gupta Efficiency
LULC	: Land Use and Land Cover
MAM	: March, April, May
mHM	: Mesoscale Hydrologic Model
MME	: Multi-model Ensemble
MPR	: Multiscale Parameter Regionalization

NCL	: NCAR Command Language
NSE	: Nash-Sutcliffe Efficiency
USGS	: United States Geological Survey
PDF	: Probability Density Function
PET	: Potential Evapotranspiration
RCM	: Regional Climate Model
RCP	: Representative Concentration Pathways
SG	: Streamflow Gauges
SON	: September, October, November
TR	: Tigris River
TWAP	: Transboundary Waters Assessment Program
UFZ	: Helmholtz Institute for Environmental Research
VIC	: Variable Infiltration Capacity
WWF	: World Wildlife Fund

SYMBOLS

F_m	: Cumulative Distribution Function
F_o^{-1}	: The Quantile Function Corresponding to P_o
P_o	: Observed Variable
P_m	: Modeled Variable
Q_g^t	: Observed Flow at Time Step t
Q_m^t	: Modeled Flow at Time Step t
$\bar{Q}_g$	: Observed Mean Flow
T	: Total Time Step
σ_g	: Standard Deviation of the Observations
σ_m	: Standard Deviation of the Model Simulations
μ_g	: Mean of the Observations
μ_m	: Mean of the Model Simulations



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HYDROCLIMATIC ANALYSIS OF THE EUPHRATES-TIGRIS BASIN FOR THE 21ST CENTURY REGARDING RCP2.6 AND 8.5

SUMMARY

Hosting Türkiye, Syria, Iraq, and Iran, Euphrates-Tigris Basin is a significant case facing the earliest consequences of climate change. Considering its semi-arid nature and lack of hydro-political governance among its riparians, consistency of hydroclimatic research over the region is vital. Accordingly, in the first part of this research, historical and future simulations of three regional climate models (RCMs) (CLMcom-KIT-CCLM5-0-15, GERICS-REMO2015, and ICTP-RegCM4-7) dynamically downscaled from three earth surface models (ESMs) (HadGEM2, MPI-ESM, and NorESM1) (total of nine) by Coordinated Regional Climate Downscaling Experiment's Africa domain (CORDEX-Africa) were evaluated over the Euphrates and Tigris Basin (ETB). Biases of these RCMs were showcased by comparing the reference period to the corresponding ERA5 reanalysis, considering the mean daily surface temperature at 2 meters (°C) and daily total precipitation (mm/day). Distinctions emerge in the analysis of bias maps. Seasonal analysis of the RCMs during the reference period further exhibits these distinctions. Multi-model ensembles (MME) were created to increase the certainty of future predictions regarding RCP2.6 and RCP8.5. MMEs outperform each RCM in terms of hindcasting. To overcome remaining systematic biases and preserve the extremes for future periods, bias corrections were carried out using empirical quantile mapping. Corrected data indicate increased temperatures for ETB regarding both scenarios by the end of the century (up to 1.5°C for RCP2.6 and 5.7°C for RCP8.5). Since ETB is a semi-arid region, changes in precipitation and potential evapotranspiration over the basin were not remarkable reaching up to 0.1 mm/day increase for RCP 2.6 and RCP8.5. The resulting data presents the changes in the basin's climate in the 21st century, provide a comprehensive retrospective benchmarking opportunity for the developing datasets in the CORDEX family (e.g., CMIP6), and offer strategic insight regarding in-situ data scarcity over the region. During the second part of this research, obtained MME data were used to run The Mesoscale Hydrologic Model (mHM) to investigate the changes in routed streamflow, total surface runoff and the depth of snowpack within ETB. The outputs of mHM show up to 15% increase for Euphrates and up to 10% decrease for Tigris River systems in terms of routed streamflow by the end of the century regarding RCP2.6. RCP8.5 showcases more drastic changes reaching up to 25% decrease in the discharge levels for the last period of this investigation. Up to 25% increase is expected on the southeastern parts of the basin as the amount of increasing precipitation also supports this outcome. Decrease in the depth of snowpack and the apparent shift in snowmelt is remarkable over the mountainous areas which needs further investigation. Overall, ETB is likely to face substantial changes in the near and the distant future, as these changes put the water, food, and energy nexus in danger, threatening the ETB's prosperity and sustainable development.



FIRAT-DİCLE HAVZASININ 21. YÜZYIL İÇİN RCP2.6 VE RCP8.5 SENARYOLARI ÜZERİNDEN HİDROKLİMATOLOJİK ANALİZİ

ÖZET

Su insanlığın seçimlerini şekillendiren, refahı sembolize eden, medeniyetlerin yükselişine ve yok olmasına sebep olabilen ve en önemlisi yaşamın sürdürülebilmesi için hayati önem taşıyan sonlu bir kaynaktır. “İki nehir arasındaki topraklar” anlamına gelen Mezopotamya, tarihte su açısından hem bolluğu hem de yokluğu yaşamış bir bölge olarak bilinir. Bu topraklar, Sümerler’den Osmanlılar’a kadar pek çok uygarlığa ev sahipliği yapmış ve onları tarih boyunca kuraklıkla sınamıştır. Bolluk zamanlarında, tarımsal üretimin doğuşuna, günümüze uzanan sulama tekniklerinin geliştirilmesine ve hidroliğin ilk yasalarını kullanarak kanallar inşa edilmesine bu bölgenin tarihinde rastlanır. Ancak kuraklığın hâkim olduğu zamanlarda önemli toplumsal çöküşler, salgın hastalıklar ve savaşlar da yine bu bölgede kaydedilmiştir. Binlerce yılı kapsayan arkeoloji ve paleoiklim verileri, aşırı sıcaklar, yüksek toz salımı ve yağışa bağımlı tarımdaki aksamalarla kitlesel göçler arasında bir ilişki olduğunu göstermektedir.

Türkiye, Suriye, Irak ve İran’ın sınırları dahilinde bulunan Fırat ve Dicle Havzası (FDH) küresel iklim değişikliği etkilerinin dünya üzerinde en erken ve en belirgin şekilde gözlemleneceği hassas havzalardan biridir. FDH’nin hidroiklimine dair gerçekleştirilmiş araştırmalar incelendiğinde, bölgede karşılaşılan kurak dönemlerin sıklığında artışların meydana geldiği ve bu dönemlerin sürelerinin uzadığı görülmektedir. Sıklaşan ve süresi uzayan kurak dönemlerin yol açtığı su bütçesi açıklarını gidermek içinse sulama alanları genişlemekte ve baraj sayılarında artış gözlemlenmektedir. Fakat bu gelişmeler su, atmosfer ve toprak üçlüsü arasındaki enerji bütçesinin dengesiyle oynamaktadır. FDH’deki sulama alanlarının genişlemesi, literatürdeki çalışmalarda detaylı bir biçimde ortaya konduğu üzere, daha yüksek buharlaşma oranlarını beraberinde getirmektedir. Diğer bir yandan, yağışların azalması ve kar örtüsünün erimeye başlama mevsiminin ilkbahardan kışa kayması bölgenin suya bağımlı tarımı üzerinde baskın bir etki kurmaktadır. Değişen su dengesi, akış rejimlerinin zayıflamasına neden olmakta, zayıflayan akış rejimleri ise sadece sucul ekosistemi ve su kalitesini olumsuz yönde etkilemekle kalmayıp (örneğin deniz suyunun Şattülarap Nehri’nin yatağına karışması) havzada bulunan bataklıkların da kurumasına yol açmaktadır. Bugün havzadaki bataklık alanlar, artan toprak tuzluluğu ve toprak kaymaları sebebiyle çölleşmeyle karşı karşıyadır. Çölleşme; tarımı, ekolojii ve havza refahını tehdit etmektedir. Ayrıca bu durum, bölgenin yakın ve uzak tarihinde izine defalarca rastlanan sağlıkla ilgili sorunlara ve günlük yaşamda aksaklıklara yol açan atmosferik toz konsantrasyonunun artışına da sebep olmaktadır.

Yarı kurak iklimi ve havza paydaşları arasındaki su yönetişimi gayretleri göz önünde bulundurulduğunda, bölgedeki hidroiklim araştırmalarının sürekliliği ve niteliği yukarıda sıralanan sebepler dolayısıyla büyük önem taşımaktadır. Bu doğrultuda, gerçekleştirilmiş araştırmamız, havzaya dair literatürdeki benzerlerine kıyasla dahyüksek çözünürlüklü ve daha fazla sayıda bölgesel modeli incelemeyi, elde ettiği yanlılığı giderilmiş topluluk verisini gelişmiş ve daha önce havzanın geneli üzerinde kullanılmamış yeni bir hidrolojik modelle değerlendirerek hidrolojik çıktılar üretmeyi amaçlamıştır.

Bölge üzerinde gerçekleştirdiğimiz iklim araştırmaları esnasında Koordineli Bölgesel İklim İndirgeme Deneyi (Coordinated Regional Climate Downscaling Experiment, CORDEX) dahilindeki üç farklı yer sistem modelinden (HadGEM2, MPI-ESM ve NorESM1) indirgenen üç farklı bölgesel iklim modelinin (CLMcom-KIT-CCLM5-0-15, GERICs-REMO2015 ve ICTP-RegCM4-7) (toplam dokuz) simülasyonları, 21. Yüzyıl için Fırat ve Dicle Havzası özelinde Temsili Konsantrasyon Yolları (Representative Concentration Pathways) 2.6 ve 8.5 senaryolarına bağlı olarak incelenmiştir. Havzanın iklim incelemeleri esnasında sıcaklık ve yağış değişkenleri 1986-2005 referans dönemi, 2021-2040 yakın dönem, 2051-2070 orta dönem ve 2081-2098 ileri dönem olmak üzere ilgili bölgesel model projeksiyonları dahilinde araştırılmıştır. Modellerin referans dönemini tahmin etmedeki başarısı, geriye yönelik gözlem verileriyle zenginleştirilmiş ERA5 modeli analizleriyle kıyaslamalar yapılarak ortaya konmuştur.

Çalışmada hidrolojik modellemede kullanılmak üzere her iki senaryo için ayrı, eşit ağırlıklı ortalamalardan oluşan, günlük ortalama, minimum ve maksimum sıcaklıklar ile toplam yağış veri setleri oluşturulmuştur. Oluşturulan veri setlerinin indirgendikleri yer sistem modeli kaynaklı yanlılıkları, ilgili değişkenin ERA5 Reanalizleri'ndeki karşılıklarına sadık kalınarak, parametrik olmayan nicelik haritalaması metodu ile giderilmiştir. Veriler arasında yer alan günlük minimum ve maksimum sıcaklıklar çalışmada kullanılan hidrolojik modelin ihtiyaç duyduğu potansiyel evapotranspirasyon (PET) verisi hesabında kullanılmıştır. PET hesaplamaları esnasında FDH'deki radyasyon verisi eksiklikleri sebebiyle Hargreaves-Samani (HS) Metodu benimsenmiştir.

Araştırmanın birinci bölümünü oluşturan yanlılık düzeltmesi gerçekleştirilmiş çoklu model topluluğu verileri FDH üzerindeki sıcaklıkların yüzyılın sonuna kadar her iki senaryoda da arttığını göstermiştir (RCP2.6 için 1.5°C'ye ve RCP8.5 için 5.7°C'ye kadar). FDH'nin yarı kurak karakteristiği sebebiyle, havza üzerindeki yağış ve potansiyel evapotranspirasyondaki değişimler oldukça düşük değerlere sahiptir. (RCP 2.6 ve RCP 8.5 için 0.1 mm/gün'e kadar artış). Elde edilen veriler, havzanın 21. yüzyıldaki iklimsel seyrini ortaya koymakta, CORDEX ailesi bünyesinde gelişmekte olan veri setleri (örneğin CMIP6) için kapsamlı bir biçimde geriye dönük kıyaslama fırsatı sunmakta ve bölgedeki veri rehabeti kaynaklı oluşabilecek yanlılıklara dair bilimsel bir hafıza sağlamaktadır.

Araştırmanın ikinci bölümünde ise, birinci bölümde hazırlanan çoklu model topluluğu verileri Helmholtz Çevre Araştırmaları Merkezi (UFZ) tarafından geliştirilen Orta Ölçekli Hidrolojik Model'inin (mHM) koşturulmasında kullanılmıştır. mHM grid tabanlı bir model olarak; Avrupa, Afrika ve Asya'daki birçok nehir havzasının yanı sıra Türkiye'de de Karasu Nehri üzerinde gerçekleştirilen çeşitli çalışmalarla test edilmiştir. Hydrologiska Byråns Vattenbalansavdelning (HBV) ve Variable Infiltration Capacity (VIC) gibi literatürdeki yaygın hidrolojik modellerin çalışma esaslarına dayanan mHM; aktüel evapotranspirasyon, kar birikimi ve erimesi, toprak

nemi dinamikleri, süzülme, yüzey akışı ve nehir debilerindeki değişimler gibi süreçlere dair yüksek çözünürlüklü sonuçlar elde etmek için kullanılmaktadır. Model, saatlik ve günlük meteorolojik verilerle (sıcaklık, yağış, potansiyel evapotranspirasyon, vb.) toprak dokusu, bitki örtüsü gibi havzanın fiziksel özelliklerini ortaya koyan jeomorfolojik verileri de dikkate alarak çalışmaktadır.

Kendinden önceki hidrolojik modellerin çalışma prensiplerini geliştirmeyi başaran mHM, çok ölçekli parametre yerelleştirme (MPR) tekniği aracılığıyla aşırı parametrisasyonu önler ve bu süreçleri çalışma alanının genelinde değil, grid bazında yönetir. Modelin bu yeteneği bir yandan hesaplama gücünden tasarruf sağlarken diğer bir yandan da ayrıntılı sonuçlar üretir. MPR, özünde farklı çözünürlüklerdeki girdiler arasında iletişim kurar ve model çalışmaları sırasında farklı çözünürlüklerdeki meteorolojik ve jeolojik katmanlar arasında eşleştirmeler gerçekleştirir. Böylece, yüksek çözünürlüklü veriler transfer fonksiyonları yardımıyla kilometre altı ölçeklerden yüzlerce kilometreye kadar çeşitli çözünürlüklerdeki verilerle uyumlu hale gelir.

mHM modelinde kullanılan meteorolojik, hidrolojik ve jeomorfolojik parametreleri içeren katmanlar Şekil 1'de gösterilmektedir. mHM, bu üç seviye arasında veri transferi yaparak farklı parametreleri çeşitli çözünürlüklerde ele almaktadır. Seviye-0 jeomorfolojik veri katmanını temsil etmektedir. Diğer üç katman arasında en ince çözünürlükte yükseklik, eğim, toprak ve arazi kullanımı gibi parametreleri içerir. Seviye-1 hidrolojik modelin çalıştığı katmandır ve model çıktılarının oluşturulduğu çözünürlük seviyesini temsil eder. Son olarak, Seviye-2 meteorolojik katmandır. Hesaplamalar sırasında kullanılacak yağış, sıcaklık ve potansiyel evapotranspirasyon parametrelerini yönetir. Modele farklı çözünürlüklerde beslenen Seviye-0 ve Seviye-2, sırasıyla üst katman (Seviye-2) için yukarı ölçekleme ve alt katman (Seviye-0) için aşağı ölçekleme ile eşleştirilir. Ayrıca MPR sayesinde kalibrasyon sırasındaki işlem hacmi önemli ölçüde azalmaktadır.

Devlet Su İşleri'nden (DSİ) alınan akım gözlem istasyonları verilerinin sürekliliğindeki, veri güvenliği kaynaklı, eksikler sebebiyle model kalibrasyonunda çeşitli zorluklarla karşılaşılrsa da model koşullarından elde edilen veriler literatürdeki benzer çalışmaların sonuçlarıyla uyumlu değerler üretmiştir. Ek olarak belirtilmelidir ki, araştırma çıktıları ve bilimsel edinimleri ileride, Türkiye özelinde, mHM ile yürütülebilecek daha kapsamlı çalışmalara umut vaat eder nitelikte olup koşulların gerçekleştirildiği havzanın büyüklüğü göz önünde bulundurulduğunda ulusal bütüncül hidrolojik modelimizin geliştirilmesine dair öncül tecrübeler sunabilecektir.

Modelin ürettiği veriler incelendiğinde özellikle havzanın yüksek kesimlerinde depolanan karın erime mevsiminin her iki iklim senaryosunda da kuzey yarım kürenin ilkbaharından kışına doğru kaydığı görülmüştür. Bu durum özellikle havzadaki tarım ürünlerinin hasat mevsimini değiştireceğinden havzadaki gıda güvenliğine dair bir uyarı niteliğindedir. Yüzyılın sonunda artmaya devam eden sıcaklıklar yüzeyde akışa geçen su miktarını kış mevsimi için artırırken ilkbahar mevsiminde önemli su bütçesi açıklarına yol açmıştır. Çıktı olarak 0.015^0 çözünürlüklü veriler üreten mHM, havzanın Türkiye sınırlarında ilkbahar mevsimi için yüzeyde akışa geçen suda grid başına RCP2.6 senaryosuna göre 150 milimetreyi bulan azalmalara işaret ederken, RCP8.5 senaryosuna göre 320 milimetreyi aşan azalmalar kaydedilmiştir. Benzer azalmalar her iki senaryo dahilinde modelin kar örtüsü üzerinde yaptığı tahminlerde de görülmektedir. RCP 2.6 senaryosuna göre kar kalınlığındaki azalmalar Türkiye'nin güneydoğu kesimlerinde 900 milimetre seviyesine ulaşırken RCP 8.5 senaryosunda 1000 milimetre üzerinde azalmalar görülmektedir. Bu değerler nicelik olarak çeşitli

gridlerde %100'e varan azalmalar olduğuna işaret etmektedir ki, buradan yola çıkarak FDH özelinde kar örtüsüne dair daha hassas çalışmaların gerekliliği ön plana çıkmaktadır. mHM çıktıları nehir Fırat-Dicle Ağı debileri özelinde RCP2.6'ya göre yüzyılın sonuna kadar Fırat Nehri için yaklaşık %15'e varan artışlara ve Dicle Nehri için %10'a varan azalmalara işaret etmektedir. RCP8.5 senaryosu araştırmanın son dönemi için nehir debilerinde %25 oranında daha şiddetli azalmalar sergilemektedir. Ancak, her iki senaryoda da yüzyılın sonuna doğru, havzanın güneydoğu kesimlerinde artan yağış miktarına paralel olarak, nehir debilerinde %25 mertebesine varan bir artış olduğu görülmektedir. Belirtilen bölgedeki yağışların artışı, sıcaklıklardaki yükselişle beraber Basra Körfezi'nin başlangıcında artması beklenen konvektif hareketlere bağlanmaktadır.

Sonuç olarak, özellikle artan sıcaklıklar ve buna bağlı olarak FDH'nin su bütçesinde meydana gelen pertürbasyonlar, havzanın su, gıda ve enerji üçlüsü sürdürülebilirliğini, bölgenin refahını ve kalkınma çabalarını tehdit etmektedir. Gerçekleştirilen çalışma bu bağlamda çevre kaynaklı potansiyel riskleri ortaya koymaktadır. Havzayı paylaşılanlar tarafından literatüre kazandırılan bilimsel çalışmalar ortak su yönetimi çabalarındaki iş birliklerinin sayısını artıracak ve ilgili süreçleri kolaylaştıracaktır. Gelecekteki çalışmalara ışık tutmayı ve havzaya dair bilimsel hafızanın gelişmesini hedefleyen bu araştırma aynı zamanda sahip olduğu yenilikçi yaklaşımlarla özgün çıktılar üretmeyi amaçlamıştır.

1. INTRODUCTION

Water shapes humanity's choices, symbolizes prosperity, and makes civilizations rise and fall, but most importantly, it is vital for the sustenance of life. Mesopotamia, the land between two rivers, is known for its bipolar nature in terms water. It catered many civilizations from Sumerians to the Ottomans, and challenged them with droughts. Times of abundance allowed Mesopotamian people to invent novel irrigation techniques for improving agricultural production and to build canals through the use of preliminary laws of hydraulics. However, during droughts, history unfolded for worse; bringing societal collapse, epidemics, and wars. Archeological and paleoclimate data covering millennia suggests correlation between low precipitation, higher dust output and decline of rain dependent agriculture beyond sustainable limits, leading to nomadization and mass exodus from the region.

Today, shared by Turkey, Syria, Iraq, and Iran, the Euphrates-Tigris Basin (ETB) continues to be a region of social and environmental challenges. The political bodies in the region lag in sustainable governance in the face of changing climate, rising population and non-legal actors. Existing research recognizes that there is a willingness for transboundary cooperation among the riparian states; however, the social and political complexities of the region hinder the path to a conclusive ending (Al-Muqdad, 2019; Kibaroglu and Sayan, 2021, Dezfouli et al., 2022). Therefore, scientists suggest that societal adjustment may alleviate the political lethargy. As more than 80% of the water within the ETB is used for agriculture, public awareness programs on innovative and advanced agricultural plans may pave the way to better water management practices (Al-Ansari, 2013). Decreased water stress and shared goals among the stakeholders may enhance the region's adaptive capacity and also catalyze the establishment of mutual trust and a cooperative environment (Kibaroglu, 2008). Yet, discrepant and classified data lead to an incomplete understanding of water

availability, hindering such efforts. Thus, hydroclimatic studies on the region are of critical importance. ETB is a relatively underdeveloped region with fewer anthropogenic perturbations on climate (e.g. urban heat island effect). Therefore, the traces of climate change are more evident in the region, aside the consequences of climate variability (Cullen and deMenocal, 2000; Öñol and Semazzi, 2009; Kahya, 2011; Bozkurt et al., 2015; Hussein et al., 2023). The existing body of research on the region's hydroclimate proves that drought events are increasing, and their periods are getting longer (Amini et al., 2016; Yılmaz, 2019; Rateb et al., 2021). To overcome droughts, widening irrigation areas and the rising number of dams alter the water and surface energy budget. The expansion of irrigated lands results in higher evaporation rates, as presented in various studies (Kavvas et al., 2011; Bozkurt et al., 2015; Yılmaz et al., 2019). Declining precipitation and the shift in snowmelt have a dominant effect on water balance (Flint et al., 2011; Öñol et al., 2014). Altered water balance leads to weakened flow regimes (Bozkurt et al., 2015). Weakened flow regimes not only affect the aquatic ecosystem and water quality (e.g. intrusion of sea water in Shatt al-Arab) but also affect marshlands (Sultan et al., 2008; Ben-Hasan et al., 2018; Boloorani et al., 2021). Today marshlands in the basin face the implications of desertification, such as increased soil salinity and landslides (Bozkurt and Şen, 2011; Abdallah and Jaafar, 2019). Desertification threatens agriculture, ecology, and communities. It also raises atmospheric dust concentrations which may lead to health-related problems and disruptions in daily life (Hamidi, 2020; Boloorani et al., 2022; Montazeri et al., 2022).

