AMERICAN UNIVERSITY OF BEIRUT

IMPACT OF INTEGRATING DESICCANT DEHUMIDIFICATION PROCESSES TO CONVENTIONAL AC SYSTEM ON URBAN MICROCLIMATE AND ENERGY USE IN BEIRUT CITY

by
ZEINAB NAJI GHADDAR

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Mechanical Engineering
to the Department of Mechanical Engineering
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
August 2017

AMERICAN UNIVERSITY OF BEIRUT

IMPACT OF INTEGRATING DESICCANT DEHUMIDIFICATION PROCESSES TO CONVENTIONAL AC SYSTEM ON URBAN MICROCLIMATE AND ENERGY USE IN BEIRUT CITY

by
ZEINAB NAJI GHADDAR

Approved by:

Prof. Kamel Ghali, PhD, Professor — Advisor
Department of Mechanical Engineering

Prof. Nesreen Ghaddar, PhD, Professor — Co-Advisor
Department of Mechanical Engineering

Prof. Issam Srour, PhD, Associate Professor — Member of Committee
Department of Civil and Environmental Engineering

Prof. Ghassan Chehab, PhD, Associate Professor — Member of Committee
Department of Civil and Environmental Engineering

Date of thesis defense: August 22, 2017

AMERICAN UNIVERSITY OF BEIRUT

THESIS, DISSERTATION, PROJECT RELEASE FORM

Student Name: Ghaddar Zeinab Naji
Last First Middle

☑ Master's Thesis ○ Master's Project ○ Doctoral Dissertation

☑ I authorize the American University of Beirut to: (a) reproduce hard or electronic copies of my thesis, dissertation, or project; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes.

☐ I authorize the American University of Beirut, to: (a) reproduce hard or electronic copies of it; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes
after: **One — year from the date of submission of my thesis, dissertation, or project.**
Two — years from the date of submission of my thesis, dissertation, or project.
Three — years from the date of submission of my thesis, dissertation, or project.

12/9/2017

Signature Date

This form is signed when submitting the thesis, dissertation, or project to the University Libraries.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude for Prof. Kamel Ghali for his advisory, guidance, and patience through my graduate study.

I would also like to thank Prof. Nesreen Ghaddar for her recommendations, thoughtful ideas and help in completing this work.

I would also like to thank Prof. Issam Srour and Prof. Ghassan Chehab for being members of my thesis committee.

I would also like to show deep gratitude and appreciation to my husband, my family, and my friends for their support throughout the past year.

AN ABSTRACT OF THE THESIS OF

Zeinab Naji Ghaddar for Master of Engineering
Major: Mechanical Engineering

Title: Impact of Integrating Desiccant Dehumidification Processes to Conventional AC System on Urban Microclimate and Energy Use in Beirut City

This study investigates the anthropogenic heating of the urban environment of Beirut city due to air conditioning (AC) when integrating a desiccant dehumidification wheel into the conventional vapor compression (VC) system to reduce the high electricity consumption during the summer. Two hybrid system configurations with integrated heat exchanger (HE) and an indirect evaporative cooler (IEC) are studied. Numerical simulations of the urban microclimate for the hot humid weather of Beirut were performed. The simulation results were validated by comparing measured and predicted air temperatures in four locations of the city assuming the use of conventional VC systems. Simulations were then performed using the proposed interventions of the two hybrid systems.

The results showed that the conventional AC systems cause an average increase in the urban ambient temperature in Beirut city of 1.3 °C in day-time and 2.2 °C in night-time when compared with the case with no AC. The electrical power consumption of IEC and HE systems was lower by 53% and 38% than conventional VC systems, respectively. Compared to the conventional VC system, the sensible waste heat of Hybrid AC with IEC and Hybrid AC with HE were higher by about 2% and 10% respectively due to the regeneration process. The latent waste heat of Hybrid systems with IEC and HE were higher by 7.9 and 5.7 times the latent waste of the conventional VC system. As a result, the hybrid systems with IEC produced a lower increase in temperature by about 0.1 °C to 0.3 °C in day-time and night-time while the hybrid systems with HE produced a higher increase in temperature by about 0.1 °C to 0.3 °C in day-time and night-time, due to the higher release of sensible waste heat than conventional system. The relative humidity in the cases of HE and IEC were higher by a maximum of about 3% and 5% compared to VC case, respectively. The IEC system is therefore recommended due to its high potential for electricity savings and lower impact on the urban heat island compared to the conventional system.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOMENCLATURE

A	Area [m^2]
C	Volumetric heat capacity [$MJ.m^{-3}\cdot K^{-1}$]
d	Thickness [m]
f	Fraction [-]
H	Height [m]
k	Thermal Conductivity [$W.m^{-1}\cdot K^{-1}$]
$\dot{m}$	Mass flow rate per unit area [$kg\cdot s^{-1}\cdot m^{-2}$]
q	Heat rate [$W.m^{-2}$]
T	Temperature [°C]
V	Volumetric flow rate per unit area [$l\cdot s^{-1}\cdot m^{-2}$]
α	Albedo [-]
ε	Emissivity [-]
λ	Roughness Length [m]

ABBREVIATIONS

AC	Air Conditioning
ACH	Air Change per Hour
ADP	Apparatus Dew Point
BEM	Building Energy Model
CAS	Central Administration of Statistics
COP	Coefficient of Performance
ECMWF	European Centre for Medium-Range Weather Forecasts
HE	Heat Exchanger
IEC	Indirect Evaporative Cooler
MAE	Mean Absolute Error
OEA	Order of Engineers and Architects
PLF	Part Load Factor
RCREEE	Regional Center for Renewable Energy and Energy Efficiency
RH	Relative humidity
RMSE	Root Mean Square Error
SHGC	Solar Heat Gain Coefficient
TEB	Town Energy Balance
TMY	Typical Meteorological Year
TSBL	Thermal Standard for Buildings in Lebanon
UBL	Urban Boundary Layer
UHI	Urban Heat Island
VC	Vapor Compression

CHAPTER 1

INTRODUCTION

Artificial modifications by humans of the natural ecosystem changed the heat balance in urban regions causing urban regions to become warmer than their rural surroundings and resulting in what is identified as Urban Heat Island (UHI) [1]. One feature of UHI is the replacement of the vegetation cover with new construction materials, such as concrete and asphalt, which absorb and store more heat. This caused an increase in the outdoor temperature and in a less comfortable local climate to the urban inhabitants [2, 3]. In addition, higher outdoor temperature significantly increases the cooling loads in buildings during the summer, and consequently increases the buildings energy consumption for Air-Conditioning (AC). Furthermore, the performance of conventional Vapor Compression (VC) systems is reduced due to condensers operating at higher outdoor temperature. In Athens, the mean heat island intensity exceeded 10°C, the cooling load of urban buildings was doubled, and the peak electricity load for cooling was tripled, while the minimum coefficient of performance (COP) of air-conditioners decreased up to 25% [4].

