A NEW DEFINITION OF HEAT WAVES UNDER CLIMATE CHANGE

by

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ABSTRACT

A NEW DEFINITION OF HEAT WAVES UNDER CLIMATE CHANGE

For the last few decades, changes in frequency, intensity, and duration of extreme climate events have been detected, and these observations are linked to human-induced climate change. To state the amount of change in these extreme events is difficult, due to many variables such as internal modes of climate variables and land use changes. Also, because of rarity of reliable climate records and extreme climate events, taking the data of climate extremes which occurred in the past into consideration is risky. The definition of an extreme event is a rare occurrence, so their records are not abundant [1]. Since the meaning of extreme can change from region to region, generic explanations must be comparative with its own values. In this study, changes in heat index (HI) and wind chill index (WCI) values are stated, according to RCP 4.5 and RCP 8.5 scenarios, and analyzed by comparing each city by its own former data. This study covers ten most crowded cities in MENA (Middle East and North Africa) region: Alexandria, Amman, Ankara, Baghdad, Cairo, Istanbul, Izmir, Jeddah, Riyadh, and Tehran. The aim of this study is to assess frequency, intensity and duration changes in index values for these cities. To achieve that, four definitions are made for each index: extremely hot days, hot days, cold days, and extremely cold days. Firstly, the total counts of each term from past and model outputs are compared to observe the change in frequencies. Secondly, consecutive day counts are compared between past values and model outputs to assess the differences in duration. As a result, according to both RCP 4.5 and RCP 8.5 scenarios, number of hot days and number of extremely hot days will increase in future. Also, their durations will be longer and their observed values will be higher for each city. Nevertheless, increase rate of frequency, intensity, and duration will vary in each city.

ÖZET

İKLİM DEĞİŞİKLİĞİ ALTINDA SICAK HAVA DALGALARININ YENİ TANIMI

Son birkaç on yıldır, aşırı iklim olaylarının sıklığı, yoğunluğu ve sürelerinde değişiklikler gözlemlenmiştir ve bu gözlemler insan kaynaklı iklim olaylarıyla ilişkilidir. Bu aşırı olaylardaki değişimin miktarını belirtmek, iklim değişkenlerinin iç modları ve arazi kullanım değişiklikleri gibi birçok değişken nedeniyle zordur. Ayrıca, güvenilir iklim kayıtlarının ve aşırı iklim olaylarının nadir olması nedeniyle, geçmişte meydana gelen bu tür olayların verisinin dikkate alınması risklidir. Aşırı bir olay tanımı gereği nadir bir olaydır, ve bu nedenle kayıt altına alınmış bu tür olayların sayısı oldukça azdır [1]. "Aşırı"nın anlamı bölgeden bölgeye değişebildiğinden, genel açıklamaların kendi değerleri ile karşılaştırmalı olması gerekir. Bu çalışmada, RCP 4.5 ve RCP 8.5 senaryolarına göre, sıcaklık endeksi (HI) ve rüzgar serinlik endeksi (WCI) değerlerindeki değişiklikler belirtilmiştir ve her bir şehir, kendi geçmiş verisiyle karşılaştırılarak analiz edilmiştir. Bu çalışma MENA (Orta Doğu Kuzey Afrika) bölgesindeki en kalabalık 10 şehri kapsamaktadır: İskenderiye, Amman, Ankara, Bağdat, Kahire, İstanbul, İzmir, Cidde, Riyad ve Tahran. Bu çalışmanın amacı, belirtilen iller için endeks değerlerindeki sıklık, yoğunluk ve süre değişimlerini değerlendirmektir. Bunu başarmak amacıyla her endeks için dört tanım yapılmıştır: aşırı sıcak günler, sıcak günler, soğuk günler ve aşırı soğuk günler. İlk olarak, geçmiş verisindeki her tanıma uygun toplam gün sayıları ve model çıktıları, frekanslardaki değişimleri gözlemlemek için karşılaştırılmıştır. Daha sonra, süre değişimlerini değerlendirmek için tanımlara uygun ardışık gün sayıları, geçmiş değerler ile model çıktıları karşılaştırılmıştır. Sonuç olarak, hem RCP 4.5 hem de RCP 8.5 senaryolarında sıcak gün sayıları ve aşırı sıcak gün sayılarında artış gözlemlenmiştir. Ancak bu tanımların, sıklık, yoğunluk ve sürelerdeki artış oranı şehir bazında değişiklik göstermektedir.

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LIST OF SYMBOLS

RH	Relative humidity
T	Temperature
V	Wind speed
μ	Mean value
σ	Standard deviation

LIST OF ACRONYMS/ABBREVIATIONS

CORDEX	Coordinated Regional Climate Downscaling Experiment
DI	Discomfort Index
GCMs	Global Circulation Models
HI	Heat index
LAMs	Limited Area Models
MENA	Middle East and North Africa
RCP	Representative concentration pathway
RegCM	Regional Climate Model
WCI	Wind chill index
WCT	Wind chill / temperature index

1. INTRODUCTION

For the last few decades, changes in frequency, intensity, and duration of extreme climate events have been observed. It is observed that these changes are linked to human-induced climate change. To state the amount of change in these extreme events is difficult to quantify due to many variables such as internal modes of climate variables and land use changes. Also, due to rarity of reliable climate records and rarity of extreme climate events, taking the data of climate extremes which occurred in the past into consideration is risky. The definition of an extreme event is a rare occurrence, so records of them are not abundant [1]. Since the meaning of extreme can change from region to region, generic explanations must be comparative with its own values. For example, Perkins used heat index as minimum 90^{th} percentile and maximum 90^{th} percentile to express extreme values [2]. Also, daily maximum and minimum values can be used to explain extreme events' durations, frequencies and intensities [3]. The definition of the extreme event can change based on location; it is related to the mean of the climatic condition of specified locations. Probability, duration, and seasonality are some of the many characteristics of extreme climate events [2].

Heat index was firstly introduced in 1959 by E.C. Thom to assess apparent temperature from dry bulb temperature and humidity [4]. Since humidity had an effect on people feeling discomfort from hot weather, it was necessary to assess an index for it. His formula was $DI = T – (0.55 – 0.0055 \times RH) \times (T – 14,5)$ where T is dry bulb temperature in Celsius and RH was relative humidity in percentile. The table below shows the discomfort conditions according to the index:

Table 1.1. Heat index chart with air temperature in Celsius and relative humidity in percentile with formula: $DI = T – (0.55 – 0.0055 \times RH) \times (T – 14,5)$ where T (dry bulb temperature) in Celsius and RH (relative humidity) in percentage [5].

Condition	**DI**
No discomfort	<21
Under 50% of the population feels discomfort	21 - 24
Over 50% of the population feels discomfort	25 - 27
Most of the population suffers from discomfort	28 - 29
Everyone feels stressed	30 - 32
State of medical emergency	>32

Relative Humidity (%)

Air Temperature (°C)

	25	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
42	32	32	33	33	34	34	35	35	36	36	37	37	37	38	38	38
41	31	32	32	33	33	34	34	35	35	35	36	36	37	37	37	37
40	30	31	31	32	32	33	33	34	34	35	35	35	36	36	36	37
39	30	30	31	31	32	32	33	33	34	34	34	35	35	35	36	36
38	29	30	30	31	31	31	32	32	33	33	34	34	34	35	35	35
37	28	29	29	30	30	31	31	32	32	32	33	33	33	34	34	34
36	28	28	29	29	30	30	30	31	31	32	32	32	33	33	33	34
35	27	27	28	28	29	29	30	30	30	31	31	32	32	32	33	33
34	26	27	27	28	28	29	29	29	30	30	30	31	31	31	32	32
33	26	26	27	27	27	28	28	29	29	29	30	30	30	31	31	31
32	25	25	26	26	27	27	27	28	28	29	29	29	30	30	30	30
31	24	25	25	26	26	26	27	27	27	28	28	28	29	29	29	30
30	24	24	24	25	25	26	26	26	27	27	27	28	28	28	29	29
29	23	23	24	24	25	25	25	26	26	26	27	27	27	27	28	28
28	22	23	23	23	24	24	25	25	25	25	26	26	26	27	27	27
27	22	22	22	23	23	23	24	24	24	25	25	25	26	26	26	26
26	21	21	22	22	22	23	23	23	24	24	24	25	25	25	25	25
25	20	21	21	21	22	22	22	23	23	23	23	24	24	24	25	25
24	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24
23	19	19	20	20	20	21	21	21	21	22	22	22	22	23	23	23
22	18	19	19	19	19	20	20	20	21	21	21	21	22	22	22	22

Studies show that morbidity and mortality are related to extreme events [6]. For instance, European heatwave in 2003 had resulted in loss of many lives [7]. Temperature had exceeded mean temperatures of 1961 - 1990 by 6°C in summer [8]. In 2003, a heatwave had a major effect on mortality. Europe faced a major heat wave with severe results. The number of deaths exceeded the statistical mortality rates between 22000 and 35000. Also, in France, mortality rate increased by 54% in the first half of August 2003 [9]. In 1995, Chicago faced over 500 deaths caused by extreme heat [10]. Climate extremes also have many outcomes which have an effect on survival such as forest fires, crop loss and increase in electric usage etc. For instance, 2003 heat wave had resulted in crop loss around $14 billion [9]. On 14 July 1995, in Chicago, electric usage exceeded 19200 MW which was the highest usage value until that time [10]. Furthermore, a lot of livestock died from excessive heat in 1995 [10]. The summer of 2010 was also very warm in Europe and in parts of Russia. With increase in concentration of greenhouse gases; daily mean temperatures, nighttime and daytime temperatures were exceptionally high in that summer. 2010 heat wave had exceeded 2003 heat wave in the area spanned and magnitude. The temperature exceeded mean values around one standard deviation in these heat waves. Also, in 2010 heat wave, an extensive fire resulted from the heat wave caused 53 deaths, and over 3000 people lost their homes [11]. Barriopedro et al. showed that in future, it is very likely that heat waves will occur in highly populated areas [11]. Since heat waves have a severe impact on human life, in this study the changes in duration and frequency of heat index were observed.

Around 1919, Sir Leonard Hill and his associates made a dry kata-thermometer to observe the cooling rate of the wind. This thermometer was just like a regular thermometer, but it was heated above the human blood temperature (around 98.4°F). The purpose of the experiment was to find the average time for 1°F change. They measured the time of cooling of the thermometer below the human blood temperature and they took the average time for this purpose. The experiment setup was exposed to wind, but they avoided direct sunlight. There were some other experiments like Hill's one, but it was impossible to design a device that measures cold sensation because human head shapes and dimensions are different from one another. For the purpose of finding a wind chill temperature index, Siple and Passel made an experiment in

Antarctica and they published an article from their findings. Experiment setup was a cylinder with length in 5.875 and diameter in 2.259 made from pyrroline which is hung down from a 10-feet-tower. The reason why pyrroline cylinder was used is that this matter has similar conductivity to human skin. The cylinder was filled with 250 grams of water, and after adding thermohm, it was sealed. The purpose of using pyrroline cylinder filled with water was to simulate human face. They collected wind speed and heat data from an anemometer which was hanged at the same height with cylinder and the thermohm inside the cylinder. They measured the time needed for water to freeze. Data were collected at night to prevent the heating effect of direct sunlight. Since absolute humidity was too low and outgoing radiation always exceeded incoming radiation, humidity and radiation were neglected. In this experiment, there were some issues that could affect the results. Due to the limitations in low wind speed measurements such as turbulence's effect at low wind velocities, the results were underestimated [12].

According to Dr. Maurice Bluestein, wind chill index is overestimated because the assumption of facial skin temperature is unrealistic, it is accepted as constant 33°C but under extremely cold weather conditions, facial skin temperature can be much lower [13] [14]. For instance, exposure to - 5°C air without wind for three minutes can drop the temperature of face about 10°C [15]. Also, the experimental setup was 10 feet above the ground, so it gave different wind speed data from an average human faced. Especially for urban areas, wind speed data was misleading. Since solar radiation was neglected, even though the heating effect of direct sunlight on a clear day could compensate the wind chill, it was not taken into account for the index calculations [16]. Water might lose its purity and get mixed with pyrroline, so freezing point might have been changed [12]. The thermal resistance of pyrroline container might have changed the formula, but in Siple and Passel experiment, water temperature was accepted as surface temperature. Furthermore, heat loss caused by radiation and convection was not considered in calculations [13].

On the other hand, due to the thickness of the cylinder surface used in Siple and Passel's experiment, heat loss per unit area was similar to human face [17]. Osczevski modeled heat loss from human face mathematically and he had indicated that even though wind chill index has flaws, it could be used as an indicator of human sensations. One of the assumptions to create this new model was that the main exposure to cold and wind occurring in facial area. Since facial skin temperature was closely related to wind chill index, the main sensation of wind chill might be caused by temperature drop on facial skin [18]. After Osczevski had renovated wind chill index with a mathematical model, in 2005 he and his colleagues made a new experiment setup which included a cylinder with 18cm diameter tilted with 50° angle to simulate cheeks exposed to direct wind-. The new wind chill temperature chart is shown below:

Table 1.2. New wind chill chart with air temperature in Celsius and wind speed in kilometer per hour unit with formula:

$$WCT = 13.12 + 0.6215 \times T - 11.37 \times V^{0.16} + 0.3965 \times T \times V^{0.16}$$

Frostbite can occur in the shaded parts [18].

Air Temperature (°C)

Wind Speed (km/h)	**10**	**5**	**0**	**-5**	**-10**	**-15**	**-20**	**-25**	**-30**	**-35**	**-40**	**-45**	**-50**
10	9	3	-3	-9	-15	-21	-27	-33	-39	-45	-51	-57	-63
15	8	2	-4	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66
20	7	1	-5	-12	-18	-24	-31	-37	-43	-49	-46	-62	-68
25	7	1	-6	-12	-19	-25	-32	-38	-45	-51	-57	-64	-70
30	7	0	-7	-13	-19	-26	-33	-39	-46	-52	-59	-65	-72
35	6	0	-7	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73
40	6	-1	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74
45	6	-1	-8	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75
50	6	-1	-8	-15	-22	-29	-35	-42	-49	-56	-63	-70	-76
55	5	-2	-9	-15	-22	-29	-35	-42	-48	-55	-63	-70	-77
60	5	-2	-9	-16	-23	-30	-37	-43	-50	-57	-64	-71	-78
70	5	-2	-9	-16	-23	-30	-37	-44	-51	-59	-66	-73	-80
80	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81

To find the combined effect of climate variables on live beings, wind chill index is used by many researchers. For instance, R. A. Hill and his colleagues have shown that behaviors of primates are correlated with wind chill index [19]. Also, wind chill effect causes people to feel discomfort under certain air temperatures and wind speeds [20].

In this study, changes in frequency, intensity and duration of heat index and wind chill index of 10 most crowded cities over CORDEX-MENA Region are analyzed according to RCP 4.5 and RCP 8.5 scenarios between 2070 and 2100 by comparing with past data (1970-2000).

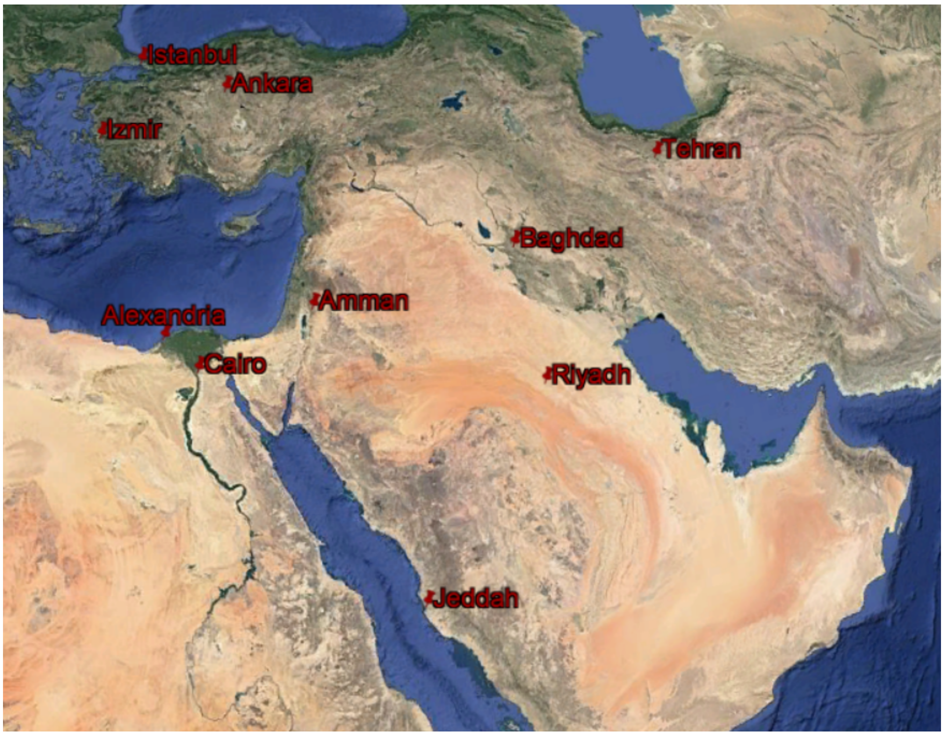

Figure 1.1. Selected cities for study in CORDEX-MENA region.

2. METHOD

2.1. The Representative Concentration Pathways (RCPs)

The Representative Concentration Pathways (RCPs) were designed to assist researchers on effects of potential policies on climate change by giving pathways of greenhouse gases concentrations and emissions [21]. Representative Concentration Pathways (RPCs) are the scenarios which give an upper limit to radiative forcing. There are four scenarios with radiative forcing 2.6 W/m^2, 4.5 W/m^2, 6 W/m^2 and 8.5 W/m^2 [22]. To follow RCP 2.6 carbon emission should decline by 50% by mid-century; however, according to many researchers, to achieve it is more than challenging [23]. Since RCP 8.5 is the worst-case scenario and RCP 4.5 is a possible scenario, in this study radiative forcing levels are taken as 8.5 W/m^2 and 4.5 W/m^2.

2.2. Global Circulation Models (GCMs)

Global Circulation Models (GCMs) are numerical models which process physical properties such as oceans and land surface to simulate response of climate variables such as greenhouse gasses concentrations in atmosphere. Three dimensional grids over the globe with horizontal resolutions between 250 to 600 km and 10 to 20 vertical layers in the atmosphere are used in GCMs [24].

2.3. Regional Climate Models (RegCMs)

Since GCMs resolutions are low RegCMs are developed. Regional Climate Model (RegCM) was firstly introduced in the second half of 1980's. Since then, model has evolved to new versions. RegCM 4.0 is released in June 2010 from ICTP as prototype and the full version RegCM 4.1 released in May 2011. Limited Area Models (LAMs) are designed as one-way nesting. Outputs of General Circulation Models (GCMs) are taken as initial conditions and boundary conditions to regional models for high resolution. GCMs does not take feedback from RegCMs.

The RegCM modeling system has four components: Terrain, ICBC, RegCM, and Postprocessor. Terrain and ICBC are the two components of RegCM preprocessor. Terrestrial variables (including elevation, land-use and sea surface temperature) and three-dimensional isobaric meteorological data are horizontally interpolated from a latitude-longitude mesh to a high-resolution domain on either a Rotated (and Normal) Mercator, Lambert Conformal, or Polar Stereographic projection. Vertical interpolation from pressure levels to the σ coordinate system of RegCM is also performed. σ surfaces near the ground closely follow the terrain, and the higher-level σ surfaces tend to approximate isobaric surfaces.

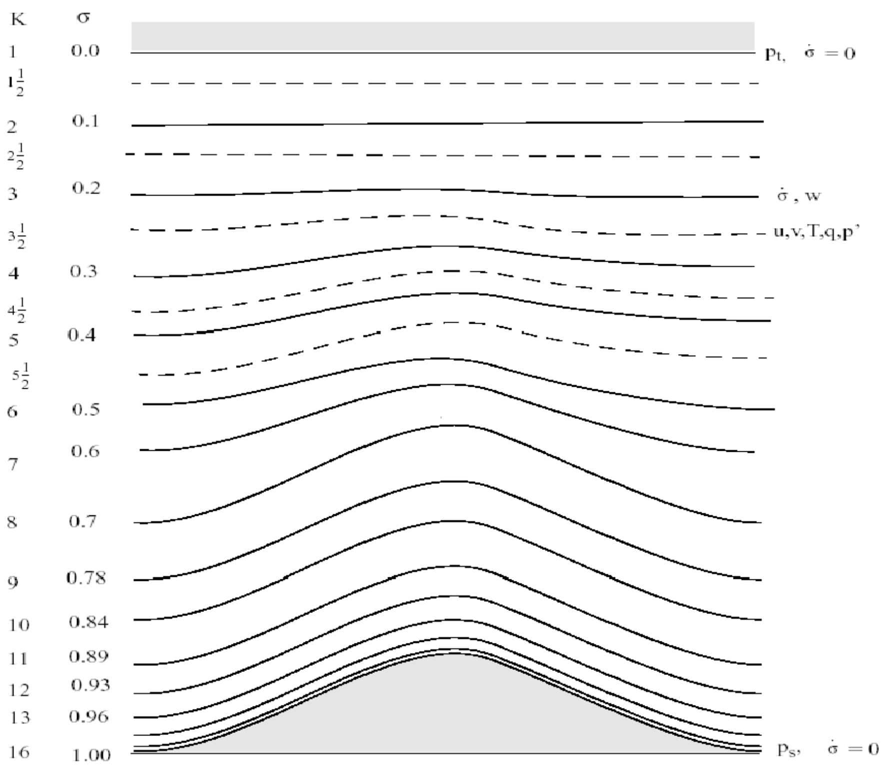

Figure 2.1. Schematic representation of the vertical structure of the model. Dashed lines denote half-sigma levels, solid lines denote full-sigma levels [25].

The modeling system has a choice of four map projections. Lambert Conformal is suitable for mid-latitudes, Polar Stereographic for high latitudes, Normal Mercator for low latitudes, and Rotated Mercator for extra choice. The x and y directions in the model do not correspond to west-east and north-south except for the Normal Mercator projection, and therefore the observed wind generally has to be rotated to the model grid, and the model u and v components need to be rotated before comparison with observations. These transformations are accounted for in the model preprocessors that provide data on the model grid (Please note that model output of u and v components, raw or post-processed, should be rotated to a lat/lon grid before comparing to observations). The map scale factor, m, is defined by:

$$m = \frac{model\_grid\_distance}{real\_earth\_distance} \tag{2.1}$$

and its value is usually close to one, varying with latitude [25].

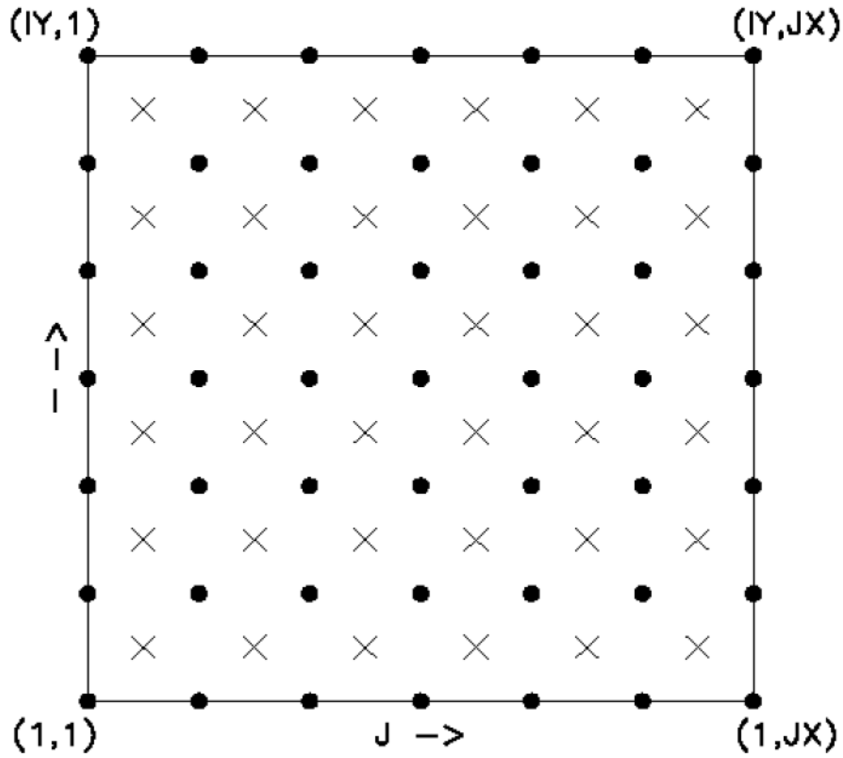

Figure 2.2. Schematic representation showing the horizontal Arakawa B-grid staggering of the dot and cross grid points [25].

2.4. Coordinated Regional Climate Downscaling Experiment (CORDEX)

Coordinated Regional Climate Experiment is the program which creates downscaled regional climate models from global climate models [26]. There are fourteen regions:

- Region 1: South America
- Region 2: Central America
- Region 3: North America
- Region 4: Europe (EURO)
- Region 5: Africa
- Region 6: South Asia
- Region 7: East Asia
- Region 8: Central Asia
- Region 9: Australasia
- Region 10: Antarctica
- Region 11: Arctic
- Region 12: Mediterranean (MED)
- Region 13: Middle East and North Africa (MENA)
- Region 14: South East Asia (SEA)

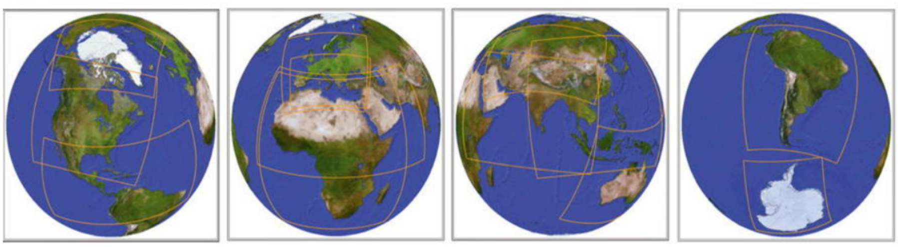

Figure 2.3. All CORDEX Regions [27].

The goal of CORDEX is to understand regional climate by downscaling. Also, to understand how models can be improved or what are the accuracy of them. Furthermore another goal is to spread downscaling to worldwide projections.

In this study over CORDEX 13 Region: MENA (Middle East and North Africa) the most crowded ten cities are selected.

2.5. The Empirical Rule

Empirical Rule gives the probability of occurrence of a value in a normal distribution. It is also known as 68–95–99.7 rule as the probabilities lies between percentage of values that lie within a band around the mean in a normal distribution with a width of two, four and six standard deviations, respectively.

