Heat wave hazard modelling: Qatar case study

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ABSTRACT

Heat waves are considered to be the major cause of environmental and weather-related fatalities. Heat waves also have a severe impact on people with chronic cardiac and respiratory diseases, such as asthma. With climate change and global warming processes taking place, general global climatic models predict that heat wave events will increase in frequency, duration, and intensity. Therefore, heat wave modelling has attracted considerable attention from scientists and decision-makers alike. Yet it remains challenging, complex, and an imperative problem. This complexity is introduced mainly by land surface and atmospheric spatial variability, such as land use and air pollution concentration. This study addresses this spatial complexity by using remotely sensed thermal data in the form of Land Surface Temperature (LST) images, along with meteorological data to model heat waves in Qatar. Multi-criteria/multi-parameters/multi-layer analysis is carried out using Geographic Information System (GIS) by combining many complex parameters that influence or determine heat waves in the region. Gumble statistical frequency analysis is carried out on time series data to predict heat wave events. Results from the model show that a high portion of the population’s vulnerable age groups are likely to be severely affected by future heat wave events in Qatar based on a five year return period. The analysis revealed that at least 87% of children aged 4 or under would be exposed to a very high intensity level of heat wave events, while more than 86% of elderly people, over 65 years of age, would be exposed to the same intensity level of hazard.

The study proves that thermal satellite imaging improves heat wave hazard modelling, as it addresses the complex spatial variability of land surface. The developed model is applicable at a local, as well as regional, scale, making an original contribution to heat wave modelling.

Keywords: heat wave hazard modelling, land surface temperature, thermal remote sensing, GIS
1. BACKGROUND
1.1. Introduction

The adverse effects of heat waves on human health and well-being are well known. Inconvenience and discomfort due to high temperatures are examples of the least importance compared to the morbidity and mortality that it causes.1–3 Heat waves are considered to be the major cause of environmental and weather-related fatalities.4 The U.S. National Oceanic and Atmospheric Administration (NOAA) rates heat as the number one weather-related killer in the U.S.5 For example, during the summer of 2003, in Europe, more than 70,000 additional deaths were recorded in twelve countries.6,7 In France and Italy, resultant mortality reached 19,490 and 20,089 deaths, respectively. Other countries, including Germany, Portugal, Spain and the United Kingdom were also affected. Heat waves have a severe impact on people with chronic cardiac and respiratory diseases, such as asthma. A study carried out by the International Study of Asthma and Allergy in Childhood (ISAAC) among school children aged 6–14 years in Qatar, shows that “the population sample had a high prevalence of diagnosed asthma (19.8%), allergic rhinitis (30.5%), eczema (22.5%), and chest infections (11.9%)”.8 For these reasons a study of heat waves is considered important for Qatar.

Furthermore, heat waves have negative economic impacts, such as damage to crops and agriculture, destruction of forests by setting off forest-fires and causing the depletion of water resources. In the 2003 European heat wave economic loss is estimated to have been more than $13 billion.7 These reports may make the heat wave of that summer the worst natural disaster in the world of that year.9

Many climate models and studies anticipate that heat wave episodes will increase in frequency, intensity and duration,2,4,10–13 due to current global climate change and global warming. Climate change and global warming are attributed to anthropogenic causes resulting from increasing concentration of greenhouse gases in the atmosphere.

Another anthropogenic climatic phenomenon that operates at a local level and also contributes to heat wave events is the Urban Heat Island (UHI). Studies show that urban centres have temperature warming trends higher than their rural surroundings10,14 and urban heat island temperatures, in general, increase as the population increases.15 In dry and desert environments, such as the one in which Qatar lies, the UHI effect is noticeable: the sand in the surrounding desert has a higher albedo (reflects more solar energy, hence warms up more slowly) and a higher porosity, therefore tends to lose heat more quickly than urban centres, where land surface changes, surface waterproofing16 and soil compaction take place.

Anthropogenic heat is one of the main causes of UHI in cities. The sources of this heat include waste heat from cooling and heating buildings, industrial processes and transportation (e.g. highways and airports).16,17 Other causes of UHI include: air pollution; surface waterproofing; thermal properties of building fabric and surface geometry.17 A strong positive relation between LST and ambient air temperature has been found and determined16,18

In Qatar, fossil fuel is used in power plants to generate electricity. More than 60% of the electricity is used for the air-conditioning (AC) of buildings. Furthermore, a good part of this energy is lost as heat-waste from AC that heats up the ambient air. During hot summer days, the increased demand for energy for cooling buildings results in increased air-pollution through burning these fossil fuels. This in turn results in more heat being generated and entrapped by the pollution. This entrapped heat increases the ambient air temperature that in turn creates further electric energy demands. These factors and processes function and operate at different time scales.