Emerging water-related environmental concerns justify the necessity of continuous hydroclimatic research on the region. Up to now, a number of studies have analyzed the outcomes of various climate scenarios partially or entirely covering ETB (Kavvas et al., 2011; Chenoweth et al., 2011; Özdoğan, 2011; Bozkurt et al., 2012; Öñol et al., 2014; Adamo et al., 2018; Salman, 2018; Yılmaz, 2019; Yıldırım et al., 2021; Akbulut et al., 2023). Some of these studies aimed to mimic the basin's water balance, while others investigated the accuracy and precision of the related climate and hydrologic models of different resolutions and boundary conditions. Kavvas et al. (2021) performed their water balance assessment of the ETB between 1957 and 1969 water years (the period with extreme hydrologic conditions before the large dam projects) using the RegHCM-TE regional hydroclimate model. Chenoweth et al. (2011) used PRECIS model to investigate the impacts and implications of climate change on the

water resources of the eastern Mediterranean and Middle East. Özdoğan investigated the effects of climate change on snow water availability in ETB using the Variable Infiltration Capacity (VIC) macro scale hydrologic model with a set of 13 earth surface models (ESMs) under B1 and A2 scenarios by Intergovernmental Panel on Climate Change (IPCC) (2011). Önoğlu et al. (2014) used ICTP-RegCM3 regional climate model (RCM) for the twenty-first century driven by three global circulation models (MPI-ECHAM5, NCAR-CCSM3, and HadCM3) and three scenarios (A2, A1F1, and B1) over Eastern Mediterranean and Black Sea Region. Bozkurt et al. (2015) ran a hydrological discharge model of Max Planck Institute for Meteorology forced with two ESMs (ECHAM5/MPIOM and MPI-ESM-LR) and two climate scenarios (A1B and RCP 4.5). Adamo et al. (2018) performed their studies using the soil and water assessment tool (SWAT) on five tributary basins of the Tigris River considering six ESMs under IPCC's A1, A2, B1 and, B2 scenarios. Salman et al. (2018) carried a hybrid approach on four ESMs (HadGEM2-AO, HadGEM2-ES, MIROC5, and MIROC-ESM) and four climate scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) to determine the most suitable model for making projections over Iraq being the most vulnerable country of the basin. Yılmaz et al. (2019) investigated the hydroclimatic effects of land use and land cover changes (LULC) over ETB to make approximations on irrigation and water surfaces. With a similar approach to this project on a smaller scale, Yıldırım et al. (2021) investigated the impact of climate change on the flow rate of the Alata River Basin in Mersin province (Türkiye) considering RCP8.5 using a semi-distributed hydrological model named Hydrological Predictions for the Environment (HYPE). Akbulut et al. (2023) investigated the performance of machine and federated learning over Upper Euphrates in terms of stream flow estimations.

As a novel continuation of research, this study aims (i) to make hydroclimatic projections for ETB, (ii) provide a comprehensive retrospective benchmarking opportunity for the developing datasets in the CORDEX family (e.g., CMIP6), (iii) to offer strategic insight regarding in-situ data scarcity over the region, (iv) and to contribute to the literature of the basin which will facilitate the possibility of collaborations for shared water management efforts. Introducing an innovative hydrologic modeling approach over ETB, this research also showcases the capabilities and performance of Mesoscale Hydrologic Model (mHM) by Helmholtz Institute for Environmental Research (UFZ) especially under scarce observational data conditions.

Inferences on the future of the water-food-energy (WFE) nexus of ETB will be provided through discussions over the results using interconnections between the regional climate models and hydrologic model outputs. Moreover, suggestions regarding further research over the region will be concluded.



2. STUDY REGION

2.1 The Euphrates River Course

Being the longest river in Southwest Asia with a 2786 km length, the Euphrates River (hereafter ER) is formed by two tributaries: Karasu and Murat Rivers. The northernmost branch of the ER rises in Akyurt, Erzurum, at 1383m elevation, where Tuzla Creek meets Karasu River (Figure 2.1). Karasu River originates near Şenyurt, Erzurum, at 2744m elevation. Another major tributary of the ER originates on the slopes of Ala Dağ (Mount Ala) at an elevation of 3135m, located north of Lake Van, near Diyadin, Ağrı. Today, the Murat River meets the ER by joining the waters of the Keban Dam near Muratbağı, Elazığ. The ER then passes through the southeastern Taurus Mountains and enters Syria at Karkamış, Gaziantep.

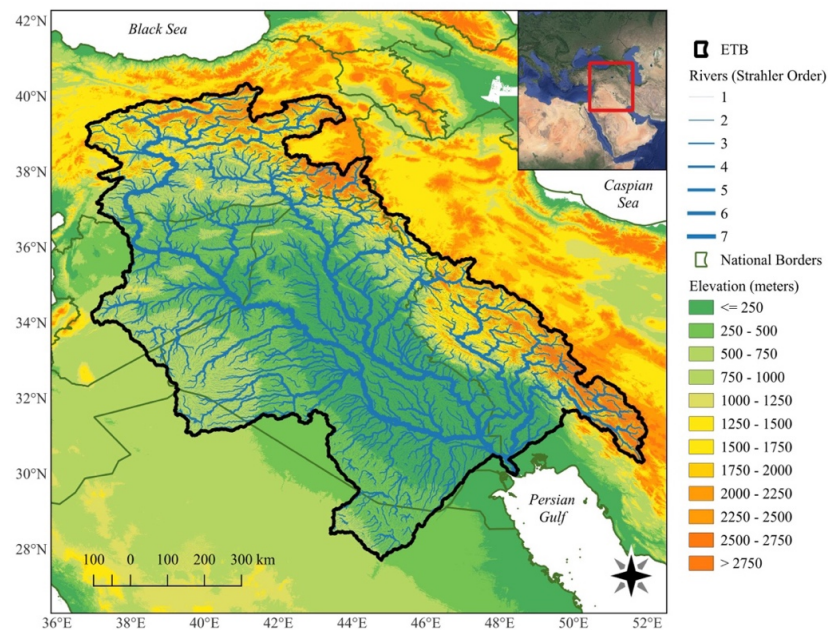


Figure 2.1 : The Euphrates and Tigris River Network in Strahler Order with Elevation, National Borders, and Basin Boundaries.

Within the boundaries of Syria, ER crosses Lake Assad (reservoir of the Tabqa Dam), after which it is joined by the rivers Balikh and Khabur. Both tributaries pass through the Eastern plateau of Syria, joining the main branch near Ar Raqqa and Al Busayrah, respectively. ER enters Iraq near the town of Al-Qa'im. ER meanders between the major lakes Therthar and Habbaniyah before reaching its alluvial plain near Al-Fallujah and Baghdad. Due to natural and anthropogenic reasons, ER loses part of its waters to desert depressions and distributaries (Kolars and Mitchell, 1991). ER joins Tigris, forming Shatt al-Arab at the town of Qurna, approximately 450 km southeast of Al-Fallujah.

As mentioned earlier, ER has three riparians, which are Türkiye, Syria and Iraq. However, the basin spreads among five countries; Türkiye (28%), Syria (22%), Iraq (47%), Saudi Arabia (2.97%), and Jordan (0.03%). According to the 2013 Inventory of Shared Water Resources in Western Asia, The Euphrates Basin has a total area of 440.000 km². Before the damming projects over ER, between the period of 1930 and 1973, mean annual flow rate is stated as 30 km³/year. After the damming projects, for the period between 1974 and 2010, the basin has a total of 25 km³/year mean annual flow rate with a maximum total dam capacity of 144 km³ and an overall actual fill rate over 60 km³ (UN-ESCWA and BGR, 2013). Between the period of 1914 and 2000, 12 dams were constructed over ER. Serving for irrigation, hydropower generation, flood control and flow diversion purposes, five dams are located in Türkiye, three dams in Syria and four dams in Iraq.

2.2 The Tigris River Course

Being the second longest river in southwest Asia with an 1840 km length, the Tigris River (TR) originates in Sivrice at 1150 m elevation. The river then flows southeast to the city of Cizre, forming the Turkish-Syrian border for 32 km before crossing to Iraq. Sourcing its waters seeping from the mountains of Eastern Anatolia and Lake Hazar located in Elazığ, TR also feeds on some other important tributaries joining the river system in Turkey and Iraq. Entering Iraq near Faysh Kabur, TR joins Mosul Dam Lake and then reaches the city of Mosul after flowing nearly 100 km downstream. On its way from Tikrit to Samarra, TR forms its delta, creating the eastern part of the complex Euphrates and Tigris River System, which is responsible for both irrigating and draining the lowlands of Mesopotamia (Kolars and Mitchell, 1991). During its course

in Iraq, TR is joined by the tributaries Greater and Lesser Zab, Adhaim, and Diyala, flowing westwards from the Zagros Mountains. ER and TR join each other in southern Iraq in al-Qurnah and form the freshet Shatt al-Arab for the last 190 km until meeting the Persian Gulf.

TR has four riparians: Türkiye, Syria, Iraq and Iran. Similarly, the TR Basin is shared by Türkiye (24.5%), Syria (0.4%), Iraq (56.1%) and Iran (19%). Having a surface area of 221.000 km², TR host for 14 dams with a maximum storage capacity of 116.5 km³, serving for the irrigatin-drainage systems. According to the measurements near Kut, Iraq, the mean annual flow rate of the TR is approximately 26 km³ as of 2013. The flow rate before the 1973 is considered to be at its natural pace. After 1973 distinctive flow rates are observed at Kut with no significant changes at Mosul within the same period (UN-ESCWA and BGR, 2013). In comparison with ER's flow regime TR's high-flow season is longer and more striking, mainly because of the higher precipitation rates over a greater area. The peak level in discharge can be observed in April, a month before the peak levels of ER. The period between March and August accounts for the 56% to 75% of the total annual flow of TR (Beaumont, 1998). The lowest level of discharge occurs in September. With monthly rate of 87.7 m³/s, 1935 was the year with the lowest recorded discharge. For the same year, measurements near Kut, indicates a minimum of 219 m³/s.

2.3 The Euphrates and Tigris Basin

Being one of the major transboundary basins, ETB is located within the territories of six countries: the Republic of Türkiye (22%), the Syrian Arab Republic (11%), Iraq (46%), The Islamic Republic of Iran (19%), the Kingdom of Saudi Arabia (1.9%), and the Hashemite Kingdom of Jordan (0.03%). With a total drainage area of 868.060 km², the basin hosts more than 65 million. The Euphrates and Tigris rivers originate in the highlands of Eastern Türkiye. The northern and eastern boundaries of the basin are framed by the Alpine-Himalayan Belt, with elevations exceeding 3000 meters (Figure 2.1). The eastern highlands of the basin are majorly located on the ranges of the Zagros Mountains. Shatt al-Arab River forms at the confluence of these two rivers, flowing through some 200 kilometers on a flat and arid route to meet the Persian Gulf. Almost one-third of the basin extends over the arid Mesopotamia Plain (MP) with elevations under 250 meters.

There are several factors beneath the semi-arid nature of ETB's climate. One of them is the latitudinal location of the basin. In addition, northward expansion of Hadley Cell brings dry spells over the region. Also, the regional topography effects the prevailing meteorological conditions within the basin. On a diagonal axis from northwest to southeast, ETB has a wide temperature gradient. The sub-tropical Mediterranean climate characteristics dominate Southeastern Türkiye, Northern Iraq, and Syria, with wet winters and dry summers enabling rain-fed agriculture during the winter and spring seasons. Irrigation-aided agriculture sustains multiple crop yields during the year for these parts of the ETB. Conversely, MP experiences considerably arid climatic conditions, with mean daily total precipitation rarely exceeding 0.54 mm/day. Warmer and drier summers, with maximum daily temperatures exceeding 50°C and relative humidity under 15%, these lands demand intensive irrigation and suffer from loss of water through evapotranspiration.

3. DATA AND APPROACH

In its first part, this project investigates the historical simulations of the RCMs named CLMcom-KIT-CCLM5-0-15, GERICS-REMO2015, and ICTP-RegCM4-7, which are dynamically downscaled from the ESMs named HadGEM2, MPI-ESM-LR & MR, and NorESM1 within the CORDEX database (Figure 3.1). Africa domain was chosen as it was the only domain offering the highest data diversity over ETB. In other words, unlike other domains within the CORDEX family, CORDEX-Africa offers the largest examples of

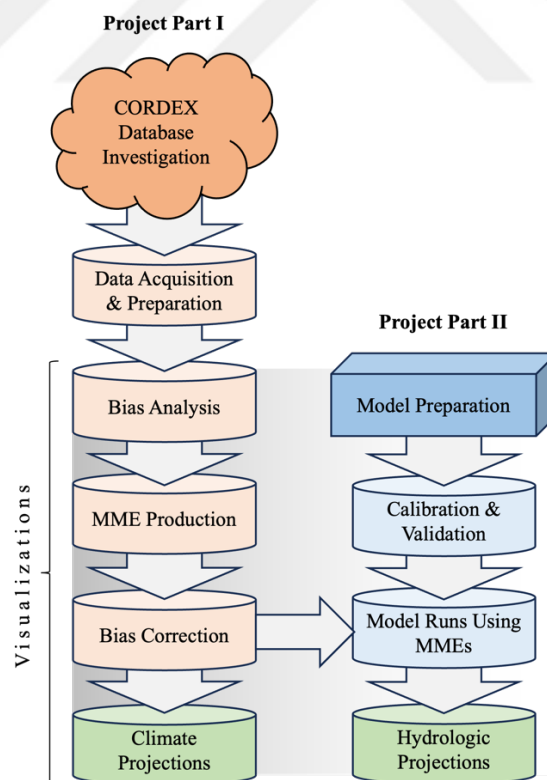


Figure 3.1 : Flow Chart of the Project.

models with the finest spatial resolution (0.22 x 0.22 degrees) concerning the highest number of scenarios (Table 3.1). Our intention regarding diversity and resolution among the models and projections was fulfilled by RCP2.6 and RCP8.5, the scope of our study was built around these scenarios. Since ETB is a data-scarce transboundary region with hydropolitical significance, ERA5 reanalysis (ECMWF Reanalysis v5) was considered as the observations. All related climate data to this study were acquired from the Copernicus Data Store. To showcase the performance of the RCMs, bias analysis was then carried. Following this procedure multi model ensembles (MMEs) for temperature and precipitation were produced to be used in both the climate projections and hydrologic projections which were to be obtained from the distributed hydrologic model. In its second part, this project carried out hydrologic modeling over ETB to investigate the discharge rates within the river systems, as well as surface runoff and depth of snowpack concerning the water budget of the basin. Model preparation stage was completed by creating the flow accumulation system of ETB by calibrating the digital elevation data and streamflow gauges. After obtaining a satisfactory validation MMEs were fed into the model to obtain hydrologic projections for the 21st century over ETB. The digital elevation data was also used in the visualization of the study area which has a 30-arc second resolution and is a product of GTOPO30 global digital elevation model (DEM). Related data was downloaded from the United States Geological Survey (USGS) Earth Explorer platform. The shapefiles for the river network and basin boundaries were downloaded from The HydroSHEDS project by the World Wildlife Fund (WWF).

3.1 Bias Correction

Our reference period starts in 1986 and ends in 2005. Future projections were divided into three periods of the early, mid, and late 21st century: 2021-2040, 2051-2070, and 2081-2098, respectively. The end of the century was chosen by the end of the year 2098 because of the data availability in the CLMcom-KIT-CCLM5-0-15 downscaled from the MOHC-HadGEM2-ES. CCCma-CanESM2 was left out from the scope of this study since this data set was not serving RCP2.6 scenario (Table 3.1). All nine of the RCMs were first bilinearly interpolated and converted into the same coordinate system to prevent potential discrepancies for further manipulations and visualizations.

Table 3.1 : Data Availability of Consistency over ETB within the CORDEX-Africa Domain.

Global Circulation Model	Regional Climate Model	Historical	RCP2.6	RCP4.5	RCP8.5
CCCma-CanESM2 (Canada)	CCCma-CanRCM4 (Canada)	✓	X	✓	✓
MOHC-HadGEM2-ES (United Kingdom)	CLMcom-KIT-CCLM5-0-15 (Germany)	✓	✓	X	✓
	GERICS-REMO2015 (Germany)	✓	✓	X	✓
	ICTP-RegCM4-7 (Italy)	✓	✓	X	✓
MPI-M-MPI-ESM-LR (Germany)	CLMcom-KIT-CCLM5-0-15 (Germany)	✓	✓	X	✓
	GERICS-REMO2015 (Germany)	✓	✓	X	✓
	ICTP-RegCM4-7 (Italy)	✓	✓	X	✓
MPI-M-MPI-ESM-MR (Germany)	ICTP-RegCM4-7 (Italy)	✓	✓	X	✓
NCC-NorESM1-M (Norway)	CLMcom-KIT-CCLM5-0-15 (Germany)	✓	✓	X	✓
	GERICS-REMO2015 (Germany)	✓	✓	X	✓
	ICTP-RegCM4-7 (Italy)	✓	✓	X	✓

All annual and seasonal calculations regarding daily means and sums were conducted using Climate Data Operators (CDO) and NCAR Command Language (NCL). For zonal calculations, basin boundaries were determined according to the shapefile obtained from HydroSHEDS. Temperature values were investigated in Celsius degrees, and precipitations were calculated as millimeters per day. Annual and seasonal bias maps, box plots, and graphs showcasing probability density functions (PDF) were created in NCL. Additional visualizations used in this study were carried out using QGIS software.

Bias corrections were done in R, which offers various quantile mapping options. Since non-parametric quantile mapping using a robust empirical quantiles method (ERQM) was proven more effective, especially in the preservation of extremes in precipitation data, corrections were done accordingly (Boé et al., 2007; Gudmundsson et al., 2012; Enayati et al., 2021; Holthuijzen et al., 2022). During the corrections, first, the values of the quantile-quantile relation of observed (ERA5) and modeled (CORDEX) time

series for regularly spaced quantiles using local linear least square regression were estimated. Then, quantile mapping was performed by interpolating the empirical quantiles. Such statistical transformation is generally expressed as;

$$P_o = F_o^{-1}(F_m(P_m)) \quad (3.1)$$

where P_o is the observed and P_m is the modeled variable, F_m is the cumulative distribution function (CDF) of P_m , and F_o^{-1} is the quantile function corresponding P_o . In our case, equation 3.1 was carried using the empirical CDFs of observed and modeled values instead of assuming parametric distributions. Wet days (days with precipitation equal to or more than 1 mm) were carefully considered during the precipitation data correction (Boé et al., 2007). The empirical probability of the wet days in ERA5 was found by selecting the corresponding CORDEX data as a threshold. Therefore, all values below this threshold in related CORDEX grids were set to zero in the corrected series. Corrections were carried out seasonally to preserve the seasonal characteristics of the MMEs.

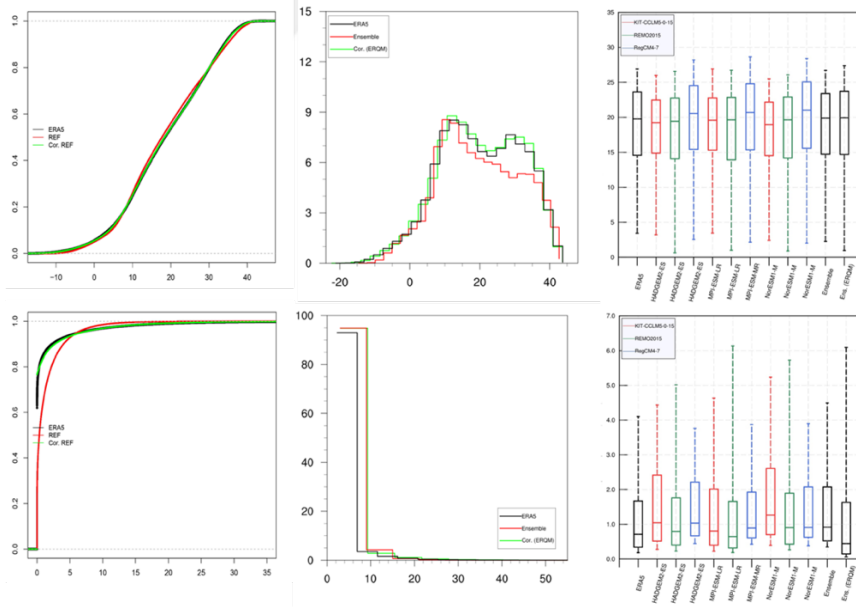


Figure 3.2 : Comparisons between ERA5, Raw, and Corrected CORDEX MMEs. a) PDF for Temperature, b) CDF for Temperature, c) Box plot for Temperature (includes MME members), d) PDF for Precipitation, e) CDF for Precipitation, f) Box plot for Precipitation (includes MME members).

For a, b, d, and e, black lines represent ERA5, red lines represent the raw form of the MME data, and green lines represent bias-corrected MMEs. The first row represents

the temperature data. Analysis regarding temperature, both the PDF and CDF graphs show that the corrected data outperform the raw form. In the temperature CDF, corrected data includes the second peak around 30°C, while the non-corrected MME fails to do so. Box plot for temperature in c showcases the performance of the corrected data to contain the lower quadrant. The second row represents the precipitation data. In both d and e, the corrected precipitation converges with ERA5 data more successfully. f represents the box plot for precipitation. The corrected data includes the upper tail of the MME members, which ensures the ERQM's performance to be adequate for the corrections of the future projections regarding especially precipitation extremes. As also can be seen in Figure A.1 and Figure A.2 differences between seasonal raw and corrected data series are remarkable. Bias corrections carried out on the meteorological parameters provide improved results especially for the grids lying within the basin borders. It should also be mentioned that for both temperature and precipitation data bias corrections cause slight increases in standard deviation but ensures better mean values in exchange (Table E.1 and Table E.2).

