PROJECTION AND PREDICTION OF HEAT WAVES FOR AN ARID REGION IN THE CONTEXT OF CLIMATE CHANGE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

OCTOBER 2019

ACKNOWLEDGEMENT

I take this opportunity to thank my supervisor Dr. Shamsuddin Shahid for his scholastic guidance, constant encouragement, inestimable help, valuable suggestions and great support throughout my study. His valuable feedback and encouragement kept me motivated to complete this thesis.

I am also thankful to Dr. Tarmizi Ismail for being my co-supervisor. Special thanks to Prof. Eun-Sung Chung and Prof. Xiao-Jun Wang for their encouragement, guidance, and support. Also, I find myself in debt to anonymous reviewers for reviewing my work in various international journals and sharing their valuable knowledge.

I am grateful to the Pakistan Meteorological Department (PMD) for providing meteorological data of Pakistan.

I acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the World Climate Research Programme’s (WCRP) Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP5 multi-model dataset. I also acknowledge the developers of PGF, CPC, BEST, APHRODITE for providing gridded temperature and precipitation datasets.

I am also indebted to the Higher Education Commission (HEC) for the funding my study. At last but not the least, I feel highly indebted to my beloved family and friends for their unconditional support, patience and love which were always there for me.

ABSTRACT

Forecasting temperature extremes especially heat waves are extremely important for developing preparedness and planning mitigation measures, particularly in the context of climate change. The major objective of the present study was to assess the ongoing changes and possible future changes in heat waves and development of robust statistical model for forecasting heat wave which can adapt with changing climate. Pakistan, which is one of the most affected countries of the world to heat waves in recent years was considered as the study area. Novelties of the study are the methods proposed for defining heat waves, reliable projection of heat waves with associated uncertainties, and development of robust forecasting models which can adapt with climate change. Available in-situ temperature records, gauge-based gridded temperature data and temperature simulations of general circulation data (GCM) of Coupled Model Intercomparison Project Phase 5 (CMIP5) were used for defining heat waves and assessment of historical changes and future projections of temperature extremes and heat waves, while the reanalysis atmospheric data of National Centres for Environmental Prediction (NCEP) was used for the development of heat wave forecasting models. A threshold-based approach which able to demarcate the historical heat wave affected area is proposed for defining heat waves, GCMs were selected based on their capability to simulate different characteristics of heat waves and different state-of-the-art machine learning methods (ML) were used for the development of the seasonal and daily heat wave forecasting models. The study revealed that the daily maximum temperature more than 95-th percentile threshold for consecutive five days or more can well reconstruct the spatial pattern of heat wave in Pakistan. The assessment of trends in heat waves based on the derived definition revealed increase in heat wave duration and affected area in Pakistan at a rate of 0.71 days/decade and 1.36% of the total area of Pakistan per decade respectively. Four GCMs namely, CCSM4, CESM1(BGC), CMCC-CM and NorESM1-M were found to have better ability for the projection of all the characteristics of heat waves. The projection of heat waves using the selected GCMs revealed a high increase in the heat wave indices particularly for representative concentration pathways (RCP) 8.5. Heat wave frequency was projected to increase up to 12 events per year in most parts of the country, while some areas would experience heat waves for more than 100 days in a year. The higher increase in heat waves indices was projected in highly populated eastern and southern coastal regions which are already prone to high occurrence of heat waves. Forecasting models were developed for the prediction of triggering date and seasonal number of heat waves days in order to aid in coping and mitigation capacity revealed that the Quantile Regression Forests (QRF) models were able to forecast the triggering and departure dates of heat waves with an accuracy of up to ±5 days. On the other hand, the Support Vector (SVM) model was found to have the higher skills in forecasting number of heat wave days with a month time-lag (R^2: 0.89-0.9, NRMSE%: 32.6-31.8, rSD: 0.98-0.96, and md: 0.8). The analysis of synoptic patterns revealed that the wind vectors, relative humidity and geopotential height are the most potential indicators of heat waves in Pakistan. The forward-rolling based forecasting model proposed for the prediction of heat waves to accommodate the changing pattern of the atmospheric variables responsible for heat waves due to the changes in climate was found to forecast heat waves reliably.