The objective of this paper is to develop a methodology for comprehensive modelling of heat waves and their hazard levels at local and country scales, that take into account both atmospheric and land surface complexities. An earlier regional model developed by El Morjani focused only on atmospheric variability (EL Morjani, 2011).26 The study area is the State of Qatar.

1.2. What is a Heat wave?

There is no universal definition of heat wave that could be found in literature.4,10,13,20 However, a heat wave can be seen as an extended period of unusually high atmosphere-related heat stress, which causes temporary modifications in lifestyle and may have a notable impact on human comfort, mortality, regional economies and ecosystems.1,3,11,13,21

The identification of the duration and heat intensity required for an event to be considered a heat wave, depends therefore on the region in which the definition is applied.7,11,22
There is a consensus on some spatial and temporal distribution issues of heat wave events and these are:

The impact of a long-duration heat wave (more than four days) is 1.5 to 5 times higher than that of a short heat-wave.¹⁰

The perception of heat depends on livelihood activities. Most of the definitions require the identification of a maximum temperature value threshold to define what a hot day is. The identification

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**Figure 1.** Land surface temperature (LST) image of Qatar (°C), derived from 2003 Landsat image.
Figure 2. Sabkha/Salids soils overlaid on the LST map. These salty soils show higher LST values than their surrounding soils.
of this value requires a deep understanding of the meteorology and climatic phenomena in each region, otherwise it could be deemed subjective.

2. METHODS

The approach adopted in this study avoids specifying a maximum temperature threshold value. Instead, it calculates the Heat Index (HI) for time series historical data records and identifies extreme HWI values and their frequencies. These values are then projected and used as the basis of the modelling.

The HI used here is Steadman’s Heat Index (SHI), which combines ambient air temperature with relative humidity. The SHI is based on physiological studies on human evaporative skin cooling. It measures how hot it feels when the relative humidity is combined with the observed ambient temperature. The US National Climatic Data Centre (NCDC) used Steadman’s measurements to calculate the HI formula, shown in Equation (1) below.

\[
\text{Heat Index} = -42.379 + 2.04901523T_a + 10.14333127rh - 0.22475541T_a rh - (6.83783 \times 10^{-3}T_a^2) - (5.481717 \times 10^{-2}rh^2) \\
+ (1.22874 \times 10^{-3}T_a^2 rh) + (8.5282 \times 10^{-4}T_a rh^2) - (1.99 \times 10^{-6}T_a^2 rh^2)
\]  

(1)

Where:

- $T_a$: ambient temperature (°F)
- $rh$: relative humidity (%).

The SHI is found suitable for this study as it is based on human health impact, which is a major concern in this hot desert environment, where the exposure to heat is high.
2.1. Daily Heat Index Calculation

Daily HI values were calculated using Equation (1) above, ambient air temperature and humidity data from twelve meteorological stations in Qatar, for the period 2002–2011. The location of the stations is shown in Figure 1. The data was provided by the climate section of the Meteorological Department, Civil Aviation Authority of Qatar.

2.2. Calculation of the Heat Wave Index (HWI)

The daily HI, calculated above, was then used to calculate the average daily heat index for 5 consecutive days. This calculation was carried out using the EatlasClimMod 1.0, developed for the WHO e-atlas of disaster risk. Over the 5 consecutive days HI average is referred to as the HWI. The annual maximum HWI was then calculated for each station.

2.3. Application of the frequency analysis function

The Gumbel extreme value distribution function was used to predict the annual maximum HWI values for return periods of two years and five years. The Gumbel function seeks to identify the temporal distribution of extreme values for various return periods. It uses time series analysis to examine the relationship between the magnitude, frequency of occurrence- and therefore duration- of the phenomena under investigation in order to identify a trend. The results of this analysis are annual maximum HWI predictions for 2 and 5 years return periods for the twelve stations.

2.4. Creating the Land Surface Temperature (LST) image

Remotely sensed data is used to analyse the effect of the land surface temperature on heat waves. The thermal band of a 2003 Landsat ETM (band 6) and Planck’s function were used to derive the LST, shown in Figure 1.