3.2 The Mesoscale Hydrologic Model

mHM is an open-source, physics-based hydrologic model developed by the UFZ in 2010. As a grid-based model, it has been tested in various studies for many river basins in Europe, Africa, Asia and also in Türkiye for Karasu River (Kumar et al., 2010; Samaniego et al., 2010; Pomeon et al., 2018; Busari et al., 2021). Based on the well-known hydrologic models in the literature such as Hydrologiska Byråns Vattenbalansavdelning (HBV) and Variable Infiltration Capacity (VIC), mHM simulates processes such as evapotranspiration, snow accumulation and melting, soil moisture dynamics, infiltration, and surface runoff to obtain high-resolution results (Liang et al., 1994; Hundecha and Bardossy, 2004;). mHM can operate using hourly and daily meteorological data (temperature, precipitation, potential evapotranspiration) and requires soil texture, vegetation and other geomorphological data describing the physical characteristics of the basin. As a novel feature, mHM stands out by tackling overparameterization constraints on a grid-specific basis, managing parameter overuse through a multi-scale parameter localization (MPR) technique (Samaniego et al., 2010). At its core, MPR communicates between different input resolutions and connects meteorological and geological parameters at different

resolutions during the model runs (Figure 3.3). This enables high resolution data to be transformed in various resolution ranges from sub kilometer to hundreds of kilometers.

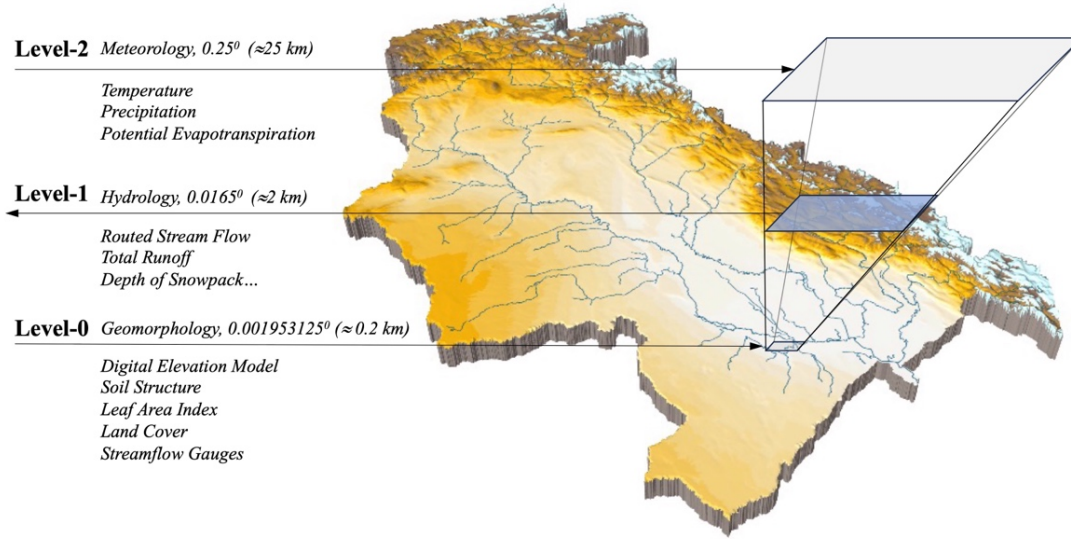


Figure 3.3 : Hierarchy of data and modeling levels in mHM demonstrated over ETB.

The levels containing the meteorological, hydrological and geomorphological parameters used in mHM simulations. As mentioned earlier, mHM handles related parameters at varying resolutions by transferring data between these three levels. Level-0 stands for the geomorphological data layer and contains parameters such as elevation, slope, soil and land use at the finest resolution among the other layers. DEM data (200 meters resolution) was used in calibrating the mHM's flow accumulation structure and was provided by UFZ.

Level-1 is the layer where the hydrologic model operates and represents the resolution level where model outputs are created. Finally, Level-2 is the meteorological layer. It governs the precipitation, temperature and potential evapotranspiration parameters to be used during the calculations. Level-0 and Level-2, which are fed to the model at different resolutions, are matched by upscaling for the upper layer (Level-2) and downscaling for the lower layer (Level-0) respectively. In addition, thanks to MPR, the processing volume during calibration is considerably reduced.

3.2.1 Model calibration and validation

To obtain hydrological projections, which accounts for the second part of this research, observational data at the streamflow gauges (SG) needed for the calibration of mHM

was requested from the State Hydraulic Works (DSİ). After finding the most continuous and coherent gauge data, seven active gauges in ETB were used in the calibration of mHM, given in Table 3.2 for the period between 2000 to 2020.

Table 3.2 : Applicable Gauges Data for Model Calibration Obtained from DSİ.

Gauge IDs	River	Gauge Names	Longitude	Latitude
D21A167	Fırat N.	Kisre C. Necmettin	26°22'12"	41°42'38"
D21A231	Fırat N.	Badisan D. Karakaya	26°34'20"	41°38'50"
D21A287	Fırat N.	Kamışlı D. Tatar	26°37'57"	41°21'50"
D26A012	Dicle N..	Basnik C. Salat	27°21'6"	41°21'3"
D26A037	Dicle N.	Zap S. Geyman Kop.	27°28'36"	41°12'8"
D26A054	Dicle N.	Kızılsu Kasrik Bogazi	26°57'27"	41°22'9"
D26A055	Dicle N.	Catak S. Dalbasti Kop.	26°19'10"	40°56'24"

Mentioned data were organized and fed to mHM as required. PET data was calculated using the Hargreaves-Samani method (HS) (Hargreaves & Samani, 1985). In the layer represented by Level-1, the resolution of the hydrological outputs to be obtained from the mHM model is specified. Level-0 indicates the resolution of the Digital Elevation Model (DEM), soil texture, root depth, Leaf Area Index, land cover, river network and location data of flow observation stations, which express the geomorphological characteristics of the study basin. Table 3.3 presents the resolution of meteorological,

Table 3.3 : Data Required by mHM.

Level-2: Meteorology, 0.25° (≈25 km)	
Temperature, Precipitation, Potential Evapotranspiration	CORDEX Africa (Copernicus Climate Change Service, Climate Data Store, 2018) and ERA5 (Sabater et al., 2019)
Level-1: Hydrology 0.0165° (≈2 km)	
Level-0 : Geomorphology 0.001953125° (≈0.2 km)	
Digital Elevation Model (DEM)	Shuttle Radar Topographic Mission (SRTM) (Far et al., 2007)
Soil Structure	SoilGrid Database (Rakovec et al., 2019)
Leaf Area Index (LAI)	MODIS MOD16A2.v061 (Running et al., 2015)
Land Cover	MODIS MOD16A2.v061(Running et al., 2015)
Streamflow Gauges (AGI)	DSİ

hydrological and geomorphological data which are fed to the model in different resolutions. The resolution of meteorological data is 0.25° (≈25 km), the resolution of hydrological outputs is 0.0165° (≈2 km) and the resolution of geomorphological data is 0.001953125° (≈0.2 km). Proceedings from the geomorphological layer to the

meteorological layer, the spatial resolution should increase by an integer factor. Since mHM treats the data layers in its structure as a grid, the resolution of the data layers is calculated as an integer factor. Thus, compliance with the operational principle of the model were fulfilled.

In the calibration phase, mHM model uses streamflow data at the gauges and matches related data with the grid system. Since ERA5 reanalysis data is used as observation data to verify model projections and bias correction in the thesis study, ERA5 reanalysis data for precipitation and temperature parameters were used as observational data in mHM calibration.

The performance of hydrological model is evaluated by numerical approaches that express the similarity between the observed and simulated flow obtained after the calibration (Gupta et al., 2009). In hydrological modeling studies, Nash-Sutcliffe efficiency coefficient (NSE) and Kling Gupta efficiency coefficient (KGE) are used to evaluate the performance of the model. Equation 3.2 shows the formula of the NSE efficiency coefficient (Nash and Sutcliffe, 1970).

$$NSE = 1 - \frac{\sum_{t=1}^T (Q_m^t - Q_g^t)^2}{\sum_{t=1}^T (Q_g^t - \bar{Q}_g)^2} \quad (3.2)$$

Where T is the total time step, Q_m^t is the modeled current at time step t, Q_g^t is the observed current at time step t, and $\bar{Q}_g$ is the observed mean flow rate. An NSE equal to 1 indicates ideal agreement between the modeled and observed current values.

The Kling-Gupta efficiency coefficient (KGE), shown in equation 3.3, is based on the NSE but has been increasingly used in recent studies as a means of measuring model performance. The calculation of the KGE efficiency coefficient is shown shown below.

$$KGE = 1 - \sqrt{(\text{cor}(Q_g, Q_m) - 1)^2 + \left(\frac{\sigma_m}{\sigma_g} - 1\right)^2 + \left(\frac{\mu_m}{\mu_g} - 1\right)^2} \quad (3.3)$$

Here, σ_g is the standard deviation of the observations, σ_m is the standard deviation of the model simulations, μ_m is the mean of the model simulations and μ_g is the mean of the observations. Similar to the NSE, KGE equal to 1 indicates ideal agreement between model simulations and observations.

In the validation phase, the best performance of the model over the basin was determined by using different combinations for seven stations, both collectively and individually. The data of Badisan and Basnik stations numbered D21A231 and D26A012, located at the headwaters of ETB, was determined as the stations with the best performance having the KGE of 0.63224 and 0.62541 and NSE 0.32346 and 0.25971 respectively. Parameter sets obtained from this calibration were used to run the future periods of the model operations.





4. CLIMATE PROJECTIONS

4.1 ERA5 Reanalysis

Results presented in this section consist of annual means for 2-meter temperature given in Celcius (°C) and annual sums for daily total precipitation in millimeters per day (mm/day) within the ETB. Basin boundaries are highlighted in bolder black lines, national borders are in light grey, and the water bodies are masked in white for visualizations (Figure 4.1). The annual zonal mean temperature for the reference period within the ETB for ERA5 is 18.8°C, where the annual zonal mean of daily total precipitation is 1 mm/day (Table B.1 & Table B.3).

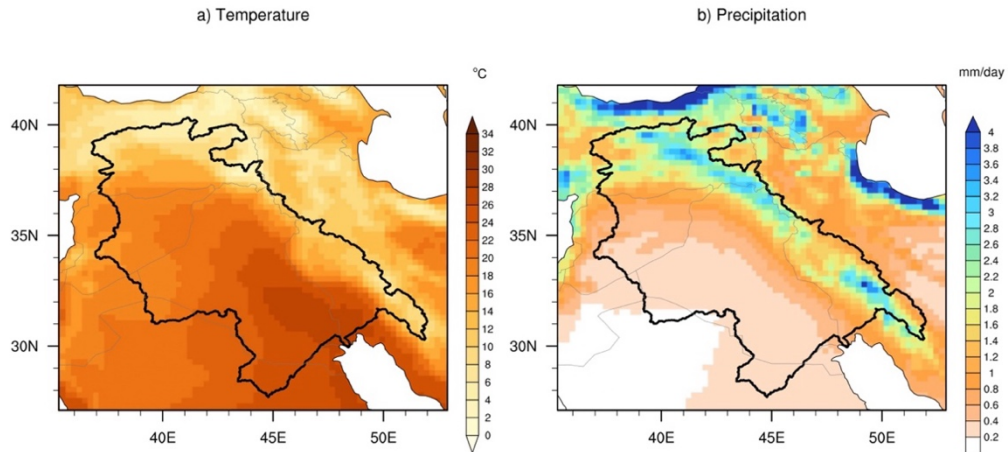


Figure 4.1 : ERA5 a) Annual Mean Temperature (°C) and b) Annual Daily Precipitation (mm/day) over ETB for the reference period (1986-2005).

Mean temperatures increase over the watercourse towards the Shatt al-Arab River, and the maximum temperature means of the basin are located near the Persian Gulf. Daily precipitation mean follows a gradient concerning the elevation. The eastern boundaries of the basin are colder and wetter, whereas the remaining areas are warmer and drier.

Seasonal investigations for temperature show similarities in this direction (Figure 4.2). Seasonal mean temperatures for DJF, MAM, JJA, and SON are 6.5°C, 17.7°C, 30.6°C, and 20.2°C, respectively.

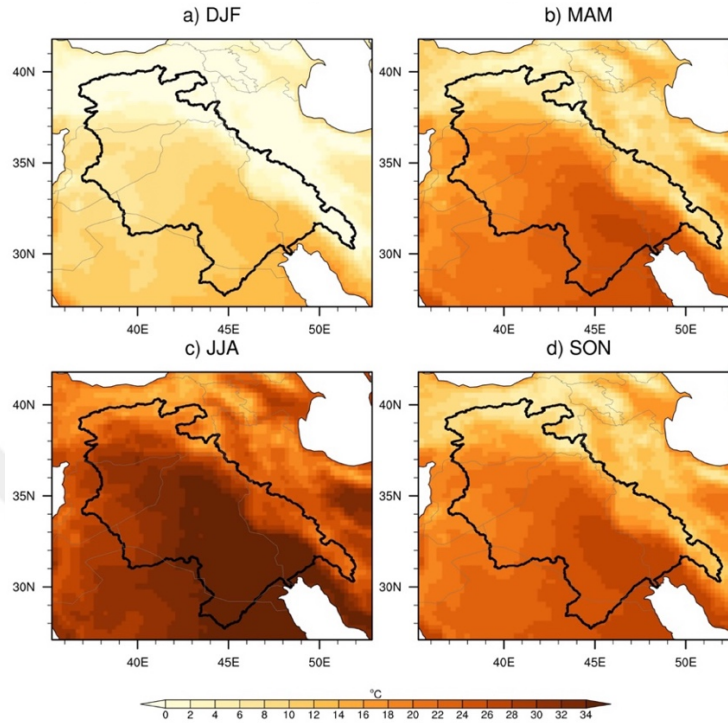


Figure 4.2 : ERA5 Seasonal Mean Temperatures over ETB (°C) during the reference period (1986-2005); a) DJF, b) MAM, c) JJA, and d) SON.

Grids with lower mean temperatures spread over the eastern Black Sea Mountains towards the Eastern Taurus Mountain ranges and extend over the Zagros Mountains, having values of -8.4°C, 1.5°C, 14.8°C and 4.9°C from DJF to SON. Grids with higher mean temperatures from DJF to SON are 14.3°C, 26.7°C, 38.8°C and 28°C as they gradually increase following the Euphrates and Tigris rivers' routes on their way to the Persian Gulf (Table B.1). Almost all Iraqi lands of the basin account for mean temperatures higher than 34°C during JJA. The coldest part of the basin during the reference period is in the southeastern corner of Türkiye, where the cities of Hakkari and Yüksekova are located on the ranges of Kavuşşahap, Cilo, and İkiyaka Mountains at elevations exceeding 3000 meters. The seasonal zonal daily precipitation (Figure 4.3) during the reference period over the ETB is 1.9 mm/day, 1.4 mm/day, 0.1 mm/day, and 0.7 mm/day for DJF, MAM, JJA, and SON, respectively. Means for maximum seasonal total precipitation are 8.4 mm/day, 5.7 mm/day, 3.5 mm/day, and 3.3

mm/day, and the minimum seasonal precipitation means are 0.3 mm/day, 0.2 mm/day, under 0.2 mm/day, and 0.2 mm/day (Table B.3).

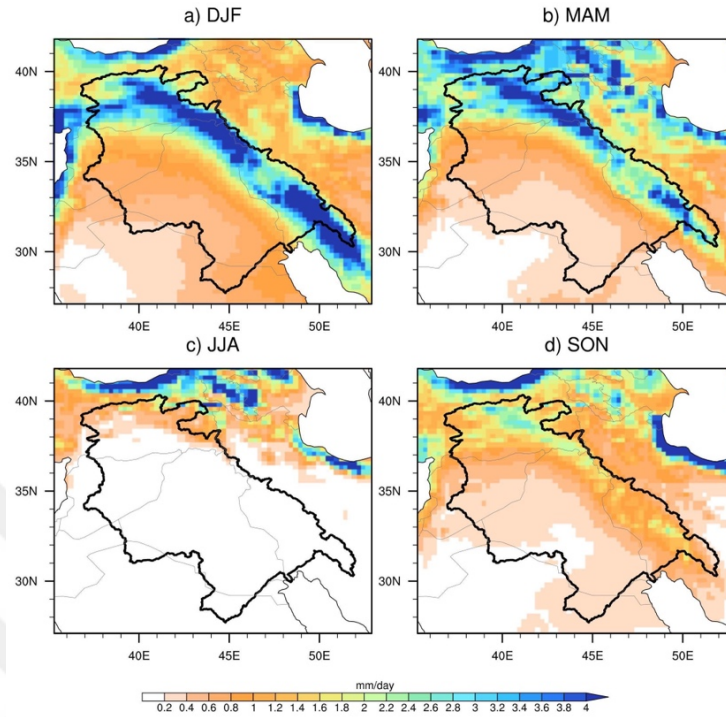


Figure 4.3 : ERA5 Seasonal Daily Precipitation over ETB (mm/day) during the reference period (1986-2005); a) DJF, b) MAM, c) JJA, and d) SON.

Mountainous areas arching the northwestern and southeastern parts of the ETB receive the highest precipitation in DJF and MAM. Upstream regions of the basin continue receiving precipitation during JJA and SON and account for higher precipitation throughout the seasons. Except for the upper Euphrates and the region where northern Iraqi and Iranian borders meet, the basin receives less than 0.2 mm/day during the JJA. During SON, lands to the southwest of Karbala remain arid. Higher precipitation values follow the topography, highlighting the mountainous areas mentioned earlier.

4.2 CORDEX-Africa Analysis

4.2.1 Reference period

Annual mean temperatures are given in Celcius ($^{\circ}\text{C}$) and the annual precipitation is given in daily totals as mm/day. Analysis and visualizations continued coherently with the previous sections. Rows in these plots represent ESMs, while columns represent RCMs. Rows follow HADGEM2-ES, MPI-ESM LR&HR, NorESM1-M in order, while columns are listed as KIT-CCLM5-0-15, REMO2015, and RegCM4-7. In

general, RCMs present similar patterns following the topography for the investigations considering temperature (Figure 4.4).

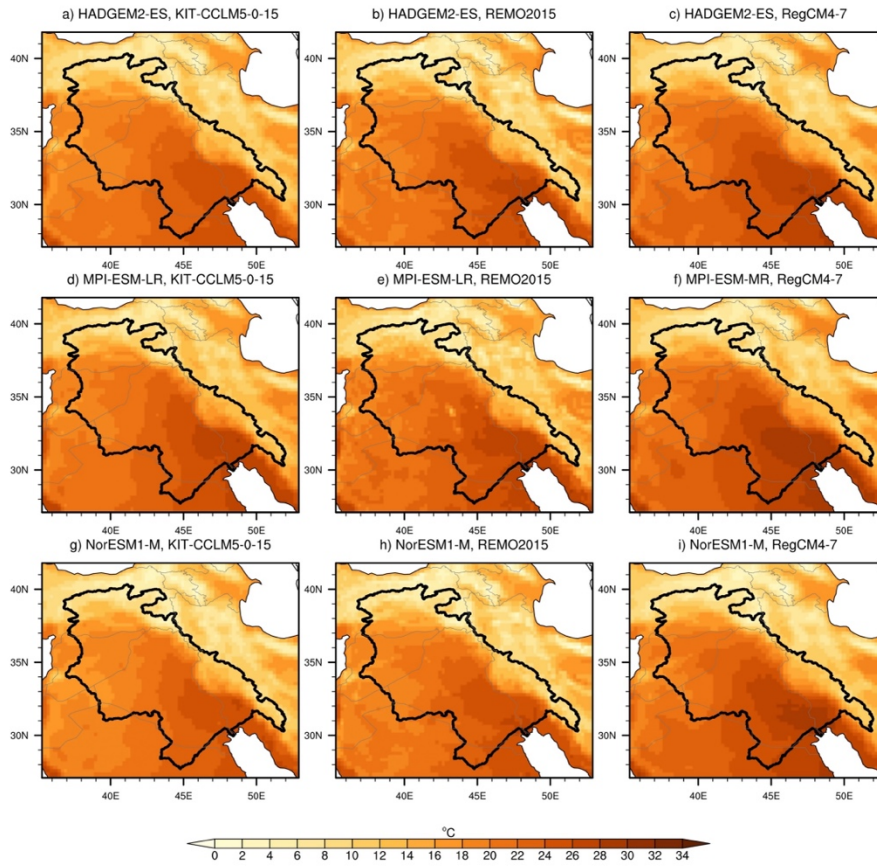


Figure 4.4 : CORDEX-Africa RCMs, Annual Mean Temperature (°C) over ETB for the reference period (1986-2005).