ABSTRAK

Ramalan suhu ekstrem terutama gelombang haba amat penting bagi merancang langkah-langkah persediaan dan mitigasi terutamanya dalam konteks perubahan iklim. Objektif utama kajian ini adalah untuk menilai perubahan gelobang panas yang berlaku dan kemungkinan perubahan pada masa depan serta pembangunan model statistik yang mantap bagi ramalan gelombang haba yang boleh diadaptasikan dengan perubahan iklim. Pakistan, salah satu daripada negara-negara yang paling terjejas di dunia dalam pemanasan gelombang pada tahun-tahun kebelakangan ini dijadikan sebagai kawasan kajian. Kebaharuan kajian ini adalah pembangunan kaedah cadangan untuk menentukan gelombang haba, unjuran gelombang haba yang boleh dipercayai berserta dengan faktor ketidakpastian, dan pembangunan model ramalan yang mantap yang boleh diadaptasi dengan perubahan iklim. Rekod suhu ditapak, data suhu simulasi bergrid dan data suhu simulasi dari *General Circulation Model* (GCM) bagi *Coupled Model Intercomparison Project Phase 5 (CMIP5)* digunakan untuk menentukan gelombang haba dan penilaian perubahan sejarah dan unjuran masa depan suhu ekstrem dan gelombang haba, manakala data atmosfera yang dianalisis semula oleh *National Centres for Environmental Prediction* (NCEP) digunakan untuk pembangunan model ramalan gelombang haba. Pendekatan berasaskan keupayaan yang dapat menanda kawasan yang terjejas dimasa lampau dengan kesan gelombang haba dicadangkan untuk menentukan gelombang haba. GCM dipilih berdasarkan keupayaan mereka untuk mensimulasikan ciri-ciri gelombang haba yang berbeza dan kaedah *machine learning* (ML) digunakan untuk pembangunan model ramalan gelombang haba harian dan bermusim. Kajian itu mendedahkan bahawa suhu maksimum harian lebih daripada persentil lingkungan yang ke 95 peratus untuk lima hari berturut-turut atau lebih boleh membina semula corak ruang gelombang panas di Pakistan. Penilaian corak gelombang panas berdasarkan definisi yang diperolehi menunjukkan peningkatan tempoh gelombang haba dan kawasan yang terjejas di Pakistan masing-masing pada kadar 0.71 hari /dekad dan 1.36% daripada jumlah kawasan Pakistan setiap dekad. Empat *GCM* iaitu *CCSM4*, *CESM1 (BGC)*, *CMCC-CM* dan *NorESM1-M* didapati mempunyai keupayaan yang lebih baik untuk unjuran semua ciri-ciri gelombang haba. Unjuran gelombang panas menggunakan GCM terpilih menunjukkan peningkatan yang tinggi dalam indeks gelombang haba terutamanya untuk *Representative Concentration Pathways* (RCP 8.5). Kekerapan kejadian gelombang panas dijangka meningkat sehingga 12 kali setiap tahun di kebanyakan kawasan di Pakistan, manakala sesetengah kawasan akan mengalami gelombang panas dalam tempoh lebih daripada 100 hari dalam setahun. Peningkatan indeks gelombang haba dijangka lebih tinggi di rantau berpenghuni tinggi di pesisiran pantai timur dan selatan yang sudah terdedah kepada kejadian gelombang haba yang tinggi. Model ramalan telah dibangunkan bagi ramalan tarikh kejadian dan bilangan harian gelombang musim panas untuk membantu dalam mengatasi dan memitigasi kapasiti kejadian berkenaan. Model *Quantile Regression Forests* (QRF) yang dicadangkan dalam kajian ini mampu meramalkan tarikh pencetus dan keberangkatan gelombang haba dengan ketepatan sehingga ± 5 hari. Sebaliknya, model *Support Vector Machine* (SVM) didapati lebih berupaya dalam ramalan bilangan harian gelombang haba dengan masa lag bulanan (R^2: 0.89-0.9, NRMSE%: 32.6-31.8, rSD: 0.98- 0.96, dan md: 0.8). Analisis pola sinoptik menunjukkan bahawa vektor angin, kelembapan relatif dan ketinggian geopotential adalah petunjuk paling berpotensi bagi gelombang haba di Pakistan. Model ramalan gelombang haba yang dicadang berasaskan *forward rolling* yang mantap bagi menampung perubahan corak pembolehubah atmosfera yang bertanggungjawab keatas gelombang haba akibat perubahan iklim didapati mampu meramal gelombang haba dengan berkesan.