Cities worldwide consume more electrical energy in the summer to meet the cooling requirements that are mainly provided by the conventional vapor compression AC systems. For ventilation loads characterized by high latent loads, a possible measure to reduce the electrical energy consumption is the integration of a desiccant dehumidification wheel to the vapor compression system [5]. The fresh air is directed to the desiccant wheel to decrease its humidity. However, the latent load removal by the desiccant system imposes additional sensible load on the VC unit. One of the methods of reducing the load is to exchange the heat carried by the process air leaving the desiccant wheel with the cooler exhausted room space air. Ghali found that this configuration of hybrid desiccant system could reduce the size of VC unit by 35% [5]. Another method allowing to achieve further reduction of the additional load is to cool the process air leaving the desiccant wheel by indirect evaporative cooling, and thus further electrical energy savings up to 55% can be obtained [6-8].

Even though the hybrid desiccant systems reduce the electricity consumption, they have adverse effect on the outdoor climate. The hybrid systems release more sensible and latent waste heat to the urban environment than the conventional VC systems due to the regeneration of the desiccant wheel. In hot humid climate, the regeneration temperature could exceed 80°C [9], implying that an air stream of high temperature and humidity is exhausted to the outdoor. The collective use of the hybrid systems in a city may therefore result in the increase in the contribution of AC system in the anthropogenic sensible and latent heat, thus in the aggravation of the urban heat islands. The ambient temperature and humidity in the city may increase, as well as the buildings' sensible and latent loads which may prevent the achievement of the desired benefit of reduced electrical energy consumption in buildings. In in literature, the hybrid desiccant system was recommended as it achieves electrical energy savings, without taking into consideration its impact on the urban microclimate [5, 6, 10, 11].

It is important to assess the implication of the hybrid desiccant systems, not only on the electrical energy consumption, but also on the urban microclimate. A method of assessment by researchers has been by performing simulations using coupled models for air-conditioning systems in buildings and the outdoor microclimate [12, 13]. Meso- and micro-scale climate numerical models have been used to simulate the local climate for cities [12, 13]. Meso-scale models solve for the atmospheric variables such as temperature, moisture, velocity, and winds in large 3-D domains above the urban canopy level, defined as the height slightly above the level of the buildings roofs [12]. Meso-scale models ignore the complexity of the urban canopy and assume it as an aerodynamic roughness. However, micro-scale models use the surface energy balance equation proposed by Oke [13] to solve for the heat fluxes in the urban canopy layer. Micro-scale models represent the urban geometry by one building and road, and compute the temperature and the humidity in the canopy layer at street level [12]. A coupling between meso- and micro-scale models may be done at a forcing level above the canopy [14, 15]. In this case, the micro-scale model uses the atmospheric variables, called atmospheric forcing, at the top-canopy level computed by the meso-scale model to compute the temperature and humidity in the surface layer at street level, and the momentum and heat fluxes of the surface layer. The meso-scale model uses the values of these surface fluxes to compute the atmospheric variables in the open space above the surface layer that becomes the atmospheric forcing of the micro-scale model in the next iteration [15]. Several researchers integrated a building energy model (BEM) to the microscale model coupled to the meso-scale model to simulate buildings' AC systems, their thermal loads and power consumption [16-19]. For example, De Munck et al. [16] investigated the impact of various AC scenarios on the UHI during heat waves. Kikegawa et al. [18] predicted, using the same approach, the increase in cooling energy demands and evaluated the urban warming countermeasures. Similarly, Salamanca et al. [19] evaluated the impact of AC systems on the air temperature and their energy consumption.

The present study focuses on the impact of the hybrid desiccant AC systems on UHI in Beirut city. Beirut is characterized by a hot and humid climate during the summer where the UHI intensity reaches its peak. In Beirut city, the cooling is mainly provided by traditional vapor compression AC systems using the electricity as energy source [20]. Integrating a desiccant wheel to the conventional AC system in Beirut is proposed as a hybrid AC system to reduce the energy consumption [5, 6]. However, such hybrid system may have an adverse effect on the outdoor temperature and humidity due to the large amount of waste heat releases by the desiccant wheel to the environment depending on whether the hybrid system uses heat exchanger or indirect evaporative cooler.

In this study, the conventional VC system and the two configurations of the hybrid AC dehumidification system using heat exchange (HE) and indirect evaporative cooling (IEC) are evaluated in terms of energy savings and impact on the urban microclimate. The objectives are first to assess the impact of the operation of AC systems in a large scale in Beirut city on the urban microclimate; and second to evaluate the effect of the integration of the two hybrid AC systems configurations that save electrical energy but may increase the outdoor air temperature and humidity. The purpose is to make recommendations on the appropriate choice of cooling systems that not only reduce the electrical energy consumption but also do not adversely compound the urban heat island.

CHAPTER 2

RESEARCH METHODS

The study domain is Beirut city (Lat. 33° 52’ N, Lon. 35° 30’ E), the capital of Lebanon. It is situated in the Mediterranean coast and it has a cold and short winter, and a hot and humid summer. The summer is usually rainless with a monthly average high temperature of 32 °C. Beirut is the largest city of Lebanon with a population of about 1.8 million [21]. The land cover of Beirut consists of densely built areas in majority, with the presence of some vegetation covers.

To study the effect of the use of AC systems on the city microclimate, the numerical approach of using coupled meso-scale, micro-scale and building energy model is followed [16-19] where simulations are performed to predict local air temperature above ground within Beirut city. Hence, the MESO-NH software [14, 15] is used to solve the meso-scale meteorological problem. This software is coupled with SURFEX packages that includes the Town Energy Balance model (TEB) [22] which solves the micro-scale problem over urban areas. Furthermore, TEB includes a simplified Building Energy Model (BEM) [23] which computes the buildings cooling energy consumption and the resultant waste heat to the canyon. In the current work, the MESO-NH, TEB, and BEM combination is used, because it models the physical relations between the building energy consumption, the urban microclimate, and the large atmosphere. It also allows the modeling of the mutual interaction between the outdoor conditions and the AC systems loads in urban canopies.