RegCM4-7 represents a warmer interpretation during the reference period. The annual zonal means for daily 2-meter temperature in Table B.2 shows the warmest model as NorESM1-M's RegCM4-7 (up to 0.8°C) followed by MPI-ESM-MR's and HADGEM2-ES's downscaled versions. The coldest model of the nine is KIT-CCLM5-0-15 from NorESM1-M, being 1.1°C lower than the ERA5 during the reference period. It is followed by REMO2015 from HADGEM2-ES being 0.9°C colder. NorESM1-M's RegCM4-7 and HADGEM2-ES's KIT-CCLM5-0-15 share the third rank in coldest models, both being 0.8°C less than the ERA5. MPI-ESM-LR's REMO2015 makes under estimations over Lake Thartar, Van, and Urmia. On the contrary, RegCM4-7 overestimates the region around Lake Thartar in all ESMs (Figure 4.5). KIT-CCLM5-0-15 is distinct from the other regional models over the

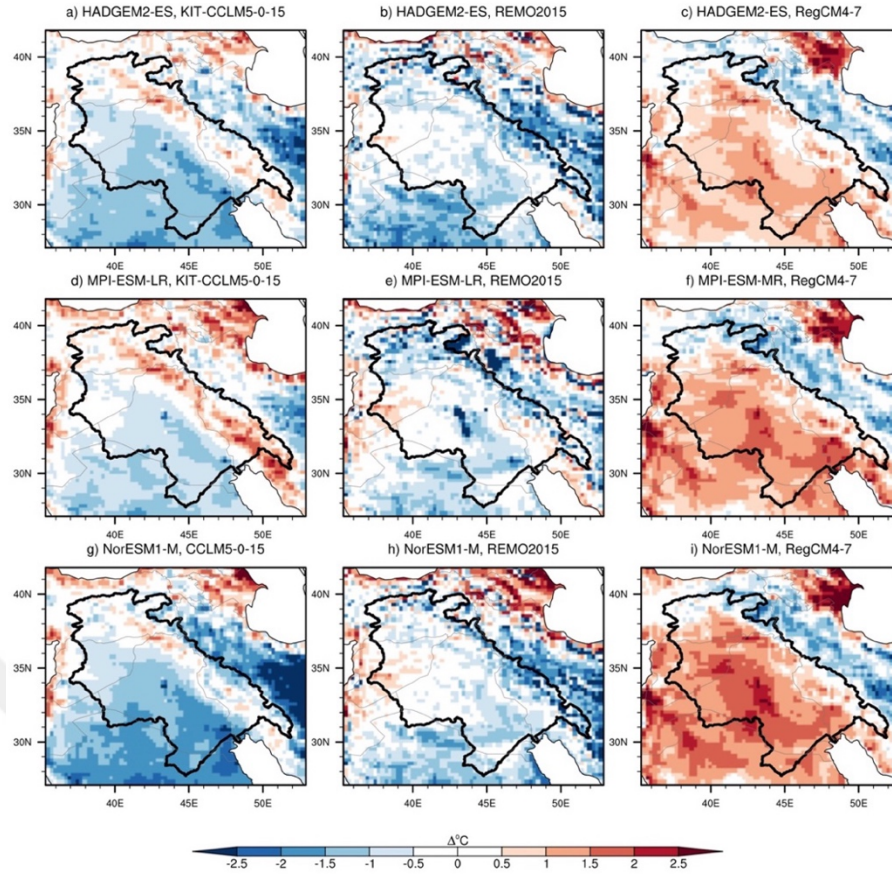


Figure 4.5 : CORDEX minus ERA5, Annual Mean Temperature Biases over ETB ($\Delta^{\circ}\text{C}$) (1986-2005).

mountainous areas. It should also be noted that, at higher altitudes, KIT-CCLM5-0-15 tends to overestimate. Visibly, KIT-CCLM5-0-15 underestimates the grids over Lake Thartar. RegCM4-7 is prone to overestimate the same grids while underestimating the Lake Van region. The highest performance over the lakes is seen in all REMO2015 versions. The coldest RCM in the investigations is CCLM5-0-15 by NorESM1-M, and the coldest ESM is NorESM1-M. Spatially, having lower bias among its peers over a larger area, REMO2015 performs better. However, it should also be noted that REMO2015 has the highest overall underestimations and biases with -0.9°C , -0.7°C , and -0.8°C downscaled from HADGEM2-ES, MPI-ESM-LR, and NorESM1-M respectively (Table B.2). The RCM with the highest bias is NorESM1-M's CCLM5-0-15, while the RCM with the lowest bias is HADGEM2-ES's RegCM4-7.

Seasonal investigations show that HADGEM2-ES's RegCM4-7 and MPI-ESM-LR's REMO2015 have a very low zonal bias during DJF (Table B.2). The highest bias belongs to KIT-CCLM5-0-15 in every case by having -1.3°C , -0.6°C , and -1.3°C for HADGEM2-ES, MPI-ESM-LR, and NorESM1-M respectively. RegCM4-7 is the only

model with overestimations during DJF; KIT-CCLM5-0-15 and REMO2015, on the other hand, tend to underestimate in this season. KIT-CCLM5-0-15 and REMO2015 make even greater underestimations during MAM, while RegCM4-7 performs the best with negligible overestimations. During JJA, RegCM4-7 has the highest bias with overestimations up to 1.9°C. The underlying physical processes of RegCM4-7 that cause the model to make warmer interpretations may be amplifying the JJA values. The RCM with the lowest biases of JJA is REMO2015, which is also the only RCM underestimating the JJA temperatures. During SON, RegCM4-7 is the lowest biased model of the RCMs, while MPI-ESM-LR & MR have the lowest biases compared with the other ESMs. It should also be noted that bias values under 0.5°C are distributed dominantly in RegCM4-7, especially in HADGEM2-ES and NorESM1-M during SON. RegCM4-7 appears to have similar grid distributions over MAM. This leads to the conclusion that RegCM4-7 is successful during SON and MAM, and seasonal shifts may be better explored.

Having the RCMs compared, with the lowest bias, RegCM4-7 performs the best despite being the only overestimating model (Table B.2). RegCM4-7 is followed by CCLM5-0-15 and finally by REMO2015, having a 0.1°C difference in underestimations. In written form, CCLM5-0-15 has underestimations in all three ESMs with values of -0.8°C, -0.4°C, and -1.1°C; REMO2015 also has underestimations in all three ESMs with -0.9°C, -0.7°C, and -0.8°C for HADGEM2-ES, MPI-ES-LR and NorESM1-M respectively. RCMs investigated in this research show peak precipitation over the mountainous areas of the basin, compared to ERA5 (Figure 4.6).

It is challenging to compare the performance of ESMs in terms of both temperature and precipitation. Panel plots in this study showcase that RCM characteristics are more dominant. Nevertheless, when both tables and figures are compared MPI-ESM tends to make warmer interpretations while NorESM is cooler. MPI-ESM is also sensitive to water bodies as well, especially when coupled with REMO2015.

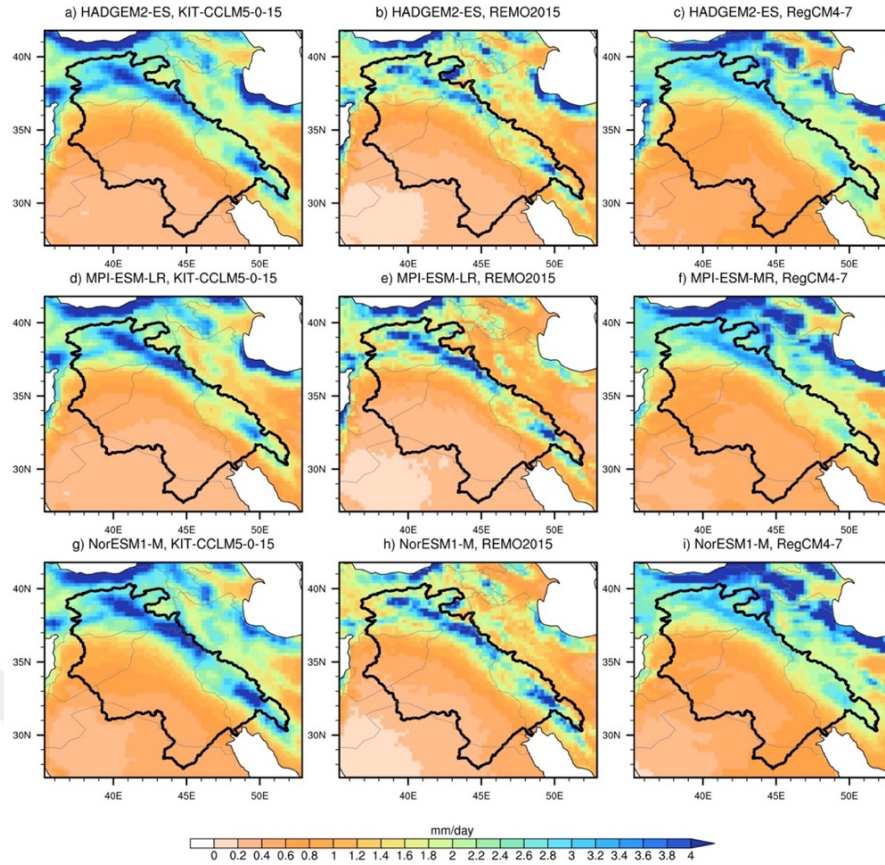


Figure 4.6 : CORDEX-Africa RCMs, Seasonal Daily Precipitation over ETB (mm/day) (REF).

Moving towards precipitation analysis, the peaks are visible over the Munzur Mountains, Kavuşşahap, Cilo, and İkiyaka ranges through the Zagros Mountains axis. These grids share similar precipitation amounts with the northeastern parts of the Black Sea Region, which hints at overestimations. The bias maps better showcase the degree of overestimations over the arid areas in Iraq's southwestern half. The performance of the RCMs is demonstrated more clearly through bias maps (Figure 4.7). Each column in the panel plots hints at the distinct uncertainties and tendencies of the models. For instance, KIT-CCLM5-0-15 tends to overestimate the upper parts of the basin. Over estimations are amplified in its NorESM1-M version. Similar to its performance in temperature hindcasting, REMO2015 spikes over the mountainous areas within the basin. Its performance over the water bodies can be further investigated concerning the overestimations over Lake Van. Compared to KIT-CCLM5-0-15, REMO2015's overestimations are more heterogenic.

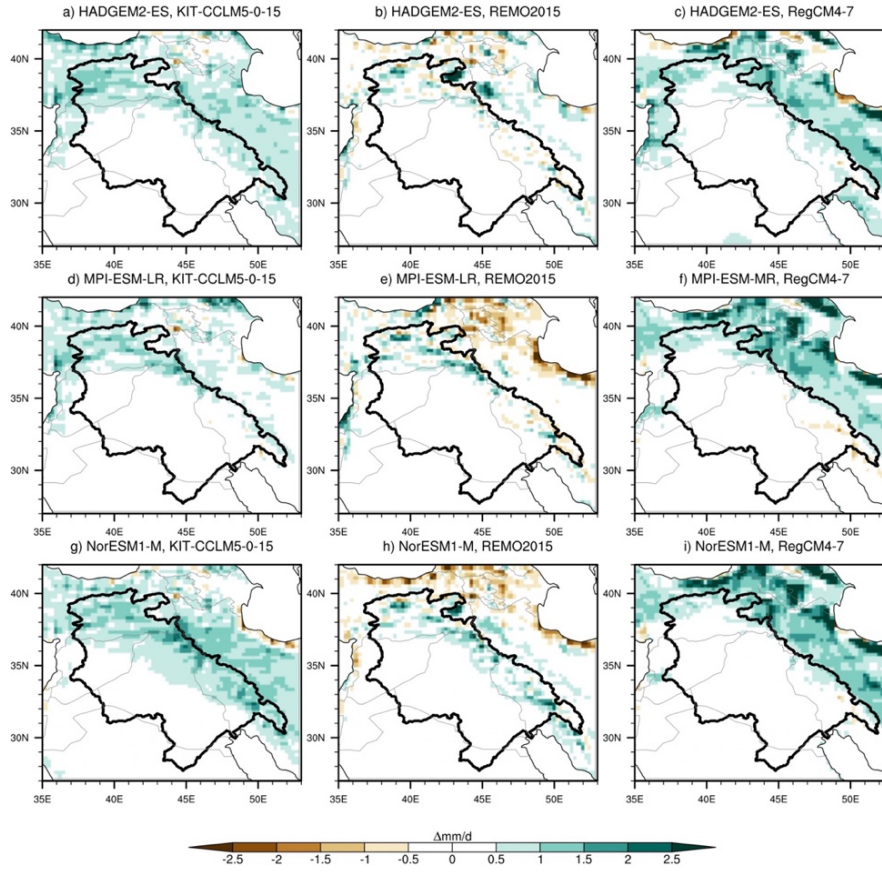


Figure 4.7 : CORDEX minus ERA5, Annual Daily Precipitation Mean Biases over ETB ($\Delta\text{mm/day}$) (REF).

When annual zonal means for daily total precipitation are investigated, REMO2015 has the closest values to ERA5 (Table B.3). However, neglecting its performance outside the basin, RegCM4-7 appears to be the best-performing RCM of the nine concerning spatial distributions within the ETB. Even though the over and under-estimations of REMO2015 cancel each other out zonally, using REMO2015's outputs in hydrological models should be done carefully.

KIT-CCLM5-0-15 is the wettest RCM among the other two (Table B.4). It overestimates 0.5mm/day, 0.3 mm/day, and 0.7mm/day in HADGEM2-ES, MPI-ESM-LR, and NorESM1-M, respectively. On the other hand, NorESM1-M is the wettest of the ESMs, while MPI-ESM-LR & MR have the lowest zonal bias in ETB. The overestimations of RegCM4-7 at high altitudes outside the basin are remarkable. More detailed research can be conducted on this issue. Seasonal variations of the RCMs show that the season with the lowest bias is JJA. DJF, SON, and MAM follow it. The season with the highest order of biases is MAM. Most of the basin, especially the Syrian and Iraqi lands, has a bias under 0.5mm/day in all RCMs (Figure 4.7).

During DJF, MPI-ESM-LR & MR demonstrate overestimations in the upper regions of the basin. All RegCM4-7 versions, especially MPI-ESM-MR and NorESM1-M, underestimate the mountainous areas of Zagros in the southeastern parts (environs of Basra and Ahvaz) of the basin. In fact, mountainous areas have biases of various orders of magnitude among all RCMs. The overestimating nature of REMO2015 over water bodies is present over Lake Van during DJF. When zonal means are investigated, RegCM4-7 of HADGEM2-ES, KIT-CCLM5-0-15 and REMO2015 of MPI-ESM-LR, and REMO2015 of NorESM1-M share the same magnitude of biases being 0.1mm/day (Table B.4). RCM with the highest bias during DJF is HADGEM2-ES's REMO2015, and the ESM with the highest magnitudes of bias is also HADGEM2-ES (Table B.4).

The RCMs included in this research overestimated MAM during the reference period. NorESM1-M's KIT-CCLM5-0-15 almost triples each RCM's magnitude of overestimation. Moreover, NorESM1-M amplifies the bias trend of each RCM during MAM. Underestimations over Ağrı Mountain are visible in nearly every RCM. Spatially, RegCM4-7 of HADGEM2-ES and MPI-ESM-MR demonstrate almost identical distributions and have an overestimation of 0.4mm/day. Even though they appear to have the lowest spatial bias during MAM, REMO2015 by MPI-ESM-LR continues to have the closest zonal mean to ERA5. JJA, the most arid season of the ETB, receives the lowest bias among models. All versions of REMO2015 zonally have the lowest biases, behaving slightly different in the upper limits of the basin around the Munzur Mountains. Similar to the MAM, KIT-CCLM5-0-15 by NorESM1-M has the highest bias with 0.6 mm/day of overestimation. Again, this is almost triple the second largest biased models, RegCM4-7 by MPI-ESM-MR and NorESM1-M, having 0.2 mm/day of overestimations (Table B.4). During SON, HADGEM2-ES stands out for its overestimations. The northwestern-southeastern axis justified to the mountainous areas within the basin is largely overestimated in HADGEM2-ES's downscaled RCMs. REMO2015 by MPI-ESM-LR has the lowest bias in this season, and it is followed by NorESM1-M's REMO2015, KIT-CCLM5-0-15 by MPI-ESM-LR and NorESM1-M respectively.

4.2.2 Future scenarios

4.2.2.1 Changes in temperature

The results for CORDEX Africa's future scenarios are analyzed through the MME data generated by nine equally weighted regional models. To obtain the highest number of regional models with continuous data, RCP2.6 and RCP8.5 scenarios were adopted (Table 3.1). Due to having developed an MME, rows of the panel plots represent seasons, while columns represent the early (2021-2040), mid-term (2051-2070), and late (2081-2099) future results regarding the 21st century. The reference period belongs to the MME results between 1986 and 2005. The results consist of the difference in the annual zonal mean 2-meter temperature given in Celcius (°C) and the difference in annual zonal sums for mean daily total precipitation in mm/day within the ETB. It should also be noted that the values of the future scenarios account for the bias-corrected values.

According to the RCP2.6 projections, temperatures rise globally during the early and mid 21st century and tend to decrease after peaking around the 2050s. Parallel to the global trend of RCP2.6, the annual zonal mean temperature over the basin shows an increase of 1.3°C during the early period and 1.5°C for the middle of the century (Table B.5). The annual mean then follows the decrease expected in RCP2.6 during the late future period, decreasing by 0.1°C up from 1.5°C, resulting in an overall increase of 1.4°C by the end of the century compared to the reference period. The highest temperature increase is expected for MAM with 1.6°C by the end of the century. DJF and JJA follow MAM at 1.5°C, and SON then follows it at 1.4°C. The highest increases expected to take place during the middle of the century are particularly evident in the Upper Euphrates and in southern parts of the basin where the Shatt al-Arab flows into the Persian Gulf (Figure 4.8). The maximums of the basin see up to 2.1°C increase in JJA during the middle of the century, while the minimums increase 1.4°C at least.

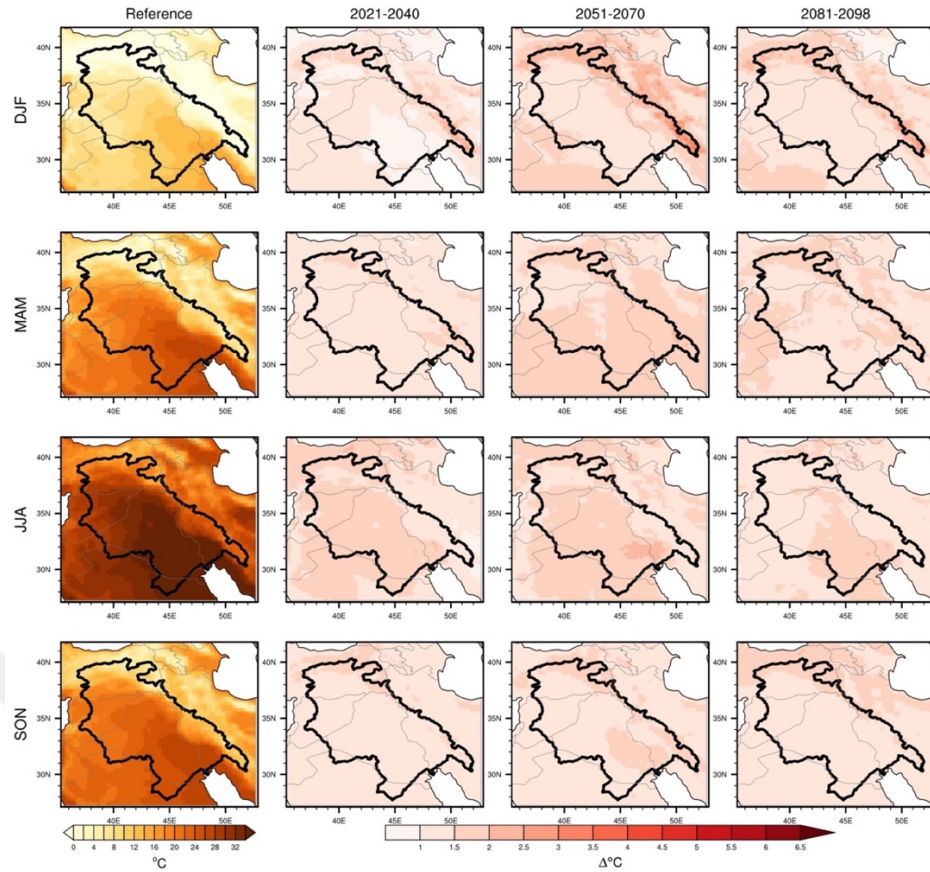


Figure 4.8 : Changes in Seasonal Mean Temperature Regarding RCP2.6 (FUT-REF, $\Delta^{\circ}\text{C}$).

Overall, as seen in Table B.5, the temperature changes in the colder grids are expected to be higher compared to the reference period, while the temperature increases in the warmer grids are milder. This may weaken the temperature gradient between the warmer and colder areas of the basin. Mountainous areas are also expected to receive increases, especially during the mid- and late-century DJF. Increases projected for DJF and MAM during the mid-century remain in the late century over the mountainous areas, especially in the northern parts of the basin.

Being the warmest scenario, RCP8.5 projects a continuous rise in temperatures throughout the century (Figure 4.9). Accordingly, ETB's mean temperatures see a zonal increase of 1.5°C , 3.5°C , and 5.7°C during early, mid, and late periods respectively. However, similar to RCP2.6's results, the grids with lower temperatures are expected to increase more than those with higher temperatures, weakening the gradient between colder and warmer grids. This is likely to cause an increase in relative humidity and evapotranspiration. During DJF, annual zonal mean temperatures increase by 1.2°C , 3.2°C , and 4.8°C .

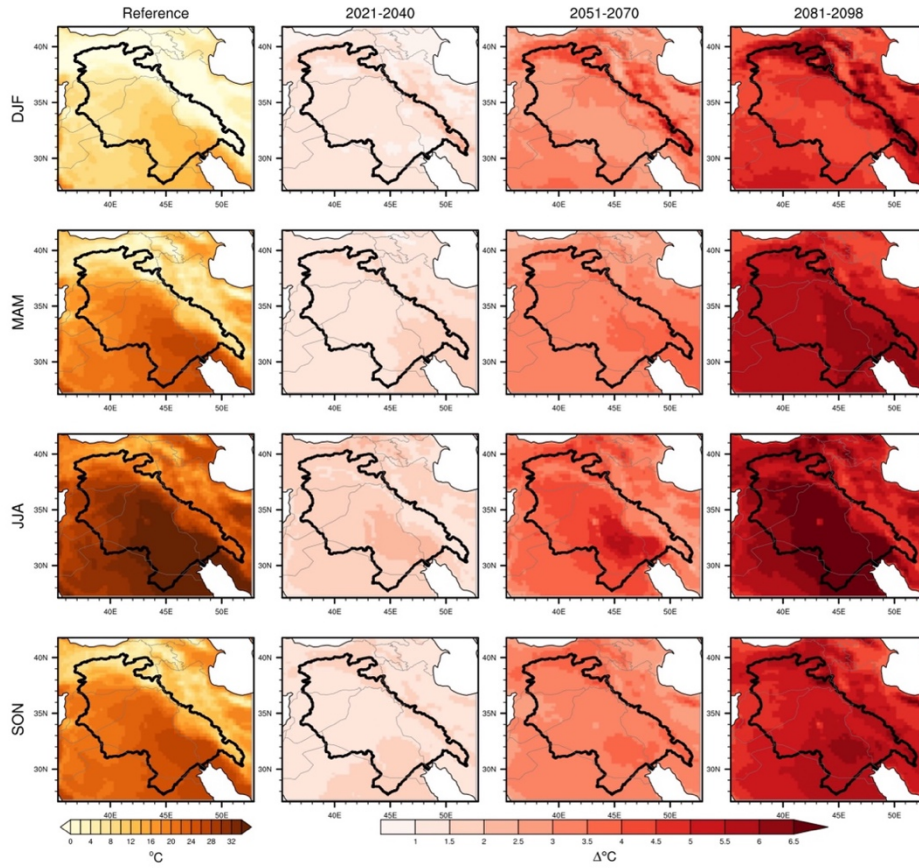


Figure 4.9 : Changes in Seasonal Mean Temperature Regarding RCP8.5 (FUT-REF, $\Delta^{\circ}\text{C}$).