The image in Figure 1 shows high LST values in Doha and along some coastal areas. When compared with the soil map of Qatar, these areas are found to correspond with areas of Sabkha/Salid soils. Sabkhas are salty supratidal surfaces that are formed along arid coastlines. It is clear from Figure 2, that Sabkhas/Salids show higher LST values than surrounding soils.

| Variable | Regression coefficient | Standard error | t value | Probability Pr(|t|) |
|----------|------------------------|----------------|---------|------------------|
| (Intercept) | -1378.75982360 | 245.7113 | -3.2386 | 0.0142 |
| d_Y | 0.0007193500 | 0.0000 | 4.2866 | 0.0036 |
| LST | 4.847404375 | 1.3836 | 3.5032 | 0.0066 |
| Residual standard error | 4.50589555 | 0.81 | 9.7168 | 0.0068 |
| Degrees of freedom | 7 | | |
| Multiple R² | 0.81 | | |
| F statistic | 9.7168 | | |
| Probability (F statistic) | 0.0068 | | |

Table 2. Results of the step-wise regression analysis for the 2 year return period annual maximum HWI.

<table>
<thead>
<tr>
<th>LST</th>
<th>d_Y</th>
<th>d_Coast</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>345.0000</td>
<td>98000.0</td>
</tr>
<tr>
<td>2</td>
<td>346.2222</td>
<td>208222.2</td>
</tr>
<tr>
<td>3</td>
<td>347.4444</td>
<td>318444.4</td>
</tr>
<tr>
<td>4</td>
<td>348.6667</td>
<td>428666.7</td>
</tr>
<tr>
<td>5</td>
<td>349.8889</td>
<td>538888.9</td>
</tr>
<tr>
<td>6</td>
<td>351.1111</td>
<td>649111.1</td>
</tr>
<tr>
<td>7</td>
<td>352.3333</td>
<td>759333.3</td>
</tr>
<tr>
<td>8</td>
<td>353.5556</td>
<td>869555.6</td>
</tr>
<tr>
<td>9</td>
<td>354.7778</td>
<td>979777.8</td>
</tr>
<tr>
<td>10</td>
<td>356.0000</td>
<td>1090000.0</td>
</tr>
</tbody>
</table>

Table 3. Changes in the values of the model parameters for the SRC sensitivity technique.
2.5. Application of stepwise regression analysis

A set of variables and parameters that influence heat waves in the study area are identified. Stepwise regression analysis was carried out between the projected annual maximum HWI values for the twelve stations obtained from the Gumbel frequency analysis above (dependent variable) and these parameters (independent variables). The independent parameters identified are: elevation (Z), slope, relative longitude (d_X) and latitude (d_Y), proximity to the coast (d_Coast), proximity to urban area (d_urb_pop), proximity to the industrial areas and power plants, land surface temperature (LST), and human impact index. The stepwise regression analysis determines the parameters that most influence the HWI, while ignoring the rest, and it derives the model accordingly. LST, d_Y and d_Coast were found to be the determining factors.

2.6. Deriving the heat wave hazard maps

The model was applied to derive 2-year return period heat wave map, using the GIS Map Algebra functionalities. The heat wave map was translated to a heat wave hazard level distribution map, using the US National Weather Service (NWS) intensity level Heat Wave hazard classification (Table 1).

2.7. Population exposure

To estimate the number of people that will be exposed to Heat Wave hazards, the 2010 population census data was analyzed with the heat wave hazard maps, using GIS methods. The census was conducted by the Qatar Statistical Authority (QSA). Figure 3 shows a small extract of the map around the capital city Doha.

The population data was converted to a Population grid layer, and overlaid on the heat wave hazard intensity level map for a 5-year return period in Figure 8. Heat-vulnerable age groups, infants and children under 4 years of age, and elderly people, aged above 65 years, were identified and targeted in the analysis.

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>bias</th>
<th>std. error</th>
<th>min. c.i.</th>
<th>max. c.i.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST</td>
<td>9.999180e-01</td>
<td>8.776780e-06</td>
<td>8.047980e-05</td>
<td>9.996979e-01</td>
<td>1.000034e+00</td>
</tr>
<tr>
<td>d_Y</td>
<td>4.021975e-05</td>
<td>2.231283e-06</td>
<td>1.048351e-05</td>
<td>7.481684e-06</td>
<td>5.148720e-05</td>
</tr>
<tr>
<td>d_Coast</td>
<td>-1.773265e-04</td>
<td>-1.739053e-05</td>
<td>4.880853e-05</td>
<td>-2.281829e-04</td>
<td>-2.575274e-05</td>
</tr>
</tbody>
</table>

Table 4. Standardized Regression Coefficients (SRC) sensitivity analysis results.
3. RESULTS

3.1. Regression analysis results

Results of the regression analysis are shown in Table 1.