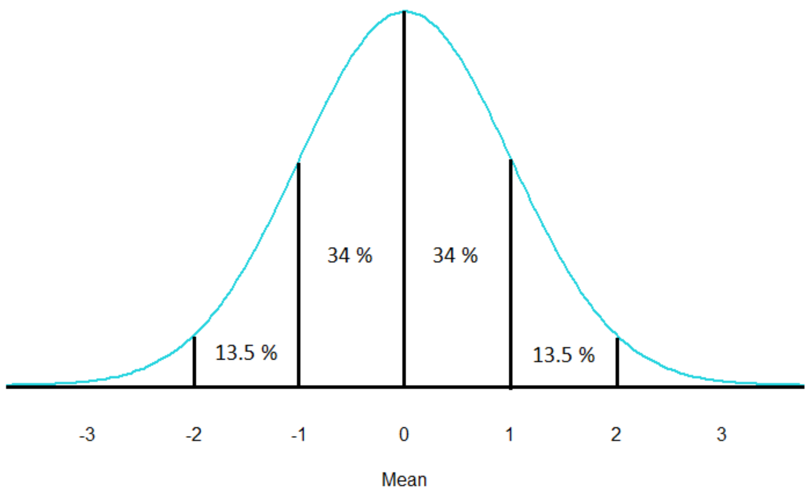

Figure 2.4. Normal distribution with percentages of data.

Formula gives probability of occurrence once:

$$1\ in\ \frac{1}{1 - erf(\frac{x}{\sqrt{2}})} \tag{2.2}$$

where x is that how many standard deviations are added to or subtracted from mean value:

$$\mu \pm x\,\sigma \tag{2.3}$$

Erf is the error function below:

$$\frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \tag{2.4}$$

[28]

2.6. Gaussian Mixture Model

Gaussian mixture is a function that is formed by many Gaussians; each identified by k ∈ 1,. . . , K, where K is the number of clusters in dataset.

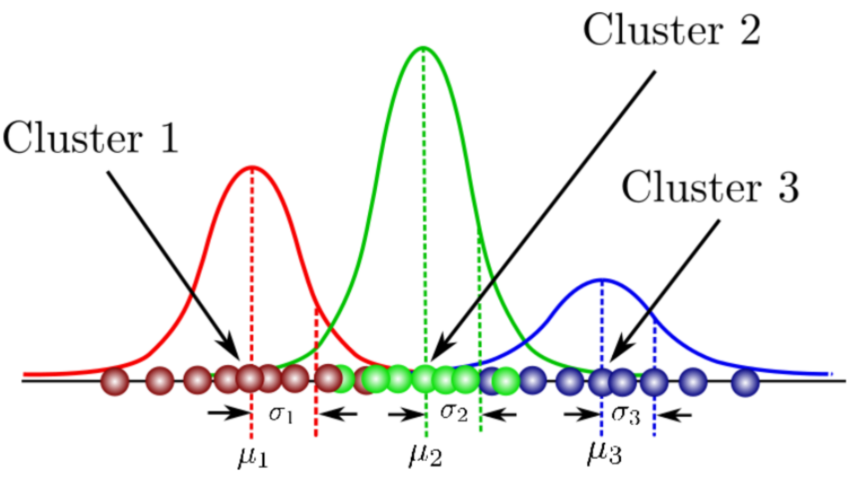

Figure 2.5. Gaussian clusters with K = 3.

In this study, to achieve to separate data into winter and summer, Gaussian Mixture Model with 2 clusters is used [29].

2.7. Methodology of the Study

Over the CORDEX-13 region (Middle East North Africa), the most crowded 10 cities were selected. For each city, dry bulb temperature, relative humidity, and wind velocity data were collected between 1970 and 1999 to assess heat index and wind chill index values. For prediction between 2070 and 2099, the outputs of Regional Climate Model (RegCM 4.4) of the Abdus Salam International Centre for Theoretical Physics (ICTP) with 50km resolution were used [30]. There were made four definitions for each index: hot days, cold days, extremely hot days and extremely cold days. To compare values between past and future, past values fit with Gaussian Mixture Model were used [31, 32]. The model gave two distinct mean and standard deviation values. Hot days were the one which future data exceeds the summation of bigger mean value and its standard deviation; cold days were the ones which were smaller than smaller mean value minus its standard deviation; extremely hot days were assessed as summation of bigger mean value and two times of its standard deviation; extremely cold days were days on which their index value is smaller than smaller mean mines two times its standard deviation.

For these four definitions of heat index and wind chill index values, two analyses were made. Firstly, the total counts of each term from past and model outputs were compared to observe the change in frequencies. Secondly, consecutive day counts were compared between past values and model outputs to assess the differences in density.

To find how many summer days in a year between 1970 and 2000, from Gaussian Mixture Model, from the mean value of second fit line 1 standard deviation was subtracted. Index values which were equal to or higher than the obtained value was the 83.14 % of all summer days according to Figure 2.4. These were the all summer days in 30 years. From that information how many summer days in 100 years were found which gave the information to Equation 2.2 to find a multiplier of the standard deviation. After that, the formula to find the probability of occurrence once in 100 years in the past was completed. To find the same value's probability of occurrence in the future, Equation 2.3 was solved with mean value and standard deviation of future summer and equalized to the number of summer days in 100 years according to past data for each RCP 4.5 and 8.5 scenarios. Then, x value in Equation 2.3 was found and Equation 2.2 was solved for this x value which gave that in how many days the rare event -which occurred once in 100 years in the past- will occur in the future.

For the winter extreme events, from Gaussian Mixture Model, 1 standard deviation was added to the mean value of the first fit line. Index values which were equal to or less than the obtained value were the 83.14 % of all winter days according to Figure 2.4. To find the probability of rare events such as once in 100 years, the same procedure with summer extremes was followed.

3. RESULTS

According to Figure 3.1 all cities except Alexandria are getting warmer in each scenario. Since Alexandria is a warm and seaside city; and also the difference between past and RCP 4.5 hot day counts are not big enough to say that it is getting colder, it can be said that Alexandria is not affected from climate change according to RCP 4.5. However, when past data are compared to future with RCP 8.5 scenario like all the other cities, the number of hot days in Alexandria increases. Figure 3.2 shows that the number of heat index extremely hot days in RCP 8.5 is much higher than the RCP 4.5 scenario and the past. The maximum increase in number of extremely hot days occurs in Jeddah. Even though according to RCP 8.5 number of hot days increases in Alexandria, the number of extremely hot days decreases. Also, the number of hot days in Tehran increases 55% but the number of extremely hot days decreases by 0.5%. Figure 3.3 indicates that the number of cold days decreases in future according to RCP 4.5 and RCP 8.5. Bigger decreases in counts of cold days for each city occur in RCP 8.5. The biggest decrease in the number of extremely cold days occurs in Izmir and also a maximum decrease in portion can be seen at Jeddah (98%).

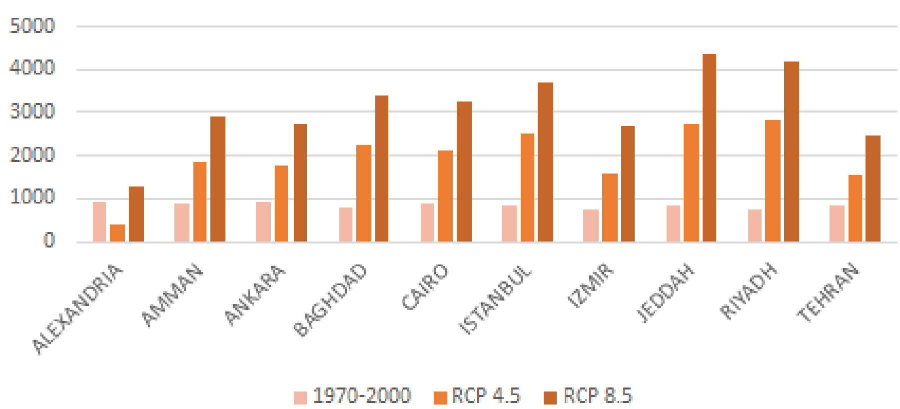

Figure 3.1. 1970-2000, RCP 4.5 and RCP 8.5 heat index hot day counts.

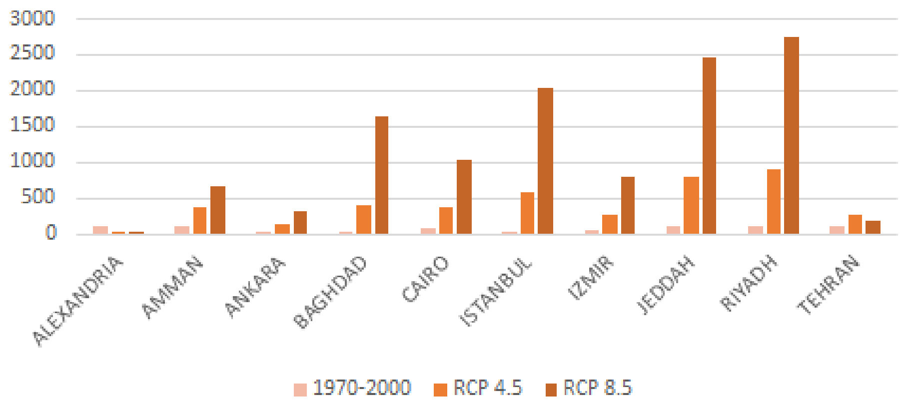

Figure 3.2. 1970-2000, RCP 4.5 and RCP 8.5 heat index extremely hot day counts.

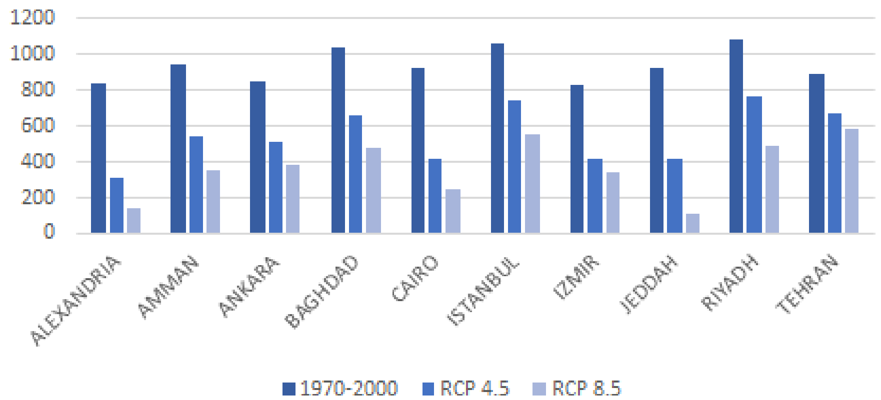

Figure 3.3. 1970-2000, RCP 4.5 and RCP 8.5 heat index cold day counts.

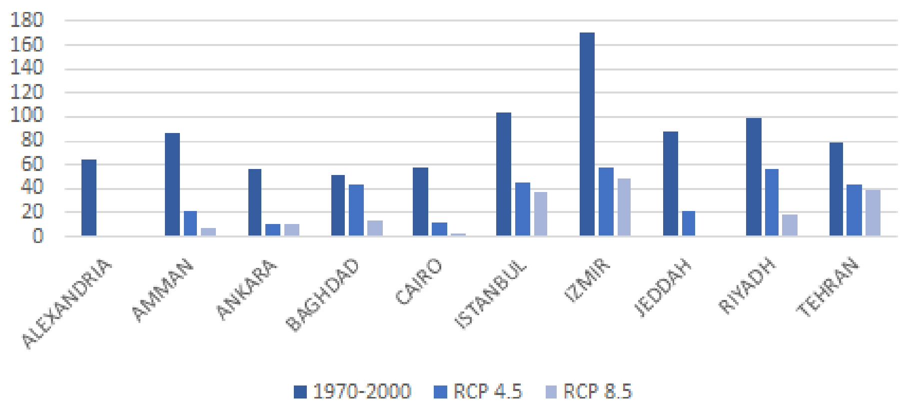

Figure 3.4. 1970-2000, RCP 4.5 and RCP 8.5 heat index extremely cold day counts.

According to Figure 3.5 the number of wind chill index hot days increases in each scenario however, the increase is bigger for RCP 8.5 for each city. The maximum number of hot days occurs in Jeddah with the RCP 8.5 scenario. According to Figure 3.5 biggest increase in the proportion of hot days for RCP 4.5 -when they are compared to past data- occurs in Alexandria. Even though according to past data the maximum number of hot days occurs in Istanbul, according to the RCP 4.5 and the RCP 8.5 scenarios, the maximum number of hot days occurs in Alexandria and Jeddah respectively. According to Figure 3.6 the number of wind chill index extremely hot days the increases for both RCP 4.5 and RCP 8.5 scenarios. Also, Figure 3.6 shows that the increase in the number of extremely hot days is much bigger in RCP 8.5 scenario than RCP 4.5 for each city. Between 1970-2000 and RCP 4.5 and RCP 8.5 scenarios, the maximum number of extremely hot days occurs in Jeddah. However, according to Figure 3.6 maximum increase in the rate of the number of wind chill index extremely hot days is in Cairo. Figure 3.7 show that according to both RCP 4.5 and RCP 8.5 scenarios the number of wind chill index cold days decreases.According to Figure 3.8 in Alexandria, wind chill index extremely cold days never happens in RCP 4.5 and RCP 8.5 scenarios. Also for each city, the number of extremely cold days decreases dramatically.

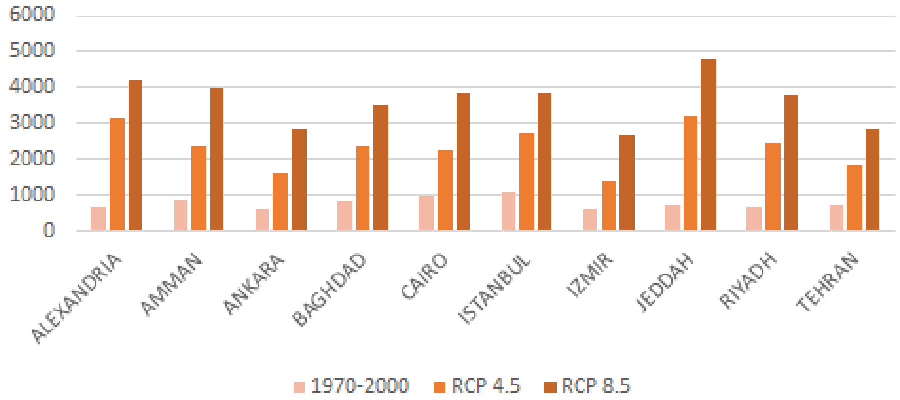

Figure 3.5. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index hot day counts.

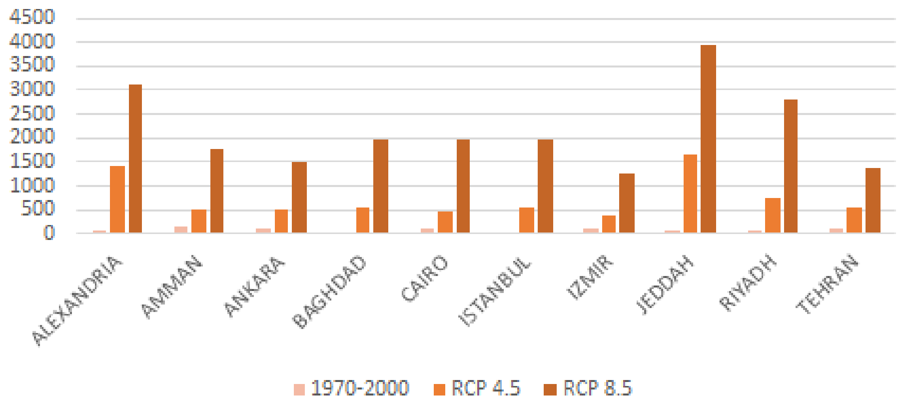

Figure 3.6. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index extremely hot day counts.

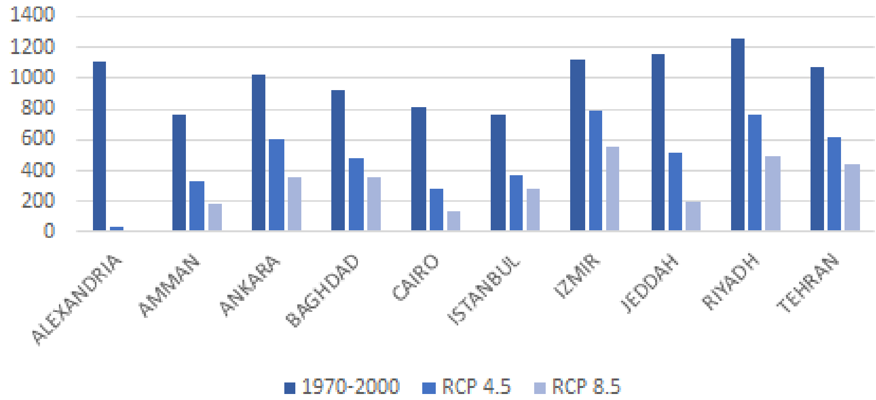

Figure 3.7. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index cold day counts.

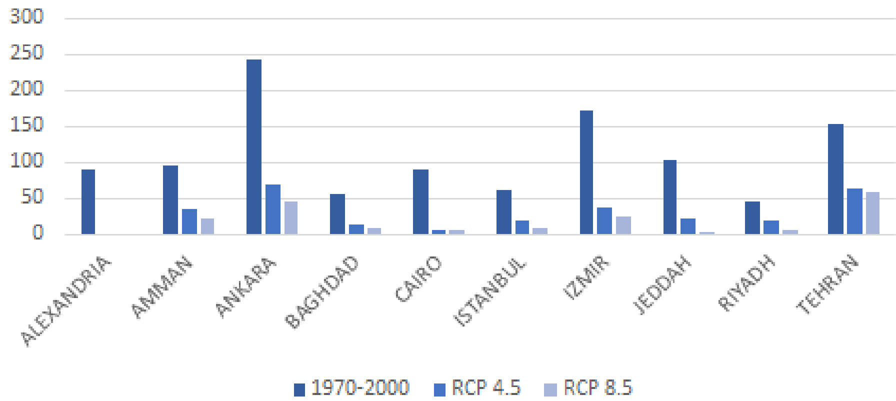

Figure 3.8. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index extremely cold day counts.

3.1. Alexandria

Alexandria is the second largest city in Egypt with population over 5.1 million [33]. It is a seaside city with length round 30 km coastline. With north wind as a main wind direction, climate of Alexandria differs from inner parts of Egypt. Summers are temperate, in peak months humidity can rise. Winters are cool and stormy which can bring torrential rains [34].

3.1.1. Heat Index Consecutive Days Distributions

Figure 3.9 shows that in Alexandria, according to RCP 8.5, the duration of hot days increases. However, according to Figure 3.10 maximum duration of extremely hot days has taken place in the past. Figures below show consecutive days for heat index in Alexandria:

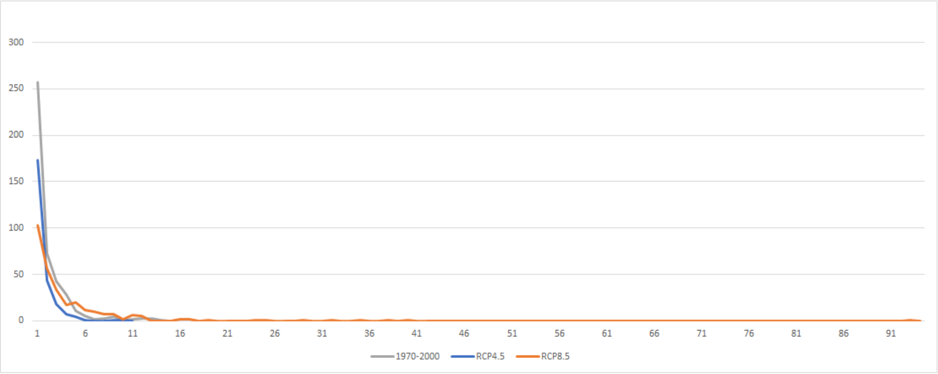

Figure 3.9. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Alexandria.

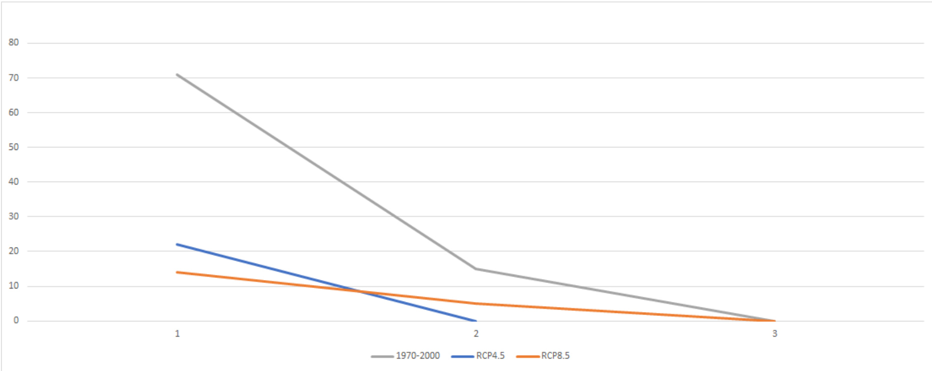

Figure 3.10. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Alexandria.

3.1.2. Wind Chill Index Consecutive Days Distributions

According to Figure 3.11, the number of wind chill index cold days decreases in Alexandria in both RCP 4.5 and RCP 8.5 scenarios. Wind chill index extremely cold days never occur in future scenarios according to Figure 3.12.

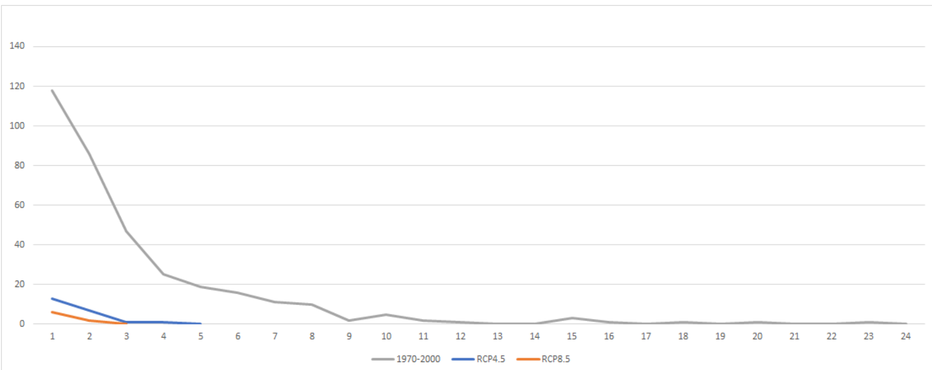

Figure 3.11. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Alexandria.

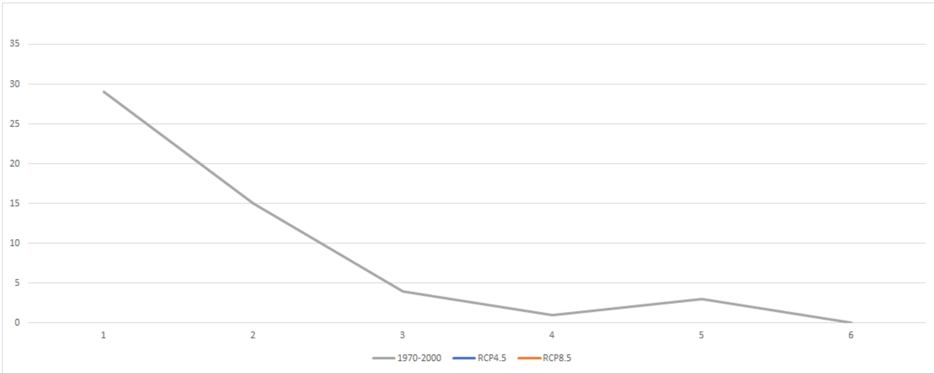

Figure 3.12. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Alexandria.

3.1.3. Heat Index Distributions

Figure 3.13 shows heat index data distribution between 1970 and 2000. Mean value of the blue fit line is 18.14 and standard deviation of it is 3.36; mean value of the red line 28.5 and standard deviation of this line is 2.94. When Figure 3.13 is compared with Figure 3.14 and Figure 3.15, it can be seen that distributions of future values are shifted to the right which means heat index values increase in RCP 4.5 and RCP 8.5 scenarios. When we compared the peak points RCP 8.5 scenario's value is bigger than RCP 4.5's heat index value. Table 3.1 shows that even though the probability of occurrence of a value which is observed once in one hundred years according to past data is decreases, mean value of heat index of summer for RCP 8.5 scenario increases. This can be seen as a conflict; however, since there is no such thing as perfect fit and the future probability of occurrence of a certain value is obtained by purely statistical calculations minor changes in mean and standard deviation could cause these results. Histograms below show the distributions of Alexandria heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

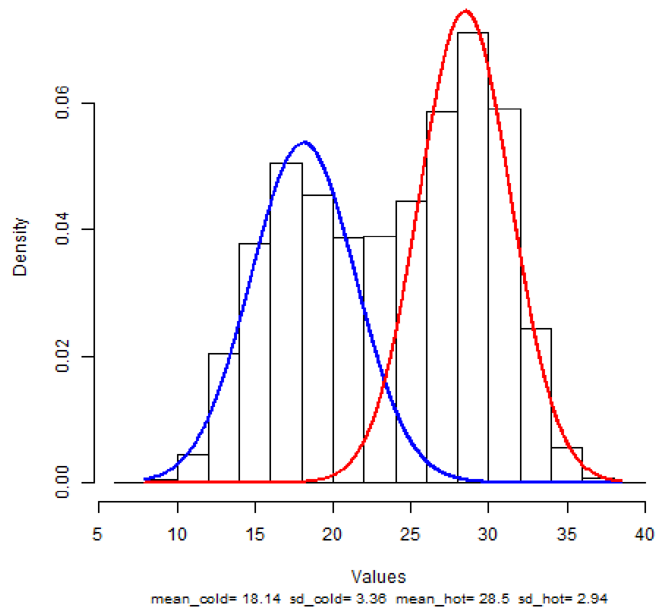

Figure 3.13. Distribution of 1970-2000 heat index values in Alexandria.

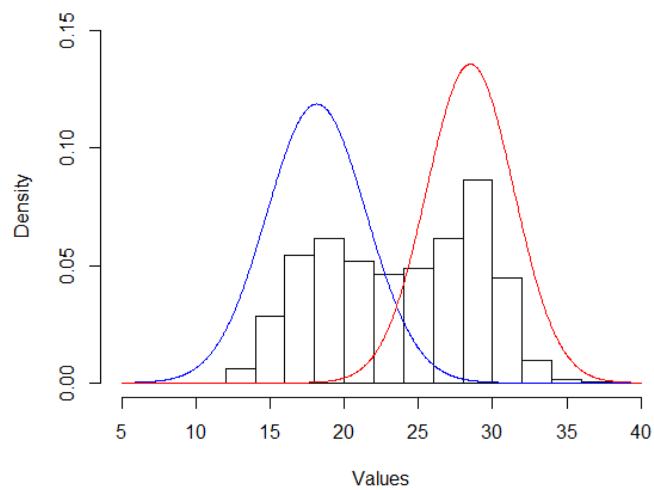

Figure 3.14. Distribution of 2070-2100 RCP 4.5 heat index values in Alexandria.