MAM temperatures increase 1.5°C , 3.4°C , and 5.9°C , JJA 1.9°C , 4.2°C and 6.8°C and SON temperatures follow this trend with 1.5°C , 3.4°C and 5.5°C increases. It should be noted that during the early periods of the century, temperature increases are quite close to RCP2.6's values (Table B.5). However, temperatures of the RCP8.5 differentiate from the beginning of the 2050s, increasing almost twice the RCP2.6 (Figure 4.9). The distinct temperature increases between Lake Thartar and Shatt al-Arab stand out during the MAM, JJA, and SON in almost all periods of the future projections. Increases extend to southern Türkiye, northeastern Syria, and almost the entire Iraq during the late century's JJA, passing over 6°C . Northern and eastern parts of the basin with higher elevations are likely to see more increases than the rest of the ETB during DJF throughout the century. The warming lag due to latent heat over Lake Thartar is visible during MAM, JJA, and SON after 2050. The fact that we are witnessing this from the MME data shows that the members share the same meteorological interpretations of the climate.

4.2.2.2 Changes in precipitation

Considering the annual daily precipitation of the ETB (1 mm/day) and RCP2.6 being the best-case scenario, the precipitation decrease in mountainous areas is dominant during DJF and MAM. Mainly during MAMs throughout the century, the northern parts of the ETB receive a decline in precipitation greater than 0.5mm/day (Table B.6). This decline spreads over almost every season, especially during the early stages of the 21st century. The amount of precipitation increases over the Taurus Mountains and Munzur Mountain during DJF in the mid-century. However, the MME also shows a decline over the same region during the early and late periods (Figure 4.10). Changes in areas outside the basin are also remarkable for DJF. Eastern Mediterranean shores see a decline in precipitation, according to RCP2.6. On the contrary, the Eastern Black Sea region sees increased precipitation at magnitudes greater than 0.5 mm/day for both DJF and MAM for the entire century. Also, early and late century periods forecast a 0.1mm/day decrease as can be seen in Table B.6.

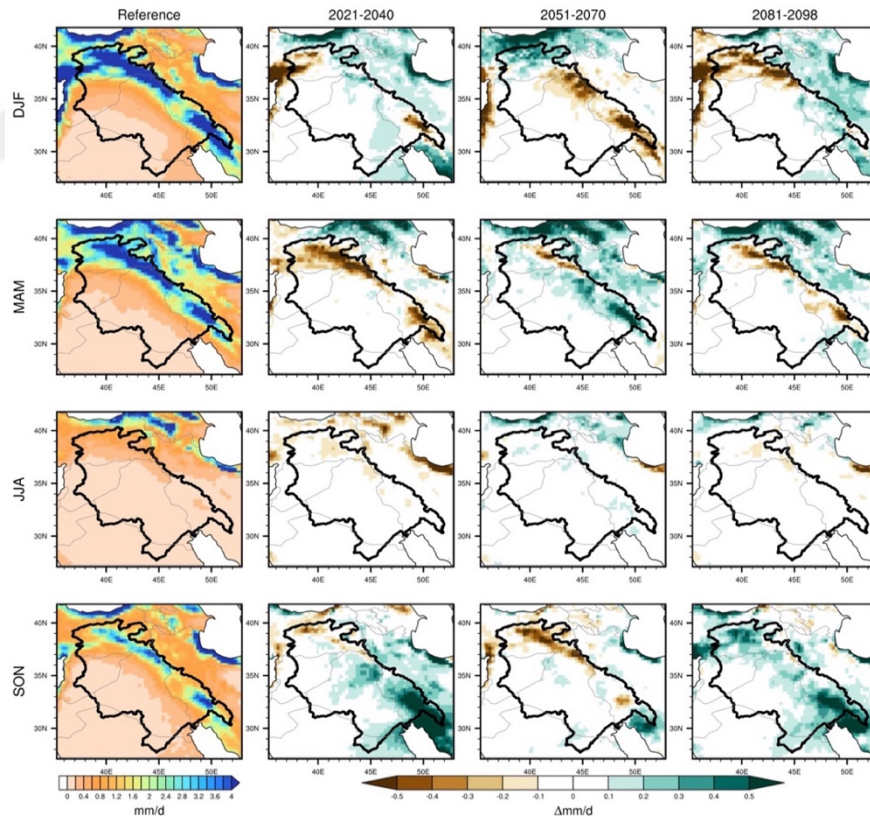


Figure 4.10 : Changes in Seasonal Daily Precipitation Mean Regarding RCP2.6 (FUT-REF, $\Delta\text{mm/day}$).

The mid-century for JJA, however, shows almost no changes in precipitation values. On the other hand, northeastern parts of the basin face slight decreases between 0.1 and 0.2mm/day during the early stages of the century. During SON, especially for the early and late periods within the century, the southeastern parts of the basin (where cities of Basra and Ahvaz are located), where the southern parts of Zagros Mountains rise, the RCP2.6 scenario projects precipitations greater than 0.5mm/day. It should also be mentioned that the scenario shows a decline ranging between 0.1mm/day to 0.5mm/day in the northern parts of the basin during the mid-21st century (Figure 4.10).

RCP8.5 scenario delivers more extreme results. The mountainous arch reaching the northern to eastern boundaries of the basin hosts significant changes except the JJA season. For the DJF, changes mentioned in RCP2.6 increase their magnitude. The decline in precipitation over the Taurus and Munzur Mountains extends its coverage to the ranges of Kavuşşahap, Cilo, and İkiyaka. Western Taurus Mountains see a similar decline in precipitations exceeding 0.5mm/day (Figure 4.11).

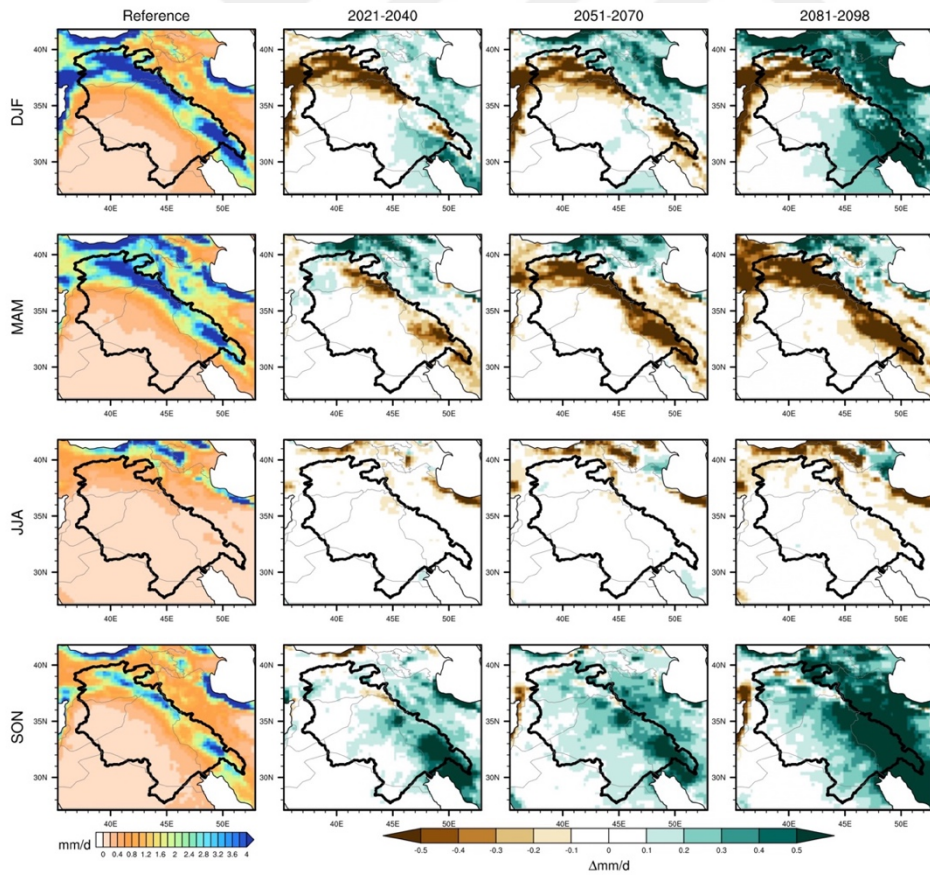


Figure 4.11 : Changes in Seasonal Daily Precipitation Mean Regarding RCP8.5 (FUT-REF, Δ mm/day).

During the DJFs throughout the century, the decrease in the Eastern Mediterranean shores became even steeper, moving inland. On the other hand, except for the mid-century projections, the basin's south to southeastern lands are likely to receive more precipitation. Especially during the late century, the precipitation increase reaches 0.5mm/day to the east of Shatt al-Arab, near the environs of Basra and Ahvaz. The northern parts of the ETB, together with the Eastern Black Sea Region, gradually exceed the 0.5 mm/day of precipitation increase. During MAM, the decline in precipitation over the eastern ETB intensifies and spreads to central Anatolia throughout the century. Except for the northern borders of Iraq, The Syrian and Iraqi lands see almost no changes during the early, mid, and late century phases. Similarly, during JJA, the ETB's annual zonal total precipitation mean decrease by 0.1mm/day. The majority of the lands lying within the boundaries of ETB remain the same precipitation values with the reference period, however, some grids are facing slight decreases around 0.1 mm/day. Along the SON, the southern ranges of Zagros Mountains become wetter, seeing increases ranging from 0.1 mm/day to 0.5mm/day and exceeding these values as the end of the century approaches. It should also be noted that there is a decline on the Eastern Mediterranean shores intensifying from the early to late century.

When the annual zonal total precipitation means for ETB are investigated, besides the local changes ranging between 0.5mm/day declines to 0.5mm/day increases, the ETB is likely to see no changes in precipitation until the 2070s. The mean difference in the annual zonal total precipitation increases by 0.1mm/day at the beginning of the late century. The early century of the ETB brings a decrease of 0.1mm/day and an increase of 0.2mm/day for JJA and SON consecutively. The mid-century seasons see a decline for the DJF with 0.1mm/day, the MAM with 0.2mm/day, and the JJA with 0.1mm/day, while during the SON, zonal means increase by 0.2mm/day. In the late century, the mean precipitation of the ETB increases by 0.1mm/day during DJF. MAM and JJA, on the other hand, receive 0.3mm/day and 0.1mm/day decreases, but SON sees a spiking 0.4mm/day increase primarily because of the increase presented over the southern ranges of the Zagros Mountains.



5. HYDROLOGICAL MODEL (mHM) OUTPUTS

Results presented in this section consist of changes in routed streamflow, total runoff and the depth of snowpack. These results are given in order following RCP2.6 and RCP8.5 scenarios. For changes in routed streamflow, values under 30 m³/s were masked to showcase the percentage changes in main river branches and complimentary tributaries exceeding that value. For total runoff maps changes over 50 m³/s were considered. For the maps presenting the changes in depth of snowpack values above 50 mm were showcased.

5.1 Changes in Routed Streamflow

Maps presenting the changes in routed streamflow consist of the reference period and the future periods determined before for the early, mid and late century. Reference map showcases the magnitude of routed streamflow especially on the main branches and how the streamflow accumulates while reaching the ETB's estuary to the Persian Gulf (Figure 5.1).

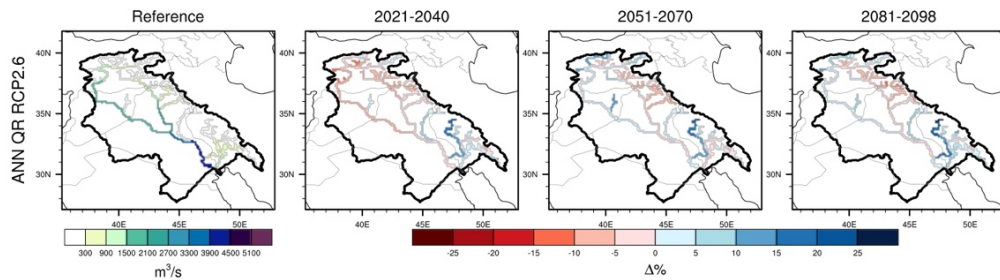


Figure 5.1 : Changes in Routed Streamflow Regarding RCP2.6 (FUT-REF, Δ%).

Discharge rates under 2700 m³/s are seen before the confluence of ER and TR. The confluence at the Shatt al-Arab is shifted northwards which needs further investigation. One of the reasons behind this shift may result from the model's

decision-making regarding the flow accumulation and DEM provided for the model. The other reason may also result from the proximity between the grids of ER and TR where model may have decided to connect these two major rivers before the confluence point. On the other hand, model's ability to capture the flow accumulation over the basin in overall is highly detailed and well proportioned. After the Shatt al-Arab confluence routed streamflow reaches almost 5500 m³/s at firth near Persian Gulf being consistent with the observations provided by GRDC (Table C.1).

When changes with respect to this study's investigation periods are analyzed, up to 5% decreases can be seen in the early period for both rivers along the river courses. Increases up to 20% is striking in the southeast portion of the basin which is likely to be related with the increase in precipitation discussed in the climate investigations. 5% decrease over the main branches of ER and TR in the early period, changes in to increases up to 10% during the mid and late century. Decreases up to 10% is distinct along the TR course in all periods. Up to 15% increases can also be seen in mid and late century periods over ER where Tuzla Creek meets Karasu River near Şenyurt, Erzurum. Same increase can also be seen within the grids near Mount Ala near Diyaradin, Ağrı where Murat River originates (Figure 5.2).

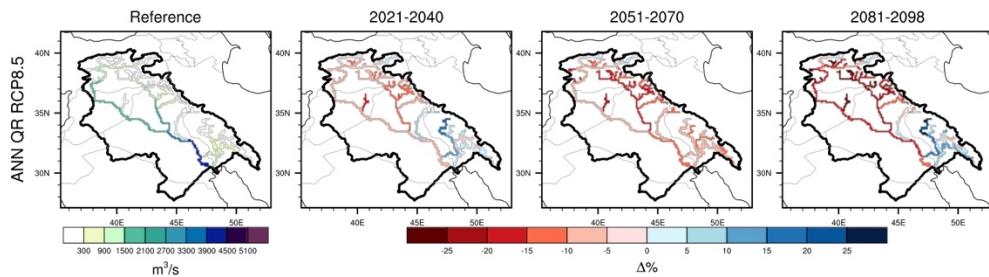


Figure 5.2 : Changes in Routed Streamflow Regarding RCP8.5 (FUT-REF, Δ%).

Changes regarding the RCP8.5 are more striking as expected. A distinct, gradual decrease can be seen among the investigation periods over both rivers. Starting with decreases up to 10%, RCP8.5 showcases drastic decreases for ER and TR, amounts exceeding 25% in the late century. Southeastern part of the basin stands out with the increasing flow rates during the early and late century. Up to 20% increase in early century and up to 25% increase in the late century can be seen in the river network near Ahvaz. Changes in Al Khabour River is remarkable in both scenarios among all periods. This tributary of ER sees increases ranging between 10-15% regarding

RCP2.6, where decreases ranging between 15 to 25% (approximately up to 750 m³/s, shown in Table C.2) can be seen according to RCP8.5.

Over the three future projection periods, streamflow rates within ETB during DJF increases up to 35% regarding RCP2.6 (Figure D.1) and over 35% regarding RCP8.5 (Figure D.4) especially in the upper parts of the basin. The surplus in the water budget over the southeastern ETB is more prominent during DJF and SON. On the other hand, decreases up to 35% regarding RCP2.6 (Figure D.1) and exceeding 35% regarding RCP8.5 (Figure D.4) are evident during MAM which hints at the snowmelt shift especially in the upper parts of the basin. In the upcoming sections, this conclusion will also be supported with complimentary model outputs.

5.2 Changes in Total Surface Runoff

Changes in total runoff are given in mm. White areas on the maps represent the grids with changes under 50 mm. The reference period presents the annual mean of the total runoff within ETB. Areas with higher elevations see higher amounts of total runoff. The diagonal axis leaning on the eastern borders of the basin has the highest elevations as discussed before. Regarding RCP2.6, decreases between 50 to 150 mms are located over Türkiye especially extending between the Palandöken, Cilo, and İkiyaka mountain ranges (Figure 5.3).

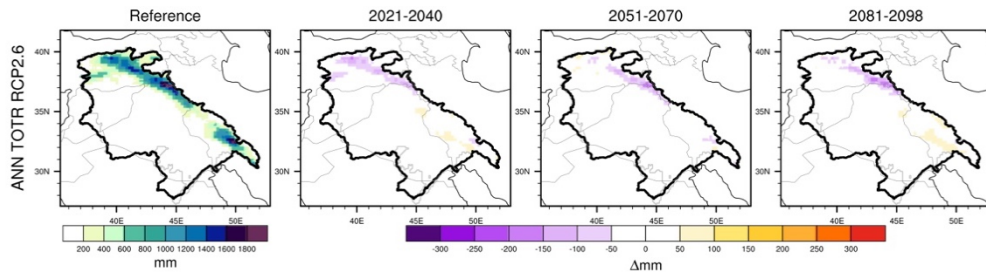


Figure 5.3 : Changes in Total Runoff Regarding RCP2.6 (FUT-REF, Δmm).

The spread of the decreases over the northern parts of the basin diminishes by the mid-century, however decreases mentioned earlier for the upper parts of the basin is likely to remain over the environs of Yüksekova where elevations exceed 3000 meters (Table C.3). The surplus in the water budget of the southeastern part of the basin is also visible in the total runoff maps with increasing values ranging between 50 to 100 millimeters

regarding RCP2.6. Mountainous areas located on the northern parts of the basin are likely to recover their runoff deficit as the 21st century proceeds.

RCP8.5 brings amplified results regarding the increasing temperatures (Figure 5.4). One of the explanations to the striking decreases in the total runoff maps of RCP8.5 can be made considering the disappearance of the snow cover which will be demonstrated in next section. Even in the earliest period of the century, areas with high elevations see drastic decreases reaching up to 200 millimeters (Table C.4). Northeastern parts of the basin see gradual but logarithmic increases by the end of the century. In the late century period decreases with over 300 millimeters spread almost the entire northern part of the basin. However, the distinct surplus of the southeastern ETB sees total runoff increases ranging between 50 to 200 millimeters regarding RCP8.5.

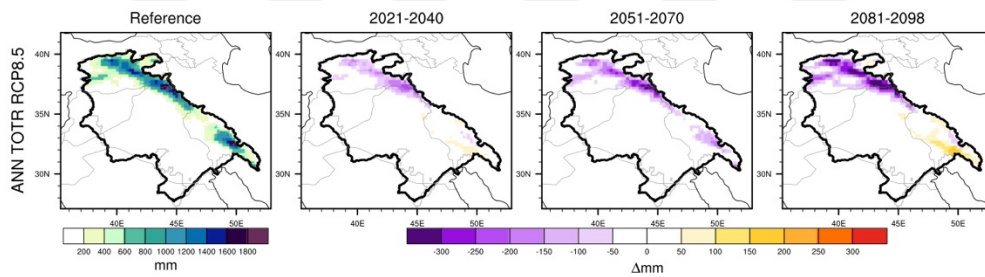


Figure 5.4 : Changes in Total Runoff Regarding RCP8.5 (FUT-REF, Δmm).

Even though the best-case scenario (RCP2.6) may portrair a recovering trend towards surface runoff by the end of the century, seasonal plots for this parameter also showcase the changing timings of snowmelt. Increases over the upper ETB up to 320 mm during DJF are seen sparsely over the maps regarding RCP2.6 (Figure D.2). However, the deficit in surface runoff ranging between 20 to 320 millimeters during MAM is distinct during all three future projection periods. Inherently, RCP8.5 produces exaggerated changes in terms of surface runoff during DJF and MAM. However, these inflated values offer the opportunity to better compare these two seasons, at what extends the seasonal shift may occur. Increases exceeding 320 mm during DJF are seen over the upper ETB by the end of the century. Peak values are mostly seen over the mountain tops, as the runoff values increase directly proportionate to the elevation. In addition to the mountainous upper ETB, gradually increasing surface runoff (starting from 20 millimeters in the early century to values exceeding 320 millimeters by the late century) over the projection periods is

pronounced over Mount Dena as well (Figure D.5). During the future MAMs, almost the entire eastern boundaries of the basin see decreases exceeding 160 and 320 millimeters. Changes seen in surface runoff values during DJF and MAM also support the seasonal shift in snowmelt.