Validation of the simulation results of the coupled models is presented by comparing the predicted ambient temperatures against measured temperatures in four locations in the city during the simulation period in the month of August when AC is extensively operated. The dispersed locations selected for validation are characterized by a diversity in buildings density, buildings types, and proximity to the coastal strip. After the validation of the model, the effect of AC waste heat on the urban heat island is assessed by computing the resultant increase in the ambient temperature in the city. This is followed by simulating the scenario of integration of desiccant dehumidification wheels to AC systems and evaluating this intervention influence on the electrical energy consumption and urban heat island.

2.1 Study Domain and Modeling Approach

The coupled meso-scale, micro-scale and building energy models [16-19], which are adopted in this work to predict the effect of AC on the microclimate of Beirut city, require the identification of the computational domains and atmospheric data. Since the atmospheric phenomena have different time and space scales influencing each other [13], three domains of different sizes and resolutions were determined in order to be able to represent large-scale and small-scale meteorological phenomena over Beirut city. Three two-way grid-nested horizontal domains were defined such that the outermost domain D1 that spanned an area of 1800 km × 1800 km; the intermediate domain D2 that spanned an area 300 km × 300 km; and the inner most domain D3 that spanned an area of 15 km × 15 km with resolutions of 12 km, 3 km, and 1 km respectively. Figure 1(a) shows the computational grid in which the atmospheric conditions are studied, while Figure 1(b) shows the map of the orography in meters (height above sea level) of domain D2 within domain D1, and Figure 1(c) shows the map of the orography of domain D3 inside domain D2. The three horizontal grid domains have the same vertical grid that is divided to 50 levels using a stretched resolution ranging from 12 m at the lowest level near the ground surface to 400 m at the highest level in the atmosphere in order to allow fine representation of the Urban Boundary Layer (UBL) near the ground level [24]. The height of the vertical domain in the model is about 14 km which is selected in meso-scale simulations such that it is in the stratosphere region to ensure that the top boundary of the atmospheric model has a free slip condition [25]. The boundary conditions and the initial values of the larger domain are obtained from analysis of the weather forecasts from the open access ERA-Interim database, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [26]. The atmospheric data are retrieved from the database for the desired dates and times of the simulation. The simulation period corresponds to two summer days in Beirut city; from 19 August at 12:00 AM until 21 August at 12:00 AM, with a spin-up of 24 hours. The spin-up time is the time required by meso-scale models to approach its own climatology after being started from initial conditions having inevitable uncertainty [27]. The days selected for simulation represent typical summer conditions [28] based on recent data of Typical Meteorological Year (TMY) of Beirut city [29], where the daily average temperature in August ranges between 24 to 31 °C [29].

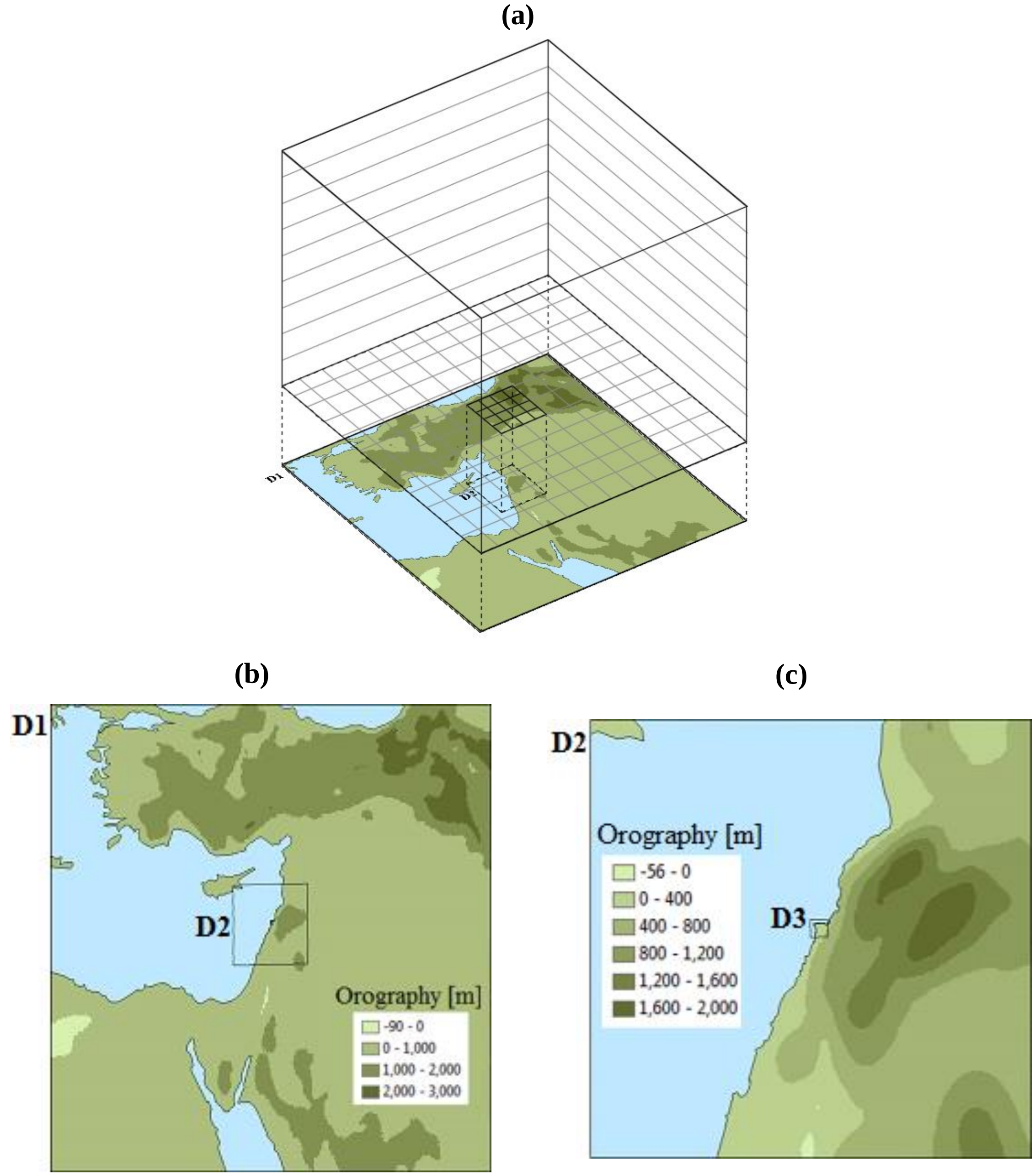


Figure 1 - The three horizontal domains defined in MESO-NH model, with (a) showing the computational grid in which the atmospheric conditions are studied, (b) showing the map of the orography in meters (height above sea level) of domain D2 within domain D1, and (c) showing a map of the orography of domain D3 inside domain D2.