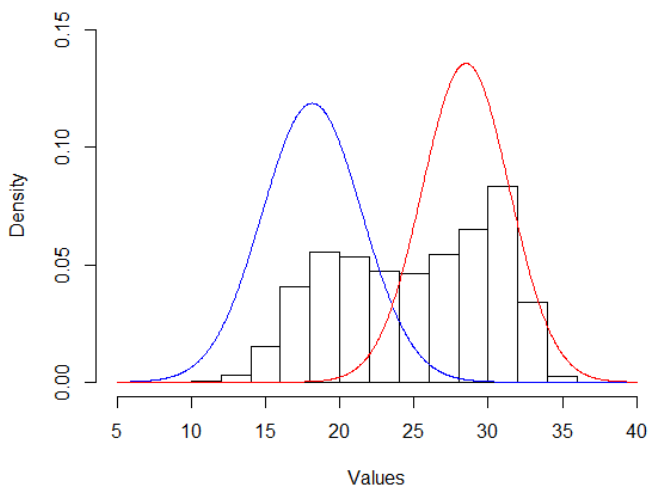

Figure 3.15. Distribution of 2070-2100 RCP 8.5 heat index values in Alexandria.

Table 3.1. Alexandria HI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurence (1 in x years)**	μ	σ	**occurence(1 in x years)**
1970-2000	28.504	2.944	100	18.136	3.358	100
2070-2100RCP 4.5	28.229	2.357	22766.431	19.359	2.992	6631.346
2070-2100RCP 8.5	29.977	2.048	15552.138	21.123	3.549	1708.782

3.1.4. Wind Chill Index Distributions

Figure 3.16 shows the wind chill index distributions with two fit lines for the time between 1970 and 2000. When it is compared to Figure 3.17 and Figure 3.18, the distribution of index slightly changes. It can be explained with the fact that Alexandria is a very warm city. According to Table 3.2 the probability of occurrence of a value which is occurred in the past in a century increases significantly in future scenarios for summers. In RCP 4.5 scenario this certain value can be seen twice in a year. On the other hand, winter extreme values' occurrences decrease drastically.

Histograms below show the distributions Alexandria wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

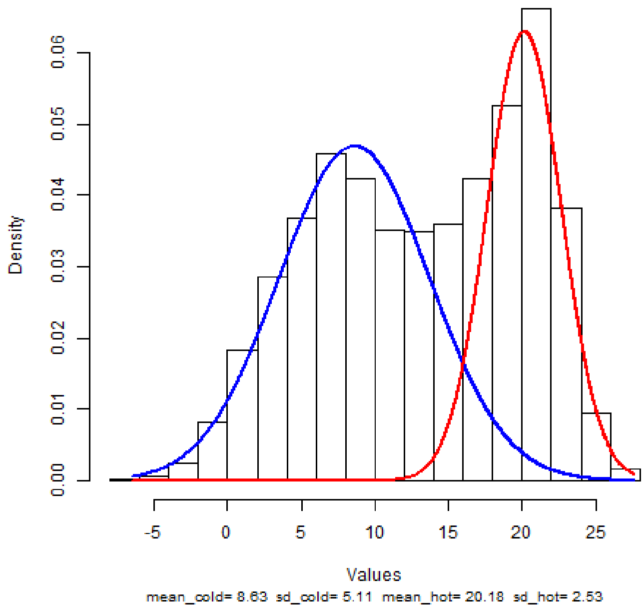

Figure 3.16. Distribution of 1970-2000 wind chill index values in Alexandria.

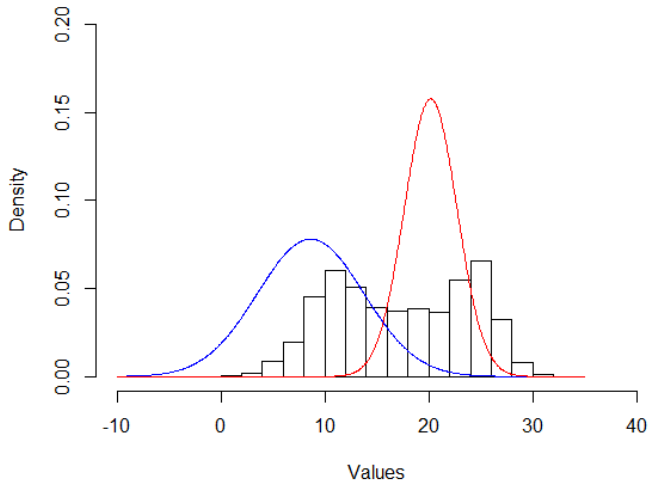

Figure 3.17. Distribution of 2070-2100 RCP 4.5 wind chill index values in Alexandria.

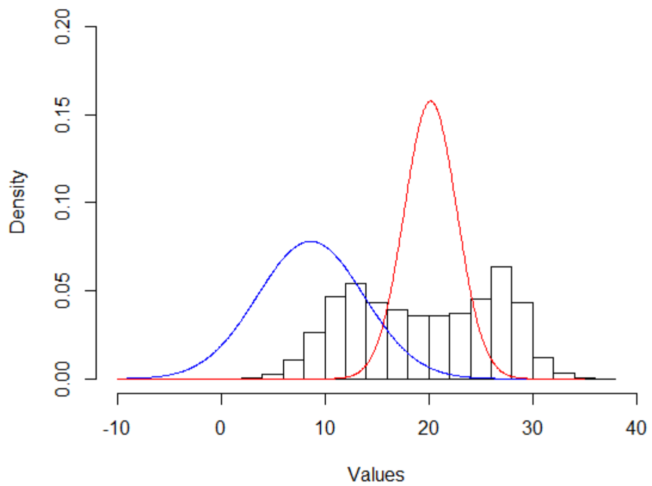

Figure 3.18. Distribution of 2070-2100 RCP 8.5 wind chill index values in Alexandria.

Table 3.2. Alexandria WCI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	20.184	2.532	100	8.63	5.11	100
2070-2100RCP 4.5	24.009	2.47	0.598	12.904	4.071	6471092.72
2070-2100RCP 8.5	26.11	2.954	0.042	14.324	4.08	56425065.932

3.2. Amman

Amman is the largest city and the capital of Jordan with population over 1.2 million [35]. The city does not have a coast and since the city was build over mountains -modern city lying on nineteen hills-, each region can have different climate values. For instance, when one part of city faces a cold winter day, in another part of the city, the weather can be mildly cold. City is colder when its compared to the areas around [36].

3.2.1. Heat Index Consecutive Days Distributions

Figure 3.19 shows that in Amman, according to RCP 8.5 duration of hot days increases. Also, according to Figure 3.20 the maximum duration of extremely hot days occurs in RCP 8.5 scenario. Furthermore, both RCP 4.5 and RCP 8.5 scenarios have longer extremely hot days.

Figures below show consecutive days for heat index in Amman:

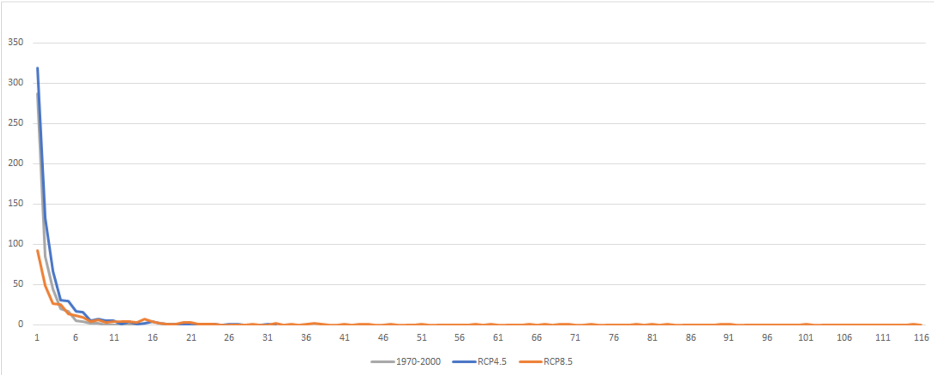

Figure 3.19. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Amman.

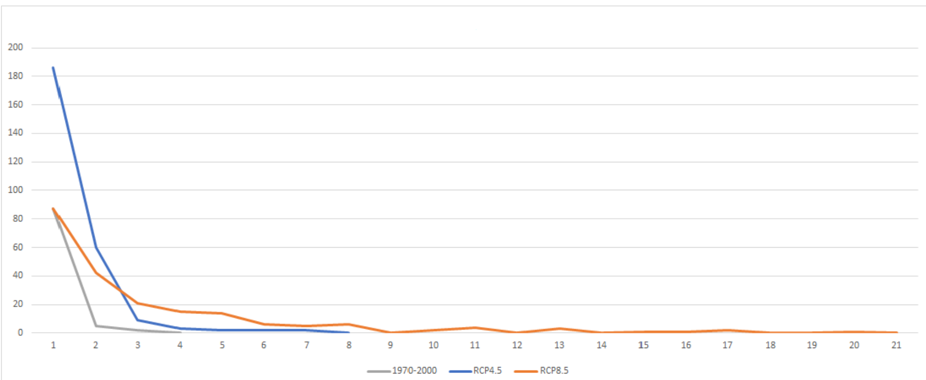

Figure 3.20. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Amman.

3.2.2. Wind Chill Index Consecutive Days Distributions

According to Figure 3.21, the number of wind chill index consecutive cold days decreases in both scenarios, but in RCP 8.5 scenario drop in the number of consecutive days is much bigger. According to Figure 3.22, RCP 8.5 scenario faces a bigger decrease in number of wind chill index extremely cold days.

Figures below show consecutive days for wind chill index in Amman:

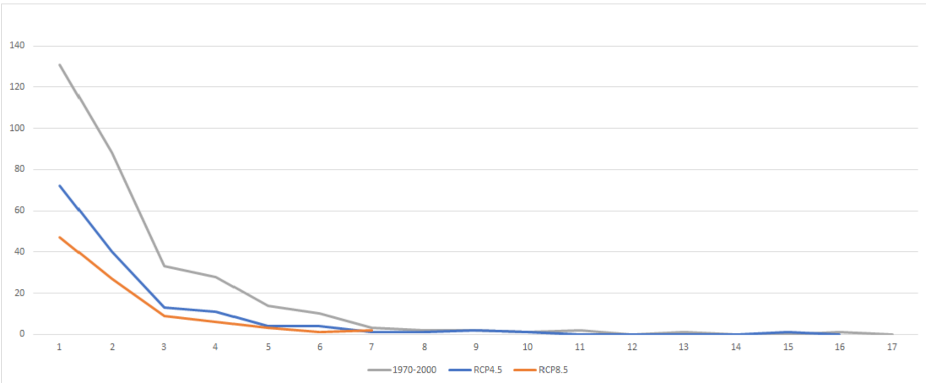

Figure 3.21. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Amman.

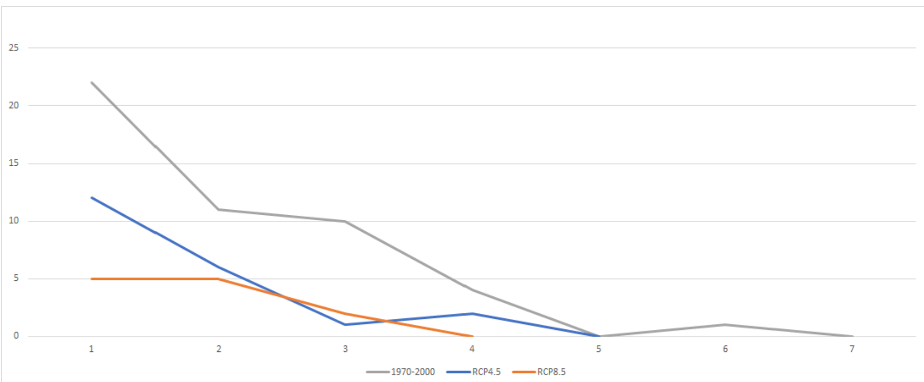

Figure 3.22. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Amman.

3.2.3. Heat Index Distributions

Figure 3.23 shows the heat index values between 1970 and 2000. Mean value for the cold fit line (blue) is 17.39 and standard deviation of blue line 4.6; mean value for the hot fit line (red) is 27.57 and the standard deviation of it 2.89. When Figure 3.23 is compared with Figure 3.24 and Figure 3.25, histograms are shifted to higher values for RCP 4.5 and 8.5 scenarios. The shift is more drastic in RCP 8.5 scenario according to Figure 3.25. Table 3.3 shows that occurrence of extremely hot values increases in RCP 4.5 and RCP 8.5 scenarios.

Histograms below show the distributions of Amman heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

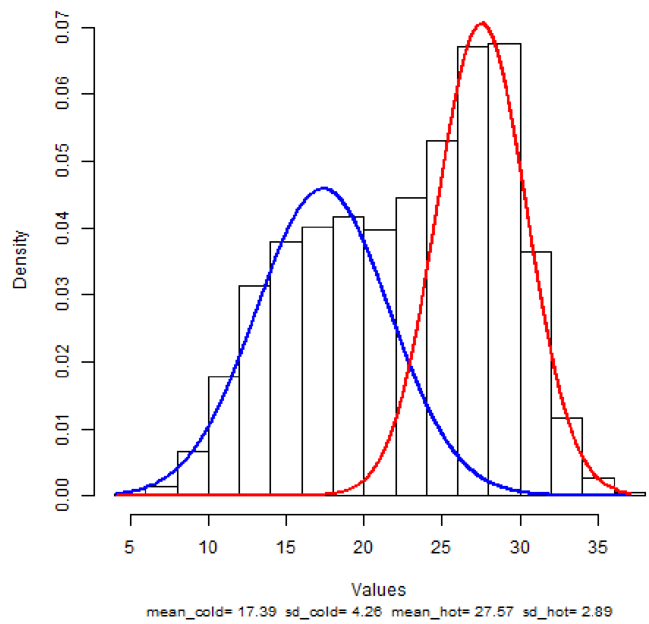

Figure 3.23. Distribution of 1970-2000 heat index values in Amman.

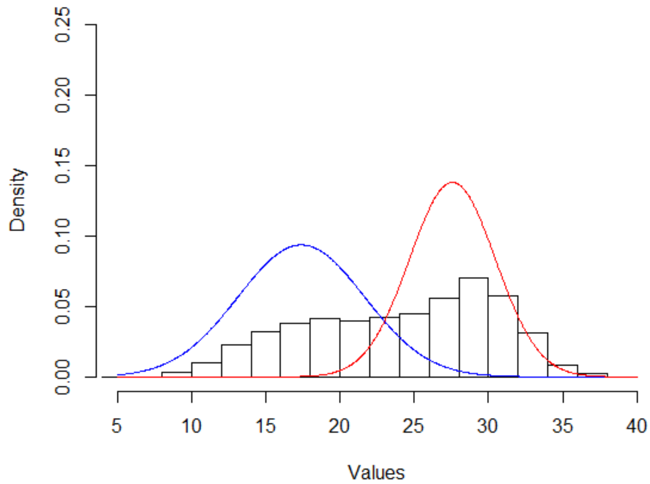

Figure 3.24. Distribution of 2070-2100 RCP 4.5 heat index values in Amman.

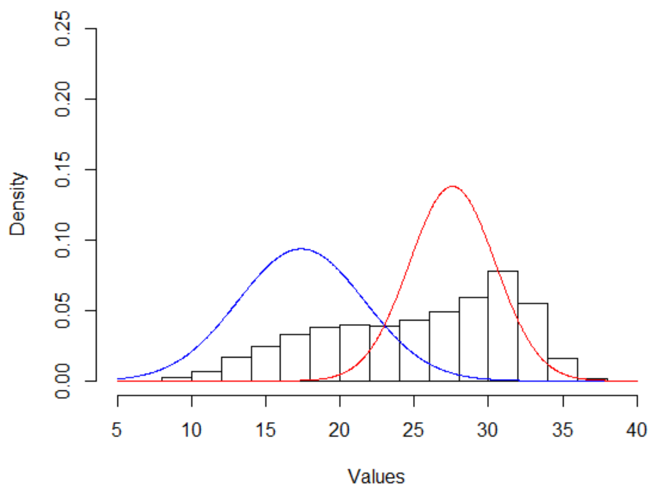

Figure 3.25. Distribution of 2070-2100 RCP 8.5 heat index values in Amman.

Table 3.3. Amman HI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	27.571	2.89	100	17.393	4.263	100
2070-2100RCP 4.5	29.100	2.957	8.844	18.845	4.333	326.753
2070-2100RCP 8.5	30.885	2.255	25.661	21.27	5.144	131.153

3.2.4. Wind Chill Index Distributions

According to Figure 3.26 there are many wind chill index values below zero between 1970 and 2000. However, when Figure 3.26 is compared with Figure 3.27 and Figure 3.28,it is quite clear that the number of subzero values decreases. Both Figure 3.27 and 3.28 show that wind chill index values have been shifting to higher ones when they are compared to the past. Furthermore, Figure 3.28 shows that increase in wind chill index values is bigger in RCP 8.5 scenario than RCP 4.5 when it is compared with Figure 3.27. According to Table 3.4 wind chill index hot value occurred in the past once in one hundred years occurs more often in both RCP 4.5 and RCP 8.5 scenarios (almost 3 times in a year according to RCP 8.5 scenario). Also, Table 3.4 shows that probability of wind chill index extremely cold value (probability of occurring ones in a century according to past data) observed decreases according to both RCP 4.5 and RCP 8.5 scenarios.

Histograms below show the distributions Amman wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

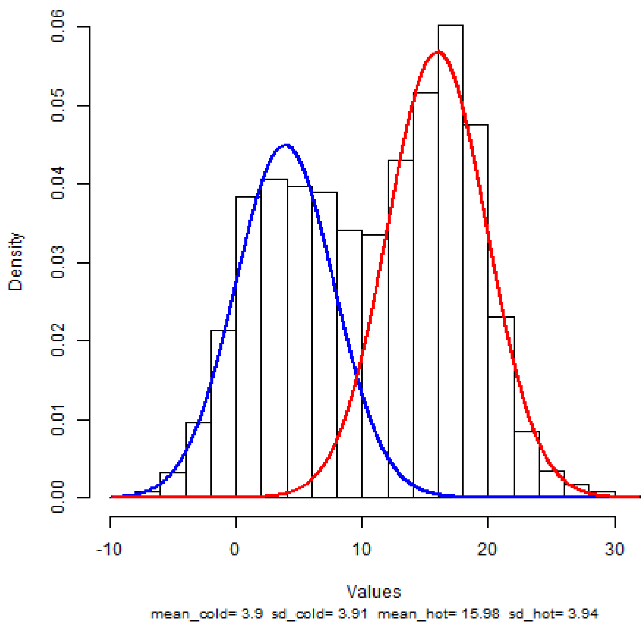

Figure 3.26. Distribution of 1970-2000 wind chill index values in Amman.

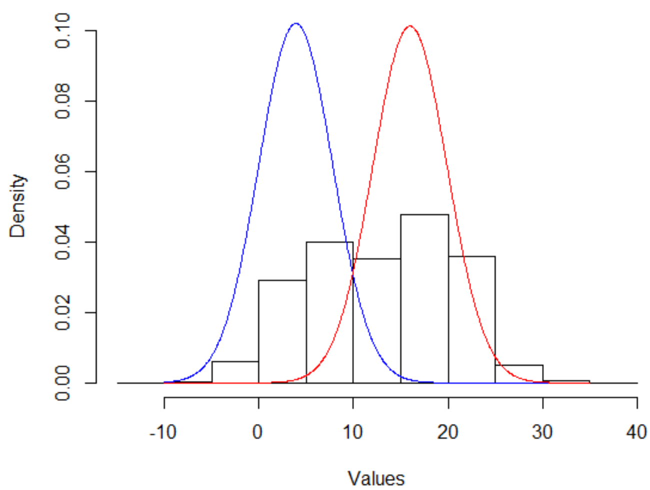

Figure 3.27. Distribution of 2070-2100 RCP 4.5 wind chill index values in Amman.

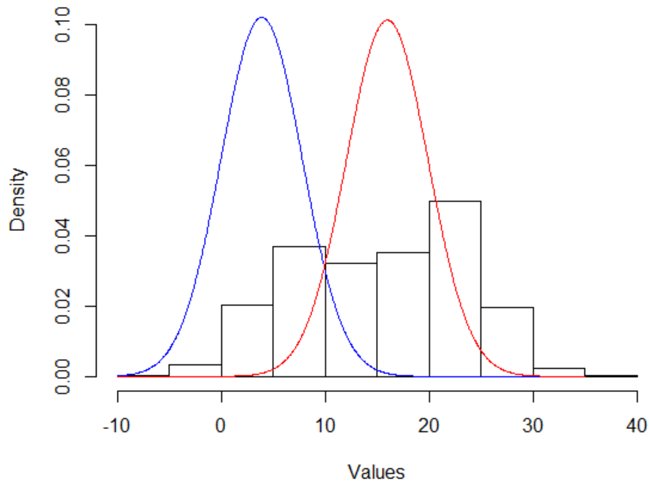

Figure 3.28. Distribution of 2070-2100 RCP 8.5 wind chill index values in Amman.

Table 3.4. Amman WCI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	15.977	3.936	100	3.904	3.907	100
2070-2100RCP 4.5	18.925	3.913	5.657	6.61	4.386	216.821
2070-2100RCP 8.5	21.89	4.088	0.353	8.389	4.786	238.098

3.3. Ankara

Ankara is the capital of Turkey with population of 5 million [37]. The city is surrounded with lands and it has not seashore. It has continental climate which means city suffers from cold winters, and hot and dry summers.

3.3.1. Heat Index Consecutive Days Distributions

Figure 3.29 shows that in Ankara, according to RCP 8.5 duration of hot days increases. Also Figure 3.30 shows that the maximum duration of extremely hot days occurs in RCP 8.5 scenario.

Figures below show consecutive days for heat index in Ankara:

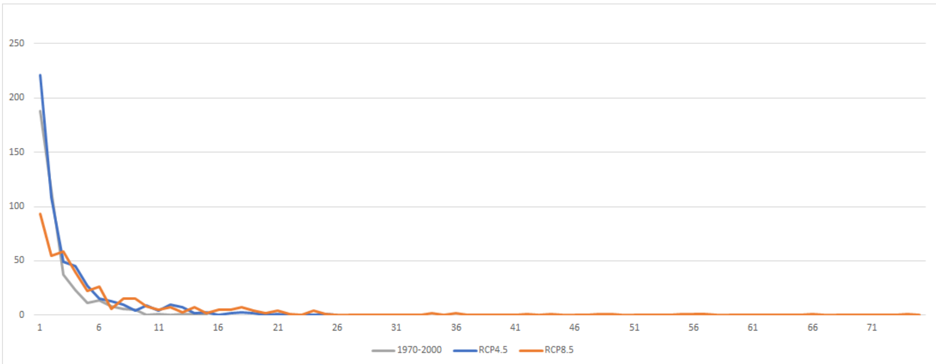

Figure 3.29. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Ankara.

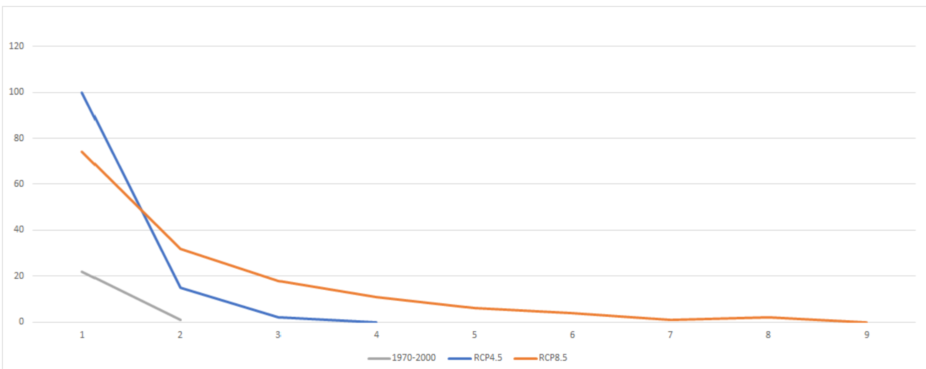

Figure 3.30. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Ankara.

3.3.2. Wind Chill Index Consecutive Days Distributions

When wind chill index cold days of past, RCP 4.5 scenario and RCP 8.5 scenario are compared, Figure 3.31 shows that the duration of wind chill index cold day decreases in future scenarios. Moreover, Figure 3.32 shows decrease in wind chill index extremely cold days in future scenarios.

Figures below show consecutive days for wind chill index in Ankara:

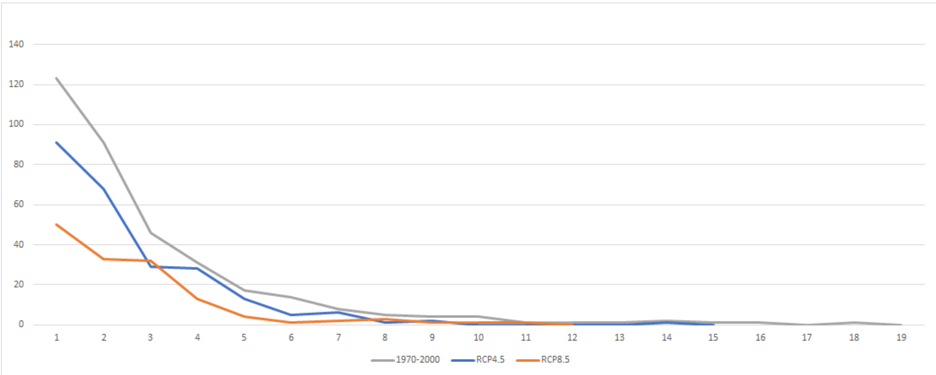

Figure 3.31. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Ankara.

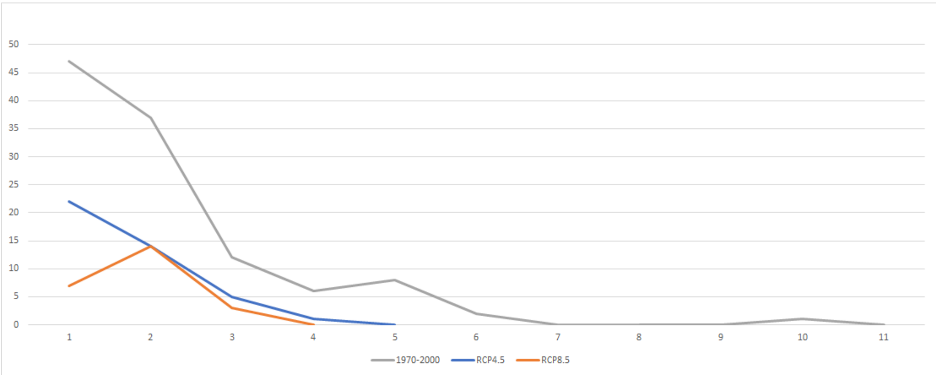

Figure 3.32. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Ankara.