From Table 2, the relation between the HWI and the determined variables can be expressed as:

\[
\text{HW}_2 = 4.847404375 \times \text{LST} + 0.000193500 \times \text{d}_Y \\
- 0.000715972 \times \text{d}_\text{Coast} - 1.378.71988236
\]

where, LST is the land surface temperature; \( \text{d}_Y \) is the relative latitude; \( \text{d}_\text{Coast} \) is the distance to the coast.

From Table 2, 81% of the spatial variability in an extreme heat wave is explained by the three variables retained in the regression equation (\( R^2 = 0.81 \)). The model is considered valid and reliable because of the strong correlation (\( R = 0.9 \)) and the high degree of confidence that exists in the selected variables (very small probability [F statistic]).

3.2. Sensitivity analysis

To determine the degree of influence of the individual parameter in the model (Eq. 2) the Standardized Regression Coefficient (SRC) sensitivity analysis function in R language was used. SRC takes into account the combined variability resulting from considering all input parameters simultaneously.\(^\text{28,29}\)

The input parameters in the model are changed by specific units simultaneously and the magnitude of influence/change of that on the heat wave (output) is calculated. The input parameters’ standard deviation from their mean is standardized. Standardization removes the influence of units and places all parameters on an equal level.\(^\text{28}\)

Table 3 shows LST was changed by 1 Kelvin, \( \text{d}_Y \) by over 20 km (from 1 to 180 km to cover the whole length of the country), and \( \text{d}_\text{Coast} \) by 1 km, in order to calculate the relative sensitivity of the model to these parameters. Results of the SRC coefficients are shown in Table 4 and Figure 4.

These results show that relative altitude (\( \text{D}_Y \)) has very small positive influence (0.0004) on the model compared to LST (0.9999), while the distance from the coast (\( \text{d}_\text{Coast} \)) has a very small negative impact (\( -0.000177 \)).
These influences could be attributed to the fact that LST conveys a lot of information on land cover type, soils, land use, slopes, topography, terrain, and other physical and chemical characteristics of the land surface. Figure 5 below shows the resulting map depicting the two year projection of HWI. The resulted heat wave hazard distribution map is shown in Figure 6. Results for the 5 year return period stepwise regression analysis are shown in Table 5. The five-year projection HWI model, therefore, was expressed as:

\[
HW_{5} = 5.669480917 \times \text{LST} + 0.000241385 \times \text{d}_{Y} - 0.000810942 \times \text{d}_{\text{Coast}} - 1625.804413997
\]  

(3)

The LST is found also to be the most determining parameter of HWI in this return period.

Figure 6. Heat wave hazard level distribution map for a 2-year return period.
The HWI map for the 5-year return period was constructed using the model in Equation (3). The map is shown in Figure 7.

The Projected Heat Wave Hazard map (5-year return period), is derived from the HWI map in Figure 6, and is shown in Figure 8.

### 3.3. Population exposure analysis

The number of people in each age-group in each hazard intensity class, of the 5-year return period, has been calculated, as shown in Table 6.

The above results show that at least 87% of infants under 4 years of age and more than 86% of the elderly in Qatar will be at a high level of heat wave hazard. These two groups are very vulnerable to heat hazard. For all age groups, more than 80% of the total population could be exposed to a high heat wave hazard intensity level at least once every five years.

| Variable   | Regression coefficient | Standard error | t value   | Probability Pr(>|t|) |
|------------|------------------------|----------------|-----------|---------------------|
| (Intercept)| -1625.844439           | 663.38749315   | -2.450761328 | 0.044098050         |
| d_Y        | 0.000241385            | 0.0000070343   | 3.43155518  | 0.010462044         |
| d_Coast    | -0.000810942           | 0.000293392    | -2.764027389 | 0.027933398         |
| LST        | 5.669480917            | 2.156206652    | 2.629377465  | 0.033943308         |

The above results show that at least 87% of infants under 4 years of age and more than 86% of the elderly in Qatar will be at a high level of heat wave hazard. These two groups are very vulnerable to heat hazard. For all age groups, more than 80% of the total population could be exposed to a high heat wave hazard intensity level at least once every five years.
3.4. Discussion and analysis

The Heat Wave Hazard model developed in this study suggests that there will be a clear increase in heat and heat wave hazard in Qatar between the 2-year and 5-year return periods, as depicted in Figures 6 & 8. The model and its results are based on daily records of meteorological data for 12 years over 2000–2011. The model’s increase in heat wave was found to be in the northern coastal areas and in urban areas, such as in the Doha area. On the northern coast the increase is attributed to an increase in humidity, ambient temperature related to air pollution from industrial expansion (oil and petrochemical industry) and a specific soil type, the Sabkha/Salid soils.