The adopted MESO-NH model is coupled to four surface-atmosphere energy-exchange models under the SURFEX numerical tool that contains the TEB model and the BEM sub-model [30]. The four surface-atmosphere energy-exchange models in SURFEX identifies four surface types: town, nature, sea, lakes, and provide the momentum and heat fluxes produced by each surface type to the atmospheric model MESO-NH. Consequently, it is important to identify the area fraction of each surface type in each of the three domains at the ground level. The surface-type fractions from the total land area in domains D1 and D2 are obtained from ECOCLIMAP database [31]. However, the surface-type fractions in domain D3 are obtained from actual GIS data for Beirut metropolitan area.

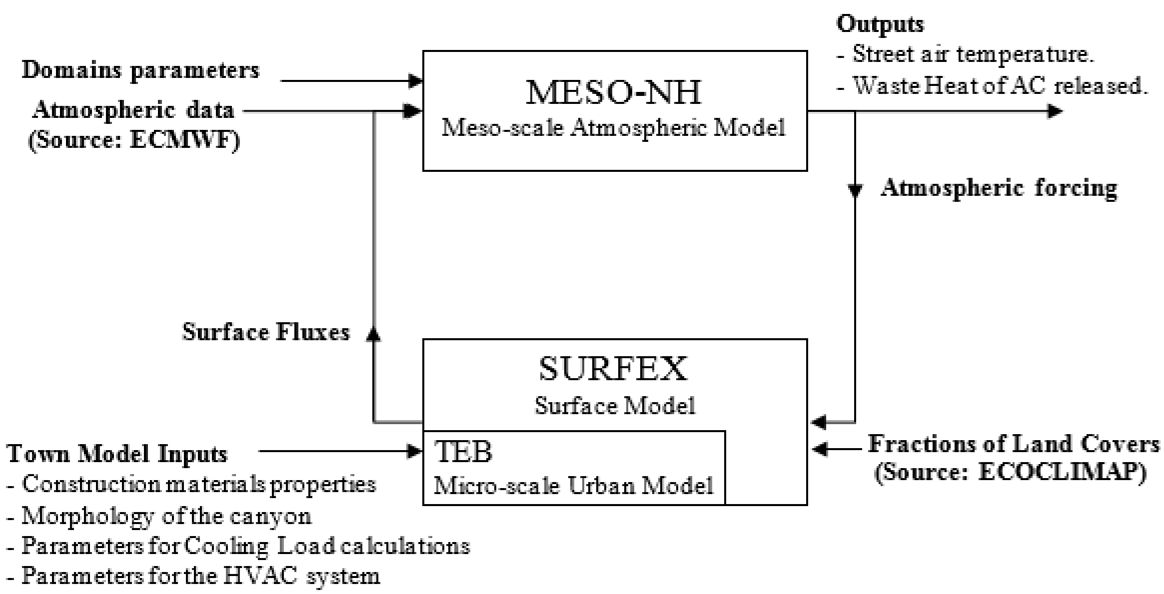


Figure 2 - Schematic drawing showing the interaction between the atmospheric and the surface models.

Figure 2 illustrates the interaction between the meso-scale atmospheric model MESO-NH and the surface model SURFEX (which includes the micro-scale urban model TEB), as well as the inputs of the various models. During each time step, SURFEX receives from MESO-NH the atmospheric forcing data at a height above the canopy layer [32]. Then, SURFEX computes the averaged surface fluxes of momentum, sensible and latent heat over each surface-type in each grid cell, and then sends these aggregated quantities back to MESO-NH, which uses them to solve the momentum and heat equations in the atmosphere.

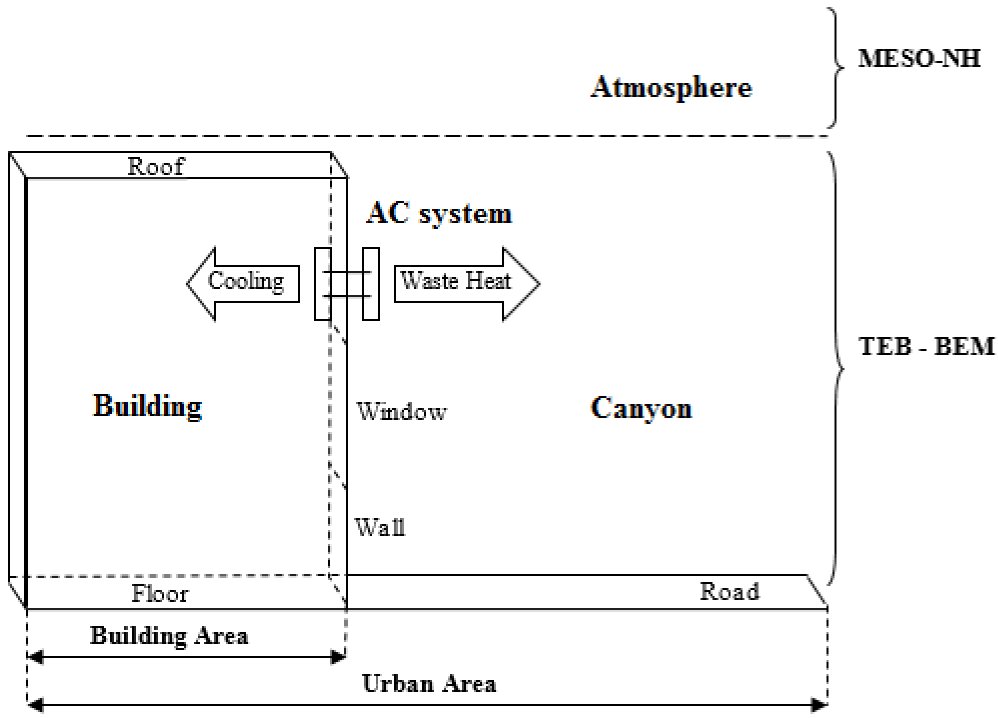


Figure 3 - Schematic drawing showing TEB, BEM, and MESO-NH models.