5.3 Changes in Depth of Snowpack

Similar to the distributions seen in annual total runoff figures, changes in snow cover are spread over the eastern borders of ETB. Reference map (on the left) shows the mean depth of annual snowpack. Accordingly, the remaining maps show changes in the mean depth of annual snowpack. Lying on a diagonal axis from northwest to southeast, the thickest snow cover of the basin is located over the northeastern parts of the basin where Otlukbeli, Kop and Palandöken Mountain ranges are located. Maximum values in snowpack depth are seen over the environs of Yüksekova where the elevation generally exceeds 3000 meters. Mount Dena, where the highest peak of Zagros Mountains is located, also stands out in the reference period with values lying in the higher end of the snowpack depth (Figure 5.5)

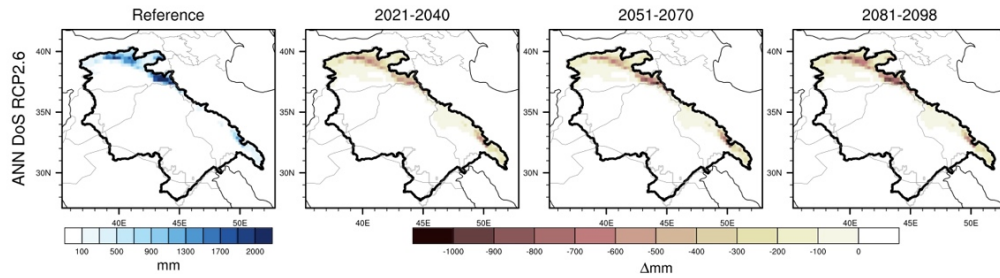


Figure 5. 5 : Changes in Depth of Snowpack Regarding RCP2.6 (FUT-REF, Δmm).

Changes according to the RCP2.6 are seen over the diagonal axis from the upper parts of the basin and extending to the Zagros Mountains ranges. Over this axis, the depth of snowpack is predicted to decrease between 100 to 800 millimeters. Northernmost parts of the basin see higher decreases especially by the end of the century. Otlukbeli, Kop, Palandöken and Hakkari Mountain ranges are likely to see the biggest decreases ranging between 600 to 1000 millimeters. Change over Mount Dena is seen in the higher end of the scale with decreases up to 700 millimeters (Table C.5).

RCP8.5 presents heightened levels of loss in snowpack depth. A gradual decrease throughout the century affects almost the entire basin areas with elevations higher than

1500 meters (Figure 5.6). During the early period of the century, hotspots that stand out in almost every parameter investigated, remain their significance in terms of change in the depth of snowpack. The decrease over the mountains of Türkiye within the ETB is drastic. The amount of decrease in snowpack depth becomes striking especially after the mid-century and surpasses 1000 millimeters by the end of the century (Table C.6).

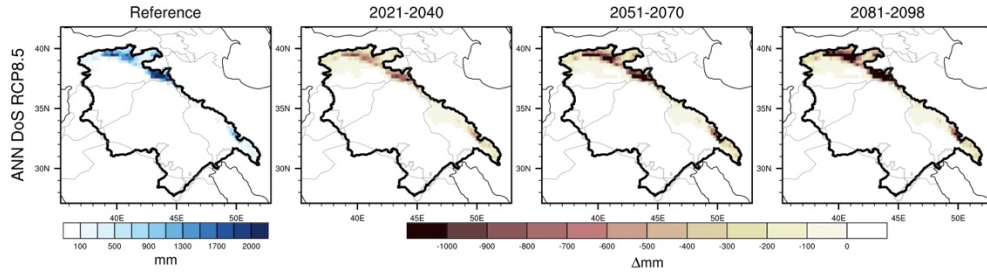


Figure 5.6 : Changes in Depth of Snowpack Regarding RCP8.5 (FUT-REF, Δmm).

Seasonal changes in depth of snowpack are more pronounced over the upper ETB among two scenarios. Regarding RCP2.6, decreases ranging between 200 to 400 millimeters are seen in the future DJFs while even heightened decreases are seen during MAMs with values ranging between 400 to 800 millimeters (Figure D.3). Decreases up to 200 millimeters are also seen during future SON periods. RCP8.5 showcases higher amounts of loses in the snowpack with values increasing from 200 to 400 millimeters to 800 to 1000 during DJF. MAM also sees snowpack decreases that gradually increase from 200 to 1000 millimeters moving from early to late century. During the late century MAMs, extreme decreases are seen over Yüksekova (Figure D.6).

6. CONCLUSIONS AND RECOMMENDATIONS

The comprehensive analysis of the CORDEX-Africa RCMs and related RCP scenarios presented in this study provides a nuanced understanding of past and future climate dynamics within the ETB, unraveling intricate patterns of temperature and precipitation variability that have critical implications for multi-model regional climate studies. The outcomes of this research are also coherent with the previous studies in the literature concerning the preceding climate scenarios and models. It is important to notice that some of these studies focus on ETB's climate in particular while some of them have broader study areas. For this reason, with the addition of this research to the literature, we can assume that the uncertainties in the climate projections are diminishing for the course of ETB's climate as it was investigated even more thoroughly and in higher resolution during this study.

Beginning with the examination of historical climate data from the ERA5 dataset, the reference period annual mean temperature and daily total precipitation for the ETB are 18.8°C and 1 mm/day, respectively. Temperature distributions show an increase from the upper parts of the ETB towards the Shatt al-Arab estuary at the Persian Gulf. The lower temperatures of the basin are seen over the eastern Black Sea Mountains towards the eastern Taurus Mountains and extend over the Zagros Mountains. Most Iraqi lands of the basin account for mean temperatures reaching over 34°C during JJA between 1986 and 2005. The coldest part of the basin within the reference period is located on the ranges of Kavuṣṣahap, Cilo, and İkiyaka mountains at some 3000 meters. The mountainous areas arching the ETB's northwestern and southeastern parts receive the highest precipitation (up to 8.4 mm/day), especially in DJF and MAM (Table B.5). Upper parts of the basin continue to receive precipitation during JJA and SON, accounting for comparatively higher precipitations throughout the remaining seasons.

Analysis of the RCMs over the reference period shows similar spatial distributions in terms of elevation and latitudinal gradients. However, the examination of the bias maps reveals significant differences (Figure 4.5 and Figure 4.7). Seasonal bias maps and tables for the RCMs within the reference period further exhibit these differences. For the reference period, with an average of 0.6°C warmer than the rest, the warmest RCM is the RegCM4-7 among its peers. The coldest interpretation of the reference period comes from KIT-CCLM5-0-15 by NorESM1-M, being 1.1°C colder than the ERA5's zonal mean. The influence of water bodies (like Lake Thartar, Van, and Urmia) on temperatures showcases diverse interpretations of the RCMs. For instance, REMO2015, downscaled from MPI-ESM-LR, underestimates the temperatures over water bodies, while RegCM4-7 tends to overestimate these grids in all versions. The RCM with the highest bias is NorESM1-M's CCLM5-0-15 (with a colder characteristic), while the RCM with the lowest bias is HADGEM2-ES's RegCM4-7 (with a warmer characteristic). However, for the reference JJA, RegCM4-7 has the highest bias with overestimations up to 1.9°C.

Peak precipitations are seen over the mountainous areas within the basin, detectable over the Munzur, Kavuşşahap, Cilo, and İkiyaka Mountain ranges extending through the Zagros Mountains. Accounting almost the same precipitation amounts with the eastern Black Sea Region, our investigation showcases the magnitude of overestimations of the RCMs within ETB concerning precipitation and the necessity for a bias correction to interpret their future projections. The bias maps further display the degree of overestimations over the arid areas in Iraq's southwestern half. Disregarding its remarkably overestimating performance outside the basin, RegCM4-7 appears to be the best-performing RCM concerning spatial distributions within the ETB. Even though REMO2015 presents low zonal biases, the model's over and underestimating nature should be approached carefully, especially for hydrological modeling studies. KIT-CCLM5-0-15 is the wettest RCM, and NorESM1-M is the wettest ESM during the reference period. On the contrary, every RCM underestimates precipitation over the southern Zagros Mountains up to 2.5 mm/day during DJF. RCM with the highest underestimations in precipitation during DJF is HADGEM2-ES' REMO2015. In addition, HADGEM2-ES is the most underestimating ESM of the three regarding precipitations for the DJF season. RCMs overestimate the precipitations of the MAM during the reference period. In fact, KIT-CCLM5-0-15 by

NorESM1-M nearly triples each RCM in terms of overestimation. This may primarily be because of the performance of NorESM1-M in modeling the precipitation, amplifying the bias trend of each RCM even during the JJA, where the majority of the basin receives almost no precipitation at all. There are remarkable overestimations in HADGEM2-ES during SON. The mountainous areas within the basin are vastly overestimated in each RCM downscaled from the HADGEM2-ES. REMO2015 by MPI-ESM-LR has the lowest bias during same season.

The results for CORDEX Africa's future scenarios (RCP2.6 and RCP8.5) were analyzed through a bias-corrected MME obtained from nine equally weighted RCMs. RCP2.6 projections for ETB showcase a parallel behavior to the global trends for this scenario. The annual zonal mean temperature over ETB increases by 1.3°C during the early period (2021-2040) and 1.5°C for the middle of the century (2051-2070). The increase by the end of the century (2081-2098) is expected to be 1.4°C overall compared to the reference period. Research including RCP2.6 outputs support the decreases in temperature in the environs of ETB after the mid-century (Salman et. 2018). The highest temperature increase is expected in JJA with 1.6°C during the middle of the century. This increase is expected to occur around the Shatt-al-Arab watercourse and its Persian Gulf estuary.

Regarding RCP8.5, ETB's annual zonal mean temperature increases by 1.5°C in the early period, 3.5°C for the mid-century period, and 5.7°C for the late century. These results align with the previous studies in the literature conducted via various RCMs and corresponding scenarios (Bozkurt and Şen, 2013; Önoğlu et al., 2014; Waha et al., 2017; Adamo et al., 2018, Salman et al., 2018). Like the RCP2.6 projections, grids with lower temperatures within the basin are expected to increase more than those with higher temperatures. This may lead to a decrease in relative humidity and an increase in evapotranspiration, affecting the region's water budget, which is highly influenced by agriculture and expanding irrigation areas. During the early periods of the century, the temperature increases regarding RCP2.6 and RCP8.5 are pretty similar. However, the increase in RCP8.5 by the mid-century almost doubles the increase seen in RCP2.6 during the same period.

Precipitation over the mountainous areas faces decreases during DJF and MAM concerning RCP2.6. The northeastern parts of the ETB receive more than 0.5mm/day decline during the MAM throughout the century. This decline dominates almost all of

the Turkish lands of the basin, especially during the early period of the century. However, the decline in precipitation is permanent over the ranges of Kavuşşahap, Cilo, and İkiyaka Mountains at elevations exceeding 3000 meters. The consequences of this decline may be further investigated through the region's water budget and ETB's discharge levels as most of the ETB is highly dependent on the snow water availability on the highlands of the basin. In accordance with the available literature annual (zonal) daily total precipitation over ETB is highly likely to remain almost the same in both scenarios ($\pm 0.1\text{mm/day}$) (Giorgetta et al., 2013; Bozkurt and Şen, 2013). RCP8.5 delivers more amplified results concerning precipitation distributions during DJF and MAM. The upper parts of ETB see declines exceeding 0.5mm/day for both seasons. The decline during MAM spreads almost the entire mountainous areas of the basin until the end of the century. However, it should also be noted that, RCP8.5 results of our MME projects an increase in precipitation exceeding 0.5mm/day for the DJF and SON over the environs of Basra and Ahvaz (Figure 4.11). Similar increases were mentioned priorly in the investigation of ECHAM5, HadCM3, and CCSM3 concerning corresponding scenarios with the SRES framework (Önol et al., 2014).

Results created by the mHM align with the changes seen in MME outputs. The model reflections seen in the reference period routed streamflow, in other words river discharge, are under $2700\text{ m}^3/\text{s}$ before the confluence of ER and TR at the Shatt al-Arab. However, after the confluence of these two major rivers the discharge level surpasses $6000\text{ m}^3/\text{s}$ being consistent with the GRDC data. Regarding the RCP2.6's early period, up to 5% decrease is expected for both rivers. Up to a 20% increase may be seen in the southeastern portion of the basin which is related with the increasing precipitation over the Zagros Mountains. Up to 10% decrease over the TR course are seen among all periods. Up to 15% increases are also seen during the mid and late century periods over the upstream of ER where Karasu River originates. Similarly, the second origin of the ER, Murat River, sees around 15% increases by the end of the century.

RCP8.5 showcases amplified results for both ER and TR with decreases exceeding 25% in terms of discharge levels for the late century. The southeastern part of the basin stood out with increasing flow rates especially during the early and the late periods. Increases ranging between 20% to 25% can be seen in the river network over the environs of Ahvaz, where Mount Dena is also located. Additionally, changes in the Al

Khabour River, a tributary of ER, is also remarkable as the river sees increases ranging between 10 to 15% regarding RCP2.6 and decreases ranging between 15 to 25% regarding RCP8.5.

In terms of total runoff changes regarding RCP2.6, decreases between 50 to 150 millimeters are dispersed over Türkiye, extending from Palandöken and Cilo to İkiyaka Mountain ranges. Even though these decreases diminish by the mid-century in general, the decreases mentioned for ETB's upper parts with higher elevations is likely to remain over the environs of Yüksekova. The water surplus seen in almost every water related parameter for the southern parts of the Zagros Mountains is also striking in the total runoff maps in both scenarios. The level of increases over this location are noted as 50 to 100 millimeters regarding RCP2.6 and 50 to 200 millimeters regarding RCP8.5. It should also be noted that mountainous areas on the northern ends of ETB are likely to recover their runoff deficit by the end of the investigation period.

Drastic decreases are seen over higher elevations regarding RCP8.5 among each period. These decreases gradually amplify as the 21st century proceeds. Starting with 200 millimeters in the early period, upper ETB is likely to experience decreases surpassing 300 millimeters over almost the entire basin. The distinct surplus over the southeastern ETB is also visible in the RCP8.5 case for the changes in total runoff with increases reaching up to 200 millimeters.

Changes in the depth of snowpack lies over the diagonal axis which leans on the eastern borders of ETB. For RCP2.6, mHM predicts decreases varying between 100 to 800 millimeters. Otlukbeli, Kop, Palandöken and Hakkari Mountain ranges see greater decreases reaching up to 1000 millimeters. Change over Mount Dena (hosting the highest point of Zagros Mountains) is also remarkable in terms of the shrinking snowpack. Over the ranges of Mount Dena up to 700 millimeters of decrease are also expected. More pronounced levels of loss in snowpack are seen in RCP8.5. Hotspots that stand out in almost every water related parameter remain their significant changes in terms of disappearing snowpack where the losses surpass 1000 millimeters by the end of the century. Especially the decrease over the mountains of Türkiye is drastic as also mentioned earlier in the literature (Bozkurt et al., 2010).

Supported by all model outputs regarding both scenarios, an amplified shift in snowmelt is highly likely to be occurred especially within the upper parts of ETB. According to RCP8.5, Zagros Mountains are also at risk in terms of losing their snow

water reserve. Increased routed streamflow and surface runoff during DJFs leads to a deficit during MAMs which may highly affect the regional resilience and WFE nexus. This prediction also aligns with the previous research in the literature (Yücel et al., 2015; Yılmaz, 2019).

In conclusion, the findings of this thesis reveal the details of ETB's declining water budget. These results underscore the significance of addressing climate change impacts within ETB for adaptive water management strategies, regional welfare and ecosystem conservation efforts. By integrating regional climate modeling with robust data analysis, policymakers and stakeholders can better anticipate and mitigate the multifaceted challenges posed by climate change, ensuring the long-term sustainability and resilience of ETB. Continued research and collaboration are essential in developing holistic management practices to safeguard the region's ecological integrity and socioeconomic well-being in the face of evolving hydroclimatic dynamics.

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APPENDICES

APPENDIX A	: Comparison Figures of the Raw and Corrected MMEs
APPENDIX B	: Tables of MME Members in Comparison with ERA5
APPENDIX C	: Tables of Changes in Hydrologic Outputs
APPENDIX D	: Figures of Seasonal Changes in Hydrologic Outputs
APPENDIX E	: Statistical Tables Regarding Bias Corrections

APPENDIX A

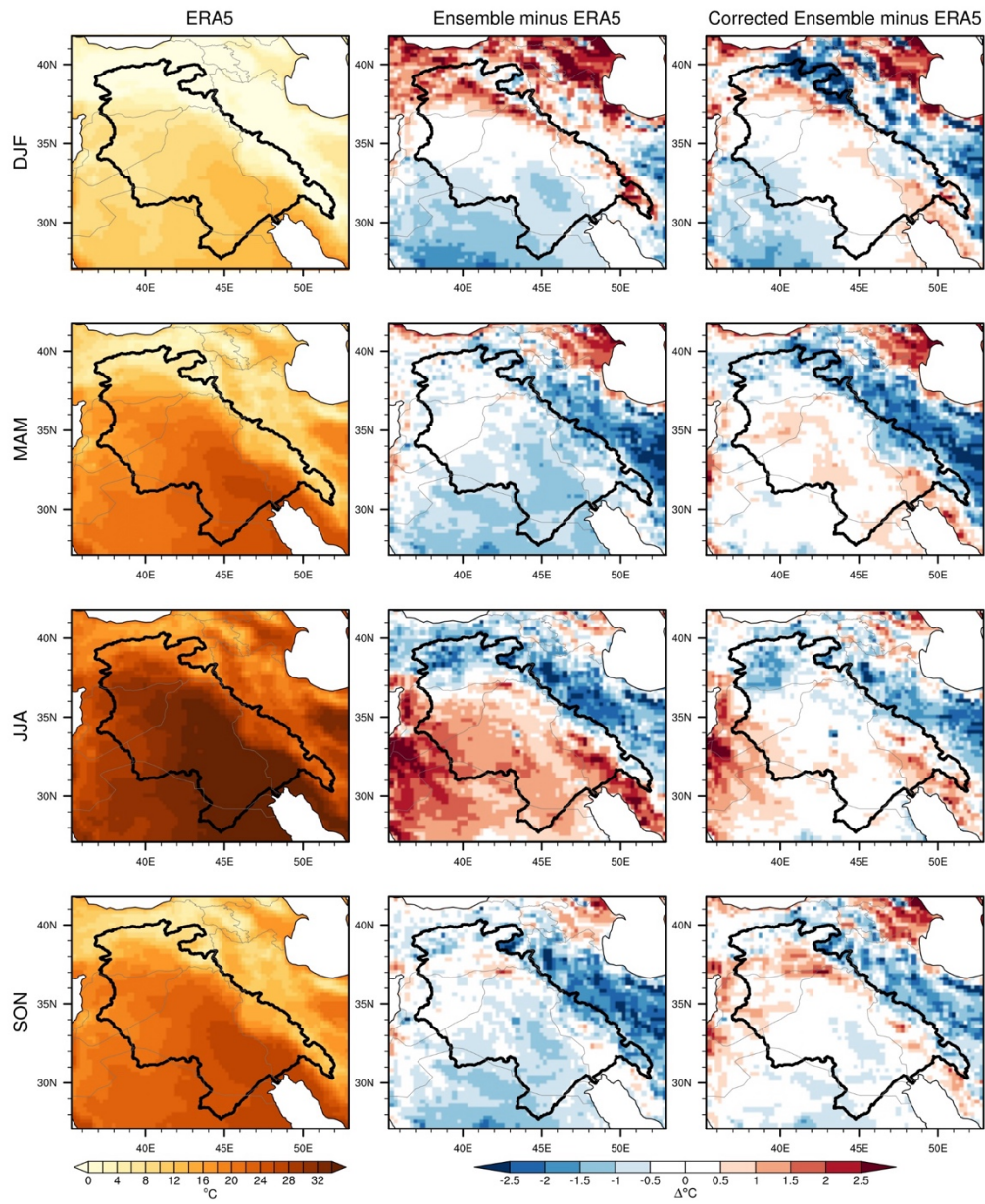


Figure A.1 : Comparison of the Raw and Corrected MMEs in terms of Seasonal Mean Temperatures.

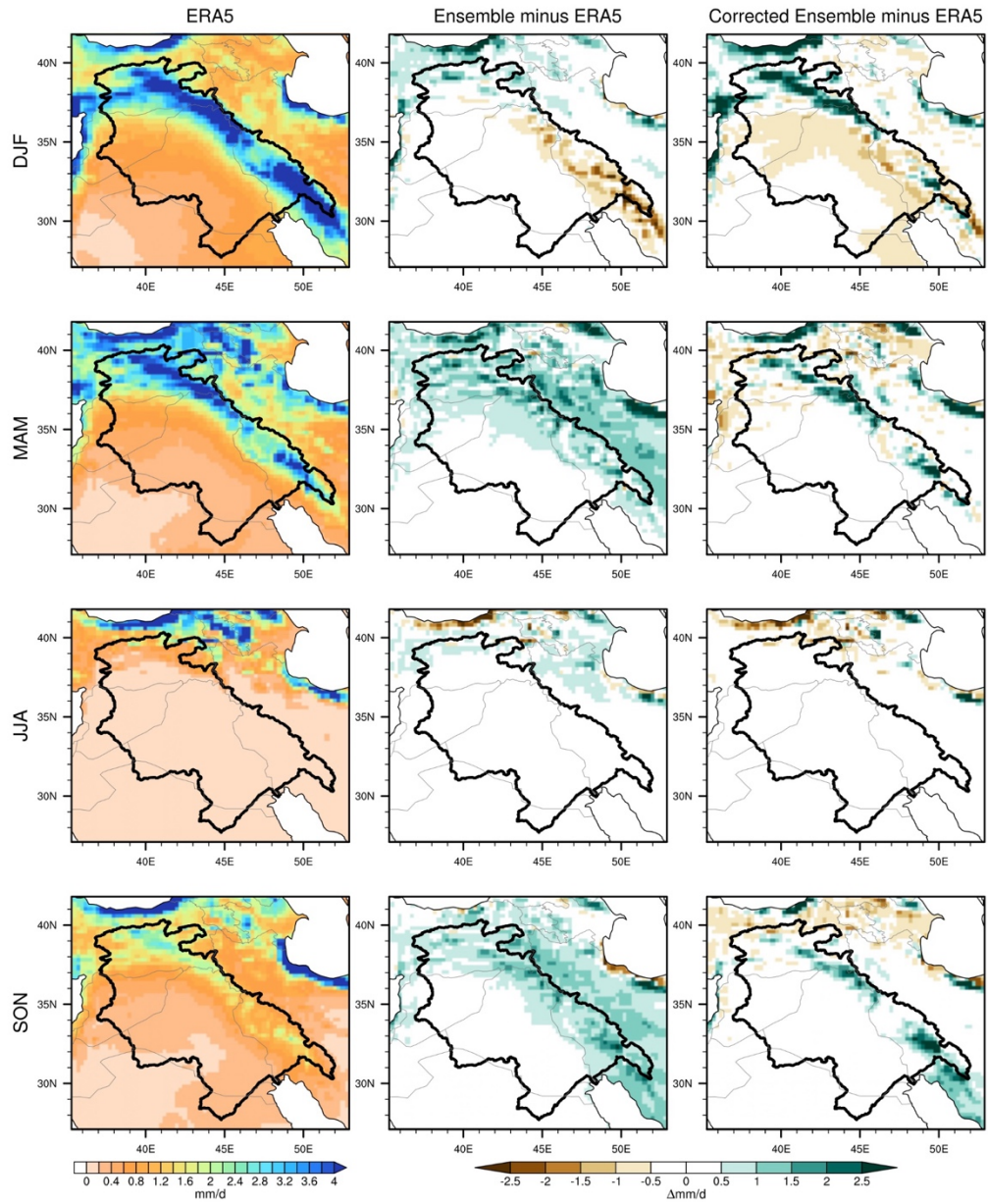


Figure A.2 : Comparison of the Raw and Corrected MMEs in terms of Seasonal Daily Precipitation ($\Delta\text{mm/day}$).

