MODELING IMPACTS OF CLIMATE CHANGE ON ARIDITY AND CROP WATER DEMAND IN SYRIA

MOHAMAD RAJAB HOUMSI

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Rising temperature and changing rainfall patterns due to global warming would cause a shift in aridity, particularly in the dry regions of the world which may subsequently affect several sectors particularly the agricultural and water resources. The effect of climate change may severely affect the livelihood of the vast population depending on agriculture in dry regions if proper adaptation and mitigation measures are not taken. The major objective of the present study is to develop a framework for the projection of climate change using general circulation model (GCM) and assess the impacts of climate change aridity and crop water demand (CWD) in dry regions for different representative concentration pathways (RCP) scenarios. Syria, located in a predominantly arid region and one of the most vulnerable countries of the world to climate change was considered as the case study area. Considering scarcity of data, a gauge based gridded rainfall data of global precipitation climatology center (GPCC) and temperature data of climate research unit (CRU) for the period 1951-2010 were used. The temporal variations in aridity were estimated using the UNESCO aridity index while the CWD was estimated using a simple water balance model. A novel entropy-based method known as symmetrical uncertainty (SU) was used for the selection of GCMs to reduce uncertainties in climate change projections. The performance of four state-of-the-art bias correction approaches was compared for selecting the best method for reliable downscaling of climate using model output statistics (MOS) approach. A random forest (RF) based regression was used for the generation of the multi-model ensemble (MME) mean projections of climate. Results revealed an increase in aridity and crop water demand in Syria during 1981-2010 compared to 1951-1980. The temperature was found to be the dominating factor for defining aridity in semi-arid regions in the north while rainfall as the dominating factor in the arid south. Four GCMs namely HadGEM2-AO, NorESM1-M, CSIRO-Mk3.6.0, and CESM1-CAM5 were found to be the most suitable for the projection of rainfall and temperature in Syria. Performance assessment of bias correction methods revealed linear scaling (LS) as the most suitable for downscaling of both precipitation and temperature using the MOS approach. The LS downscaled GCM simulations were found to replicate the mean, variability and temporal distribution of GPCC/CRU precipitation/temperature reliably. Future projection of rainfall and temperature using MME for the period 2010 – 2100 revealed a decrease in precipitation in the range of -30 – 85.2% mostly in the coastal areas while it was projected to increase next to those areas in the range of 18 – 87.3%. The MME projected an increase in temperature in the range of 0.0 – 5.1°C over the entire country for different RCPs. All the RCPs projected a higher increase in average temperature in the east, particularly northeast and least in the western coastal region. The change in precipitation and temperature would cause an increase in aridity and CWD in Syria. The aridity and CWD were projected to increase more in the western coastal region where precipitation was projected to decrease more. Besides, those were projected to increase in most of the areas of the country used for agriculture. It is expected that the methodology proposed in this study can be used as a tool for providing the information required for climate change adaptation and mitigation planning.