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LIST OF ABBREVIATIONS

1DMn	-	Minimum 1-day temperature in a year
1DMx	-	Maximum 1-day temperature in a year
ACHW	-	Area having both maximum and minimum temperature above a certain percentile
AHW	-	Affected area by heat waves
ANN	-	Artificial Neural Network
APHRODITE	-	Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation
AR5	-	Fifth Assessment Report
AT	-	Atmospheric Temperature
BEST	-	Berkeley Earth Surface Temperature
CMIP	-	Coupled Model Intercomparison Project Phase
CP	-	Compromise Programming
CPC	-	Climate Prediction Centre
CTHW	-	Cumulative temperature during heat waves
CW	-	Cold Wave
d	-	Index of agreement
DCHW	-	Period for which both maximum and minimum temperature above a certain percentile
DHW	-	Maximum duration of heat wave
DTR	-	Diurnal Temperature Range
ECMWF	-	European Centre for Medium-Range Weather Forecasts
ENSO	-	El Niño–Southern Oscillation
F-test	-	Fisher Test
GCM	-	General Circulation Model
HGT	-	Geopotential Height
HWD	-	Heat Wave Days
HWI	-	Heat Wave Index
HWI	-	Heat wave index
IPCC	-	Intergovernmental Panel on Climate Change

KNN	-	k-Nearest Neighbours
LTP	-	Long Term Persistence
md	-	Modified Index of agreement
MI	-	Mutual Information
MK	-	Mann-Kendall Test
ML	-	Machine Learning
MLR	-	Multiple Linear Regression
MMK	-	Modified Mann-Kendall Test
NCAR	-	National Centre for Atmospheric Research
NCEP	-	National Centre for Environmental Prediction
NRMSE	-	Normalized Root Mean Square Error
NSE	-	Nash–Sutcliffe model efficiency coefficient
Pbias	-	Percentage Bias
PC	-	Principal Component
PCA	-	Principal Component Analysis
PCMDI	-	Program for Climate Model Diagnosis and Intercomparison
PEM	-	Physical Empirical Model
PMD	-	Pakistan Meteorological Department
QRF	-	Quantile Regression Forests
RCP	-	Representative Concentration Pathway
RF	-	Random Forests
RH	-	Relative Humidity
rSD	-	Ratio of Standard Deviation
SLP	-	Sea Level Pressure
SRES	-	Special Report on Emissions Scenarios
SST	-	Sea Surface Temperature
SU	-	Symmetrical Uncertainty
SVM	-	Support Vector Machines
SVM-RFE	-	Support Vector Machine - Recursive Feature Elimination
THW	-	Maximum temperature during heat waves
UW	-	Eastward Wind
VW	-	Northward Wind
WCRP	-	World Climate Research Programme

LIST OF SYMBOLS

%	-	Percent
mm	-	Millimeter
Km	-	Kilometer
>	-	Greater than
<	-	Less than
W/m^2	-	Watt per square metre