Figure 8. Heat wave hazard level distribution map for a 5-year return period.
Urban expansion and change in the land surface are principal factors along with air pollution: CO₂ emission from vehicles, electricity generation activity and heat emission from air conditioning systems in buildings. Population growth and change of lifestyle, by migration to urban centres, is not only contributing to heat wave increase, but is also leading to an increase in the number of people who are exposed to its hazard.

The south-eastern and south-western coasts of Qatar encounter high heat hazard levels because of the presence of the Sabkhas/Salids in many areas. Locations that are at “low hazard” to heat wave are found in the central and southern areas because: they are far away from a coastline and have low humidity; they lack urban centres; they have no significant modifications to the land surface/cover type.

Another factor that influences heat emission, as this study found in Qatar, is the soil type, and this could be the case in arid zones where vegetation is scarce.

However, a very low percentage (5.62%) of the population will be inside the very high hazard level category. This is due to the fact that most of the “very high hazard” areas are non-residential areas, such as industrial areas, coastal resorts, and Sabkha soils.

5. CONCLUSIONS AND RECOMMENDATIONS

Modelling heat waves is a complex process. The complexity is mainly introduced by land-surface and atmospheric variability. Many modelling studies focus merely on atmospheric variability, for example. This study has put more emphasis on land surface variability and how it influences heat wave modelling. In fact, land surface variability can influence atmospheric variability at a local and regional scale.

This study shows that LST, derived from satellite images in the thermal band, can be used to address the issues of a complex land surface and variability. Variations in heat emitted from these surfaces convey the complex spatial variability in them and their types. We have found that in this region of contrasting dry and humid climates where there is little vegetation cover, some soil types, especially Sabkhas/Salids, play a large role in determining heat flux and heat wave. This is clearly shown in the model and by the LST image we have assessed.

The Gumbel analysis used in this study is suitable for heat wave analysis as it is applicable to the analysis of extreme values and events. It takes into account the magnitude and frequency of the events.

Different levels of heat wave hazards in Qatar have been identified and mapped by the model. The resulting maps were analysed with reference to population maps. It was revealed that more than 87% of the children aged 4 and less are at high risk of heat wave hazard exposure, while more than 86% of elderly people—those over 65 years—are at a similar level of hazard exposure.

The model and results developed in this study can be of great help to decision-makers and planners to make informed decisions on:

1. Siting new hospitals and healthcare centres. These should be located in low heat wave hazard areas. Also, it is advisable to relocate existing ones that are in high hazard areas, especially cardiac, respiratory, and children’s hospitals.
2. Siting new children schools in low risk areas, as the relocation of existing schools is advisable.
3. Putting in place mitigation measures (green parks, selection of building materials) in order to reduce temperature.
4. The locations for future urban expansions and new cities need careful consideration.
5. Measures need to be established for the protection of crops and agriculture, and also electrical infrastructure, from heat wave damage. For crops this could be achieved by growing only heat-resistant crops on farms that are located in high risk zones.

### Table 6. The number and percentage of people of vulnerable age groups and their Heat Wave Hazard intensity levels, 5-year return period.

<table>
<thead>
<tr>
<th>Heat wave exposure</th>
<th>All age groups</th>
<th>Age group 0 - 4 years</th>
<th>Age group &gt; 65 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity level</td>
<td>Population</td>
<td>%</td>
<td>Population</td>
</tr>
<tr>
<td>Low</td>
<td>&lt; 32 °C</td>
<td>7,253</td>
<td>0.43</td>
</tr>
<tr>
<td>Medium</td>
<td>33 - 41</td>
<td>225,417</td>
<td>13.43</td>
</tr>
<tr>
<td>High</td>
<td>42 - 54</td>
<td>1,351,305</td>
<td>80.51</td>
</tr>
<tr>
<td>Very High</td>
<td>≥ 54</td>
<td>94,401</td>
<td>5.62</td>
</tr>
</tbody>
</table>

Zine El Abidine et al. QScience Connect 2014:9
6. Estimating future electric energy consumption/demand for air-conditioning and cooling in built-up areas.

The model is applicable to many dry-land countries, and can be replicated in different parts of the world at local/county, as well as regional scales.

LIST OF ABBREVIATIONS

AC: Air conditioning
GIS: Geographical Information System
HI: Heat Index
HW: Heat wave
HWI: Heat wave index
ISAAAC: International Study of Asthma and Allergy in Childhood
LST: Land Surface Temperature
NOAA: US National Oceanic and Atmospheric Administration
UHI: Urban Heat Island
WHO: World Health Organization

COMPETING INTERESTS

We declare that we have no competing financial, professional or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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