ABSTRAK

Suhu yang meningkat dan perubahan pola hujan disebabkan oleh pemanasan global akan menyebabkan perubahan kekeringan, terutamanya di kawasan kering di dunia yang mungkin menjejaskan beberapa sektor terutamanya pertanian dan sumber air. Kesan perubahan iklim mungkin menjejaskan kehidupan kebanyakan penduduk yang bergantung kepada pertanian di kawasan kering, jika langkah pengadaptasian dan mitigasi yang sesuai tidak diambil. Objektif utama kajian ini adalah untuk membangunkan rangka kerja untuk pengunjuran perubahan iklim menggunakan Model Edaran Umum (GCM) dan menilai impak kekeringan perubahan iklim dan Keperluan Air Tuaian (CWD) di kawasan kering bagi Jalan Perwakilan Penumpuan (RCP) yang berbeza senario. Syria, yang terletak di rantau yang sebahagian besarnya kering dan salah satu negara yang paling terdedah di dunia terhadap perubahan iklim telah dipertimbangkan sebagai kawasan kajian. Memandangkan kekurangan data, data hujan bergrid berasaskan tolok daripada Pusat Iklim Hujan Global (GPCC) dan data suhu daripada Unit Penyelidikan Iklim (CRU) untuk tempoh 1951-2010 telah digunakan. Variasi temporal dalam kekeringan dianggarkan menggunakan indeks kekeringan UNESCO sementara CWD dianggarkan menggunakan model imbangan air mudah. Kaedah nobel berasaskan entropi yang dikenali sebagai Ketidaktentuan Simetri (SU) digunakan untuk pemilihan GCM untuk mengurangkan ketidakpastian dalam unjuran perubahan iklim. Prestasi empat pendekatan pembetulan bias yang terkini telah dibandingkan untuk memilih kaedah terbaik bagi penurunan iklim menggunakan pendekatan Model Keluaran Statistik (MOS). Regresi berasaskan Hutan Rawak (RF) digunakan untuk menghasilkan purata unjuran Model Pelbagai Himpunan (MME) untuk iklim. Hasil kajian menunjukkan peningkatan kekeringan dan Keperluan Air Tuaian di Syria pada tahun 1981-2010 berbanding 1951-1980. Suhu didapati menjadi faktor yang dominan dalam menentukan kekeringan di kawasan separa kering di utara manakala hujan menjadi faktor yang dominan di kawasan kering di selatan. Empat GCM iaitu HadGEM2-AO, NorESM1-M, CSIRO-Mk3.6.0 dan CESM1-CAM5 didapati paling sesuai untuk unjuran hujan dan suhu di Syria. Penilaian prestasi kaedah pembetulan bias mendedahkan Penskalaan Linear (LS) paling sesuai untuk penurunan kedua-dua hujan dan suhu menggunakan pendekatan MOS. Simulasi penurunan GCM berasaskan LS didapati mereplikasi dengan sesuai purata, variasi dan tempoh edaran GPCC/CRU untuk hujan/suhu. Unjuran hujan dan suhu pada masa depan yang menggunakan MME untuk tempoh 2010 - 2100 mendedahkan pengurangan hujan dalam lingkungan -30 - 85.2% kebanyakannya di kawasan pesisiran pantai sementara dijangka meningkat di sebelah kawasan tersebut dalam lingkungan 18 - 87.3%. MME mengunjurkan peningkatan suhu dalam lingkungan 0.0 - 5.1°C di seluruh negara bagi RCP yang berbeza. Semua RCP mengunjurkan kenaikan suhu purata yang lebih tinggi di timur, terutamanya timur laut dan paling kurang di kawasan pantai barat. Perubahan hujan dan suhu akan menyebabkan peningkatan kekeringan dan CWD di Syria. Kekeringan dan CWD dijangka meningkat lebih tinggi di rantau pantai barat di mana hujan diunjurkan semakin berkurangan. Selain itu, peningkatan unjuran ini meningkat di kebanyakan kawasan negara yang digunakan untuk pertanian. Metodologi yang dicadangkan dalam kajian ini dijangka dapat diguna sebagai alat untuk menyediakan maklumat yang diperlukan untuk pengadaptasian perubahan iklim dan plan mitigasi.

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LIST OF ABBREVIATIONS

%PBIAS	-	Percentage of Bias
AI	-	Aridity Index
ANN	-	Artificial Neural Network
AOGCM	-	Atmosphere-Ocean General Circulation Model
AR5	-	Fifth Assessment Report
BC	-	Bias Correction
CMORPH	-	CPC MORPHing technique
CART	-	Classification and Regression Tree
CC	-	Correlation Coefficient
CFSR	-	Climate forest system Reanalyze
CMAP	-	CPC Merged Analysis of Precipitation
CMIP5	-	Coupled Model Intercomparison phase 5
CPC	-	Climate Prediction Centre
CRU	-	Climatic Research Unit
CV	-	The Coefficient of Variation
CWD	-	Crop Water Demand
FAO	-	Food and Agricultural Organization
ET	-	Evapotranspiration
GA	-	Genetic Algorithm
GCMs	-	General Circulation Models
GEQM	-	Generalized quantile mapping
GHCN	-	Global historical climatology network
GHG	-	Greenhouse gases
GPCC	-	Global Precipitation Climatology Center
GPCP	-	Global Precipitation Climatology Project
GPD	-	Generalized Pareto Distribution
GSMaP_MVK	-	Global Satellite Mapping of Precipitation Microwave-IR Combined
H	-	Humid
IG	-	Information Gain