3.3.3. Heat Index Distributions

Figure 3.33 shows the heat index distributions of Ankara between 1970 and 2000 with two fit lines (blue for winter, red for summer). When it is compared with Figure 3.34 and Figure 3.35, it can be seen that there is a slight shift in values to hotter ones. According to Table 3.5, probability of occurrence of a heat index extremely hot day (1 in 100 years) decreases in future scenario but since it is computed statistically, this result is caused by slight increase in mean values and decrease in standard deviation.

Histograms below show the distributions of Ankara heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

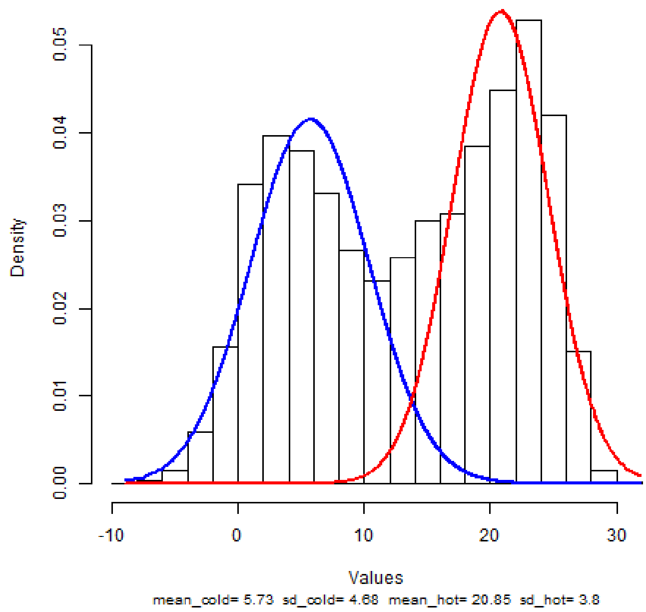

Figure 3.33. Distribution of 1970-2000 heat index values in Ankara.

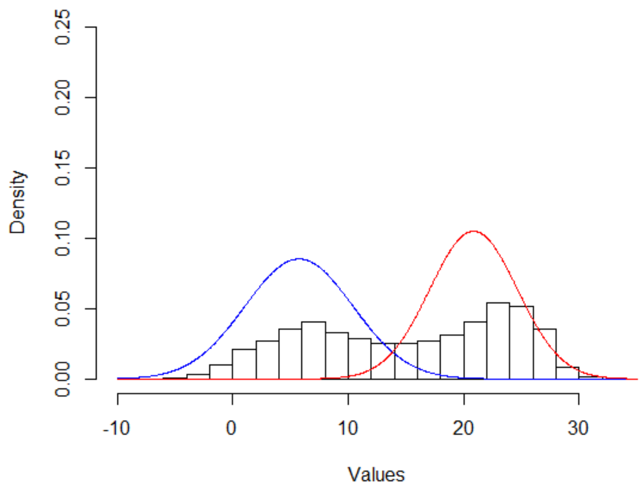

Figure 3.34. Distribution of 2070-2100 RCP 4.5 heat index values in Ankara.

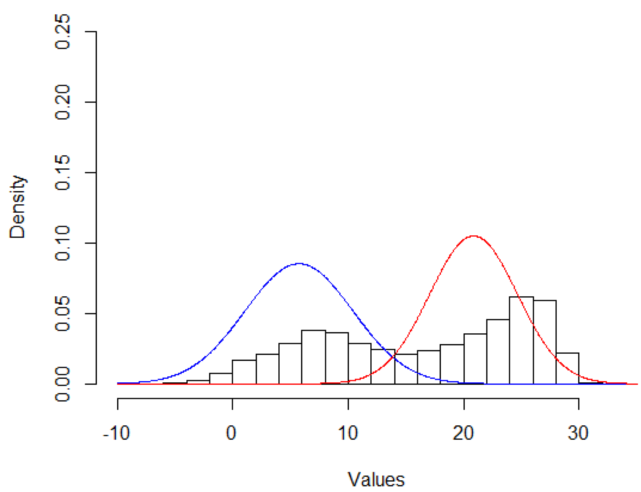

Figure 3.35. Distribution of 2070-2100 RCP 8.5 heat index values in Ankara.

Table 3.5. Ankara HI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	20.847	3.796	100	5.727	4.685	100
2070-2100RCP 4.5	23.083	3.217	113.83	8.274	5.333	95.389
2070-2100RCP 8.5	24.596	2.787	164.535	9.674	5.889	52.967

3.3.4. Wind Chill Index Distributions

Figure 3.36 shows the distribution of wind chill index between 1970 and 2000 in Ankara. To separate the winter and summer values there are two fit lines (blue for winter hot for summer) even though data is more suitable for normal distribution. According to Figure 3.37 and Figure 3.38 future wind chill index will be warmer when they are compared with past data. Table 3.6 shows that mean values of wind chill index will be increasing for both summer and winter according to RCP 4.5 and RCP 8.5 scenarios.

Histograms below show the distributions Ankara wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

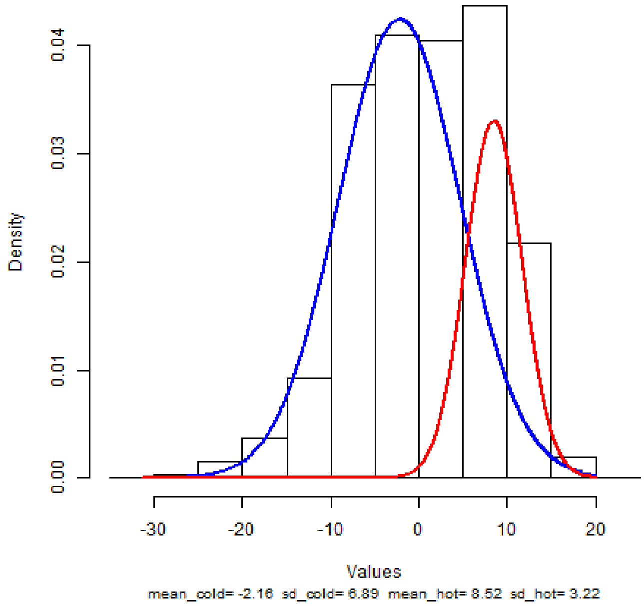

Figure 3.36. Distribution of 1970-2000 wind chill index values in Ankara.

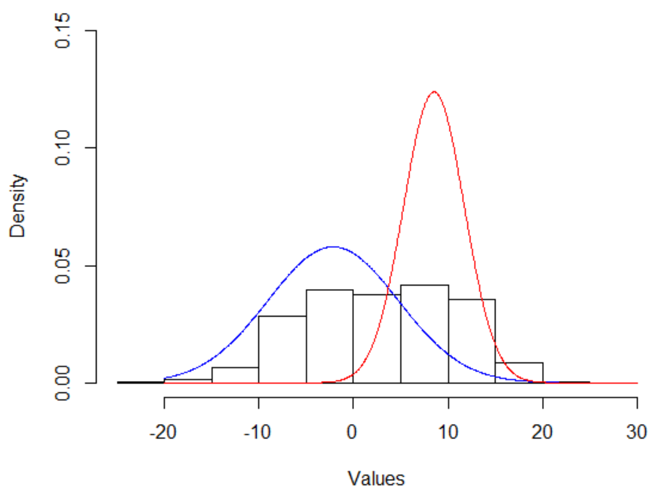

Figure 3.37. Distribution of 2070-2100 RCP 4.5 wind chill index values in Ankara.

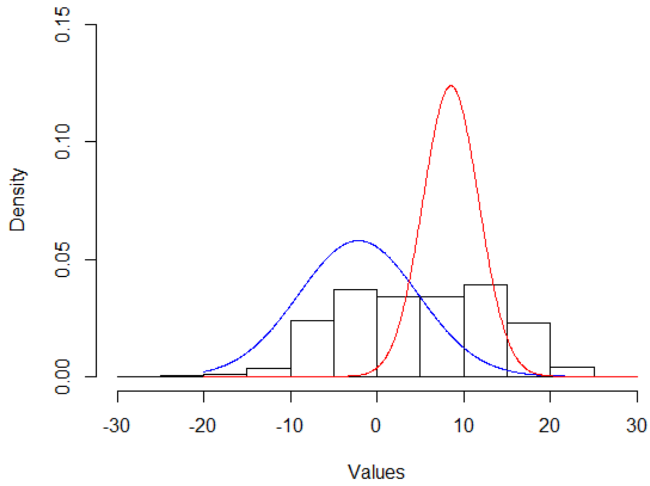

Figure 3.38. Distribution of 2070-2100 RCP 8.5 wind chill index values in Ankara.

Table 3.6. Ankara WC occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	1.156	7.772	100	-6.183	1.435	100
2070-2100RCP 4.5	10.151	3.949	1160218.305	-2.139	5.572	0.104
2070-2100RCP 8.5	12.471	4.586	777.125	-1.28	5.456	0.161

3.4. Baghdad

Baghdad is the capital of Iraq. City is built over Tigris river, and it is at the heart of the ancient Mesopotamia. The population of Baghdad is over 7.2 million [38]. The climate is hot and dry in summer, cool and damp in winter. There is no precipitation in summer, and in early summer sandstorms occur frequently [39].

3.4.1. Heat Index Consecutive Days Distributions

Figure 3.39 shows that in Baghdad, according to RCP 8.5, duration of hot days increases. Also, Figure 3.40 shows that maximum duration of extremely hot days occurs in RCP 8.5 scenario.

Figures below show consecutive days for heat index in Baghdad:

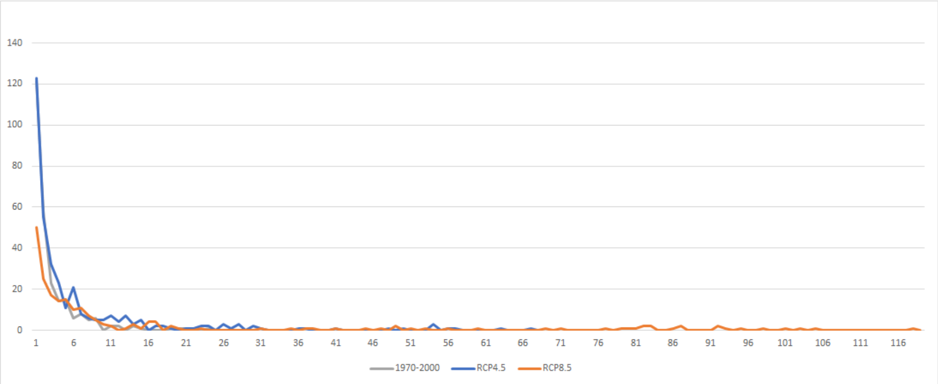

Figure 3.39. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Baghdad.

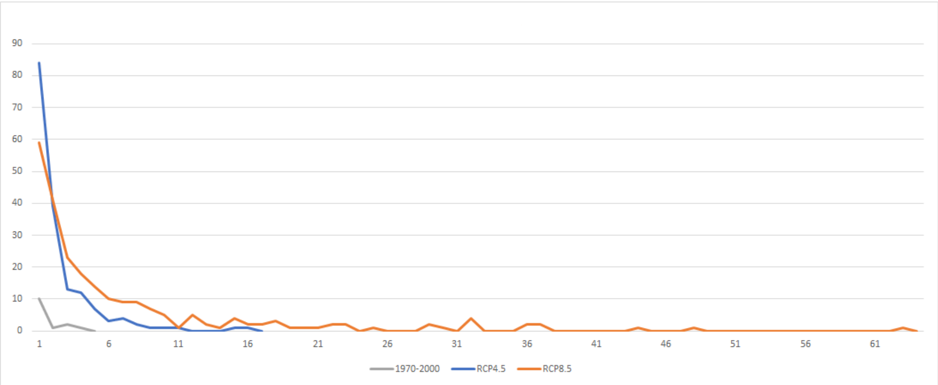

Figure 3.40. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Baghdad.

3.4.2. Wind Chill Index Consecutive Days Distributions

According to Figure 3.41, durations of wind chill index cold days will decrease in future in both RCP 4.5 and RCP 8.5 scenarios. Figure 3.42 shows that maximum duration of wind chill index extremely cold day occurs in the past.

Figures below show consecutive days for wind chill index in Baghdad:

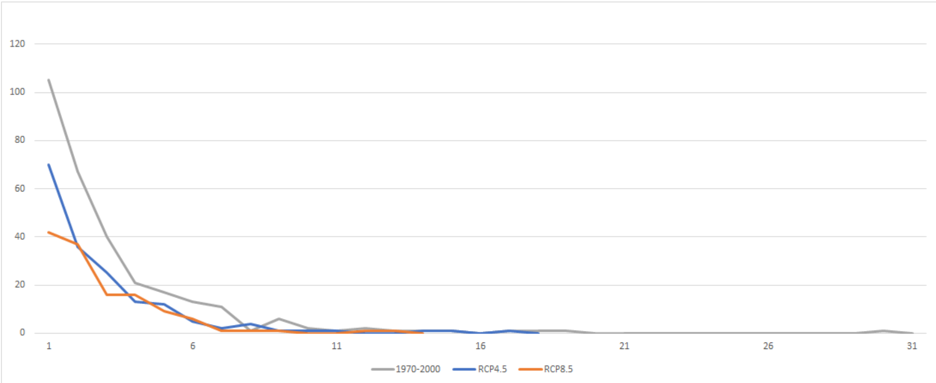

Figure 3.41. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Baghdad.

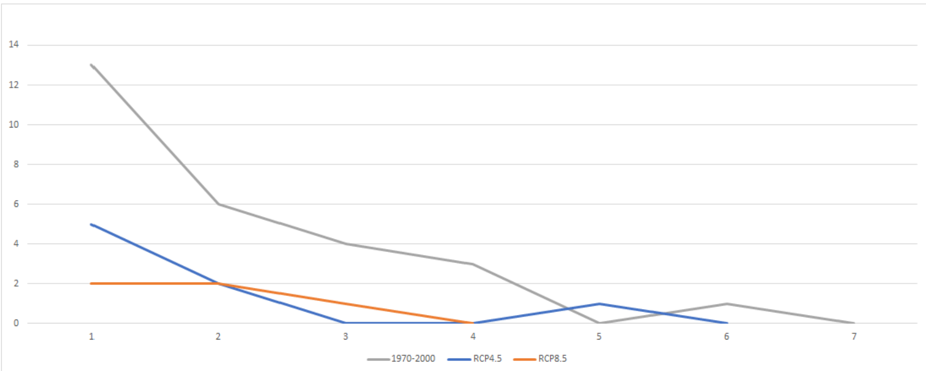

Figure 3.42. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Baghdad.

3.4.3. Heat Index Distributions

Figure 3.43 shows the distribution of heat index values between 1970 and 2000. Figure 3.44 and Figure 3.45 show that future values of heat index will be higher according to RCP 4.5 and RCP 8.5 scenarios. Furthermore, Figure 3.45 shows more increase in heat index values when they are compared to the past and RCP 4.5 scenarios. Table 3.7 shows the increase in mean values for summer according to RCP 4.5 and RCP 8.5 scenarios. In addition, extreme values (1 in a century) occur more often in future scenarios (1 day in 14 years according to RCP 4.5 scenario, 2 days in a year according to RCP 8.5 scenario).

Histograms below show the distributions of Baghdad heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

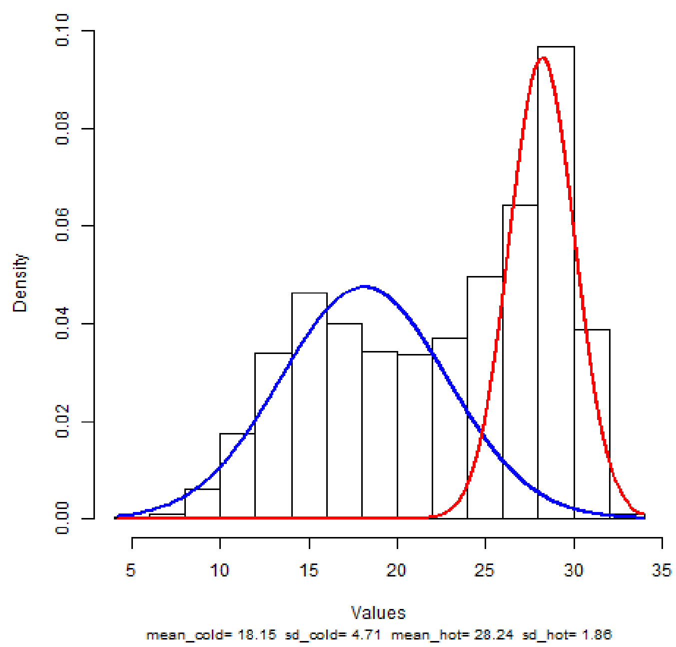

Figure 3.43. Distribution of 1970-2000 heat index values in Baghdad.

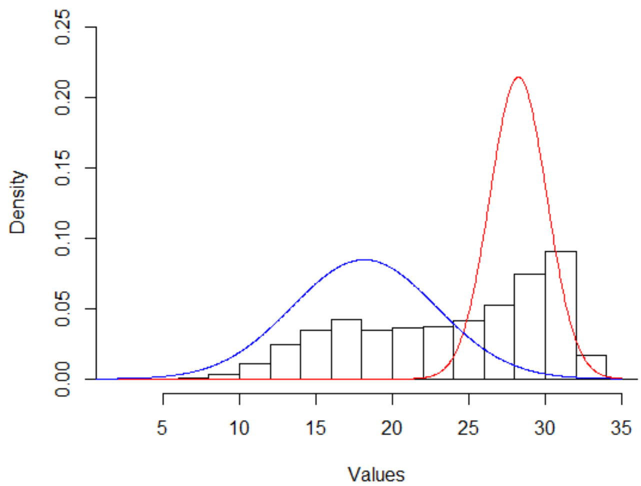

Figure 3.44. Distribution of 2070-2100 RCP 4.5 heat index values in Baghdad.

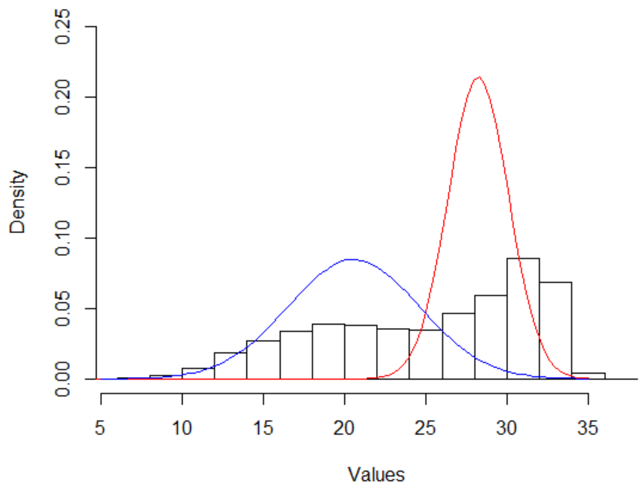

Figure 3.45. Distribution of 2070-2100 RCP 8.5 heat index values in Baghdad.

Table 3.7. Baghdad HI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	28.242	1.859	100	18.148	4.714	100
2070-2100RCP 4.5	29.858	1.653	14.664	20.119	5.169	111.072
2070-2100RCP 8.5	31.001	1.807	0.647	43.698	5.233	199.388

3.4.4. Wind Chill Index Distributions

Figure 3.46 shows the wind chill index distribution between 1970 and 2000. According to Figure 3.44 and Figure 3.44 wind chill index distributions are shifted to hotter values when they are compared to past data. Values of RCP 8.5 scenario shows more increase than RCP 4.5 data. Table 3.8 shows that mean values of wind chill index for both summer and winter are increasing in RCP 4.5 and RCP 8.5 scenarios. Also, extreme values such as occurrence once in a century will be seen more frequently (for RCP 4.5 scenario once in 12 years and for RCP 8.5 scenario twice in every year).

Histograms below show the distributions Baghdad wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

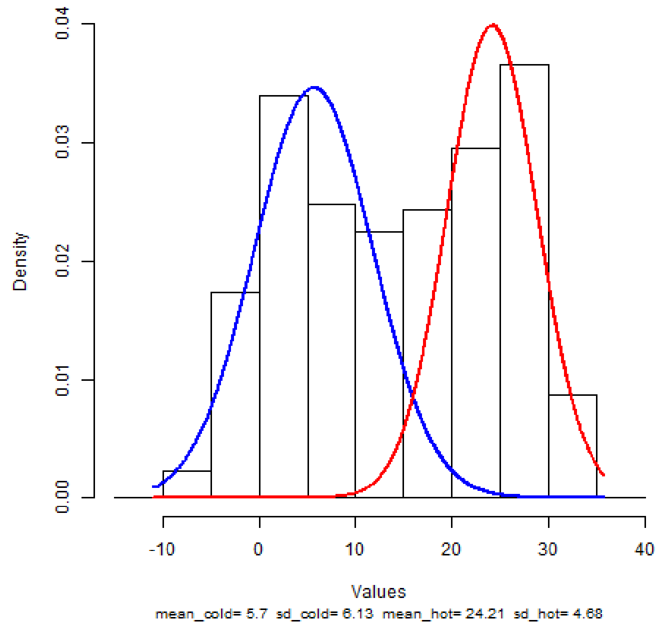

Figure 3.46. Distribution of 1970-2000 wind chill index values in Baghdad.

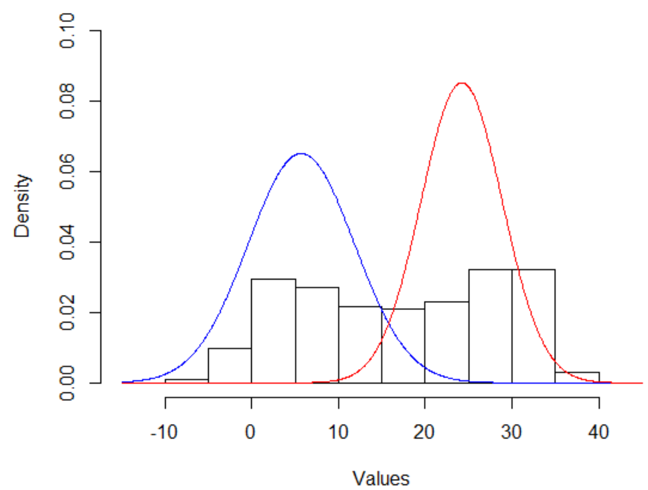

Figure 3.47. Distribution of 2070-2100 RCP 4.5 wind chill index values in Baghdad.

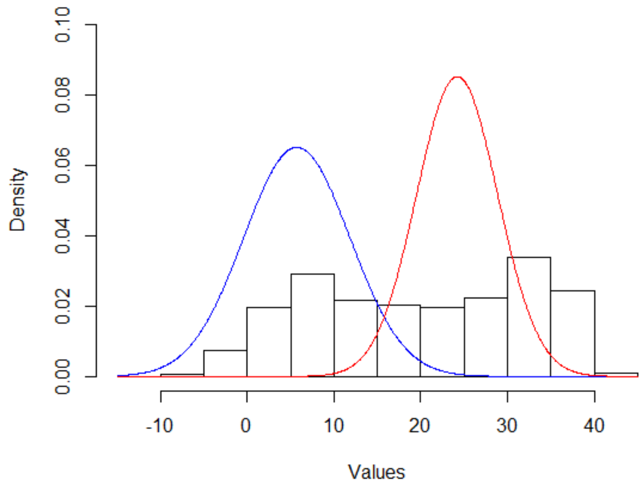

Figure 3.48. Distribution of 2070-2100 RCP 8.5 wind chill index values in Baghdad.

Table 3.8. Baghdad WCI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	24.213	4.675	100	5.703	6.134	100
2070-2100RCP 4.5	28.757	4.094	11.643	9.163	7.319	46.788
2070-2100RCP 8.5	32.704	4.087	0.499	11.814	8.268	28.578

3.5. Cairo

Cairo is the capital and the largest city of Egypt. City is located in Nile Delta. Its population is around 20 million [40]. Cairo has only two seasons: approximately eight months of summer and four months of winter. In the hottest of the summer months—June, July, and August—the average daily maximum temperature is 35 °C, and the average daily minimum is 21 °C. The summer temperature reaches as high as 47 °C [41].

3.5.1. Heat Index Consecutive Days Distributions

Figure 3.49 shows that in Cairo, according to RCP 8.5 duration of hot days increases. According to Figure 3.50, maximum duration of extremely hot days also occurs in RCP 8.5 scenario.

Figures below show consecutive days for heat index in Cairo:

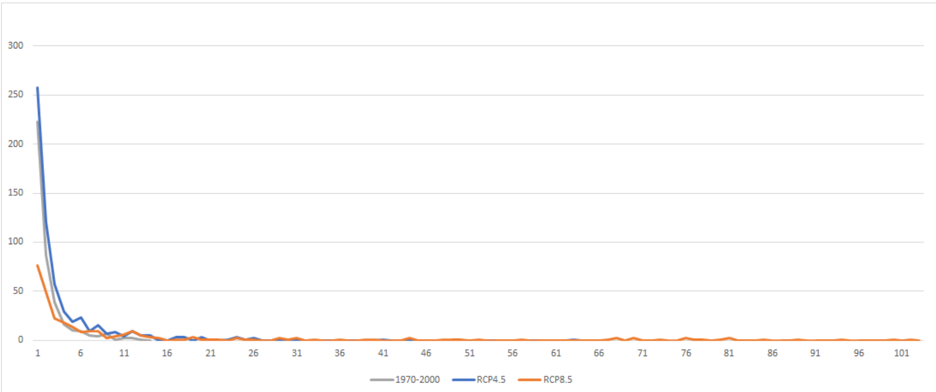

Figure 3.49. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Cairo.

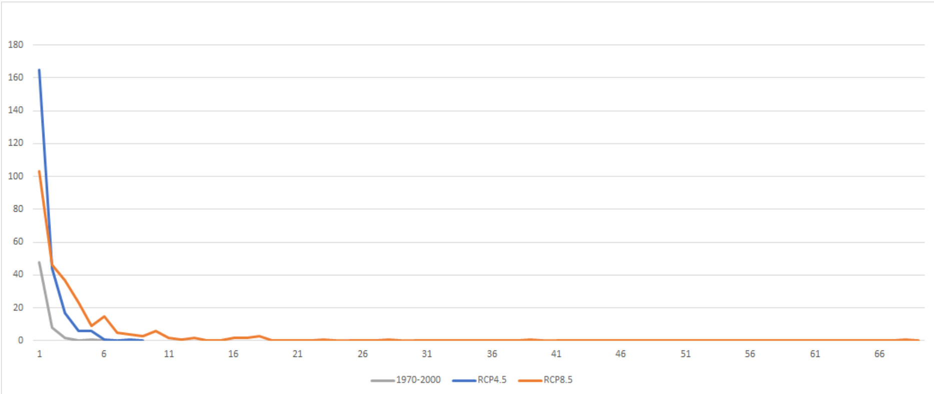

Figure 3.50. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Cairo.