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The anthropogenic activities have caused a rise in global temperature in an unprecedented amount and changed the global climate. It has been reported that the Earth temperature has increased by 0.74˚C in the last century (1906-2005). The rate has been found to be 0.15°C/decade after 1970 which is much higher than the first half of the century (IPCC, 2013). The global temperature rise is projected to continue which in turn would continue to affect the global atmospheric balance and make the climate more variable (Wang *et al.*, 2016b). A minor change in the mean and variability can cause a large change in extremes (Shahid, 2011). Thus, the rises in temperature would certainly cause an increase in the frequency and severity of the temperature extremes. Several studies have reported increase in various temperature extremes in recent years across the globe (Alexander, 2016; Brown *et al.*, 2008; Frías *et al.*, 2012; Grotjahn *et al.*, 2016). It may be more severe and frequent in the near future with the continuous rise of temperature (Ahmed *et al.*, 2016; Frías *et al.*, 2012; Nissan *et al.*, 2017; Pour *et al.*, 2014; Rodrigo, 2002; Shahid *et al.*, 2017). Among the temperature extremes, heat wave is considered as one of the most devastating outcomes of the global warming.

The rising temperature due to global warming has caused a gradual increase in frequency, intensity, duration and areal extent of heat waves (Khan *et al.*, 2019b; Wang *et al.*, 2019). Severe implications of the rising intensity and frequency of heat waves in public health (Buscail *et al.*, 2012; Kovats and Kristie, 2006), agricultural production (De Bono *et al.*, 2004; Teixeira *et al.*, 2013), ecological health (Hallegatte *et al.*, 2007) and environmental condition (Stedman, 2004), and therefore the losses of lives, damages to economy and degradation of people's livelihood (Kim *et al.*, 2017; Masood *et al.*, 2015; Rauf *et al.*, 2017) have been evidenced in recent years. Tens of thousands of death have been reported in the last few years due to climate change induced rises in heat waves (Russo *et al.*, 2014).

The knowledge on ongoing changes and possible future changes in climate are essential components of adaptive capacity and necessary in the development of effective climate change adaptation policies (Khan *et al.*, 2019b). The rises in temperature and thus, the heat waves would not be same for all parts of the world. Assessment of the changes in heat waves at regional or local scales is therefore suggested for adaptation and mitigation planning (Abatan *et al.*, 2016; Abaurrea *et al.*, 2018; Alghamdi and Harrington Jr, 2019; Brown *et al.*, 2008; Gaitán *et al.*, 2019; Gao *et al.*, 2018; Grotjahn *et al.*, 2016; Kang and Eltahir, 2018; Khan *et al.*, 2018b; Khan *et al.*, 2019b; Liu *et al.*, 2018; Nissan *et al.*, 2017; Rauf *et al.*, 2017; Saeed *et al.*, 2017; Salman *et al.*, 2017a; Soltani *et al.*, 2016).

Besides the assessment of the ongoing changes, the early warning is considered as the most important measures for coping and mitigation of heat waves. The warning system should be developed in such a way that it would able to adapt with climate change to provide reliable forecasting. Such system can serve as the key element for the mitigation and adaptions to the heat wave and protection of life and environment to ensure sustainable development (Al-Mukhtar and Qasim, 2019; Gao *et al.*, 2018; Khan *et al.*, 2019b; Singh *et al.*, 2018).