IIASA	-	International Institute for Applied Systems Analysis
IMD	-	Indian meteorological department
IPCC	-	The Intergovernmental Panel on Climate Change
JGCRI	-	Joint Global Change Research Institute
JRA-25	-	Japanese 25-Years Reanalysis
LS	-	Linear Scaling
LTP	-	Long-term persistence
MAE	-	Mean Absolute error
MBE	-	Mean bias error
MBias	-	Multiplicative bias
MD	-	Mahalanobis Distance
MK	-	Mann-Kendall test
MME	-	Multi-Model Ensemble
MOS	-	Model Output Statistics
MTS	-	Mahalanobis Taguchi System
NASAMERRA	-	NASA modern era reanalysis for reasearch and applications
NCEP1	-	National Centre for Environmental Prediction 1
NIES	-	National Institute for Environmental Studies
NOAA	-	National oceanic and atmospheric administration
PDF	-	The Probabillity Density Function
PDFs	-	Probability Distribution Functions
PERSIANN	-	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PET	-	Potential Evapotranspiration
PGF	-	Princeton Global Forcing
PM	-	Penman-Monteith
PP	-	Perfect prognosis
PREC/L	-	Precipitation Reconstruction Land
PSO	-	Particle Swarm Optimization
PT	-	Power Transformation
R2	-	The Coefficient of Determination
RBias	-	Relative bias
RCP	-	Representative Concentration Pathways

Agriculture is considered as the most vulnerable sector to climate change as it highly depends on water resources (Zhang *et al.,* 2012). In most of the arid regions, rural economies are highly dependent on agriculture land use in which cultivation is highly productive but restricted to the limited land area due to the availability of water (Nautiyal *et al.,* 2015). Therefore, the lack of water affects the livelihood of the vast population when it occurs in such a region (Al-Furaiji *et al.,* 2015). Climate-induced changes in the frequency and severity of agricultural water scarcity in the future can cause severe and long-lasting impacts on agriculture, livelihood and natural systems if proper adaptation measures are not taken (Nam *et al.,* 2015).

The most imminanat and direct impact of climate change on agriculture would be through changes in crop water demand. The crop water demand defines the total amount of water required by a crop during its whole life cycle. It is also defined as the irrigation need of the crop. Precipitation and potential evapotranspiration are used to define water balance (Thornthwaite, 1948; Tsakiris and Vangelis, 2005) and thus, crop water requirements (Kar and Verma, 2005). Potential evapotranspiration is an important index of hydrologic budgets at different spatial scales (Lu et al., 2005). The principles of atmospheric water balance defined by Thornthwaite (1948) and applied later to estimate crop water demand (CWD). The CWD is also used to analysis drought and water resource availability using standardized precipitation evapotranspiration index (SPEI) (Hui-Mean et al., 2018; Shiru et al., 2018).

Previous studies on atmospheric water balance and the effects of climate change on water use in agriculture in the form of changes in net irrigation requirements, demand, and crop water use revealed significant increase in irrigation demand in almost all regions of the globe (Al-Najar and Ashour, 2013; Azad et al., 2018; Brouziyne et al., 2018; Guo and Shen, 2016; Wang et al., 2016a; Wang et al., 2016b; Zaman et al., 2016; Zamani et al., 2017). The increases will be more in the regions where temperature is rising faster while the rainfall is decreasing or not changing significantly such as the arid region in the Middle East.