3.5.2. Wind Chill Index Consecutive Days Distributions

Figure 3.51 shows that duration of cold days in future will decrease. Also, according to Figure 3.52 maximum duration of heat index extremely cold days occurs in the past.

Figures below show consecutive days for wind chill index in Cairo:

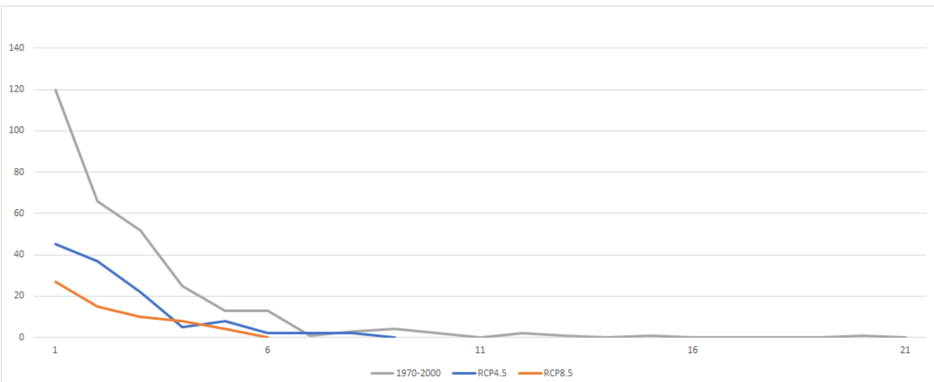

Figure 3.51. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Cairo.

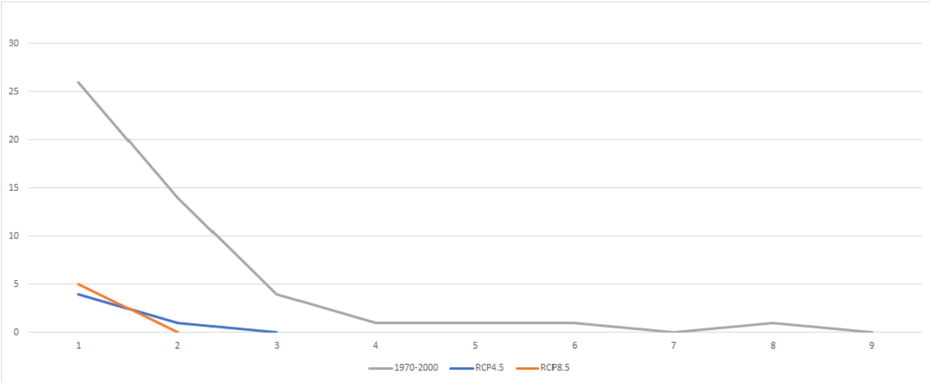

Figure 3.52. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Cairo.

3.5.3. Heat Index Distributions

Figure 3.53 shows the heat index distribution between 1970 and 2000. According to Figure 3.54 and Figure 3.55, heat index values will increase in future regarding RCP 4.5 and RCP 8.5 scenarios. Increase will be more drastic in future according to 8.5 scenario. Also, Table 3.9 shows that number of extremely hot days will be increase in future. Heat index value occurred in past once in one hundred years will be seen once in 27 years according to RCP 4.5 scenario and once in every five years according to RCP 8.5 scenario.

Histograms below show the distributions of Cairo heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

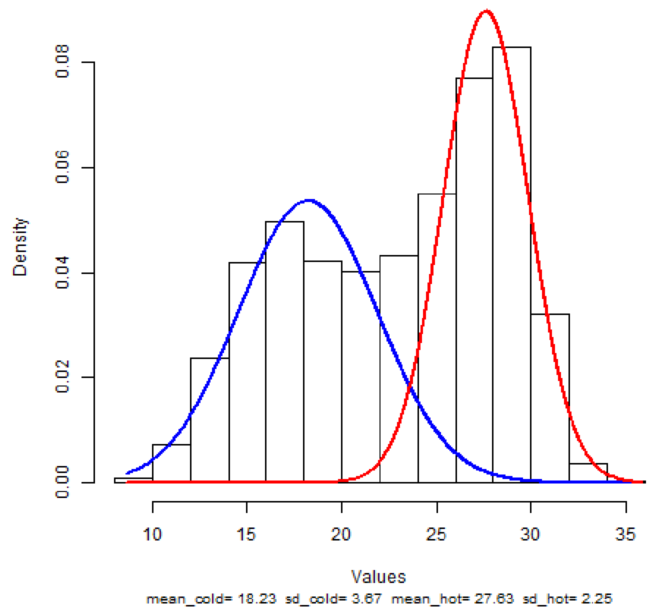

Figure 3.53. Distribution of 1970-2000 heat index values in Cairo.

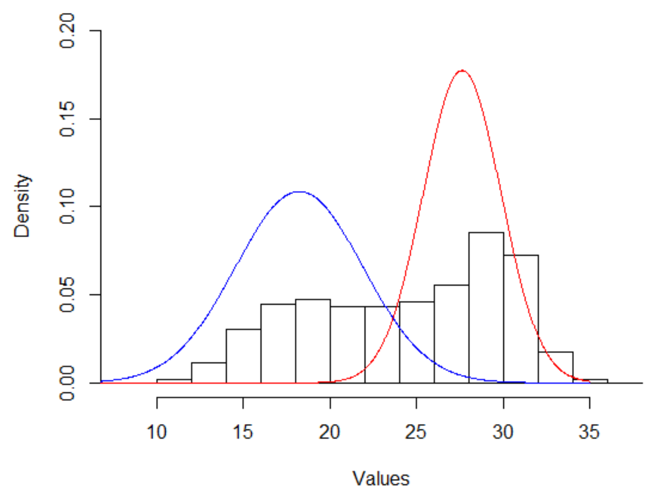

Figure 3.54. Distribution of 2070-2100 RCP 4.5 heat index values in Cairo.

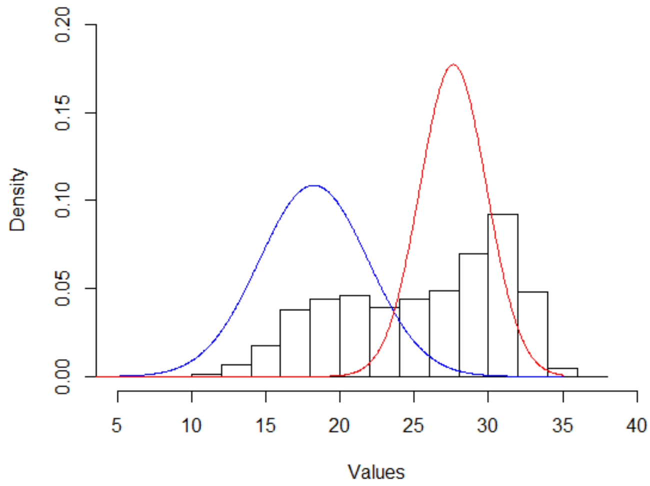

Figure 3.55. Distribution of 2070-2100 RCP 8.5 heat index values in Cairo.

Table 3.9. Cairo HI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	27.629	2.252	100	18.232	3.672	100
2070-2100RCP 4.5	29.43	1.963	26.59	20.39	4.069	180.331
2070-2100RCP 8.5	30.551	1.876	5.404	21.592	4.244	296.204

3.5.4. Wind Chill Index Distributions

Figure 3.56 shows the wind chill index distribution between 1970 and 2000. According to Figure 3.57 and Figure 3.58, wind chill index values will increase in future regarding RCP 4.5 and RCP 8.5 scenarios. Increase will be more drastic in future according to 8.5 scenario. Table 3.10 shows that number of extremely hot days will increase in future. Wind chill index value that occurred in past once in one hundred years will be seen once in 6 years according to RCP 4.5 scenario and 5 times in every year according to RCP 8.5 scenario. Also extremely cold days will occur rarely in future according to both RCP 4.5 and RCP 8.5 scenario. Wind chill value occurred once in 100 years will occur once in 712 years according to RCP 4.5 scenario and once in 456 years according to RCP 8.5 scenario

Histograms below show the distributions Cairo wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

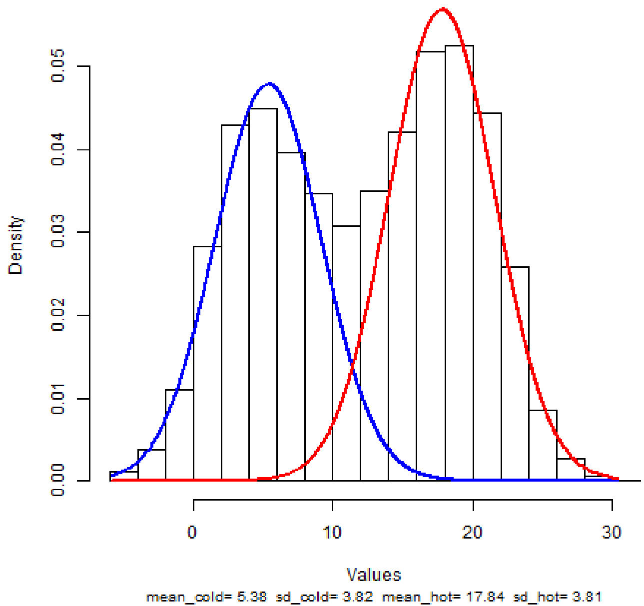

Figure 3.56. Distribution of 1970-2000 wind chill index values in Cairo.

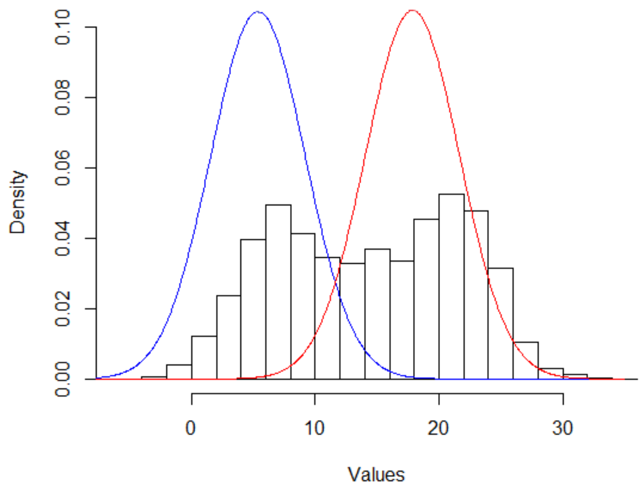

Figure 3.57. Distribution of 2070-2100 RCP 4.5 wind chill index values in Cairo.

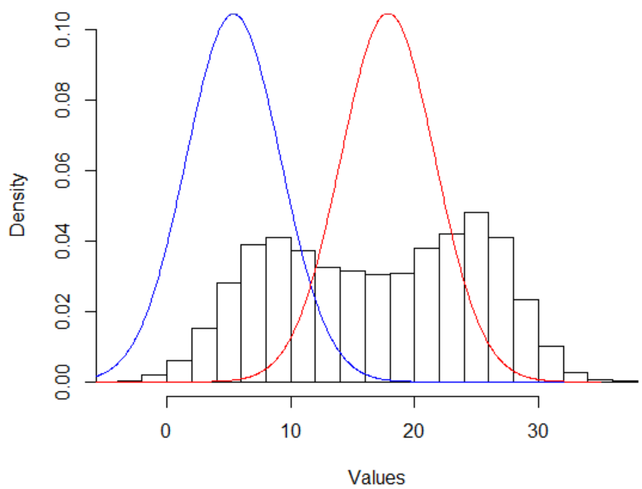

Figure 3.58. Distribution of 2070-2100 RCP 8.5 wind chill index values in Cairo.

Table 3.10. Cairo WCI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	17.835	3.806	100	5.385	3.82	100
2070-2100RCP 4.5	20.512	3.792	6.535	7.945	4.016	712.275
2070-2100RCP 8.5	23.767	4.051	0.265	9.914	4.557	456.302

3.6. Istanbul

Istanbul has both Black Sea shore and Marmara Sea shore. City lies on both Europe and Asia, and two continentals are separated by Bosporus. It has quite cold winters, but otherwise it has Mediterranean characteristics: the rainiest seasons are autumn and winter, and summer is hot and sunny. Population of Istanbul is over 15 million [42].

3.6.1. Heat Index Consecutive Days Distributions

Figure 3.59 shows that in Istanbul, according to both RCP 4.5 and RCP 8.5 scenarios, duration of hot days increases. Also, according to Figure 3.60 duration of heat index consecutive extremely hot days increases. Furthermore, according to RCP 8.5 scenario heat index consecutive extremely hot day duration increases severely.

Figures below show consecutive days for heat index in Istanbul:

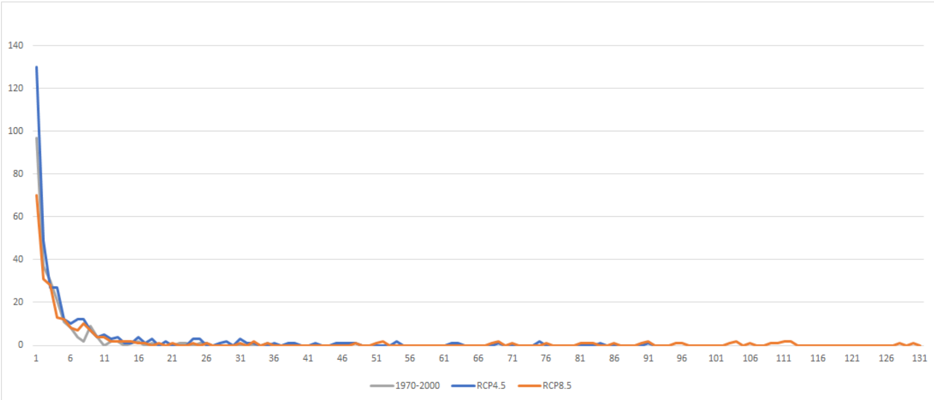

Figure 3.59. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Istanbul.

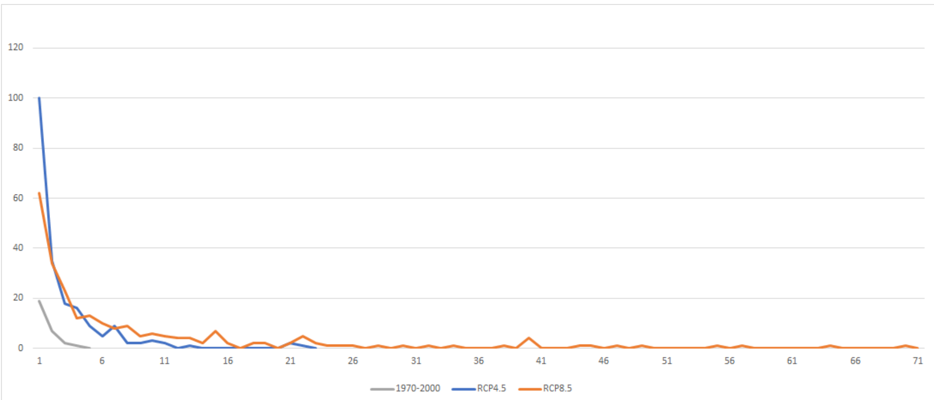

Figure 3.60. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Istanbul.

3.6.2. Wind Chill Index Consecutive Days Distributions

Figure 3.61 indicates that the duration of wind chill index cold days decreases in both RCP 4.5 and RCP 8.5 scenarios. Decrease in RCP 8.5 scenario is more appreciable. Figure 3.62 indicates that the duration of wind chill extremely cold days decreases drastically in both RCP 4.5 scenario and RCP 8.5 scenario.

Figures below show consecutive days for wind chill index in Istanbul:

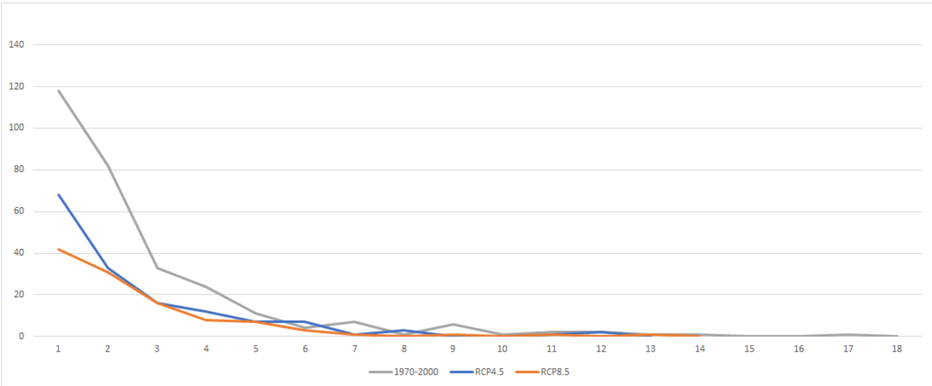

Figure 3.61. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Istanbul.

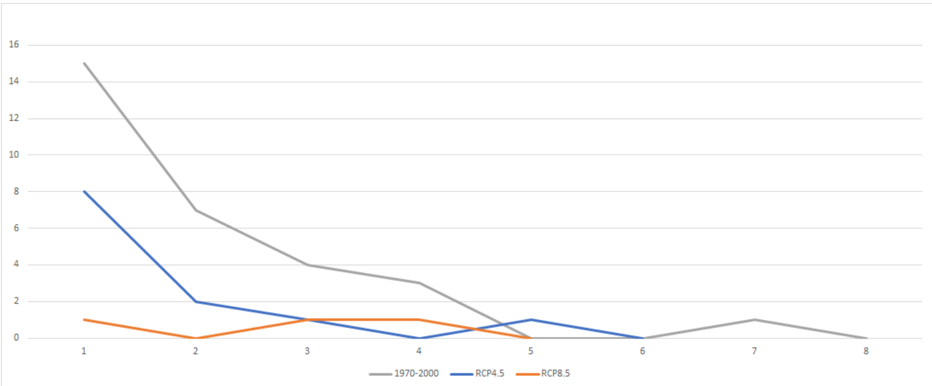

Figure 3.62. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Istanbul.

3.6.3. Heat Index Distributions

Figure 3.63 shows the distribution of heat index values between 1970 and 2000. Figure 3.64 and Figure 3.65 show that future values of heat index will be higher according to RCP 4.5 and RCP 8.5 scenarios. Figure 3.65 shows more increase in heat index values when they are compared to past and RCP 4.5 scenarios. Table 3.11 shows the increase in mean values for summer according to RCP 4.5 and RCP 8.5 scenarios. Also, extreme values (1 in a century) occur more often in future scenarios (1 day in 7 years according to RCP 4.5 scenario, three days in a year according to RCP 8.5 scenario)

Histograms below show the distributions of Istanbul heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

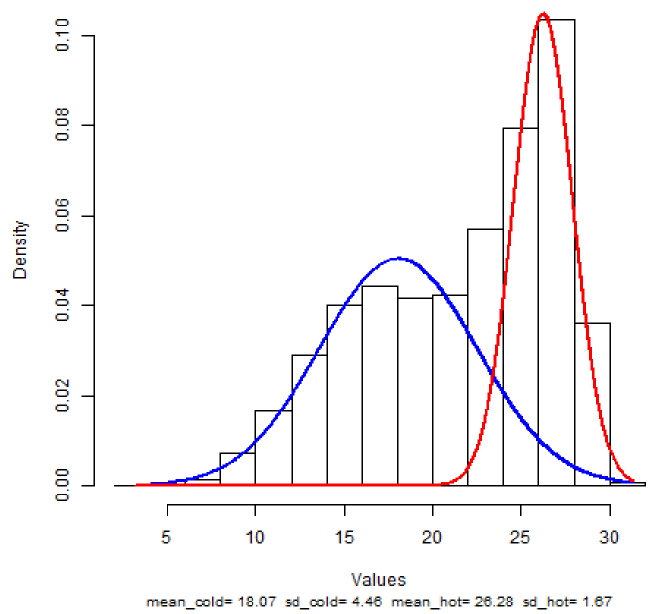

Figure 3.63. Distribution of 1970-2000 heat index values in Istanbul.

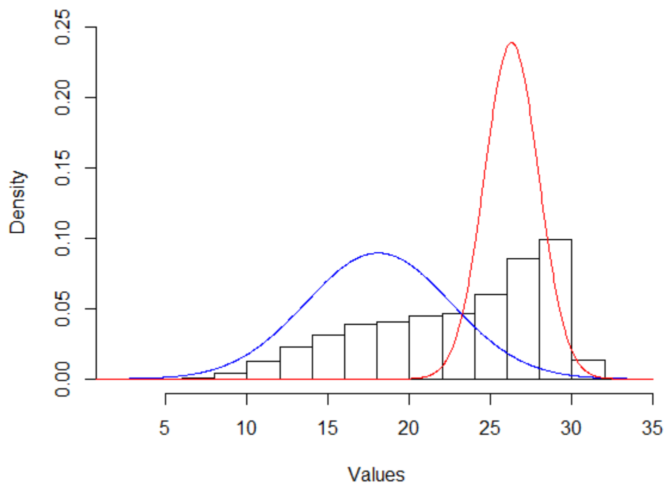

Figure 3.64. Distribution of 2070-2100 RCP 4.5 heat index values in Istanbul.

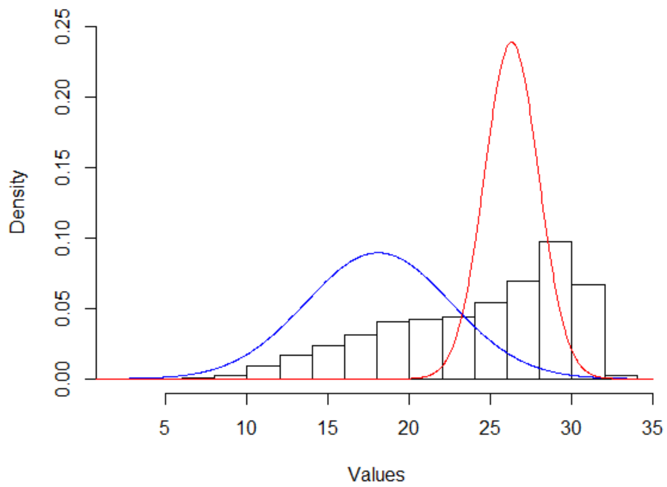

Figure 3.65. Distribution of 2070-2100 RCP 8.5 heat index values in Istanbul.

Table 3.11. Istanbul HI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	26.278	1.669	100	18.067	4.456	100
2070-2100RCP 4.5	27.831	1.543	6.985	19.645	4.695	175.768
2070-2100RCP 8.5	29.004	1.629	0.401	20.842	4.884	254.249

3.6.4. Wind Chill Index Distributions

Figure 3.66 shows the wind chill index distribution between 1970 and 2000. According to Figure 3.67 and Figure 3.68, wind chill index values will increase in future regarding RCP 4.5 and RCP 8.5 scenarios. Increase will be more drastic in future according to 8.5 scenario. Table 3.12 shows that the number of extremely hot days will increase in future. Heat index value occurred in past once in one hundred years will be seen once in five years according to RCP 4.5 scenario and once in two years according to RCP 8.5 scenario. Also, extremely cold days will occur rarely in future according to both RCP 4.5 and RCP 8.5 scenario.

Histograms below show the distributions Istanbul wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

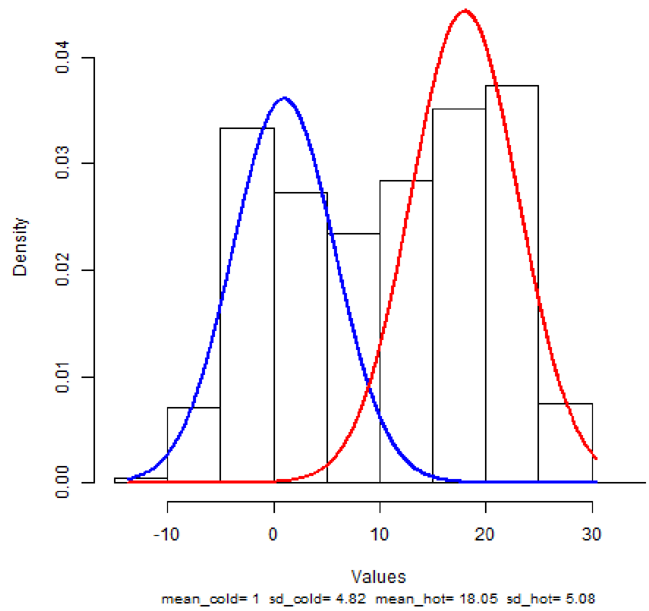

Figure 3.66. Distribution of 1970-2000 wind chill index values in Istanbul.

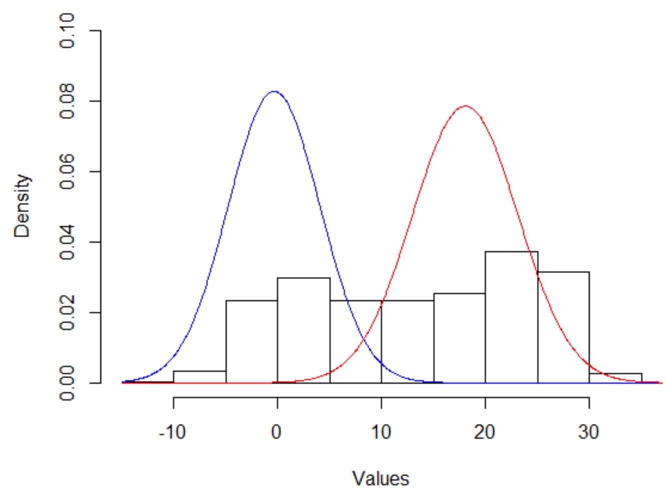

Figure 3.67. Distribution of 2070-2100 RCP 4.5 wind chill index values in Istanbul.