1.2 Statement of Problem

Heat wave is one of the most devastating temperature extremes. It is very important to understand the changes of heat waves due to climate change. However, the major challenge in the assessment of heat waves and their changes is to define the heat wave for a region. There is no universal definition of heat waves. It is mostly defined based on physical and socio-economic contexts of a region, which has made the heat wave related research an intrigue issue. Most of the heat wave definitions derived so far are based on human health outcomes where a temperature threshold in consecutive days is defined with reference to human impacts (Anderson and Bell, 2010; Cao *et al.*, 2018; Cheng *et al.*, 2018; Dong *et al.*, 2016; Fischer and Schär, 2010; Meehl and Tebaldi, 2004; Patz *et al.*, 2005; Robinson, 2001). The major limitation of heat wave definitions based on human impacts is that those are derived using a baseline climate which cannot be used to generate a complete time series of events for trend analysis (Nairn and Fawcett, 2015; Nairn and Fawcett, 2013). Furthermore, such definition cannot be used for the comparison of heat waves between two regions of a country.

To understand the impacts of climate change on temperature extremes and heat waves, it is required to assess their changes. The non-parametric Mann-Kendall (MK) trend test (Kendall, 1948; Mann, 1945) is generally used to assess the significance of trends in climate, considering that natural variability alters the climate pattern in a time scale shorter than 30 years (WMO, 1996). However, recent findings have reported that the wet or dry periods can even exist for a period greater than 50 years (Lacombe *et al.*, 2012; Salman *et al.*, 2017a). Therefore, it has been reported that many of the trends obtained using MK test are due to the multidecadal variability in the time series (Ehsanzadeh and Adamowski, 2010; Fathian *et al.*, 2015; Kumar *et al.*, 2009; Lacombe *et al.*, 2012; Salman *et al.*, 2017a; Shahid *et al.*, 2014). It is important to re-evaluate the trends considering the presence of long-term persistence (LTP) in time series in order to distinguish the multi-scale natural variability of climate from anthropogenic climate change.

Knowledge of possible future changes in heat waves is required for building adaptive capacity to mitigate the effects of heat waves. The temperature simulations of general circulation models (GCMs) are usually used for this purpose. However, due to the uncertainty possessed by different GCMs, it is required to select the most skilled GCMs for the projection of heat waves (McSweeney *et al.*, 2015). An ensemble of smaller number of GCMs are usually selected, excluding those are considered “unrealistic” for a region of interest in order to reduce the uncertainty associated with the GCMs (Lutz *et al.*, 2016). While there are several methodologies proposed to assess the performance of GCMs, the uncertainty associated with the selection of GCMs is always very high (Khan *et al.*, 2018a; Knutti *et al.*, 2013; Lutz *et al.*, 2016; Sharmila *et al.*, 2015). It is required to select GCMs based on the climate variable and phenomenon that would be evaluated using the GCMs (Lutz *et al.* (2016). Therefore, for the reliable projection of heat waves, it is required to select GCMs based on their ability to simulate the different properties of heat waves.

The devastating effect of heat waves can be mitigated significantly by forecasting heat waves (Dodla *et al.*, 2017; Stedman, 2004). The major challenges in heat waves forecasting are: (1) accurate forecasting of seasonal and daily heat wave; (2) forecasting with sufficient time-lag; and (3) incorporation of uncertainty in forecasting. A large number of studies have been conducted for the development of forecasting models, where selection of suitable predictors is given as the main emphasis. However, the performance of a forecasting model also depends on the method used for their development. Heat waves are highly influenced by one or several large-scale atmospheric variables. The influence of these factors on heat waves is highly non-linear. Advanced machine learning models can be used to simulate such highly non-linear systems. However, the use of those advanced technologies in development of heat wave forecasting models is still limited and non-deterministic.

Highly skilled climate forecasting models have been found to show low skill in recent years due to the changes in their prediction capability with the changes in climate (Gao *et al.*, 2018). Even some of the most skilled prediction models have been found to fail in the recent years to detect the forthcoming events (Rajeevan *et al.*, 2007b; Wang *et al.*, 2015). Wang *et al.* (2015) reported that skills of some of the identified predictability sources decrease due the climate change. Thus, forecasting models should consider the climate change and incorporate the climate change impacts on prediction capability for reliable forecasting of heat waves in the context of climate change.