APPENDIX B

Table B.1 : CORDEX-Africa in Comparison with ERA5 Seasonal and Annual (Zonal) Mean Temperature for ETB at 2 meters (°C) Reference Period (1986-2005).

		DJF	MAM	JJA	SON	Annual
ERA5						
	Min	-8.4	1.5	14.8	4.9	3.4
	Max	14.3	26.7	38.8	28	26.9
	Mean	6.5	17.7	30.6	20.2	18.8
HADGEM2-ES, KIT-CCLM5-0-15						
	Min	-8	-0.2	14.5	4.3	3
	Max	11.7	24.6	41.2	25.8	25.8
	Mean	5.2	16.3	31.8	18.6	18
HADGEM2-ES, REMO2015						
	Min	-11.7	-1.9	12.5	2.2	0.4
	Max	13.7	25.3	39.7	27.3	26.4
	Mean	5.9	16.5	30.3	18.9	17.9
HADGEM2-ES, RegCM4-7						
	Min	-10.3	-0.8	14.8	3.9	2.3
	Max	14.8	27.6	41.4	28.3	28
	Mean	6.5	17.7	32.4	20	19.2
MPI-ESM-LR, KIT-CCLM5-0-15						
	Min	-7.3	-0.1	13.2	5.5	3.3
	Max	12.8	25.2	40.9	28.1	26.8
	Mean	5.9	16.7	30.9	19.8	18.4
MPI-ESM-LR, REMO2015						
	Min	-10.8	-1.9	11.1	3.4	0.8
	Max	14.3	25.5	38.5	28	26.6
	Mean	6.5	16.7	29.2	19.6	18.1
MPI-ESM-MR, RegCM4-7						
	Min	-9.6	-0.6	12.2	4.3	2
	Max	15.6	27.4	40.8	29.9	28.5
	Mean	7.1	17.8	31.4	21	19.4
NorESM1-M, KIT-CCLM5-0-15						
	Min	-7.9	0.1	12.8	3.4	2.3
	Max	12.1	23.3	40.2	26.4	25.5
	Mean	5.2	16	31	18.3	17.7
NorESM1-M, REMO2015						
	Min	-10.9	-1.3	12.2	1.8	0.7
	Max	13.8	24.6	39.4	26.6	25.9
	Mean	6.3	16.5	30.5	18.6	18
NorESM1-M, RegCM4-7						
	Min	-9.6	-0.2	13	3.2	1.8
	Max	15.5	26.9	41.7	28.9	28.3
	Mean	7.4	18	32.5	20.1	19.6

Table B.2 : CORDEX-Africa minus ERA5 Seasonal and Annual (Zonal) Mean Temperature Bias for ETB at 2 meters ($\Delta^{\circ}\text{C}$) Reference Period (1986-2005).

		DJF	MAM	JJA	SON	Annual
ERA5						
	Min	-8.4	1.5	14.8	4.9	3.4
	Max	14.3	26.7	38.8	28	26.9
	Mean	6.5	17.7	30.6	20.2	18.8
HADGEM2-ES, KIT-CCLM5-0-15						
	Min	0.4	-1.7	-0.3	-0.6	-0.4
	Max	-2.6	-2.1	2.4	-2.2	-1.1
	Mean	-1.3	-1.4	1.2	-1.6	-0.8
HADGEM2-ES, REMO2015						
	Min	-3.3	-3.4	-2.3	-2.7	-3
	Max	-0.6	-1.4	0.9	-0.7	-0.5
	Mean	-0.6	-1.2	-0.3	-1.3	-0.9
HADGEM2-ES, RegCM4-7						
	Min	-1.9	-2.3	0	-1	-1.1
	Max	0.5	0.9	2.6	0.3	1.1
	Mean	0	0	1.8	-0.2	0.4
MPI-ESM-LR, KIT-CCLM5-0-15						
	Min	1.1	-1.6	-1.6	0.6	-0.1
	Max	-1.5	-1.5	2.1	0.1	-0.1
	Mean	-0.6	-1	0.3	-0.4	-0.4
MPI-ESM-LR, REMO2015						
	Min	-2.4	-3.4	-3.7	-1.5	-2.6
	Max	0	-1.2	-0.3	0	-0.3
	Mean	0	-1	-1.4	-0.6	-0.7
MPI-ESM-MR, RegCM4-7						
	Min	-1.2	-2.1	-2.6	-0.6	-1.4
	Max	1.3	0.7	2	1.9	1.6
	Mean	0.6	0.1	0.8	0.8	0.6
NorESM1-M, KIT-CCLM5-0-15						
	Min	0.5	-1.4	-2	-1.5	-1.1
	Max	-2.2	-3.4	1.4	-1.6	-1.4
	Mean	-1.3	-1.7	0.4	-1.9	-1.1
NorESM1-M, REMO2015						
	Min	-2.5	-2.8	-2.6	-3.1	-2.7
	Max	-0.5	-2.1	0.6	-1.4	-1
	Mean	-0.2	-1.2	-0.1	-1.6	-0.8
NorESM1-M, RegCM4-7						
	Min	-1.2	-1.7	-1.8	-1.7	-1.6
	Max	1.2	0.2	2.9	0.9	1.4
	Mean	0.9	0.3	1.9	-0.1	0.8

Table B.3 : CORDEX-Africa in Comparison with ERA5 Seasonal and Annual (Zonal) Daily Total Precipitation for ETB (mm/day) Reference Period (1986-2005).

		DJF	MAM	JJA	SON	Annual
ERA5						
	Min	0.3	0.2	0	0.2	0.2
	Max	8.4	5.7	3.5	3.3	4.1
	Mean	1.9	1.4	0.1	0.7	1
HADGEM2-ES, KIT-CCLM5-0-15						
	Min	0.2	0.3	0	0.5	0.3
	Max	5.5	6.1	1.6	6.1	4.3
	Mean	1.5	2	0.2	2.1	1.5
HADGEM2-ES, REMO2015						
	Min	0.2	0.2	0	0.4	0.2
	Max	7.5	6.7	1.8	5.4	4.8
	Mean	1.4	1.7	0.1	1.3	1.1
HADGEM2-ES, RegCM4-7						
	Min	0.5	0.5	0	0.8	0.4
	Max	5.5	5	2.9	4.8	3.6
	Mean	1.8	1.8	0.1	2	1.4
MPI-ESM-LR, KIT-CCLM5-0-15						
	Min	0.3	0.3	0	0.3	0.2
	Max	8.5	6.7	1.7	3.5	4.7
	Mean	2	2	0.1	1	1.3
MPI-ESM-LR, REMO2015						
	Min	0.3	0.2	0	0.2	0.2
	Max	12.4	8.3	1.3	4.1	6.2
	Mean	2	1.6	0.1	0.8	1.1
MPI-ESM-MR, RegCM4-7						
	Min	0.4	0.5	0	0.6	0.4
	Max	6	5.1	4.2	3.4	3.7
	Mean	1.7	1.8	0.3	1.4	1.3
NorESM1-M, KIT-CCLM5-0-15						
	Min	0.3	0.8	0.1	0.3	0.4
	Max	6.2	10.5	3	3.4	5.2
	Mean	1.7	3.1	0.7	1.1	1.7
NorESM1-M, REMO2015						
	Min	0.3	0.5	0	0.2	0.3
	Max	9.6	10.3	1.7	3.8	5.9
	Mean	1.8	2.4	0.1	0.9	1.3
NorESM1-M, RegCM4-7						
	Min	0.5	0.6	0	0.5	0.4
	Max	4.8	5.5	5.5	3.5	3.9
	Mean	1.6	2.1	0.3	1.4	1.3

Table B.4 : CORDEX-Africa minus ERA5 Seasonal and Annual (Zonal) Daily Total Precipitation Bias for ETB ($\Delta\text{mm/day}$) Reference Period (1986-2005).

		DJF	MAM	JJA	SON	Annual
ERA5						
	Min	0.3	0.2	0	0.2	0.2
	Max	8.4	5.7	3.5	3.3	4.1
	Mean	1.9	1.4	0.1	0.7	1
HADGEM2-ES, KIT-CCLM5-0-15						
	Min	-0.1	0.1	0	0.3	0.1
	Max	-2.9	0.4	-1.9	2.8	0.2
	Mean	-0.4	0.6	0.1	1.4	0.5
HADGEM2-ES, REMO2015						
	Min	-0.1	0	0	0.2	0
	Max	-0.9	1	-1.7	2.1	0.7
	Mean	-0.5	0.3	0	0.6	0.1
HADGEM2-ES, RegCM4-7						
	Min	0.2	0.3	0	0.6	0.2
	Max	-2.9	-0.7	-0.6	1.5	-0.5
	Mean	-0.1	0.4	0	1.3	0.4
MPI-ESM-LR, KIT-CCLM5-0-15						
	Min	0	0.1	0	0.1	0
	Max	0.1	1	-1.8	0.2	0.6
	Mean	0.1	0.6	0	0.3	0.3
MPI-ESM-LR, REMO2015						
	Min	0	0	0	0	0
	Max	4	2.6	-2.2	0.8	2.1
	Mean	0.1	0.2	0	0.1	0.1
MPI-ESM-MR, RegCM4-7						
	Min	0.1	0.3	0	0.4	0.2
	Max	-2.4	-0.6	0.7	0.1	-0.4
	Mean	-0.2	0.4	0.2	0.7	0.3
NorESM1-M, KIT-CCLM5-0-15						
	Min	0	0.6	0.1	0.1	0.2
	Max	-2.2	4.8	-0.5	0.1	1.1
	Mean	-0.2	1.7	0.6	0.4	0.7
NorESM1-M, REMO2015						
	Min	0	0.3	0	0	0.1
	Max	1.2	4.6	-1.8	0.5	1.8
	Mean	-0.1	1	0	0.2	0.3
NorESM1-M, RegCM4-7						
	Min	0.2	0.4	0	0.3	0.2
	Max	-3.6	-0.2	2	0.2	-0.2
	Mean	-0.3	0.7	0.2	0.7	0.3

Table B.5 : Changes in Seasonal and Annual (Zonal) Mean Temperature ($\Delta^{\circ}\text{C}$) for ETB regarding RCP2.6 (above) and RCP8.5 (below).

RCP2.6	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	-13.3	-1.2	13.4	3.2	1
Max	15	27.3	39.3	27.9	27.4
Mean	6.3	17.6	30.6	20.2	18.8
<i>2021-2040</i>					
ΔMin	1.4	1.5	1.9	1.7	1.5
ΔMax	0.7	1.3	2	1.3	1.2
ΔMean	1.2	1.4	1.6	1.4	1.3
<i>2051-2070</i>					
ΔMin	2	1.8	1.8	1.8	1.7
ΔMax	1.3	1.6	2.1	1.6	1.6
ΔMean	1.6	1.6	1.6	1.5	1.5
<i>2081-2099</i>					
ΔMin	1.8	1.7	1.7	1.9	1.6
ΔMax	1.1	1.4	2	1.4	1.4
ΔMean	1.5	1.6	1.5	1.4	1.4
RCP8.5	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	-13.3	-1.2	13.4	3.2	1
Max	15	27.3	39.3	27.9	27.4
Mean	6.3	17.6	30.6	20.2	18.8
<i>2021-2040</i>					
ΔMin	1.5	1.6	2.1	1.8	1.6
ΔMax	0.9	1.6	2.4	1.6	1.5
ΔMean	1.2	1.5	1.9	1.5	1.5
<i>2051-2070</i>					
ΔMin	4	3.6	4.5	4	3.8
ΔMax	2.7	3.6	5.5	3.6	3.6
ΔMean	3.2	3.4	4.2	3.4	3.5
<i>2081-2099</i>					
ΔMin	6.6	6.1	6.7	6.5	6.3
ΔMax	4.1	6.1	8.8	6	6
ΔMean	4.8	5.9	6.8	5.5	5.7

Table B.6 : Changes in Seasonal and Annual Daily (Zonal) Total Precipitation ($\Delta\text{mm/day}$) for ETB regarding RCP2.6 (above) and RCP8.5 (below).

RCP2.6	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0.1	0.1	0	0.1	0.1
Max	11.1	8.4	2	5.3	6.1
Mean	1.7	1.4	0.2	0.8	1
<i>2021-2040</i>					
ΔMin	0	-0.1	0	0	0
ΔMax	0.3	-1	-0.1	1	-0.1
ΔMean	0.1	-0.1	-0.1	0.2	0
<i>2051-2070</i>					
ΔMin	-0.1	0	0	0	0
ΔMax	-0.6	0.3	0.2	-0.1	-0.2
ΔMean	0	0.1	0	0	0.1
<i>2081-2099</i>					
ΔMin	0	0	0	0	0
ΔMax	-0.2	-0.6	0	0.4	-0.1
ΔMean	0	0	-0.1	0.2	0.1
RCP8.5	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0.1	0.1	0	0.1	0.1
Max	11.1	8.4	2	5.3	6.1
Mean	1.7	1.4	0.2	0.8	1
<i>2021-2040</i>					
ΔMin	0	0	0	0	0
ΔMax	-0.7	-0.9	-0.1	0.9	-0.1
ΔMean	0	0	-0.1	0.2	0
<i>2051-2070</i>					
ΔMin	0	0	0	0	0
ΔMax	-1.2	-1.8	-0.2	1	-0.4
ΔMean	-0.1	-0.2	-0.1	0.2	0
<i>2081-2099</i>					
ΔMin	0	-0.1	0	0	0
ΔMax	0.3	-2.4	-0.4	1.8	0
ΔMean	0.1	-0.3	-0.1	0.4	0.1

APPENDIX C

Table C.1 : Annual and Seasonal Changes in Routed Streamflow (RCP2.6) - Future minus Reference ($\Delta\text{m}^3/\text{s}$).

	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0	0	0	0	0
Max	6517,8	11861,3	2882	1081,5	5566,4
Mean	133,5	266,2	58	29,4	121,9
<i>2021-2040</i>					
ΔMin	-16,6	-1177,3	-135,9	-116,4	-186,6
ΔMax	918,6	77,3	5	120,8	44
ΔMean	19,4	-30	-3,7	-1,2	-3,9
<i>2051-2070</i>					
ΔMin	-18,6	-654,1	-14,6	-152,7	-92
ΔMax	609,9	82,5	207,6	16,1	62
ΔMean	20,3	-17,3	4,3	-3,5	0,9
<i>2071-2099</i>					
ΔMin	-8,4	-1022,5	-26,4	-6,6	-102,8
ΔMax	1011,2	33,4	70,1	211,3	66
ΔMean	22,5	-28,7	1,6	5,8	0,2

Table C.2 : Annual and Seasonal Changes in Routed Streamflow (RCP8.5) - Future minus Reference ($\Delta\text{m}^3/\text{s}$).

	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0	0	0	0	0
Max	6517,8	11861,3	2882	1081,5	5566,4
Mean	133,5	266,2	58	29,4	121,9
<i>2021-2040</i>					
ΔMin	-137,8	-1787,8	-40,4	-38,6	-323,3
ΔMax	663,2	7,5	106,1	131,3	38
ΔMean	10,4	-38,9	1,6	1,5	-6,4
<i>2051-2070</i>					
ΔMin	-69,9	-3163,2	-477,4	-40,2	-611
ΔMax	1125,6	3,6	1,1	107	6,9
ΔMean	28,5	-73,5	-8,2	0,6	-13,3
<i>2071-2099</i>					
ΔMin	-76,8	-4150,7	-727	-52,6	-750,3
ΔMax	2444,5	4,6	2	231,7	103
ΔMean	49,1	-104,8	-12,6	2,1	-16,8

Table C.3 : Annual and Seasonal Changes in Total Runoff (RCP2.6) - Future minus Reference (Δ mm).

	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0	0	0	0	0
Max	928,8	1382,1	191,7	279,3	1958,4
Mean	64,5	113,7	18,6	14,1	211,2
<i>2021-2040</i>	0	0	0	0	0
Δ Min	-61,2	-387,3	-84,3	-46,5	-160,8
Δ Max	271,8	46,2	14,7	68,7	102
Δ Mean	10,2	-13,5	-1,2	0,3	-3,6
<i>2051-2070</i>	0	0	0	0	0
Δ Min	-104,4	-392,1	-79,5	-63,9	-174
Δ Max	287,4	71,7	26,1	27	99,6
Δ Mean	8,4	-8,4	1,8	-1,5	0
<i>2071-2099</i>	0	0	0	0	0
Δ Min	-71,7	-411,3	-84	-34,5	-188,4
Δ Max	333,3	47,1	22,2	51	133,2
Δ Mean	12,3	-13,5	0,3	2,7	2,4

Table C.4 : Annual and Seasonal Changes in Total Runoff (RCP8.5) - Future minus Reference (Δ mm).

	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0	0	0	0	0
Max	928,8	1382,1	191,7	279,3	1958,4
Mean	64,5	113,7	18,6	14,1	211,2
<i>2021-2040</i>	0	0	0	0	0
Δ Min	-128,1	-398,7	-77,4	-41,7	-247,2
Δ Max	278,4	40,2	18	61,5	104,4
Δ Mean	6,9	-17,1	0	1,2	-8,4
<i>2051-2070</i>	0	0	0	0	0
Δ Min	-109,5	-759	-113,1	-54,9	-358,8
Δ Max	472,8	46,8	19,2	64,8	106,8
Δ Mean	12,6	-34,8	-2,7	0,9	-24
<i>2071-2099</i>	0	0	0	0	0
Δ Min	-144,9	-891,6	-127,2	-59,4	-445,2
Δ Max	529,8	36	22,2	120	190,8
Δ Mean	24,9	-46,2	-4,2	2,7	-22,8

Table C.5 : Annual and Seasonal Changes in the Depth of Snowpack (RCP2.6) - Future minus Reference (Δ mm).

	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0	0	0	0	0
Max	1194,9	1454,7	8,4	31,5	2601,6
Mean	61,5	44,1	0	0,3	105,6
<i>2021-2040</i>					
Δ Min	-513	-526,8	-8,4	-17,4	-831,6
Δ Max	13,2	0	0	0,3	0
Δ Mean	-22,2	-21,3	0	-0,3	-43,2
<i>2051-2070</i>					
Δ Min	-597	-723,3	-8,4	-18,9	-1062
Δ Max	54,3	0	0	0	42
Δ Mean	-22,2	-23,4	0	-0,3	-45,6
<i>2071-2099</i>					
Δ Min	-524,4	-655,5	-8,4	-22,8	-1090,8
Δ Max	0	0	0	0	0
Δ Mean	-27	-25,8	0	-0,3	-52,8

Table C.6 : Annual and Seasonal Changes in the Depth of Snowpack (RCP8.5) - Future minus Reference (Δ mm).

	DJF	MAM	JJA	SON	Annual
<i>Reference</i>					
Min	0	0	0	0	0
Max	1194,9	1454,7	8,4	31,5	2601,6
Mean	61,5	44,1	0	0,3	105,6
<i>2021-2040</i>					
Δ Min	-452,7	-616,5	-8,4	-19,5	-1040,4
Δ Max	13,2	0	0	0	0
Δ Mean	-24,3	-24,9	0	-0,3	-49,2
<i>2051-2070</i>					
Δ Min	-910,8	-1044,9	-8,4	-26,7	-1808,4
Δ Max	3,9	0	0	0	0
Δ Mean	-42,3	-35,4	0	-0,3	-78
<i>2071-2099</i>					
Δ Min	-1090,2	-1313,4	-8,4	-31,2	-2283,6
Δ Max	0	0	0	0	0
Δ Mean	-52,8	-41,7	0	-0,3	-94,8

APPENDIX D

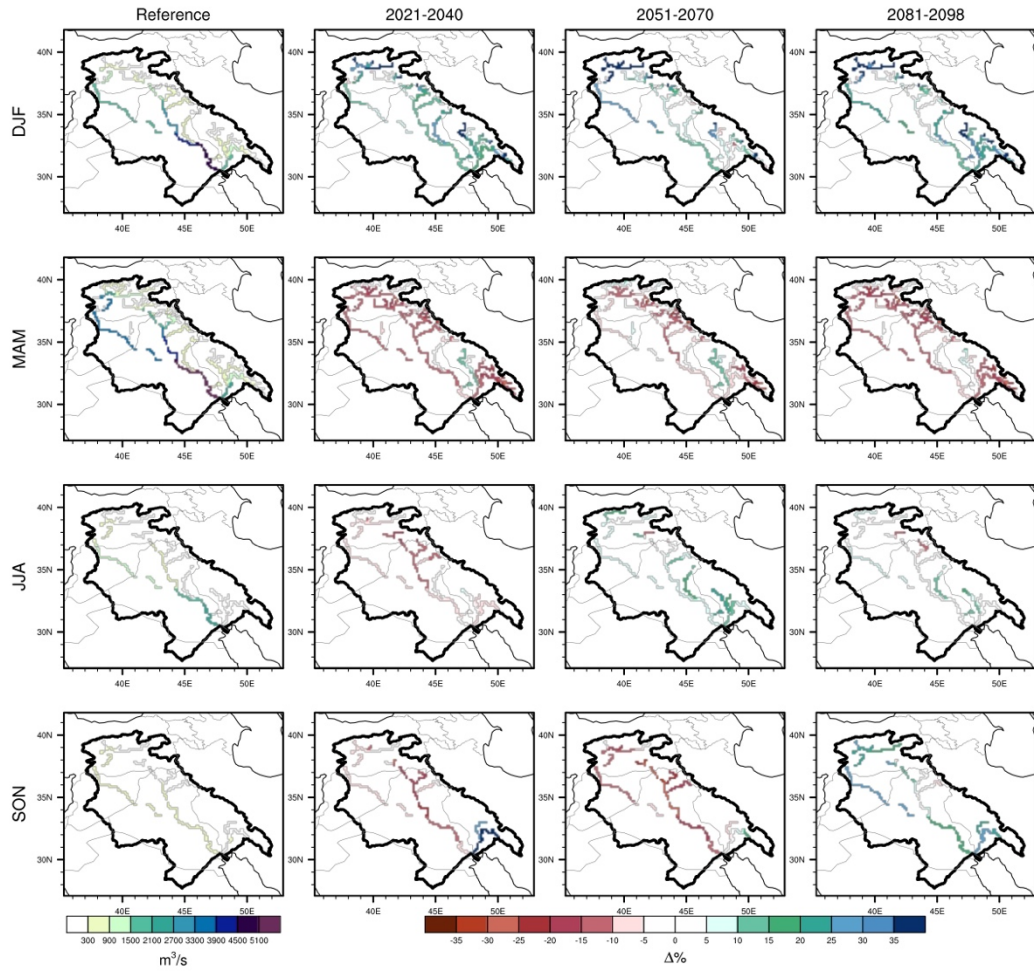


Figure D.1 : Seasonal Changes in Routed Streamflow Regarding RCP2.6 (FUT-REF, $\Delta\%$).