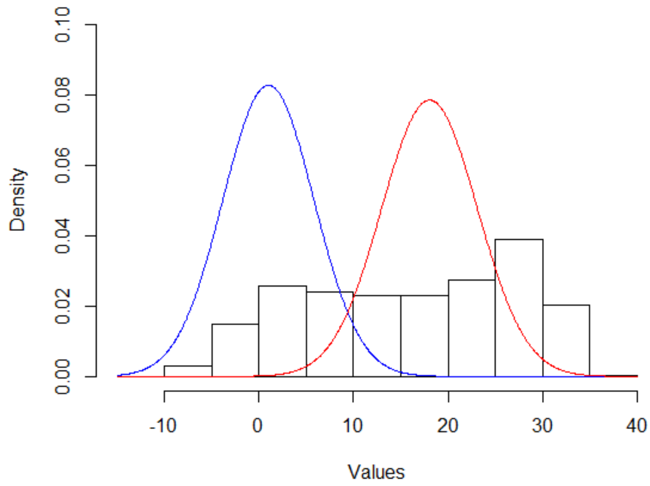

Figure 3.68. Distribution of 2070-2100 RCP 8.5 wind chill index values in Istanbul.

Table 3.12. Istanbul WCI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	18.055	5.081	100	1.005	4.824	100
2070-2100RCP 4.5	22.782	4.457	13.623	4.676	6.193	30.415
2070-2100RCP 8.5	27.213	3.831	1.779	8.873	8.029	8.873

3.7. Izmir

Izmir is the third biggest city in Turkey with population over 2.5 million [43]. The city is at Gulf of Izmir on the deeply indented coast of the Aegean Sea [44]. Izmir is the one of the warmest cities in Turkey with high precipitation amount in most of the year.

3.7.1. Heat Index Consecutive Days Distributions

Figure 3.69 shows that in Izmir, according to RCP 8.5 duration of hot days increases. However according to Figure 3.70 maximum duration of extremely hot days occured in the past.

Figures below show consecutive days for heat index in Izmir:

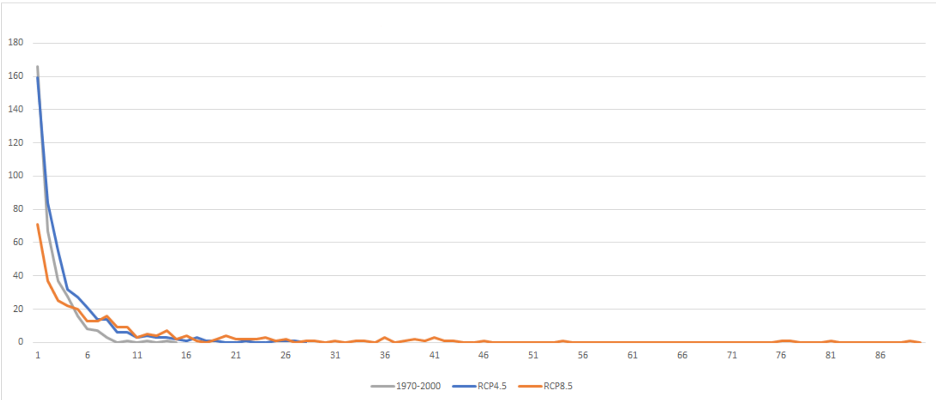

Figure 3.69. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Izmir.

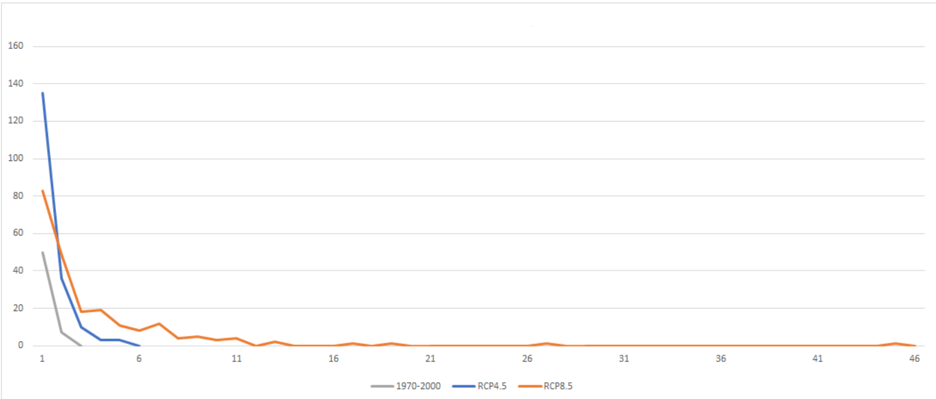

Figure 3.70. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Izmir.

3.7.2. Wind Chill Index Consecutive Days Distributions

According to Figure 3.71, durations of wind chill index cold days will decrease in future in both RCP 4.5 and RCP 8.5 scenarios. Figure 3.72 shows that maximum duration of wind chill index extremely cold day occured in the past.

Figures below show consecutive days for wind chill index in Izmir:

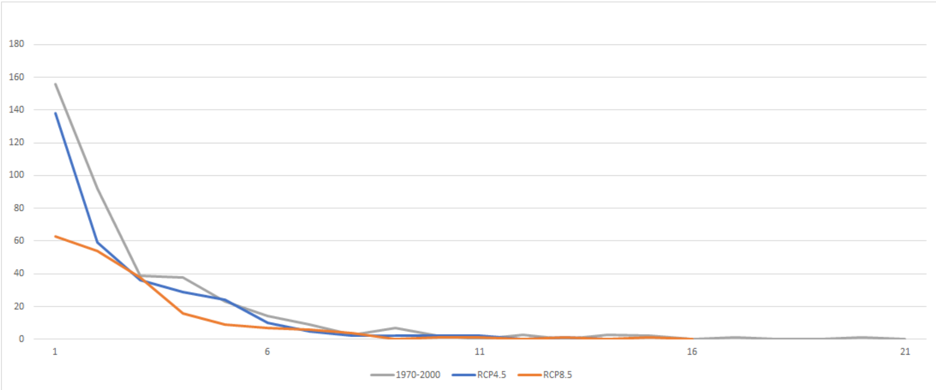

Figure 3.71. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Izmir.

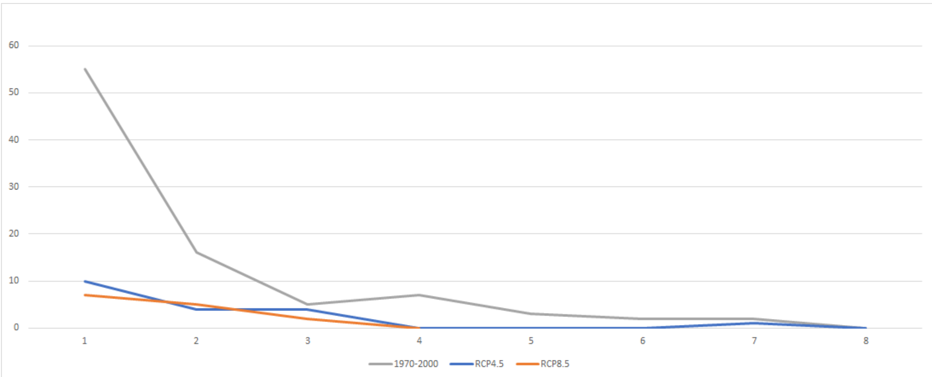

Figure 3.72. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Izmir.

3.7.3. Heat Index Distributions

Figure 3.73 shows the distribution of heat index values between 1970 and 2000. Figure 3.74 and Figure 3.75 show that future values of heat index will be higher according to RCP 4.5 and RCP 8.5 scenarios. Figure 3.75 shows more increase in heat index values when they are compared to past and RCP 4.5 scenarios. Table 3.13 shows the increase in mean values for summer according to RCP 4.5 and RCP 8.5 scenarios. Also, extreme values (1 in a century) occur more often in future scenarios (1 day in 14 years according to RCP 4.5 scenario, 1 day in 12 year according to RCP 8.5 scenario).

Histograms below show the distributions of Izmir heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

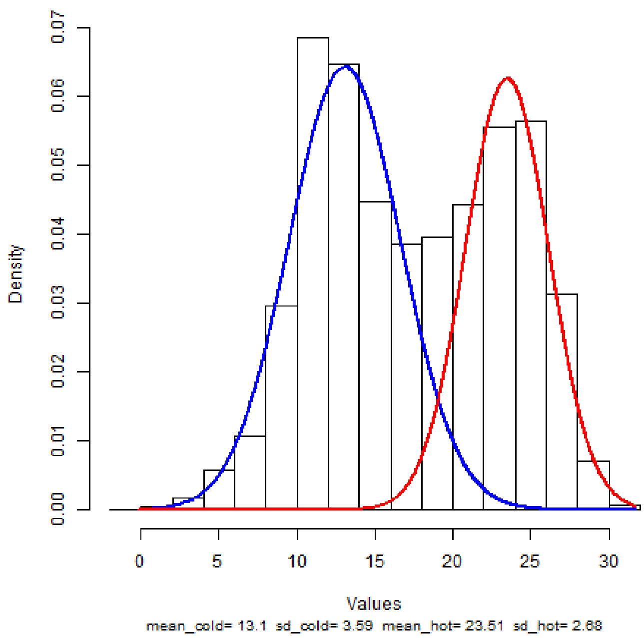

Figure 3.73. Distribution of 1970-2000 heat index values in Izmir.

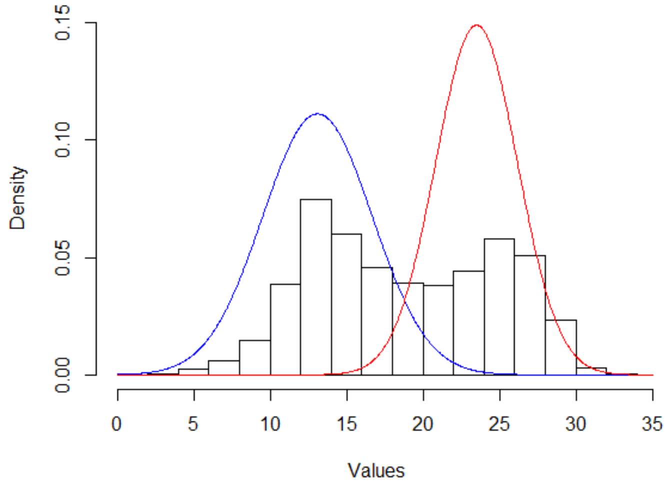

Figure 3.74. Distribution of 2070-2100 RCP 4.5 heat index values in Izmir.

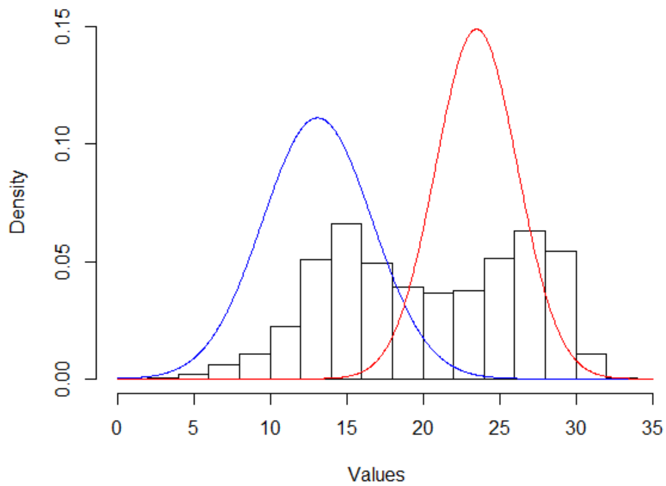

Figure 3.75. Distribution of 2070-2100 RCP 8.5 heat index values in Izmir.

Table 3.13. Izmir HI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	23.513	2.681	100	13.1	3.592	100
2070-2100RCP 4.5	25.098	2.06	14.44	14.675	3.547	942.359
2070-2100RCP 8.5	26.881	2.131	11.328	16.32	4.216	203.408

3.7.4. Wind Chill Index Distributions

Figure 3.76 shows the wind chill index distribution between 1970 and 2000. According to Figure 3.77 and Figure 3.78, wind chill index distributions are shifted to hotter values when they are compared to past data. Values of RCP 8.5 scenario show more increase than RCP 4.5 data. Table 3.14 shows unexpected results for RCP 4.5 scenario due to changes in mean value and standard deviation. However, mean values increase for summer in both RCP 4.5 and RCP 8.5 scenarios.

Histograms below show the distributions Izmir wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

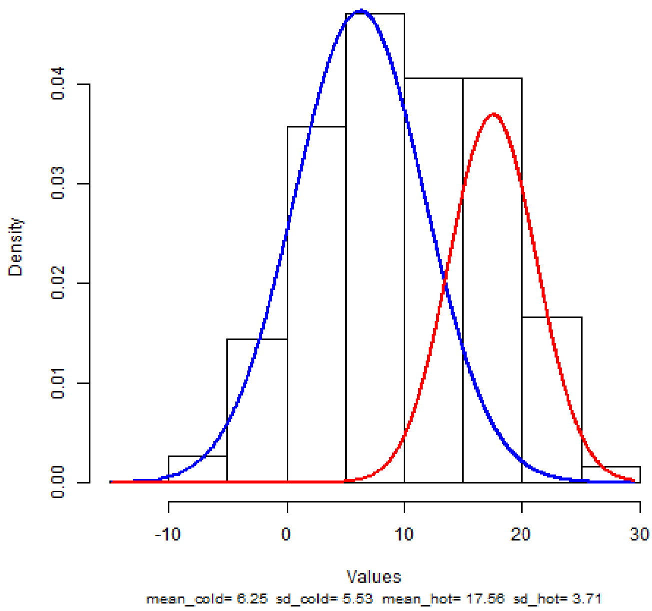

Figure 3.76. Distribution of 1970-2000 wind chill index values in Izmir.

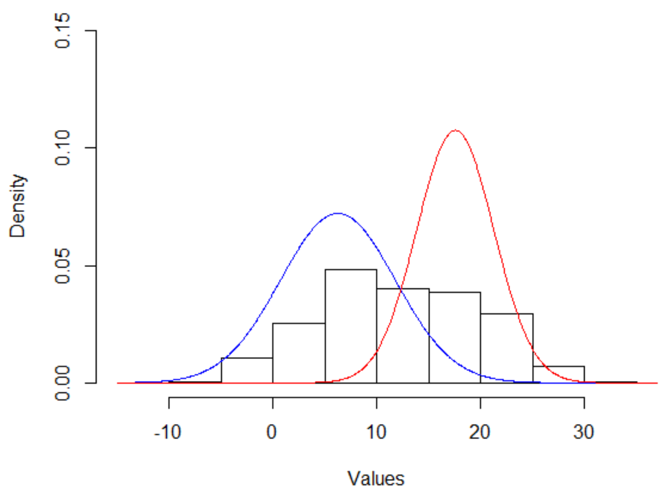

Figure 3.77. Distribution of 2070-2100 RCP 4.5 wind chill index values in Izmir.

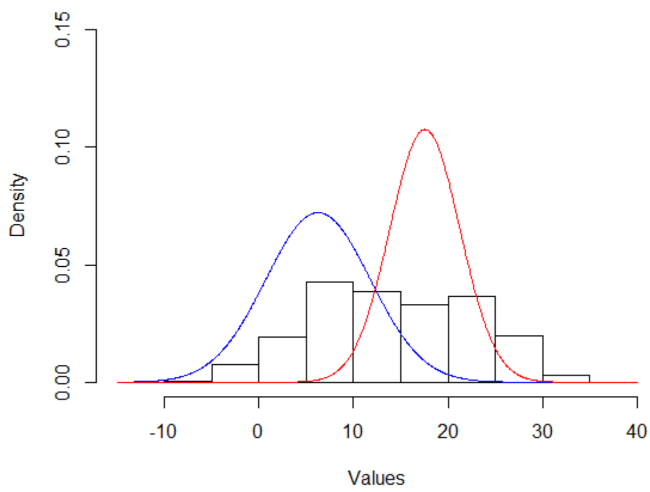

Figure 3.78. Distribution of 2070-2100 RCP 8.5 wind chill index values in Izmir.

Table 3.14. Izmir WCI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	10.507	7.384	100	4.245	1.661	100
2070-2100RCP 4.5	20.105	3.838	102990.436	8.197	5.603	0.122
2070-2100RCP 8.5	26.881	2.131	11.328	16.32	4.216	203.408

3.8. Jeddah

Jeddah is a major city built around a port in Saudi Arabia. It lies along the Red Sea west of Mecca [45]. Jeddah has desert climate (i.e. warm winters and extremely hot summers). Population of the city is over 4 million [46].

3.8.1. Heat Index Consecutive Days Distributions

Figure 3.79 shows that in Jeddah, according to RCP 8.5 duration of hot days increases. Figure 3.80 shows that maximum duration of extremely hot days occurs in RCP 8.5 scenario.

Figures below show consecutive days for heat index in Jeddah:

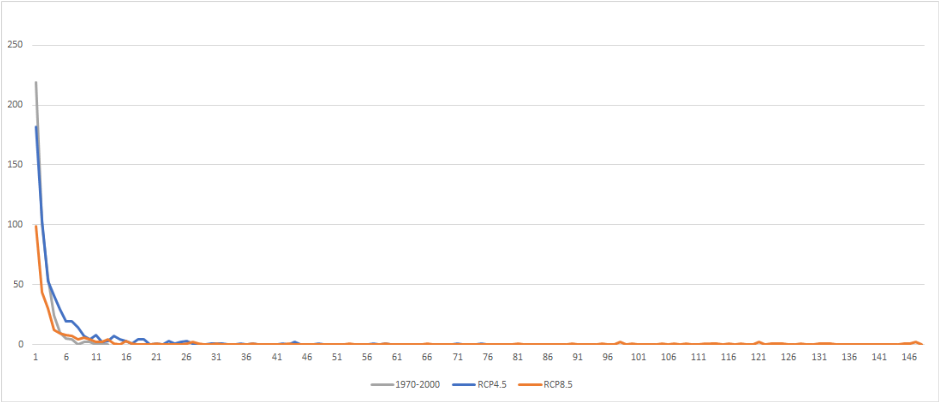

Figure 3.79. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Jeddah.

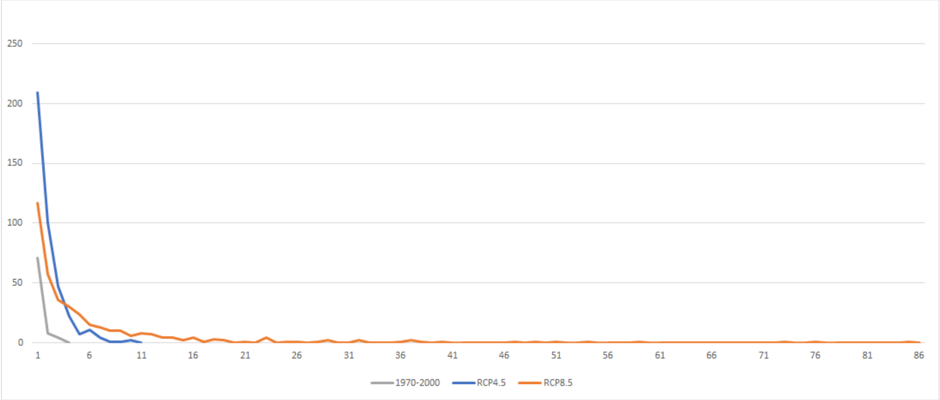

Figure 3.80. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Jeddah.

3.8.2. Wind Chill Index Consecutive Days Distributions

According to Figure 3.81, durations of wind chill index cold days will decrease in future in both RCP 4.5 and RCP 8.5 scenarios. Figure 3.82 shows that maximum duration of wind chill index extremely cold day occurs in the past.

Figures below show consecutive days for wind chill index in Jeddah:

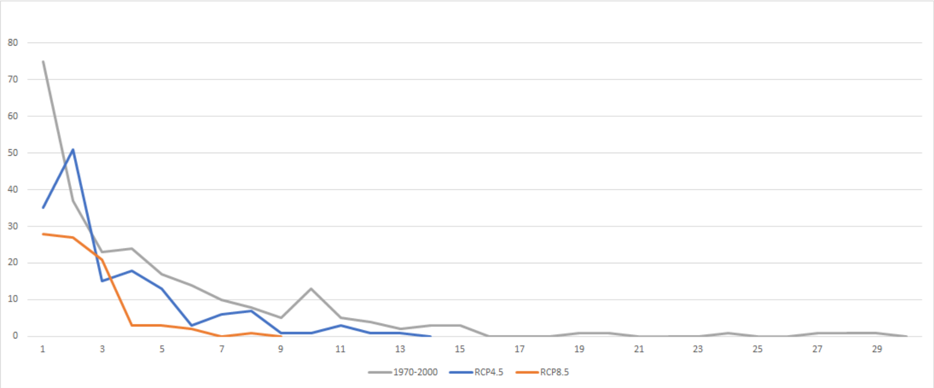

Figure 3.81. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Jeddah.

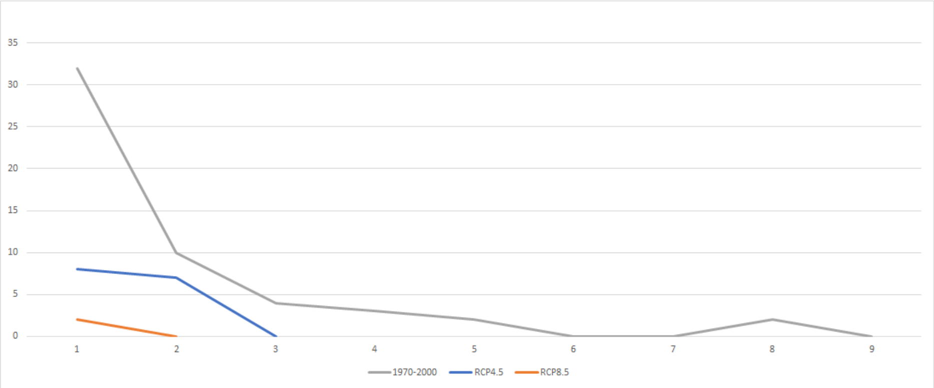

Figure 3.82. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Jeddah.

3.8.3. Heat Index Distributions

Figure 3.83 shows the distribution of heat index values between 1970 and 2000. Figure 3.84 and Figure 3.85 show that future values of heat index will be higher according to RCP 4.5 and RCP 8.5 scenarios. Also Figure 3.85 shows more increase in heat index values when they are compared to past and RCP 4.5 scenarios. Table 3.15 shows the increase in mean values for summer according to RCP 4.5 and RCP 8.5 scenarios. Also, extreme values (1 in a century) occur more often in future scenarios (1 day in every 1.5 years according to RCP 4.5 scenario, 4 days in a year according to RCP 8.5 scenario).

Histograms below show the distributions of Jeddah heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

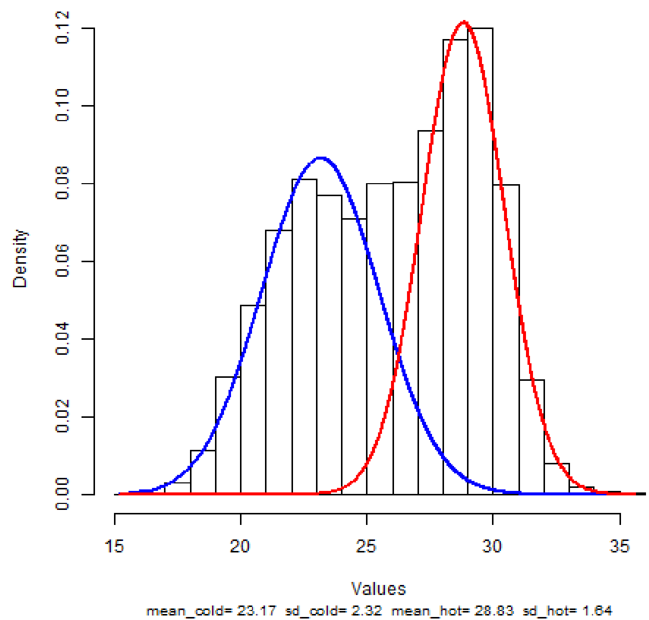

Figure 3.83. Distribution of 1970-2000 heat index values in Jeddah.

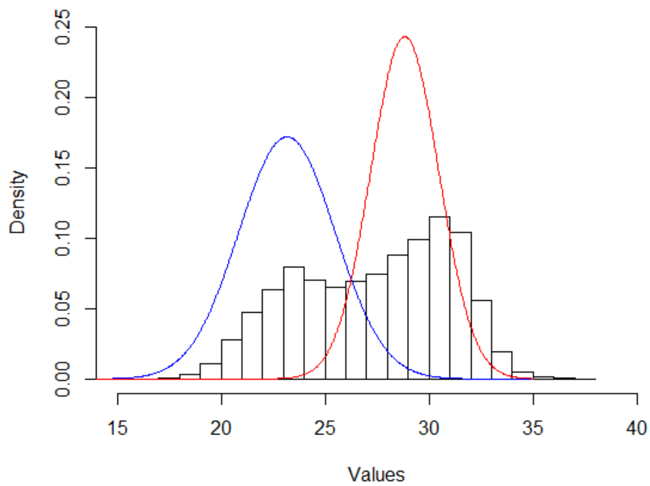

Figure 3.84. Distribution of 2070-2100 RCP 4.5 heat index values in Jeddah.

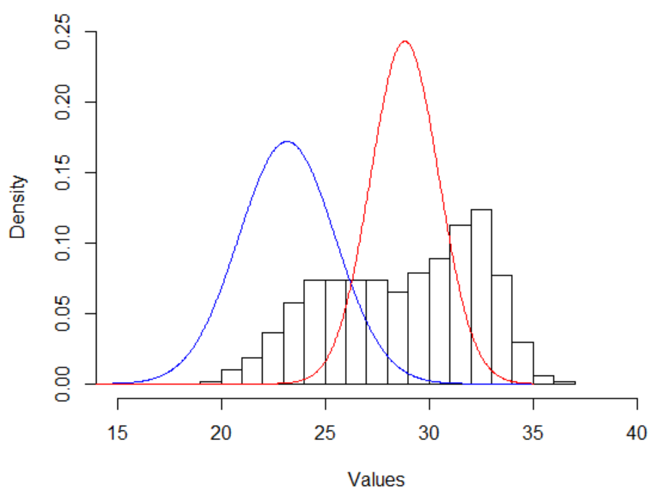

Figure 3.85. Distribution of 2070-2100 RCP 8.5 heat index values in Jeddah.

Table 3.15. Jeddah HI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	28.826	1.637	100	23.172	2.319	100
2070-2100RCP 4.5	30.206	1.784	1.592	24.14	2.343	521.254
2070-2100RCP 8.5	31.94	1.512	0.259	26.045	2.576	2672.279

3.8.4. Wind Chill Index Distributions

Figure 3.86 shows the wind chill index distribution between 1970 and 2000. According to Figure 3.87 and Figure 3.88 wind chill index distributions are shifted to hotter values when they are compared to past data. Values of RCP 8.5 scenario show more increase than RCP 4.5 data. Table 3.16 shows that mean values of wind chill index for both summer and winter are increasing in RCP 4.5 and RCP 8.5 scenarios. Also, extreme values such as occurrence once in a century will be seen more frequently (for RCP 4.5 scenario 5 days in every year and for RCP 8.5 scenario almost 3 months in every year).