1.3 Objectives of the Study

The main objective of the study is to evaluate the changes in heat wave due to climate change and develop a robust heat wave forecasting model which can adapt with climate change. The specific objectives are:

i. To define the heat wave based on temperature load in order to facilitate the assessment of the spatial and temporal variability of heat waves.
ii. To assess spatio-temporal changes in extreme temperature and heat wave using gauge-based gridded data.
iii. To generate an ensemble of GCMs based on their ability to simulate historical heat waves in order to project the heat waves for different climate change scenarios.
iv. To employ machine learning methods for the development of models for the forecasting of heat waves on daily and seasonal scales.
v. To develop a climate change resilient robust heat wave forecasting model to aid adaptation to climate change impacts on heat waves.

1.4 Scope of The Study

The study mainly focuses in the development of a framework for the assessment of heat waves and the development of the robust statistical models for the forecasting of heat waves. The methodological framework developed in the present study was implemented in Pakistan.

Among the different extreme temperature phenomena, the present study focuses on heat waves. The changes in heat waves were assessed using trend analysis. Only non-parametric trend analysis techniques were used in the study.

Considering the unavailability of long-term daily observed data of temperature for the study area, gauge-based gridded data were used for the assessment of the historical changes in heat waves. The gridded data were also used as the base for the selection of GCMs and the projection of future changes in heat waves.

Thirty-one GCMs of Coupled Model Intercomparison Project Phase 5 (CMIP5) which have projections for two Representative Concentration Pathway (RCP) scenarios namely 4.5 and 8.5 were used for the selection of GCMs for the preparation of ensemble.

Heat wave forecasting models were developed using coarse resolution atmospheric variables. The reanalyses data of National Centres for Environmental Predictions (NCEP) was used for this purpose.

1.5 Significance of The Study

The maps developed in this study that show the spatial pattern in the trends of extreme temperatures and heat waves can help policy makers to understand the vulnerable zones. Those can also be used by different organizations including disaster management for operational planning of disaster risk reduction.

The methodology proposed in the study for the selection of GCMs in a robust manner can help in reduction of uncertainty in the projection of climate change. The GCMs selected in the present study can be used for the assessment of climate change impacts in different sectors in the study area

Due to climate change, failure in different forecasting models has been reported in the recent years. The methodological framework developed in the present study can be used for reliable forecasting of heat waves in the context of climate change. Therefore, the models can be used for the adaptation to climate change.

Pakistan, a developing country is ranked as one of the most vulnerable countries in the world to climate change. It is also ranked as the 10th most affected country by extreme weather events (Kreft *et al.*, 2013). Hundreds to thousands of people die in each year due to the extreme temperature events most notably the heat waves. In recent years, Pakistan observed some of the devastating heat waves including the heat waves of 2015 and 2017. Besides the human health impact and casualty, the agricultural, ecology, environment, stress on the electric and other service sectors are some of the few examples of the affected sectors (Abaurrea *et al.*, 2018). The knowledge generated in this study would be beneficial to a number of stakeholders including the development/planning authorities to improve their understanding of heat waves and their future impact in taking policy oriented decisions.

1.6 Thesis Outline

This 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 includes the assessment of extreme temperature, definition used for heat waves, evolution of GCMs and development of forecasting models.

Chapter 3 presents the methods used in the study to achieve the objectives. The chapter describes the study area and data, methods used for the assessment of gridded temperature data, defining heat wave, selection of general circulation models, development of statistical models for forecasting heat waves, and the development of robust statistical heat wave prediction model immune to climate change.

Chapter 4 presents the results obtained in the study. It includes the results of data quality assessment, spatial and temporal changes in different temperature extreme and heat waves, selection of the GCMs based on different characteristics of heat wave, and validation of heat wave forecasting models.

Finally, the conclusions made from the study are presented in Chapter 5. Future research envisaged from the study is also given in the end of this chapter.

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