To study the urban microclimate, the sub-model TEB in SURFEX is adopted to simulate the exchanges of heat and water from road, wall, and roof surfaces in the town surface-type with the atmosphere using the surface energy balance concept [13]. The TEB software models the urban geometry as a simple set of street canyons. The TEB was validated for various cities and climates by several researchers [33-35] and was found to reproduce the town energy balance and the outdoor air temperature despite the simplification hypotheses [36]. The TEB includes a Building Energy Model (BEM) to account for the thermal mass storage term, the internal heat gains, the solar heat gains, the infiltration and ventilation, as well as the AC system model. Figure 3 illustrates a scheme of the TEB, BEM, and MESO-NH models. Both the TEB and BEM models require multiple types of inputs that include urban geometry; construction materials properties, parameters for cooling load calculations, and HVAC system performance parameters.

Table 1 - Values of the morphological parameters of Beirut city.

Morphological parameter		Value
Density of Buildings	$A_{buildings} / A_{urban}$	Range: 0.1 – 0.5 Average: 0.3
Wall to urban area ratio	A_{walls} / A_{urban}	Range: 0.1 – 3 Average: 1
Building height	$H_{building}$	Range: 9 – 18 m Average: 14 m
Floor height	H_{floor}	3 m
Facade glazing ratio	$A_{windows} / A_{wall}$	0.3
Roughness Length	λ	Range: 0.9 – 1.8 m Average: 1.4 m

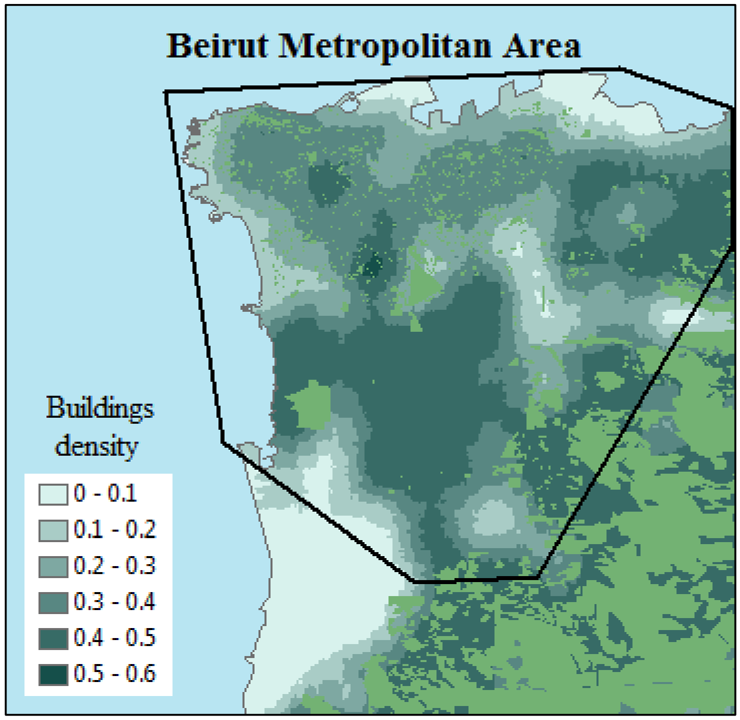


Figure 4 - Distribution of the density of buildings in Beirut metropolitan area based on GIS data. The term "Beirut Metropolitan Area" is used to indicate that the studied region is not limited to Beirut governorate, but also comprise the surrounding densely-built urban areas as shown in the figure.

Table 1 summarizes the morphological parameters of urban geometry in Beirut city. The distribution of the density of buildings in the domain D3 is obtained from GIS data for Beirut metropolitan area and shown in Figure 4. It is clear that buildings density is above 0.4 for up to of 50% of Beirut metropolitan area indicating densely built city. The wall to urban area ratio, defined as the ratio of buildings walls area to the urban area in the a land area, is estimated based on Beirut GIS data and the "Buildings and Institutions census" made by the Central Administration of Statistics (CAS) [37], which includes statistics about the number of floors in buildings in the different regions in Beirut. Typically, the floor height is 3 m. The facade glazing ratio is found to be 30% with 70% of participants to a survey done in Beirut city [38]. The roughness length parameter affects the drag and turbulence mixing caused by the buildings in the urban surface [39]. It could be estimated as 0.1 times the buildings height [39, 40].

Table 2 - Construction materials properties used in TEB and BEM.

Layer	Material	d [m]	C [$MJ.m^{-3}.K^{-1}$]	*k* [$W.m^{-1}.K^{-1}$]	α	ε
ROOF						
Layer 1 (out)	Gravel	0.05	1.8	0.2	0.4	0.9
Layer 2	Asphalt	0.01	1.7	0.2		
Layer 3 (in)	Concrete	0.1	1.58	0.93		
WALL						
Layer 1 (out)	Dense concrete	0.2	2.11	1.51	0.5	0.9
Layer 2	Concrete block	0.14	1	0.67		
Layer 3 (in)	Dense concrete	0.2	2.11	1.51		
ROAD						
Layer 1 (out)	Asphalt/concrete	0.05	1.74	0.82	0.08	0.95
Layer 2	Stone aggregate	0.2	2	2.1		
Layer 3 (in)	Gravel and soil	1	1.4	0.4		
FLOOR						
Layer 1	Concrete	0.2	2.016	1.95		

Table 2 shows the construction materials properties of the building wall, roof, floor, and the road used in TEB and BEM. The typical construction materials of the buildings in Beirut city are the concrete blocks for the buildings walls, the reinforced concrete covered with asphalt and gravel layers for the roof, and the concrete for the floor. In fact, 72% of buildings in Beirut have this construction according to the "Buildings and Institutions census" report [37]. The roads are paved with asphalt and concrete, above a layer of aggregated stone on the ground composed of gravel and soil. The thermal and radiative properties of these materials are prescribed from the literature data [33, 41]. Additionally, most of windows in Beirut are single glazed [42] with a U-factor of 5.8 $W.m^{-2}\cdot K^{-1}$, and a Solar Heat Gain Coefficient (SHGC) of 0.8 according to the Thermal Standard for Buildings in Lebanon (TSBL) [43].