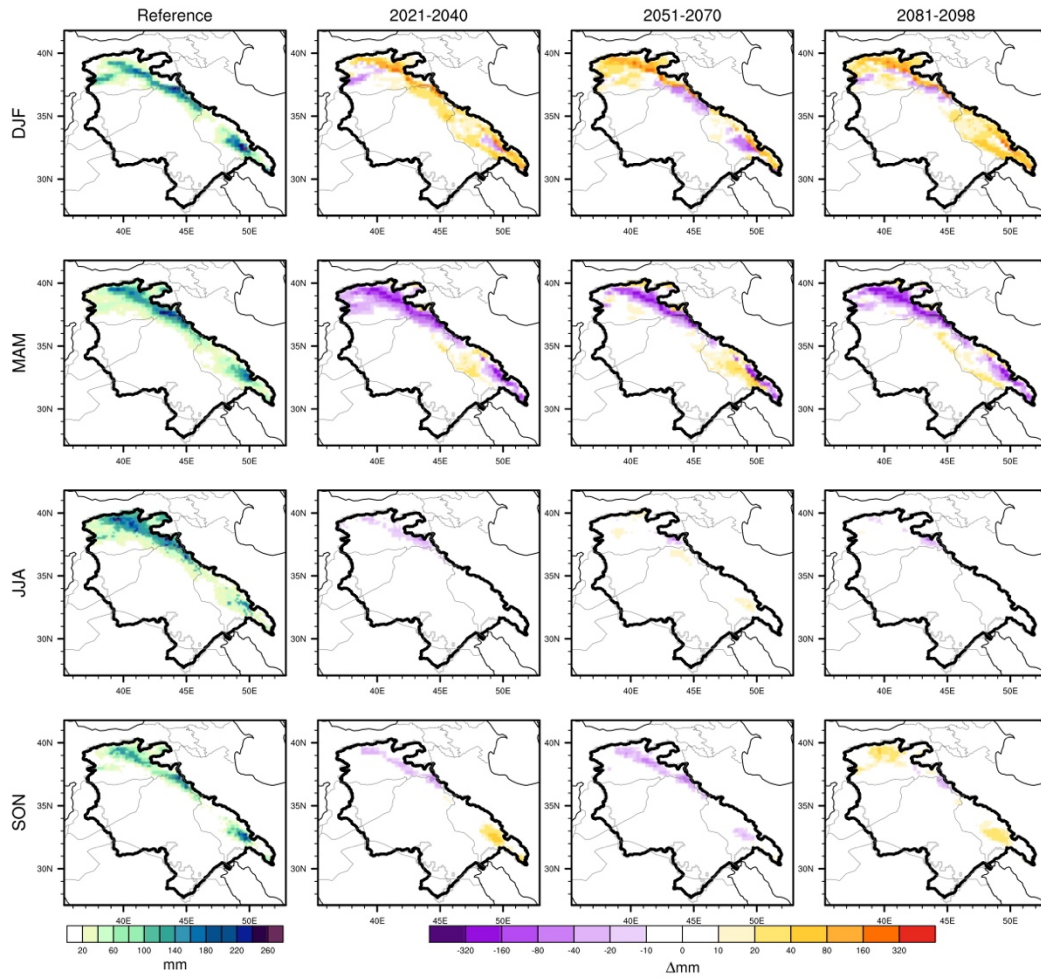


Figure D.2 : Seasonal Changes in Surface Runoff Regarding RCP2.6 (FUT-REF, Δmm).

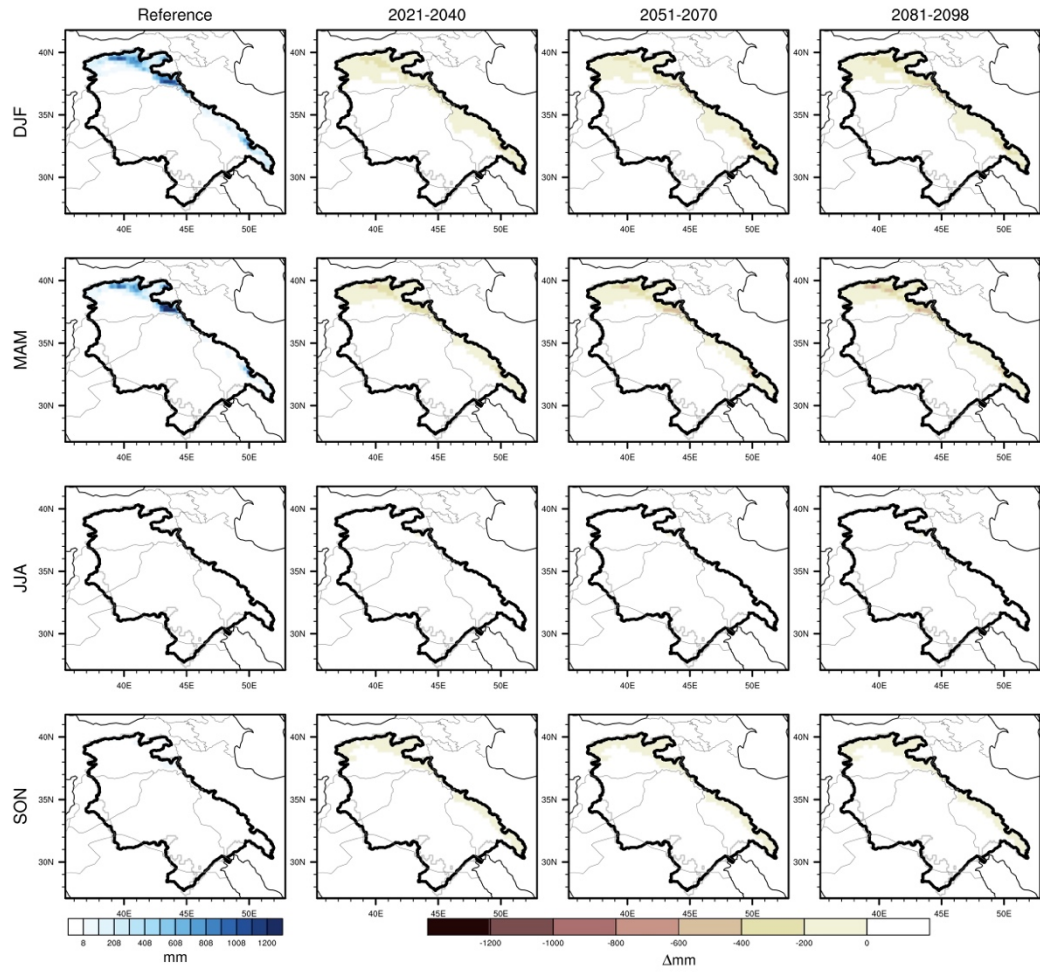


Figure D.3 : Seasonal Changes in Depth of Snowpack Regarding RCP2.6 (FUT-REF, Δmm).

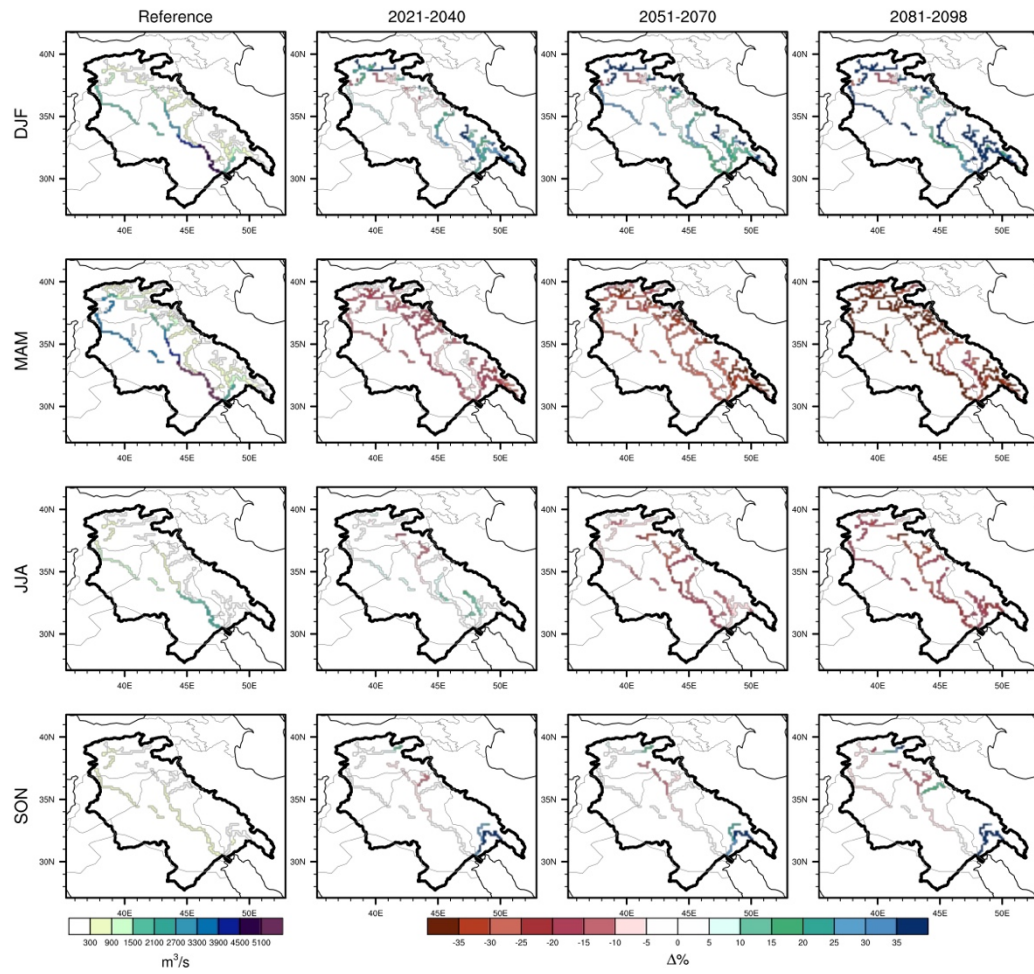


Figure D.4 : Seasonal Changes in Routed Streamflow Regarding RCP8.5 (FUT-REF, $\Delta\%$).

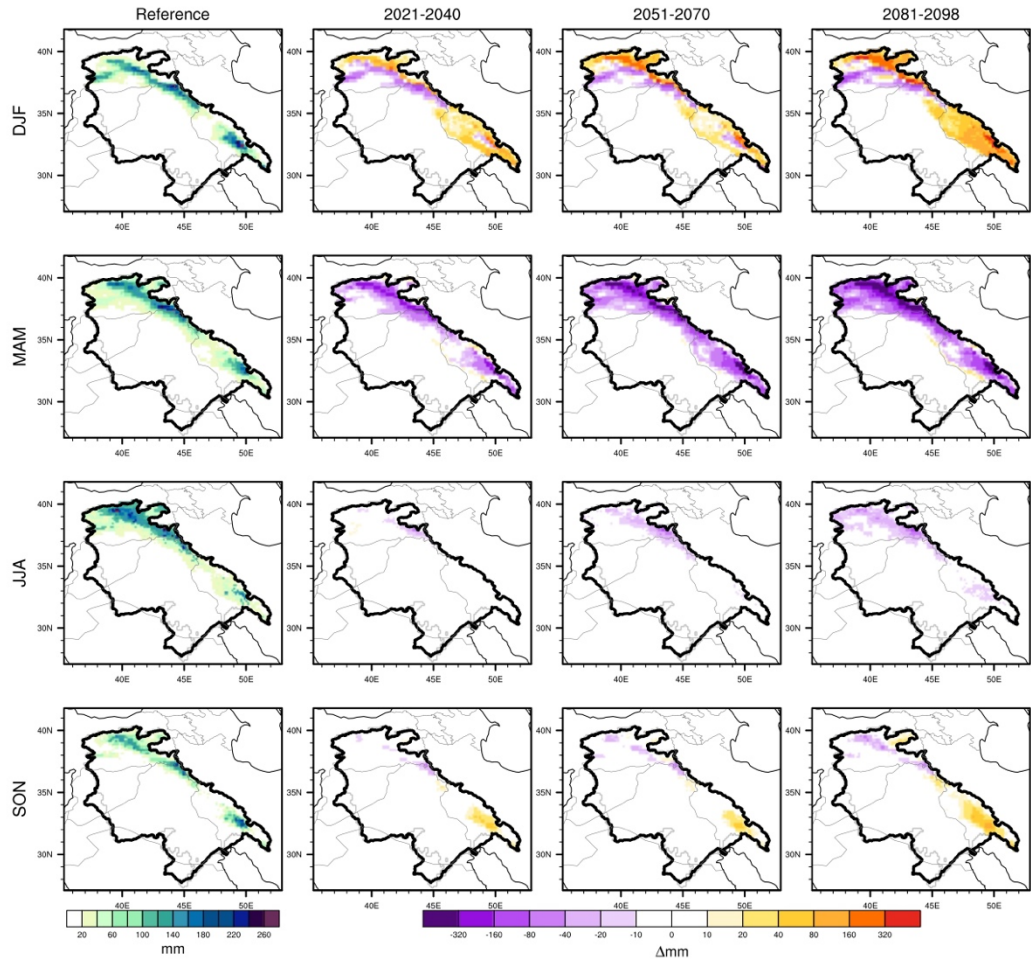


Figure D.5 : Seasonal Changes in Surface Runoff Regarding RCP8.5 (FUT-REF, $\Delta\%$).

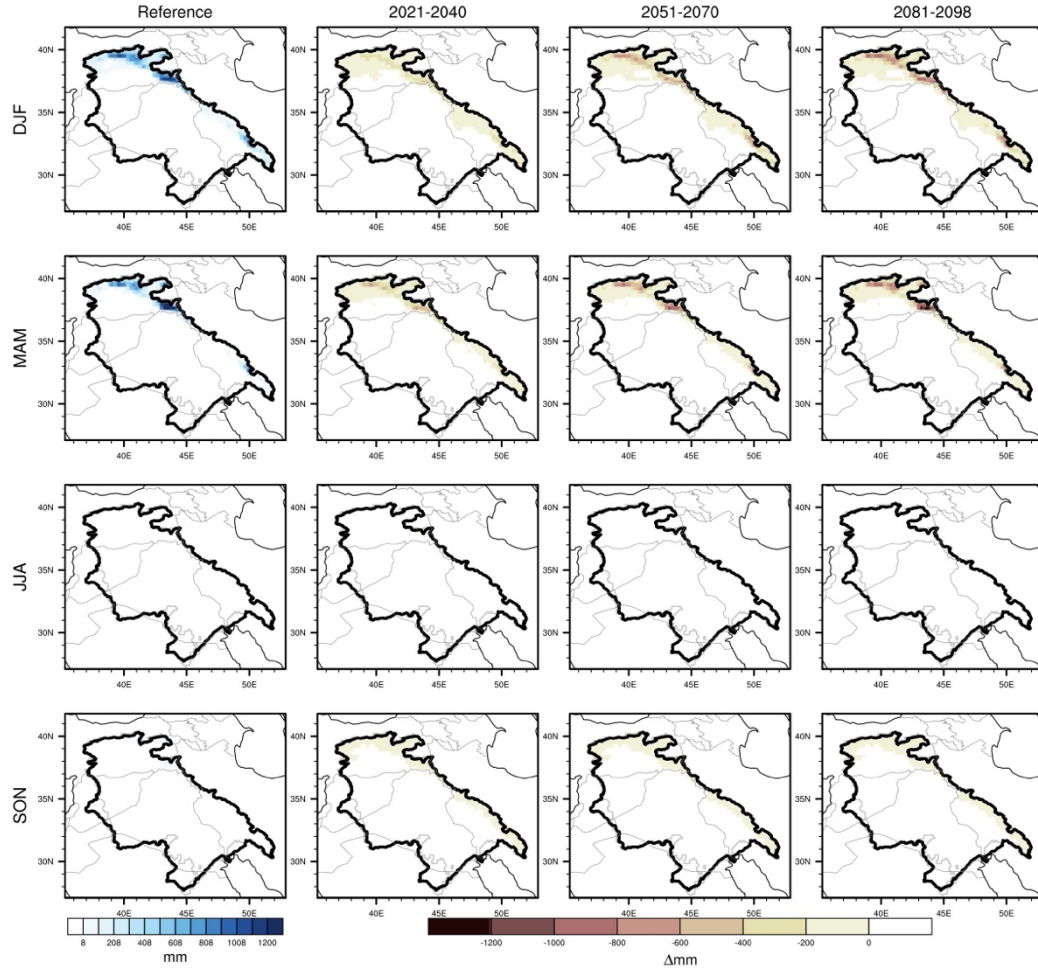


Figure D.6 : Seasonal Changes in Depth of Snowpack Regarding RCP8.5 (FUT-REF, $\Delta\%$).

APPENDIX E

Table E.1 : Statistics for Mean Daily Temperature Regarding Reference Period (°C).

Statistics for Mean Daily Temperature Regarding Reference Period (°C)										
		Min	p5	LQ	Median	HQ	p95	Max	StdDev	Mean
<i>HADGEM2-ES</i>	ERA5	3,43	6,88	14,58	19,77	23,63	26,33	26,9	5,96	18,66
	Ensemble	2,26	6,74	14,73	19,88	23,39	26	26,7	6,01	18,54
	Cor. Ens. (<i>ERQM</i>)	0,96	6,32	14,7	19,94	23,73	26,61	27,38	6,29	18,66
	KIT-CCLM5-0-15	3,22	7,17	14,89	19,23	22,47	24,99	25,99	5,52	18,03
	REMO2015	0,64	6,01	14,07	19,43	22,76	25,38	26,57	6,09	17,93
	RegCM4-7	2,55	6,83	15,42	20,55	24,52	27,16	28,2	6,31	19,27
	KIT-CCLM5-0-15	3,45	7,39	15,3	19,58	22,77	25,59	26,91	5,55	18,43
	REMO2015	1	5,94	13,92	19,63	22,85	25,54	26,72	6,1	18,05
	RegCM4-7	2,15	6,57	15,35	20,7	24,8	27,6	28,63	6,51	19,41
<i>NorESM1-M</i>	KIT-CCLM5-0-15	2,41	6,75	14,53	18,95	22,16	24,57	25,51	5,57	17,68
	REMO2015	0,9	6,14	14,18	19,64	22,91	25,36	26,07	6,08	18,05
	RegCM4-7	2,01	6,72	15,57	21,02	25,05	27,55	28,4	6,52	19,6

Table E.2 : Statistics for Daily Precipitation Regarding Reference Period (mm/day).

Statistics for Daily Precipitation Regarding Reference Period (mm/day)										
		Min	p5	LQ	Median	HQ	p95	Max	StdDev	Mean
	ERA5	0,18	0,24	0,34	0,71	1,67	2,73	4,1	0,84	1,06
	Ensemble	0,35	0,39	0,52	0,92	2,08	3,3	4,49	0,99	1,36
	Cor. Ens. (<i>ERQM</i>)	0,06	0,09	0,15	0,44	1,63	3,78	6,09	1,22	1,06
<i>HADGEM2-ES</i>	KIT-CCLM5-0-15	0,28	0,32	0,52	1,04	2,41	3,56	4,44	1,11	1,5
	REMO2015	0,23	0,26	0,4	0,79	1,76	3,03	5,01	0,94	1,17
	RegCM4-7	0,44	0,55	0,67	1,03	2,21	3,23	3,76	0,93	1,48
<i>MPI-ESM-LR</i>	KIT-CCLM5-0-15	0,22	0,25	0,4	0,8	2,01	3,47	4,63	1,07	1,27
	REMO2015	0,18	0,21	0,32	0,64	1,66	3,4	6,14	1,06	1,13
<i>MPI-ESM-MR</i>	RegCM4-7	0,43	0,49	0,61	0,89	1,92	3,24	3,87	0,91	1,34
<i>NorESM1-M</i>	KIT-CCLM5-0-15	0,39	0,47	0,7	1,26	2,61	4,02	5,23	1,17	1,72
	REMO2015	0,26	0,34	0,43	0,9	1,89	3,41	5,72	1,03	1,29
	RegCM4-7	0,38	0,5	0,62	0,91	2,08	3,08	3,9	0,88	1,36

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Salkım E., and Unal S. Y. (2024).** Climate Change Projections over Turkiye and Effects on Water Resources: Example of Euphrates Tigris River Course, *Role of Climate Change on Water Resources Management for a Sustainable Future Conference (ICCW2024)*, (Presentation), Istanbul