The indirect impact of climate change on agriculture will through the increase in aridity. Aridity is naturally produced by a permanent imbalance in the water availability (Pour et al., 2019). The expansion of aridity is considered a major environmental impact of global warming. The rise in temperature and a change in precipitation patterns have been noticed in many regions of the world due to global warming (Wang et al. 2016a; Khan et al. 2018). The annual and seasonal total potential evapotranspiration (PET) have been found to exceed the precipitation and thus, expansion of drylands in all climatic regions (Dai 2011a; Huang et al. 2016b; Huang et al. 2017; Lickley and Solomon, 2018; Zhao et al. 2019). Li et al. (2014a) reported a global increase in drylands by 3.1% during 1980-2008 compared to that from 1948–1979. The drying tendency is also projected to continue throughout the present century due to the heating of the globe (Feng et al. 2013; Asadi Zarch et al. 2017; Koutroulis 2019).

Arid lands have fragile ecosystems that are highly vulnerable to climatic changes (Huang et al., 2016a). The increases in aridity make a region more prone to droughts and higher susceptible to water scarcity (Dai, 2011a). It causes soil moisture deficits (Berg et al., 2017) and losses of agricultural productivity and thus, affects the livelihood of vast populations depending on agriculture. Besides, it significantly contributes to land degradation and losses of biodiversity (Durán et al., 2018). The intra- and inter-annual variability of climate in the dry region is usually highly (Salguero-Gómez et al. 2012; Ahmed et al. 2017), which makes the hydrological systems of the region complex and often to exhibit extreme behaviors (Buytaert and De Bièvre., 2012). Therefore, an increase in aridity makes an area more susceptible to natural disasters and climate change-related hazards (Dutta and Chaudhuri 2015). It is important to enhance the knowledge on the transition of aridity in order to improve the adaptation capability.

There is large spatial heterogeneity in CWD and aridity trends across the globe (Greve et al. 2014; Ahmed et al. 2019a). CWD and aridity in some regions has increased sharply while the increase is found negligible in many regions (Greve et al., 2014). The decreasing trend in CWD and aridity has also been reported in some regions (Finkel et al. 2016; Yin et al. 2018). The large spatial heterogeneity in aridity trends and the shift of drylands emphasize the need for assessment of aridity changes at the regional scale.

hindcasts for the development of MOS model is often very complex and challenging. It is important to search a sophisticated approach for modeling the relationship between local climate with GCM hindcast to improve the performance of MOS downscaling and reliability in climate change projections.

The non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1955) is generally used to assess the significance of trends in hydro-climatic phenomena, considering that natural variability alters the climate pattern on time scales shorter than 30 years (WMO, 1996). However, long-term persistence (LTP) can lead to a considerable reduction in the significance of trends (Koutsoyiannis 2003; (Kumar *et al.,* 2009; Ehsanzadeh and Adamowski 2010; Lacombe *et al.,* 2012; Shahid *et al.,* 2014; Fathian *et al.,* 2015; Salman *et al.,* 2017). Thus, it is important to reevaluate the trends considering the presence of LTP in time series in order to distinguish the multi-scale natural variability of climate from anthropogenic climate change.

1.3 Objectives of the Study

The major objective of the present study is to develop a methodology for systematic assessment of regional changes in climate and its impacts on agricultural water stress in a data-scarce region. The specific objectives are:

i. To evaluate the changes in aridity and crop water demand using gridded climate data over the period 1951-2010

ii. To develop an ensemble of most suitable GCMs based on their performance in simulating observed climate in order to reduce uncertainty in future climate projections

iii. To select a suitable statistical downscaling method for the reliable projection of climate at a finer spatial resolution using an ensemble of GCMs

iv. To simulate the future changes in aridity and crop water demand in order to evaluate the changes in possible agricultural water stress due to climate change projection of possible future changes in climate. It is expected that the results presented in this study will promote more research on regional scale impacts assessment for Syria.

Climate change is supposed to have strong negative effects on hydrology in arid regions with significant implications on agriculture and livelihood of people. The methodological framework developed in the present study can be beneficial for the identification of reliable gridded precipitation and temperature data and GCMs by using robust statistical methods for climate change studies.

The study will also help to improve the knowledge of climate downscaling and projections in arid regions that is generally much challenging compared to wet region due to erratic and infrequent behavior of rainfall. The methodology developed in this study for the downscaling and projection of climate can be used for reliable projection of climate with less computation and time.