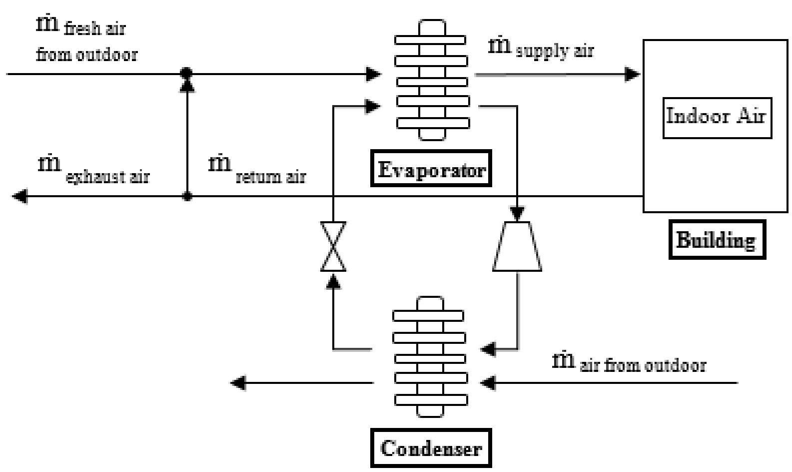


Figure 5 - Schematic drawing of the conventional vapor-compression system.

BEM computes the buildings cooling load due to heat gains from walls, roofs, floors, ventilation air, and internal gains, followed by calculations of the electrical energy consumption of the compressor of the conventional VC system, and the waste heat emissions of the condenser to the outdoor which is the sum of the cooling energy and the compressor's work. A schematic drawing for the conventional VC system is shown in Figure 5. Typical values of the conventional VC cooling system parameters such as sensible and latent internal heat gains, supply conditions, ventilation rate, and set points operated for buildings in Beirut are used in BEM, and they are summarized in the Table 3.

The sensible and latent internal heat gains in the buildings include a sensible heat from lighting of 10 W.m^{-2}, and sensible and latent heat from occupancy of 50 and 45 W.person^{-1} respectively [38]. The ventilation rate is determined according to ASHRAE ventilation standard [44]. The set point temperature and humidity are recommended by the TSBL [43]. The supply flow rate is variable, while the supply conditions are fixed to the Apparatus Due Point (ADP) conformal to the curves obtained by Kessey for the apparatus dew point with respect to the target conditions [45]. The VC system have a variable COP estimated using correlations representing the degradation of AC performance in high outdoor temperatures [46], and by the Part Load Factor (PLF) representing the degradation due to operation under part load conditions [47]. The correlations are implemented in the BEM code. Sixty percent of the total floor area is considered air-conditioned.

Table 3 - Values of the conventional VC cooling system parameters for TEB and BEM.

Parameter		Value
Sensible internal heat gains per floor area	$q_{i\text{-}sensible}$	12 W.m^{-2}
Latent internal heat gains per floor area	$q_{i\text{-}latent}$	1.5 W.m^{-2}
Ventilation rate per floor area	$V_{ventilation}$	0.6 l.s^{-1}·m^{-2}
Set point temperature for cooling	T_{indoor}	24 ^{0}C
Set point relative humidity	RH_{indoor}	50 %
Apparatus dew point temperature	T_{ADP}	12.5 ^{0}C
Apparatus dew point relative humidity	RH_{ADP}	100 %
Fraction of AC waste heat to the outdoor	f_{waste}	0.6

Anthropogenic heat fluxes are generated in the city due to industry, vehicles, buildings, and human metabolism [48]. The human metabolism is negligible according to

Sailor it mainly occurs in buildings. Industrial facilities are scarce in Beirut, thus the heat from industry is also negligible. The heat emitted from vehicles in Beirut is estimated based on the method developed by Sailor and Lu [49] and the approach of De Munck et al [16] where the energy release per vehicle per meter is 3,975 J/m vehicle travel. In the driving conditions of Beirut city, the average trip distance is about 9.6 km [50]. Lebanon has 300 passenger cars /1000 capita [51], and a population of 4.425 million, out of which 40% are present in Beirut [21], resulting 531,000 passenger cars. The global heat of cars within the city is obtained and weighted by the fraction of roads in the grid cells normalized to the total fraction within the domain. The maximum sensible and latent heat of cars in Beirut are 13 and 1 $W.m^{-2}$ urban area respectively, assuming that 92% of vehicles heat is sensible and 8% is latent [52]. The heat of traffic is variable with time according to the hourly schedule developed by Sailor and Lu [49].

2.2 Hybrid Desiccant-Based System Modeling Approach

An intervention scenario on the VC system is proposed for installing a desiccant wheel within the conventional VC system in two configurations [5, 53]. The desiccant wheel removes the latent load by dehumidifying the fresh air before reaching the VC unit that will remove the remaining sensible load. This decoupling between sensible and latent loads enhances the performance of the cooling system, especially in Beirut's hot humid climate, since the VC unit works more efficiently at higher sensible heat ratios. However, the dehumidification by the desiccant wheel produces additional sensible load. In the first configuration of the hybrid desiccant system, this additional load is removed by cooling the hot air leaving the desiccant wheel with the exhaust air from the building in a Heat

Exchanger (HE). In the second configuration, the cooling is achieved through an Indirect Evaporative Cooler (IEC), which reduces furthermore the sensible load. The regenerative heat for the desiccant wheel is provided by the waste heat generated by the condenser and by auxiliary heat.