Histograms below show the distributions Jeddah wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

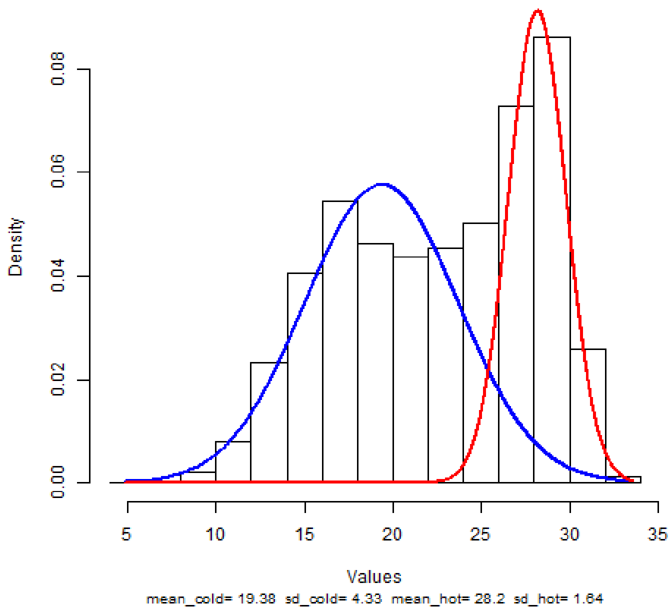

Figure 3.86. Distribution of 1970-2000 wind chill index values in Jeddah.

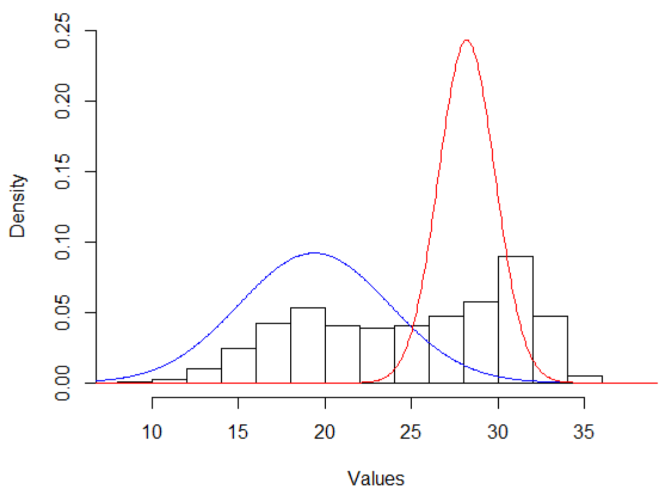

Figure 3.87. Distribution of 2070-2100 RCP 4.5 wind chill index values in Jeddah.

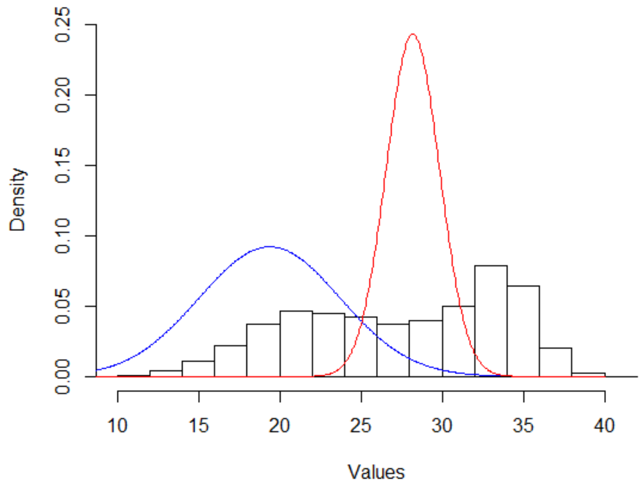

Figure 3.88. Distribution of 2070-2100 RCP 8.5 wind chill index values in Jeddah.

Table 3.16. Jeddah WCI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	28.204	1.64	100	19.38	4.331	100
2070-2100RCP 4.5	30.741	1.838	0.227	21.186	4.478	330.227
2070-2100RCP 8.5	33.434	2.114	0.013	43.547	4.585	1808.848

3.9. Riyadh

Riyadh is the capital of Saudi Arabia with population of 7 million [47]. City is surrounded with land, it has very hot summers and cold winters. The temperature difference between day and night is high. General scarcity of precipitation in the city, humidity in Riyadh remains low throughout the year, especially during the summer [48].

3.9.1. Heat Index Consecutive Days Distributions

Figure 3.89 shows that in Riyadh, according to RCP 8.5 duration of hot days increases. Also, Figure 3.90 shows that maximum duration of extremely hot days occurs in RCP 8.5 scenario.

Figures below show consecutive days for heat index in Riyadh:

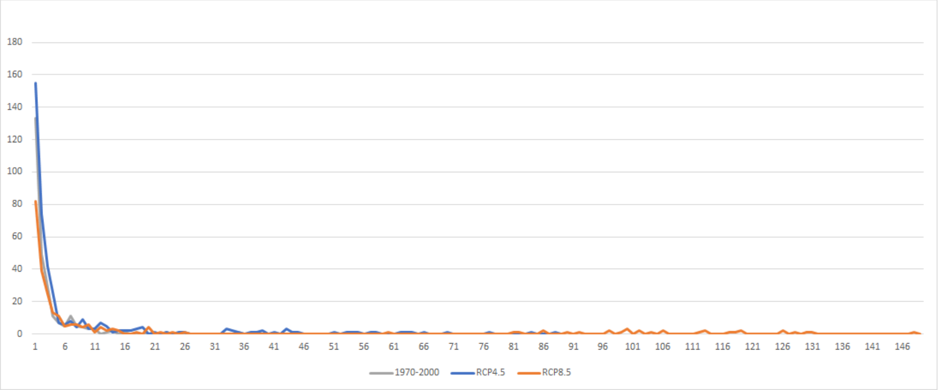

Figure 3.89. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Riyadh.

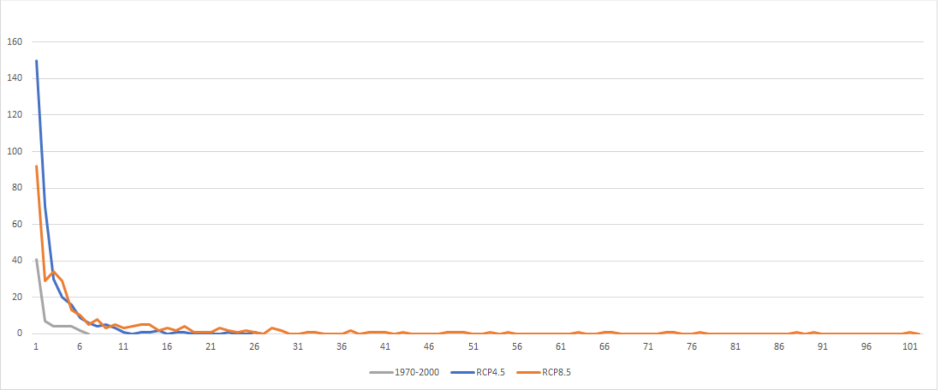

Figure 3.90. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Riyadh.

3.9.2. Wind Chill Index Consecutive Days Distributions

According to Figure 3.91, maximum duration of wind chill index cold days will not change drastically in future according to both RCP 4.5 and RCP 8.5 scenarios. Figure 3.92 shows that maximum duration of wind chill index extremely cold day occurs in the past.

Figures below show consecutive days for wind chill index in Riyadh:

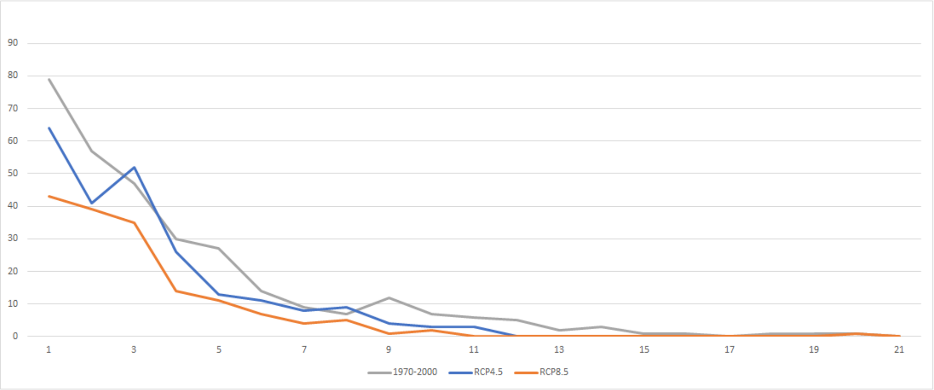

Figure 3.91. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Riyadh.

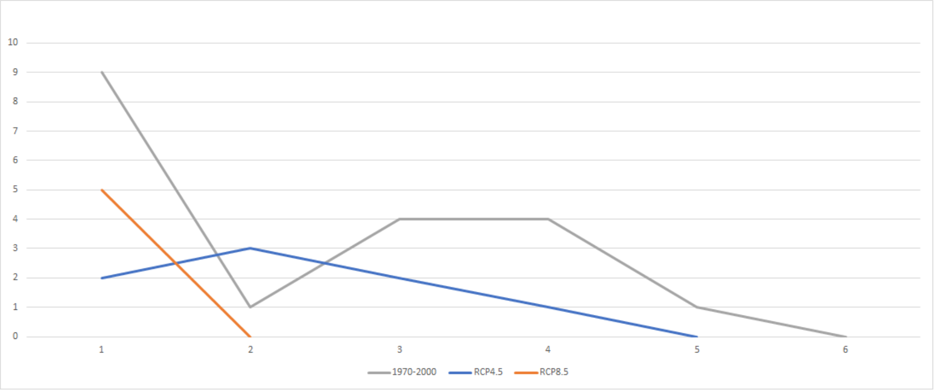

Figure 3.92. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Riyadh.

3.9.3. Heat Index Distributions

Figure 3.93 shows the distribution of heat index values between 1970 and 2000. Figure 3.94 and Figure 3.95 show that future values of heat index will be higher according to RCP 4.5 and RCP 8.5 scenarios. Also 3.95 shows more increase in heat index values when they are compared to past and RCP 4.5 scenarios. Also Table 3.17 shows the increase in mean values for summer according to RCP 4.5 and RCP 8.5 scenarios. Furthermore, extreme values (1 in a century) occur more often in future scenarios (1 day in almost every 2 years according to RCP 4.5 scenario, almost a month in a year according to RCP 8.5 scenario).

Histograms below show the distributions of Riyadh heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

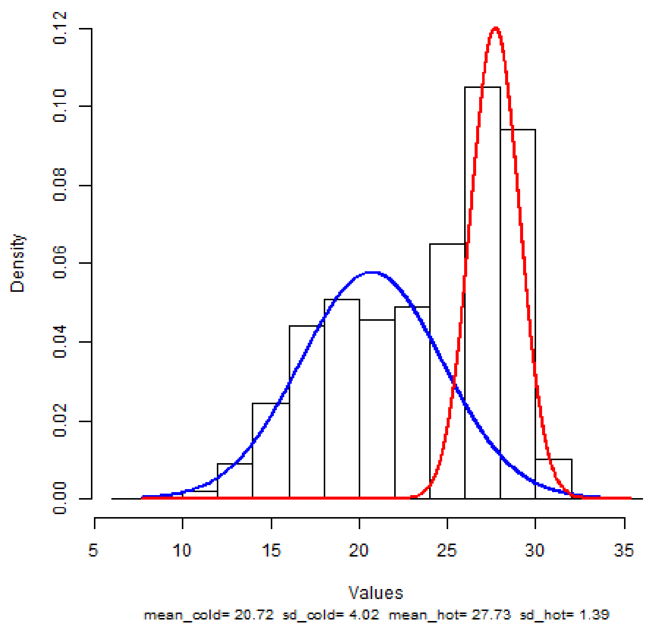

Figure 3.93. Distribution of 1970-2000 heat index values in Riyadh.

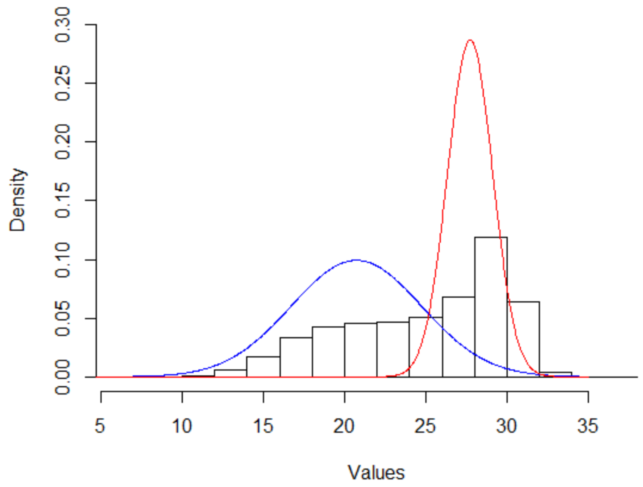

Figure 3.94. Distribution of 2070-2100 RCP 4.5 heat index values in Riyadh.

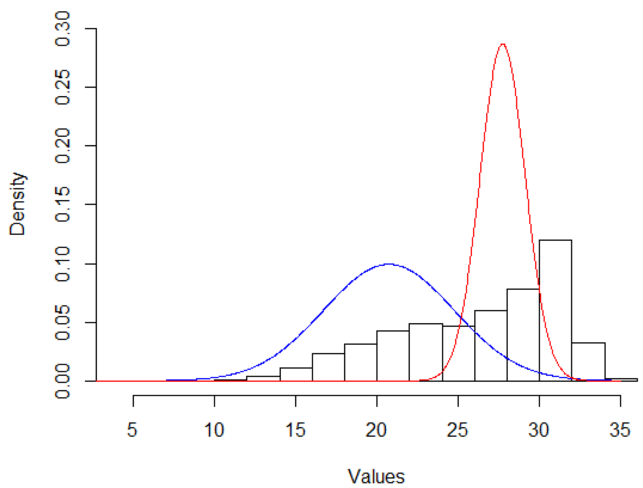

Figure 3.95. Distribution of 2070-2100 RCP 8.5 heat index values in Riyadh.

Table 3.17. Riyadh HI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	27.726	1.393	100	20.717	4.017	100
2070-2100RCP 4.5	29.248	1.345	2.397	21.993	4.251	138.718
2070-2100RCP 8.5	30.518	1.45	0.11	23.291	4.345	352.319

3.9.4. Wind Chill Index Distributions

Figure 3.96 shows the wind chill index distribution between 1970 and 2000. According to Figure 3.97 and Figure 3.98, wind chill index distributions are shifted to hotter values when they are compared to past data. Values of RCP 8.5 scenario show more increase than RCP 4.5 data. Table 3.18 displays that mean values of wind chill index for both summer and winter are increasing in RCP 4.5 and RCP 8.5 scenarios. Also, extreme values such as occurrence once in a century will be seen more frequently (for RCP 4.5 scenario 1 day in 3 years and for RCP 8.5 scenario almost 1 month in every year).

Histograms below show the distributions Riyadh wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

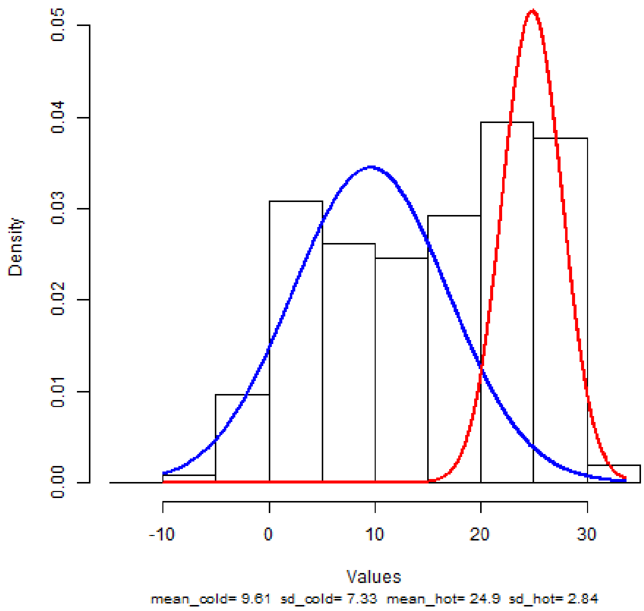

Figure 3.96. Distribution of 1970-2000 wind chill index values in Riyadh.

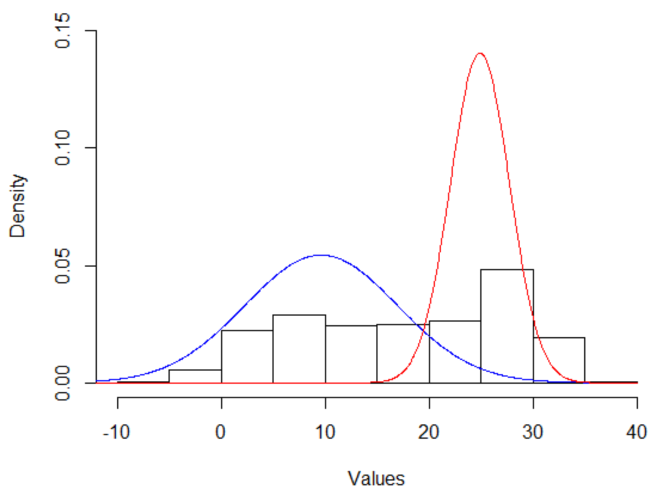

Figure 3.97. Distribution of 2070-2100 RCP 4.5 wind chill index values in Riyadh.

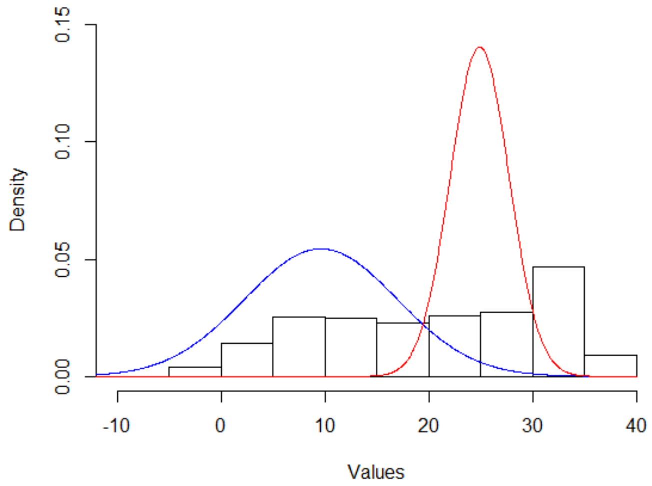

Figure 3.98. Distribution of 2070-2100 RCP 8.5 wind chill index values in Riyadh.

Table 3.18. Riyadh WCI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	24.897	2.839	100	9.614	7.334	100
2070-2100RCP 4.5	28.19	2.646	2.781	12.007	7.811	127.94
2070-2100RCP 8.5	32.055	2.62	0.061	15.241	8.774	88.35

3.10. Tehran

Tehran is the capital of Iran with population over 9 million [49]. Tehran has arid climate with long summer. Humidity of Caspian Sea is blocked by Elburz mountains [50].

3.10.1. Heat Index Consecutive Days Distributions

Figure 3.99 shows that in Tehran, according to RCP 8.5 duration of hot days increases. However, Figure 3.100 shows that maximum duration of extremely hot days occurs in RCP 4.5 scenario.

Figures below show consecutive days for heat index in Tehran:

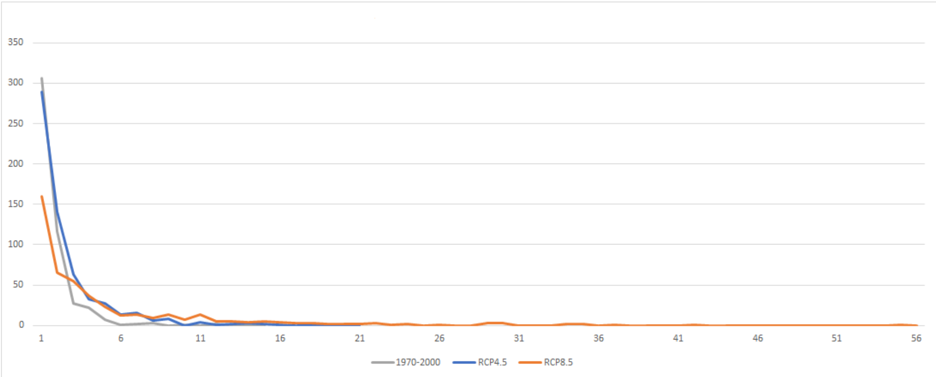

Figure 3.99. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive hot day distributions in Tehran.

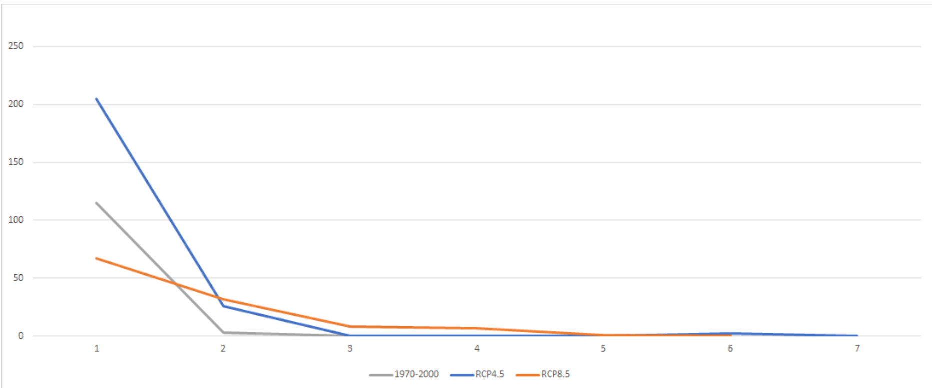

Figure 3.100. 1970-2000, RCP 4.5 and RCP 8.5 heat index consecutive extremely hot day distributions in Tehran.

3.10.2. Wind Chill Index Consecutive Days Distributions

According to Figure 3.101, durations of wind chill index cold days will decrease in future with regard to both RCP 4.5 and RCP 8.5 scenarios. However, according to Figure 3.102 maximum duration of wind chill index extremely cold day occurs both in the past and RCP 8.5 scenario.

Figures below shows consecutive days for wind chill index in Tehran:

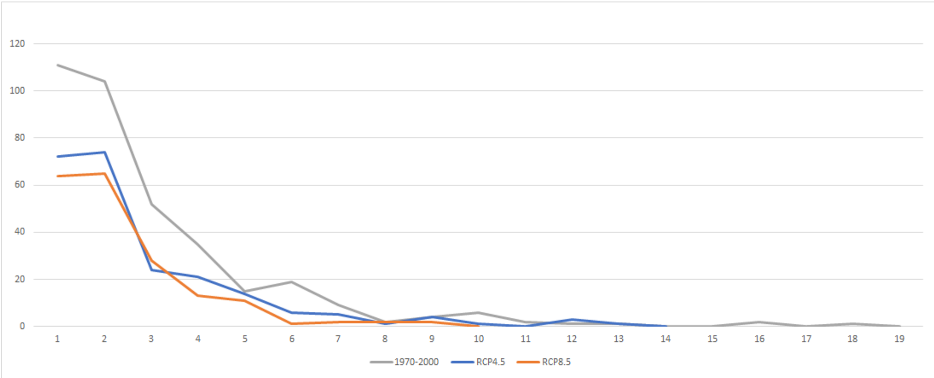

Figure 3.101. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive cold day distributions in Tehran.

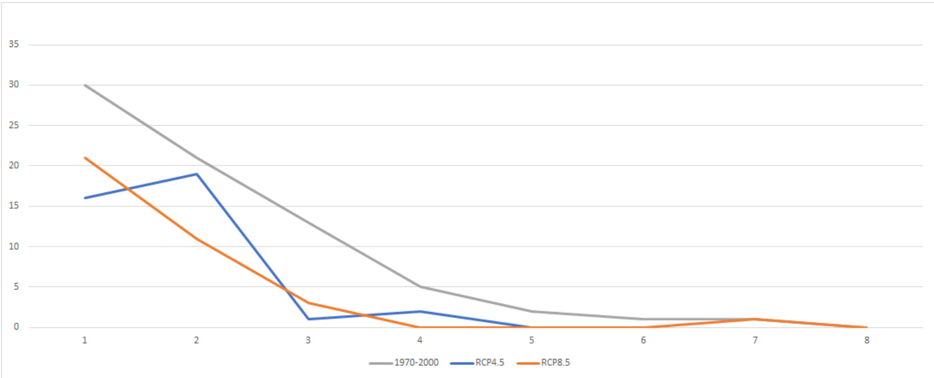

Figure 3.102. 1970-2000, RCP 4.5 and RCP 8.5 wind chill index consecutive extremely cold day distributions in Tehran.

3.10.3. Heat Index Distributions

Figure 3.103 shows the distribution of heat index values between 1970 and 2000. Figure 3.104 and Figure 3.105 show that future values of heat index will be higher according to RCP 4.5 and RCP 8.5 scenarios. Figure 3.105 shows more increase in heat index values when they are compared to past and RCP 4.5 scenarios. Also, Table 3.19 shows the increase in mean values for summer according to RCP 4.5 and RCP 8.5 scenarios.

Histograms below show the distributions of Tehran heat index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

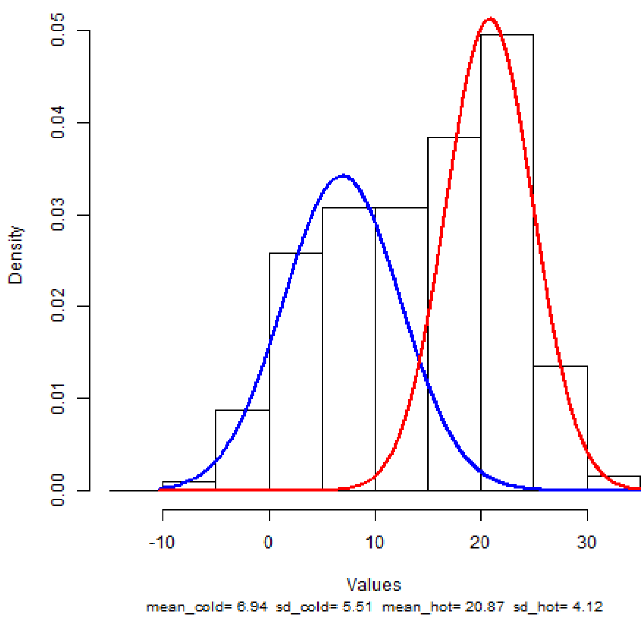

Figure 3.103. Distribution of 1970-2000 heat index values in Tehran.