Syria is a conflict-ridden country and highly vulnerable to environmental changes. The knowledge generated in this study will assist in guiding the operational responses of the various authorities, especially in terms of those interventions aimed at water stress reduction. The finding of the study will be beneficial to a number of stakeholders, particularly water resources and agricultural management, but also the development/planning authorities to improve their understanding of aridity and water stress patterns of the country.

1.6 Thesis Outline

The thesis is divided into five chapters. Descriptions of the chapters are given below in brief.

Chapter 1 gives a general introduction comprising of the background of the study, problem statement, objectives of the study, scope of the work, and significance of the study.

Chapter 2 provides a general review of relevant literature on previous studies on gridded climate data, GCM selection, climate downscaling and projection, aridity and CWD assessment.

Chapter 3 comprises of the methodology used in the study. Study area description, data and sources, and the details of the methods used for the assessment and validation of gridded data, historical and future assessment of aridity and CWD, selection of bias correction methods and downscaling of GCMs, and assessment of the impacts of the changing climate on aridity and CWD are given in this chapter.

Chapter 4 presents the results obtained in the study. It includes the results of data quality assessment, performances of gauge-based precipitation data, selection of GCMs, statistical downscaling and projection of climate, shifting in aridity and changes in CWD.

Finally, the conclusions made from the study are given in Chapter 5. Future research envisaged from the study is also discussed.

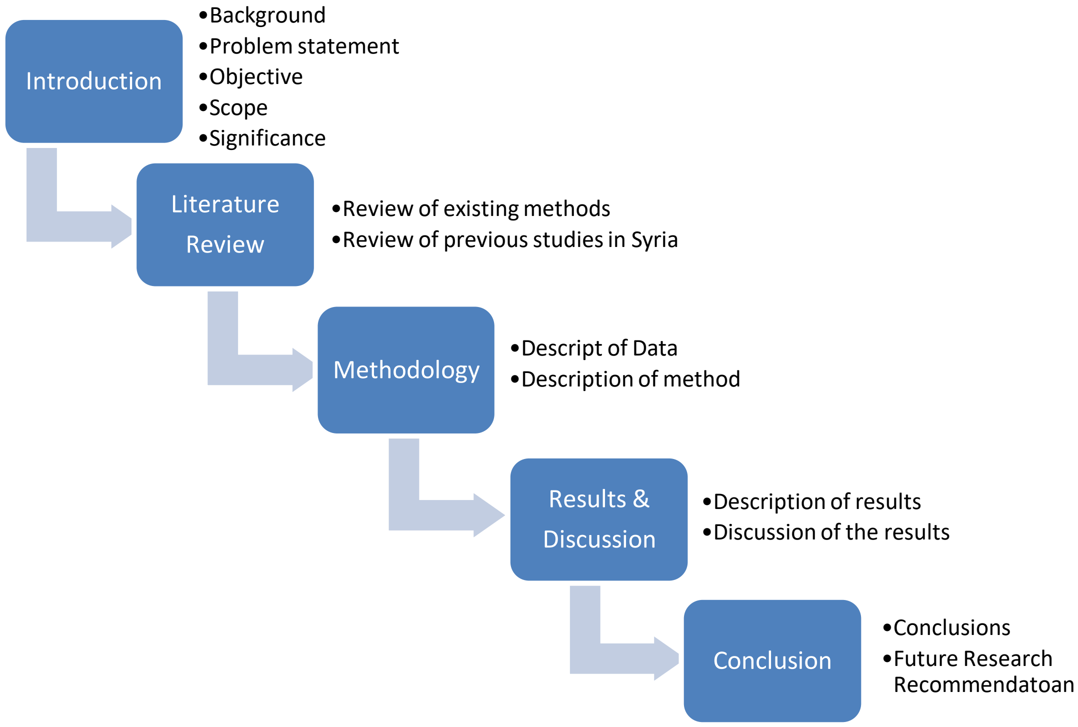

Figure 1.1 Flow showing the organization of the thesis

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