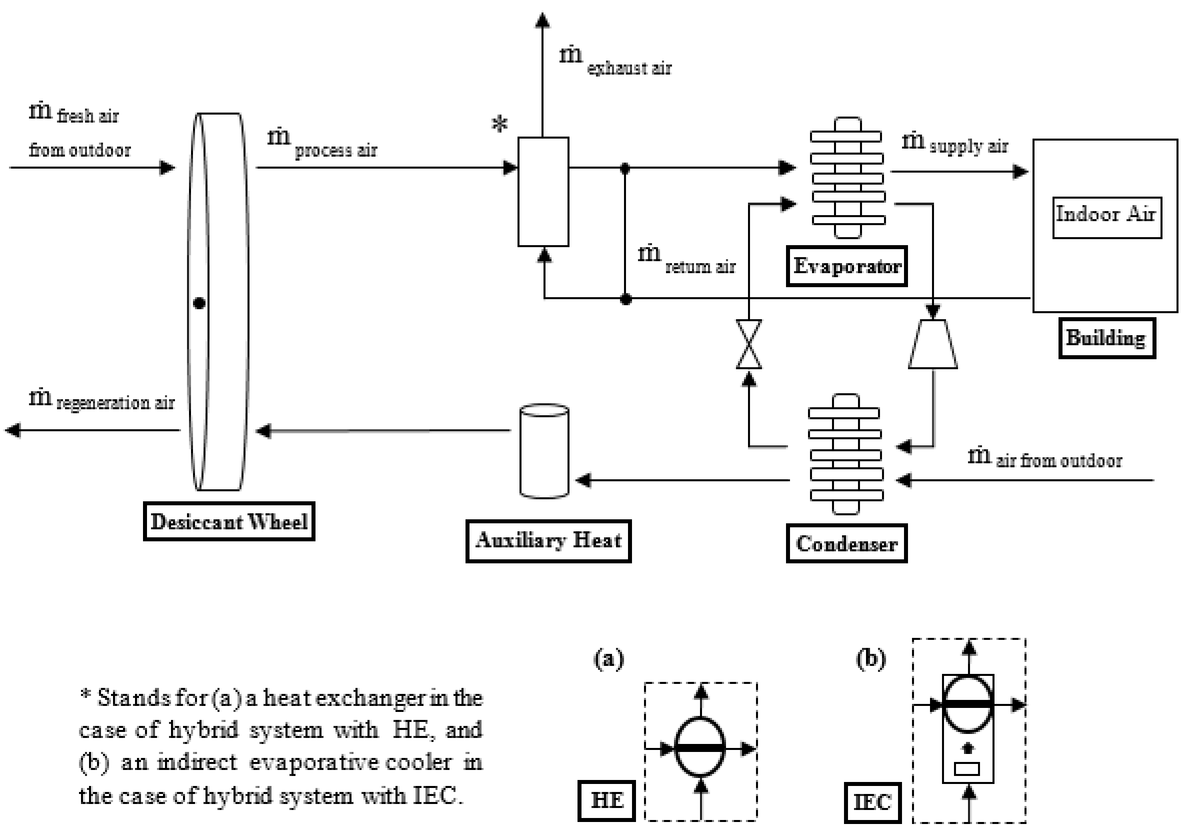


Figure 6 - Schematic drawing of the hybrid desiccant AC system.

In order to simulate the operation of the hybrid system, the BEM source code is modified and extended. The energy consumption, and the waste heat releases to the canyon are assessed by computing the thermodynamic properties of air in the different parts of the hybrid system. Figure 6 shows a schematic illustrating the desiccant wheel integrated to the conventional vapor-compression AC system. The fresh air is dehumidified by a desiccant wheel, followed by sensible cooling with the exhaust air using a heat exchanger, or an indirect evaporative cooler, and final cooling in the vapor-compression evaporator system. The empirical correlations of Beccali et al. model [54] are used to predict the state of the process air leaving the desiccant wheel. The regeneration is carried by using the outdoor air that is first heated by the condenser and then by auxiliary heater system. The regeneration temperature is set at typical value of 80 °C for effective humidity removal [55]. The hybrid system contributes to the anthropogenic heat from the two air streams that are directly exhausted to the outdoor: the regeneration air stream and the exhaust air stream, as well as the remaining waste heat released by the condenser that is not used in regeneration. The amount of heat dissipated to the environment is determined knowing the thermodynamic properties of air in these two streams, and their mass flow rates.

The implementation of the hybrid AC system is conducted by making changes to the BEM source code. The modified version of BEM computes the thermodynamic properties of air including the temperature, the humidity, and the enthalpy passing through the hybrid AC system in its different parts. In each time step, the BEM routine is called by TEB routine. The BEM routine takes as input the state of outdoor air and other variables computed by TEB to calculate the sensible and latent loads per building area. Then, it uses the outdoor conditions and the cooling loads to compute the thermodynamic properties of air passing through the hybrid AC system. Then, from the knowledge of the flow rates of the exhaust and regeneration air streams and their thermodynamic properties, the sensible and latent waste heat released by the hybrid system to the canyon are computed, and the outdoor temperature and humidity are updated and returned to TEB routine. TEB routine uses the updated waste heat fluxes from AC to compute the updated urban fluxes, which are returned to SURFEX which computes the aggregated fluxes of the four surface-types, and then returned to MESO-NH, where the fluxes values are used to compute the atmospheric variables.

2.3 Description of the Simulation Cases

To analyze the impact of the use of different AC system types on the outdoor microclimate, four simulation cases are performed as follows:

(1) The base case simulation is the case in which conventional vapor compression AC systems are used and operated in the city as per actual schedule. This case is used for validation of the simulation results.

(2) The first proposed simulation case is a reference case in which no AC systems are used (AC is turned off) during all the simulation period.

(3) The second proposed simulation case is the case in which hybrid AC systems with HE replaces the conventional AC in the city to remove latent load.

(4) The third proposed simulation case is the case in which hybrid AC systems with IEC is used to enhance the hybrid system performance.

CHAPTER 3

EXPERIMENTAL VALIDATION APPROACH

The ambient temperature, T_a, is represented by the temperature at street level affected by the artificial modifications of the natural ecosystem. Hence, the predicted air temperature in the canyon at 2 m height is validated by comparing it to measurements of near ground temperature as was conducted by Kikegawa et al [18], Lemonsu et al [34], and De Munck et al [16]. The predictions of the urban model are the results of the base case simulation, case (1), considering the use of conventional VC systems in the city.

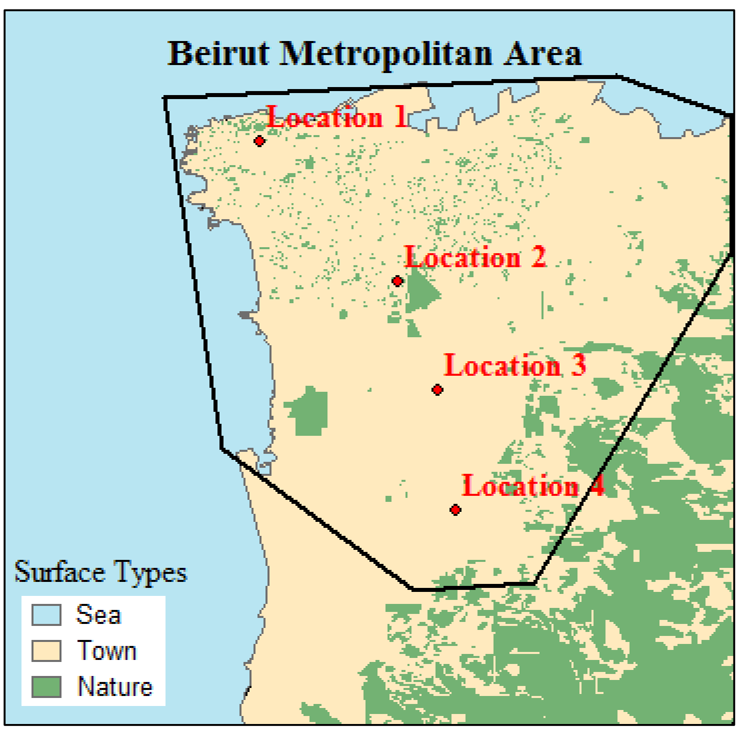


Figure 7 - Locations of the sensors in Beirut metropolitan area.