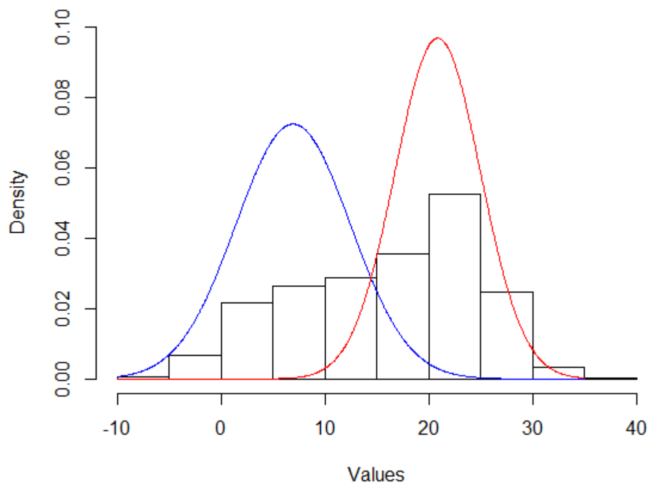

Figure 3.104. Distribution of 2070-2100 RCP 4.5 heat index values in Tehran.

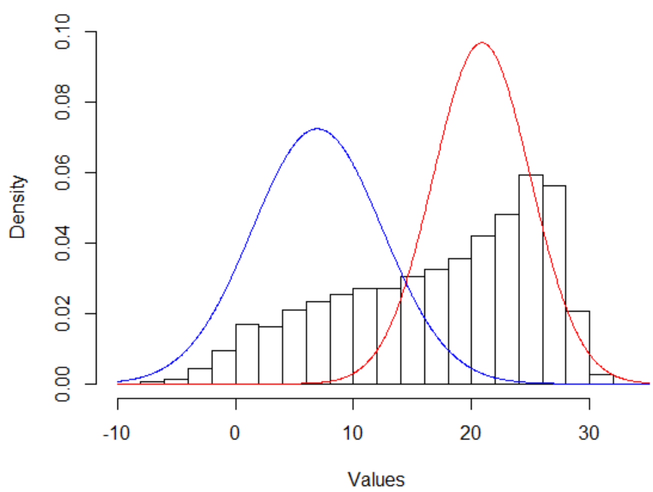

Figure 3.105. Distribution of 2070-2100 RCP 8.5 heat index values in Tehran.

Table 3.19. Tehran HI occurrence stats

	Hot			Cold		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	20.87	4.118	100	6.943	5.509	100
2070-2100RCP 4.5	22.398	4.117	21.87	8.232	5.861	91.252
2070-2100RCP 8.5	24.767	2.688	2589.62	12.075	7.352	28.018

3.10.4. Wind Chill Index Distributions

Figure 3.106 shows the wind chill index distribution between 1970 and 2000. According to Figure 3.107 and Figure 3.108 wind chill index distributions are shifted to hotter values when they are compared to past data. Values of RCP 8.5 scenario shows more increase than RCP 4.5 data. Table 3.20 shows that mean values of wind chill index for both summer and winter are increasing in RCP 4.5 and RCP 8.5 scenarios. Also, extreme values such as occurrence once in a century will be seen more frequently (for RCP 4.5 scenario 1 day in 3 years and for RCP 8.5 scenario almost 4 days in every year).

Histograms below show the distributions Tehran wind chill index values and their percentiles in the past, RCP 4.5 and RCP 8.5:

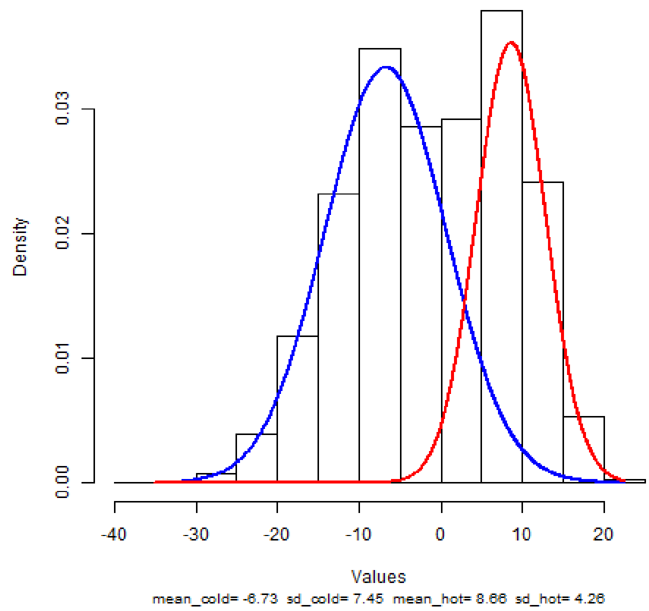

Figure 3.106. Distribution of 1970-2000 wind chill index values in Tehran.

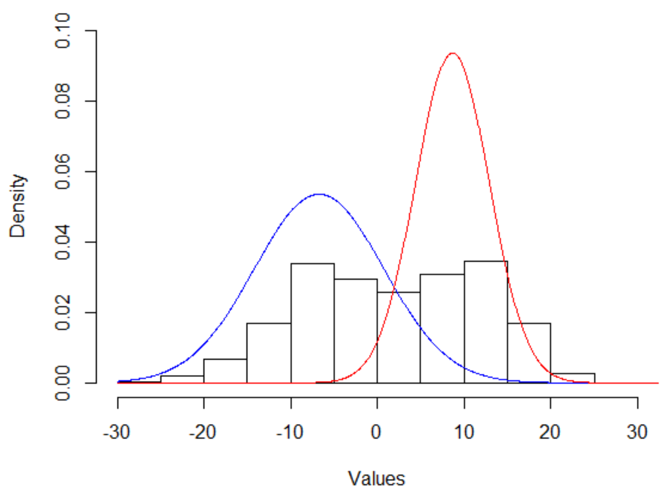

Figure 3.107. Distribution of 2070-2100 RCP 4.5 wind chill index values in Tehran.

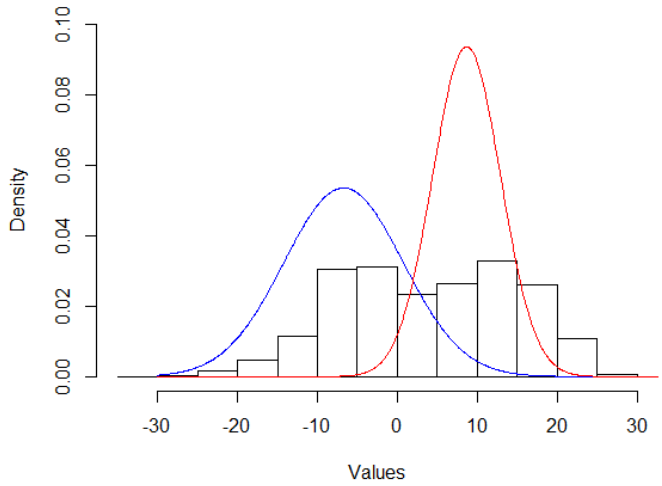

Figure 3.108. Distribution of 2070-2100 RCP 8.5 wind chill index values in Tehran.

Table 3.20. Tehran WCI occurrence stats

	Hot			**Cold**		
	μ	σ	**occurrence (1 in x years)**	μ	σ	**occurrence(1 in x years)**
1970-2000	8.658	4.259	100	-6.731	7.447	100
2070-2100RCP 4.5	11.543	4.686	2.512	-5.009	7.039	890.89
2070-2100RCP 8.5	14.135	5.077	0.279	-3.441	7.206	1531.332

3.11. Occurrence of Rare Events

Table 3.21 shows the probability of heat index extremely hot days that occurred in the past once in a hundred years, between 2070 and 2100 according to both RCP 4.5 and RCP 8.5 scenarios. Table 3.22 shows the probability of wind chill index extremely cold days occurred in the past once in a hundred years, between 2070 and 2100 according to both RCP 4.5 and RCP 8.5 scenarios.

Table 3.21. Heat Index Occurrence of Rare Events (once in x years).

	1970-2000	**2070-2100 RCP 4.5**	**2070-2100 RCP 8.5**
Alexandria	100	22766.431	15552.138
Amman	100	8.884	25.661
Ankara	100	113.830	164.535
Baghdad	100	14.664	0.647
Cairo	100	26.590	5.404
Istanbul	100	6.985	0.401
Izmir	100	14.440	11.328
Jeddah	100	1.592	0.259
Riyadh	100	2.397	0.110
Tehran	100	21.870	28.018

Table 3.22. Wind Chill Index Occurrence of Rare Events (once in x years).

	1970-2000	**2070-2100 RCP 4.5**	**2070-2100 RCP 8.5**
Alexandria	100	6471092.720	56425065.932
Amman	100	216.821	238.098
Ankara	100	0.104	0.161
Baghdad	100	46.788	28.578
Cairo	100	712.275	456.302
Istanbul	100	30.415	8.873
Izmir	100	0.122	203.408
Jeddah	100	330.227	1808.848
Riyadh	100	127.940	88.350
Tehran	100	890.890	1531.332

4. CONCLUSION

This study aimed to assess changes in heat wave and wind chill index frequencies, durations and values under climate change. Two climate change scenarios (RCP 4.5 and RCP 8.5) were applied to ten most crowded cities in MENA region. Results show that for both RCP 4.5 and RCP 8.5 number of hot days increases regarding heat index and wind chill index in all selected cities. As an exception in Alexandria, according to RCP 4.5 scenario the number of heat index hot days and extremely hot days decreases. Even though the number of heat index hot days increases in Tehran with RCP 8.5 scenario; the number of heat index extremely hot days decreases. Also, the number of heat index cold days and the number of heat index extremely cold days decrease regarding to both RCP 4.5 and RCP 8.5 scenarios. Results for wind chill index are similar with heat index's. For each city the number of wind chill index hot days and extremely hot days increase according to both RCP 4.5 and RCP 8.5 scenarios. Both indices increase in values more severely in RCP 8.5 scenarios.

When durations of heat index and wind chill index consecutive days are analyzed, it is seen that for each city, durations of heat index hot days, heat index extremely hot days, wind chill index hot days and wind chill index extremely hot days will increase in both RCP 4.5 and RCP 8.5 scenarios. Increase in duration will be more severe according to RCP 8.5 scenario. Also, severity of increase changes for each city. Furthermore, mean values for heat index and wind chill index for both summer and winter, will increase according to RCP 4.5 and RCP 8.5 scenarios. Occurrence of summer extremes will severely increase regarding to both scenarios. RCP 8.5 scenario shows that past data summer extremes will be frequently seen values.

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APPENDIX A: R CODE

Code below gives the number of occurrence of past data rare events in future according to RCP 4.5 and RCP 8.5 scenarios:

```
library(dplyr)
library(ggplot2)
library(data.table)


#### DATA PREPARATION #####
#read csv:

CITY_NAME_T_1970_2000 <-
 read.csv("path/CITY_NAME_T_1970_2000.csv")

CITY_NAME_wind_RH_1970_2000 <-
 read.csv("path/CITY_NAME_wind_RH_1970_2000.csv")

CITY_NAME_T_2070_2100_45 <-
 read.csv("path/CITY_NAME_T_2070_2100_45.csv")

CITY_NAME_wind_RH_2070_2100_45 <-
 read.csv("path/CITY_NAME_wind_RH_2070_2100_45.csv")

CITY_NAME_T_2070_2100_85 <-
 read.csv("path/CITY_NAME_T_2070_2100_85.csv")
```

```
CITY_NAME_wind_RH_2070_2100_85 <-
  read.csv("path/CITY_NAME_wind_RH_2070_2100_85.csv")



#remove duplicates:
CITY_NAME_T_1970_2000 <-
CITY_NAME_T_1970_2000[CITY_NAME_T_1970_2000$bnds==0,]
CITY_NAME_wind_RH_1970_2000 <-
CITY_NAME_wind_RH_1970_2000[
  CITY_NAME_wind_RH_1970_2000$bnds==0,]

CITY_NAME_T_2070_2100_45 <-
CITY_NAME_T_2070_2100_45[CITY_NAME_T_2070_2100_45$bnds==0,]
CITY_NAME_wind_RH_2070_2100_45 <-
CITY_NAME_wind_RH_2070_2100_45[
  CITY_NAME_wind_RH_2070_2100_45$bnds==0,]

CITY_NAME_T_2070_2100_85 <-
CITY_NAME_T_2070_2100_85[CITY_NAME_T_2070_2100_85$bnds==0,]
CITY_NAME_wind_RH_2070_2100_85 <-
CITY_NAME_wind_RH_2070_2100_85[
  CITY_NAME_wind_RH_2070_2100_85$bnds==0,]



CITY_NAME_T_1970_2000$date <-
  as.Date(CITY_NAME_T_1970_2000$time_bnds)
CITY_NAME_wind_RH_1970_2000 $date <-
  as.Date(CITY_NAME_wind_RH_1970_2000$time_bnds)
```

```
CITY_NAME_T_2070_2100_45$date <-
  as.Date(CITY_NAME_T_2070_2100_45$time_bnds)
CITY_NAME_wind_RH_2070_2100_45$date      <-
  as.Date(CITY_NAME_wind_RH_2070_2100_45$time_bnds)

CITY_NAME_T_2070_2100_85$date <-
  as.Date(CITY_NAME_T_2070_2100_85$time_bnds)
CITY_NAME_wind_RH_2070_2100_85$date <-
  as.Date(CITY_NAME_wind_RH_2070_2100_85$time_bnds)


#Take averages of variables for each city
#and remove unnecessary columns:


CITY_NAME_T_1970_2000 <-
  CITY_NAME_T_1970_2000 %>%
  select(date,tasmax,tasmin) %>%
        group_by(date) %>%
        mutate(mean(tasmax)) %>%
        mutate(mean(tasmin)) %>%
        ungroup() %>%
        rename(avg_Tmin=`mean(tasmin)`) %>%
        rename(avg_Tmax=`mean(tasmax)`)

CITY_NAME_wind_RH_1970_2000 <-
  CITY_NAME_wind_RH_1970_2000 %>%
  select(date,wind,humidity) %>%
        group_by(date) %>%
        mutate(mean(wind)) %>%
        mutate(mean(humidity)) %>%
```

```
  ungroup() %>%
  rename(avg_wind=`mean(wind)`)
 %>% rename(avg_RH=`mean(humidity)`)

CITY_NAME_T_1970_2000 <-
 CITY_NAME_T_1970_2000 %>%
  select(date, avg_Tmax, avg_Tmin) %>%
  distinct(date, avg_Tmax, avg_Tmin)

CITY_NAME_wind_RH_1970_2000 <-
 CITY_NAME_wind_RH_1970_2000 %>%
  select(date, avg_RH, avg_wind) %>%
  distinct(date, avg_RH, avg_wind)
CITY_NAME_1970_2000 <-
  full_join(
   CITY_NAME_T_1970_2000,
   CITY_NAME_wind_RH_1970_2000,
   by = "date")



CITY_NAME_T_2070_2100_45 <-
 CITY_NAME_T_2070_2100_45 %>%
  select(date, tasmax, tasmin) %>%
  group_by(date)%>%
  mutate(mean(tasmax)) %>%
  mutate(mean(tasmin)) %>%
  ungroup() %>%
  rename(avg_Tmin=`mean(tasmin)`) %>%
  rename(avg_Tmax=`mean(tasmax)`)
```

```
CITY_NAME_wind_RH_2070_2100_45 <-
 CITY_NAME_wind_RH_2070_2100_45 %>%
  select(date, wind, humidity) %>%
  group_by(date)%>%
  mutate(mean(wind)) %>%
  mutate(mean(humidity)) %>%
  ungroup() %>%
  rename(avg_wind=`mean(wind)`) %>%
  rename(avg_RH=`mean(humidity)`)

CITY_NAME_T_2070_2100_45 <-
 CITY_NAME_T_2070_2100_45 %>%
  select(date, avg_Tmax, avg_Tmin) %>%
  distinct(date, avg_Tmax, avg_Tmin)

CITY_NAME_wind_RH_2070_2100_45 <-
 CITY_NAME_wind_RH_2070_2100_45 %>%
  select(date, avg_RH, avg_wind) %>%
  distinct(date, avg_RH, avg_wind)

CITY_NAME_2070_2100_45 <-
  full_join(CITY_NAME_T_2070_2100_45,
   CITY_NAME_wind_RH_2070_2100_45, by = "date")


CITY_NAME_T_2070_2100_85 <-
 CITY_NAME_T_2070_2100_85 %>%
  select(date, tasmax, tasmin) %>%
  group_by(date) %>%
  mutate(mean(tasmax)) %>%
  mutate(mean(tasmin)) %>%
```

```
  ungroup() %>%
  rename(avg_Tmin=`mean(tasmin)`) %>%
  rename(avg_Tmax=`mean(tasmax)`)

CITY_NAME_wind_RH_2070_2100_85 <-
  CITY_NAME_wind_RH_2070_2100_85 %>%
  select(date, wind, humidity) %>%
  group_by(date) %>%
  mutate(mean(wind)) %>%
  mutate(mean(humidity)) %>%
  ungroup() %>%
  rename(avg_wind=`mean(wind)`) %>%
  rename(avg_RH=`mean(humidity)`)

CITY_NAME_T_2070_2100_85 <-
  CITY_NAME_T_2070_2100_85 %>%
  select(date, avg_Tmax, avg_Tmin) %>%
  distinct(date, avg_Tmax, avg_Tmin)

CITY_NAME_wind_RH_2070_2100_85 <-
  CITY_NAME_wind_RH_2070_2100_85 %>%
  select(date, avg_RH, avg_wind) %>%
  distinct(date, avg_RH, avg_wind)

CITY_NAME_2070_2100_85 <-
  full_join(        CITY_NAME_T_2070_2100_85,
    CITY_NAME_wind_RH_2070_2100_85,
    by = "date")
```

```
#Calculate heat index and wind chill index:

CITY_NAME_1970_2000$HeatIndex <-
 CITY_NAME_1970_2000$avg_Tmax -
        ((0.55 - (0.0055 * CITY_NAME_1970_2000$avg_RH)) *
        (CITY_NAME_1970_2000$avg_Tmax - 14.5))

CITY_NAME_1970_2000$WindChillIndex <-
 13.12 + (0.6215 * CITY_NAME_1970_2000$avg_Tmin) -
        (11.37 * ((3.6 *
         CITY_NAME_1970_2000$avg_wind)^(0.16))) +
        (0.3965 * CITY_NAME_1970_2000$avg_Tmin *
        ((3.6 * CITY_NAME_1970_2000$avg_wind)^(0.16)))
CITY_NAME_1970_2000<-as.data.frame(CITY_NAME_1970_2000)

CITY_NAME_2070_2100_45$HeatIndex <-
 CITY_NAME_2070_2100_45$avg_Tmax -
        ((0.55 - (0.0055 * CITY_NAME_2070_2100_45$avg_RH)) *
        (CITY_NAME_2070_2100_45$avg_Tmax - 14.5))

CITY_NAME_2070_2100_45$WindChillIndex <-
 13.12 + (0.6215 * CITY_NAME_2070_2100_45$avg_Tmin) - (
        11.37 * ((3.6 *
         CITY_NAME_2070_2100_45$avg_wind)^(0.16))) +
        (0.3965 * CITY_NAME_2070_2100_45$avg_Tmin *
        ((3.6*CITY_NAME_2070_2100_45$avg_wind)^(0.16)))
CITY_NAME_2070_2100_45<-as.data.frame(CITY_NAME_2070_2100_45)

CITY_NAME_2070_2100_85$HeatIndex <-
 CITY_NAME_2070_2100_85$avg_Tmax - ((0.55 - (0.0055 *
 CITY_NAME_2070_2100_85$avg_RH)) *
```

```
  (CITY_NAME_2070_2100_85$avg_Tmax - 14.5))

CITY_NAME_2070_2100_85$WindChillIndex <-
  13.12 + (0.6215 * CITY_NAME_2070_2100_85$avg_Tmin) -
            (11.37 * ((3.6 *
            CITY_NAME_2070_2100_85$avg_wind)^(0.16)))
            + (0.3965 * CITY_NAME_2070_2100_85$avg_Tmin *
            ((3.6 * CITY_NAME_2070_2100_85$avg_wind)^(0.16)))
CITY_NAME_2070_2100_85<-as.data.frame(CITY_NAME_2070_2100_85)



CITY_NAME_1970_2000 <-
 CITY_NAME_1970_2000[
   is.na(CITY_NAME_1970_2000$HeatIndex)==FALSE,]

CITY_NAME_1970_2000 <-
 CITY_NAME_1970_2000[
   is.na(CITY_NAME_1970_2000$WindChillIndex)==FALSE,]

CITY_NAME_2070_2100_45 <-
 CITY_NAME_2070_2100_45[
   is.na(CITY_NAME_2070_2100_45$HeatIndex)==FALSE,]
CITY_NAME_2070_2100_45 <-
 CITY_NAME_2070_2100_45[
   is.na(CITY_NAME_2070_2100_45$WindChillIndex)==FALSE,]

CITY_NAME_2070_2100_85 <-
 CITY_NAME_2070_2100_85[
   is.na(CITY_NAME_2070_2100_85$HeatIndex)==FALSE,]
```

```
CITY_NAME_2070_2100_85 <-
  CITY_NAME_2070_2100_85[
    is.na(CITY_NAME_2070_2100_85$WindChillIndex)==FALSE,]

##################################################################


library(mixtools)
library(pracma)

#### HEAT INDEX ###
CITY_NAME_hi_mixmdl =
  normalmixEM(CITY_NAME_1970_2000$HeatIndex)

CITY_NAME_hi_1970_2000_mean_cold<-CITY_NAME_hi_mixmdl$mu[1]
CITY_NAME_hi_1970_2000_sd_cold<-CITY_NAME_hi_mixmdl$sigma[1]
CITY_NAME_hi_1970_2000_mean_hot<-CITY_NAME_hi_mixmdl$mu[2]
CITY_NAME_hi_1970_2000_sd_hot<-CITY_NAME_hi_mixmdl$sigma[2]

#### HEAT INDEX ### RCP 45
CITY_NAME_hi_mixmdl_rcp45 =
  normalmixEM(CITY_NAME_2070_2100_45$HeatIndex)

CITY_NAME_hi_45_mean_cold<-CITY_NAME_hi_mixmdl_rcp45$mu[1]
CITY_NAME_hi_45_sd_cold<-CITY_NAME_hi_mixmdl_rcp45$sigma[1]
CITY_NAME_hi_45_mean_hot<-CITY_NAME_hi_mixmdl_rcp45$mu[2]
CITY_NAME_hi_45_sd_hot<-CITY_NAME_hi_mixmdl_rcp45$sigma[2]
```

```
#### HEAT INDEX ### RCP 85
CITY_NAME_hi_mixmdl_rcp85 = ,
 normalmixEM(CITY_NAME_2070_2100_85$HeatIndex)

CITY_NAME_hi_85_mean_cold<-CITY_NAME_hi_mixmdl_rcp85$mu[1]
CITY_NAME_hi_85_sd_cold<-CITY_NAME_hi_mixmdl_rcp85$sigma[1]
CITY_NAME_hi_85_mean_hot<-CITY_NAME_hi_mixmdl_rcp85$mu[2]
CITY_NAME_hi_85_sd_hot<-CITY_NAME_hi_mixmdl_rcp85$sigma[2]


all_stats <-
 as.data.frame(rbind(
  CITY_NAME_hi_1970_2000_mean_cold,
  CITY_NAME_hi_1970_2000_sd_cold,
  CITY_NAME_hi_1970_2000_mean_hot,
  CITY_NAME_hi_1970_2000_sd_hot,
  CITY_NAME_hi_45_mean_cold,
  CITY_NAME_hi_45_sd_cold,
  CITY_NAME_hi_45_mean_hot,
  CITY_NAME_hi_45_sd_hot,
  CITY_NAME_hi_85_mean_cold,
  CITY_NAME_hi_85_sd_cold,
  CITY_NAME_hi_85_mean_hot,
  CITY_NAME_hi_85_sd_hot))

hot_threshold <-
 CITY_NAME_hi_1970_2000_mean_hot -
 CITY_NAME_hi_1970_2000_sd_hot
```

```
x <-
 CITY_NAME_1970_2000 %>%
  select(HeatIndex) %>%
  filter(HeatIndex>=hot_threshold) %>%
  summarise(count=n())

summer_day_cnt<-
 as.numeric(((100*x)/84.13)/30)
# nof summer days in a year
summer_day_cnt
 <-round(summer_day_cnt,2)

hot_multiplier <-
  erfinv(1-(1/(summer_day_cnt*100)))*sqrt(2)

hot_value <-
 CITY_NAME_hi_1970_2000_mean_hot +
  (hot_multiplier * CITY_NAME_hi_1970_2000_sd_hot)



hot_45_multiplier <-
  (hot_value -
 CITY_NAME_hi_45_mean_hot) /
 CITY_NAME_hi_45_sd_hot

hot_day_45 <-
  ((1/(1-erf(hot_45_multiplier/sqrt(2)))) /
 summer_day_cnt)/1

output_45_hot <-
  hot_day_45/summer_day_cnt
```

```
hot_85_multiplier <-
 (hot_value - CITY_NAME_hi_85_mean_hot) /
 CITY_NAME_hi_85_sd_hot

hot_day_85 <-
 ((1/(1-erf(hot_85_multiplier/sqrt(2)))) /
 summer_day_cnt)/1

output_85_hot <-
 hot_day_85/summer_day_cnt


####
cold_threshold <-
 CITY_NAME_hi_1970_2000_mean_cold +
 CITY_NAME_hi_1970_2000_sd_cold

y <-
 CITY_NAME_1970_2000 %>%
  select(HeatIndex) %>%
  filter(HeatIndex<=cold_threshold) %>%
  summarise(count=n())

winter_day_cnt <-
 as.numeric(((100*y)/84.13)/30)
# nof summer days in a year

winter_day_cnt <-
 round(winter_day_cnt,2)
```

```
cold_multiplier <-
 erfinv(1-(1/(winter_day_cnt*100)))*sqrt(2)

cold_value <-
 CITY_NAME_hi_1970_2000_mean_cold + (cold_multiplier *
 CITY_NAME_hi_1970_2000_sd_cold)



cold_45_multiplier <-
 (cold_value - CITY_NAME_hi_45_mean_cold) /
 CITY_NAME_hi_45_sd_cold

cold_day_45 <-
 ((1/(1-erf(cold_45_multiplier /
 sqrt(2))))/winter_day_cnt) / 1

output_45_cold <-
 cold_day_45/winter_day_cnt



cold_85_multiplier <-
 (cold_value - CITY_NAME_hi_85_mean_cold) /
 CITY_NAME_hi_85_sd_cold

cold_day_85 <-
 ((1/(1-erf(cold_85_multiplier/sqrt(2)))) /
 winter_day_cnt) / 1

output_85_cold <-
 cold_day_85/winter_day_cnt
```

```
hi_outs<-
 rbind(
  output_45_hot,
  output_45_cold,
  output_85_hot,
  output_85_cold)
```