Table 4 - Characteristics of the four districts presented in the validation section.

	Position	Location	Type of buildings	Buildings Density
Location 1	North West Beirut	Coastal	Commercial, Business, and light industrial	0.5
Location 2	Central Beirut	Inland	Residential, and light commercial	0.3
Location 3	South Beirut	Inland	Residential, and commercial	0.5
Location 4	South Beirut	Suburb	Residential	0.4

The validation is carried out by installation of four temperature sensors in selected locations in Beirut city as shown in Figure 7. The four locations are sparse and have distinct features in relation to building density, buildings types, and proximity to the coastal strip and to vegetation as summarized in Table 4. The first location was at North West Beirut district close to the Mediterranean coast. The district is characterized by high density of buildings which have the mix of residential, commercial, and light industrial building types. The second location was in Central Beirut downtown district which is near a public garden constituting the largest green area in Beirut of about 330,000 m^2. It is characterized by a moderate density of buildings, and it is mainly residential, and light commercial. The other two locations are placed in the southern suburb of Beirut. The district of location 3 is residential and commercial and it is characterized by a high density of buildings. However, the district of location 4 is mainly residential and it is characterized by a slightly lower density of buildings. Green areas are almost absent in the districts of locations 3 and 4. The predicted temperatures in the grid cell corresponding to the four districts are compared to the measured temperatures recorded by the sensor in the four locations.

The sensors were placed in a street in each of the four locations at near ground height at least 1 m away from walls and roads in order to ensure that the measure is representative of the local urban environment and not influenced by the radiative effects of surfaces as recommended by Nakamura and Oke [56] and Vachon [57]. The sensors were shaded, and were not exposed to direct sun radiation. The sensors type was Omega OM-EL-USB-2-LCD with standalone data logger that measures and store up temperature readings over -35 to 80°C measurement ranges with resolution of 0.5°C, and accuracy of ±0.3°C. It is shown in Figure 8. The temperature and the corresponding time were recorded each hour by the data logger within the days corresponding to the simulation period (August 19 midnight – August 21 midnight).

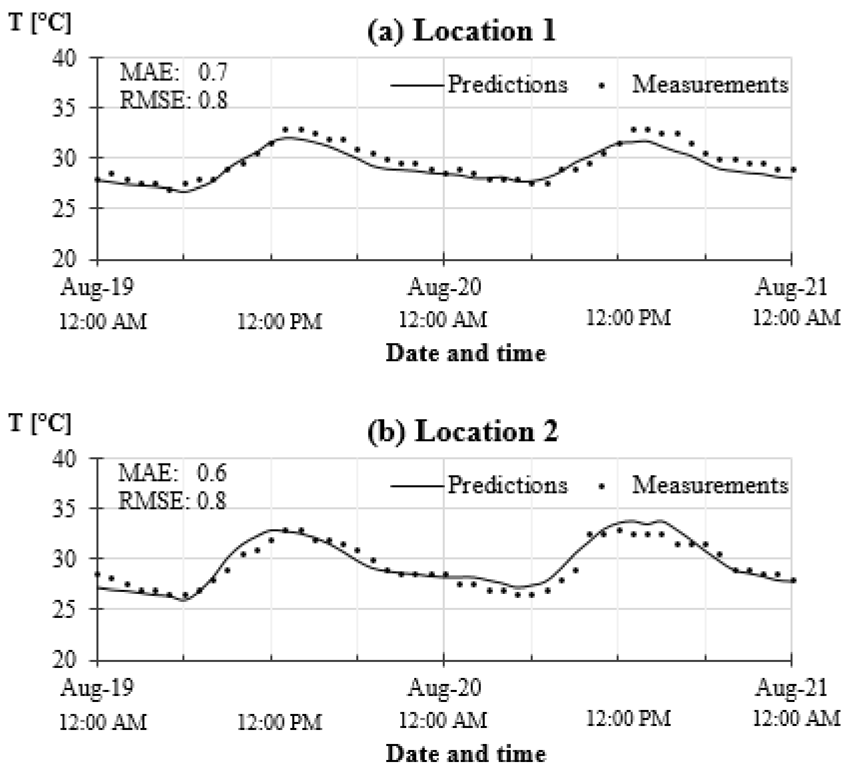
Figure 8 - Sensor used to measure the temperature.

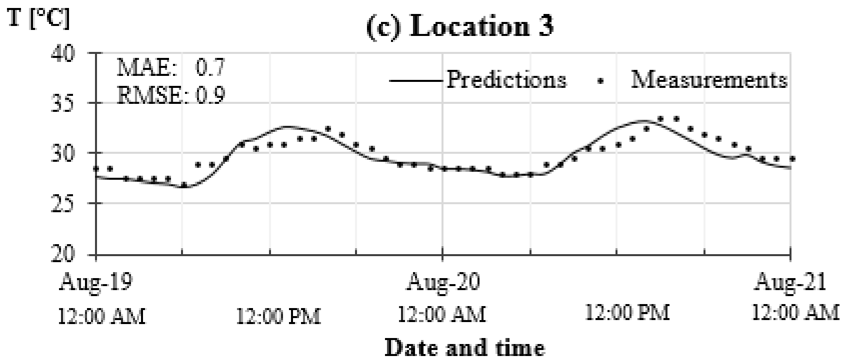
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Validation

Figure 9(a-d) shows the variation in time of the predicted ambient temperature by the base case simulation, case (1), and measured ambient temperature during the simulation period from August 19, 2016 midnight to August 21, 2016 midnight in (a) Location 1, (b) Location 2, (c) Location 3, and (d) Location 4.





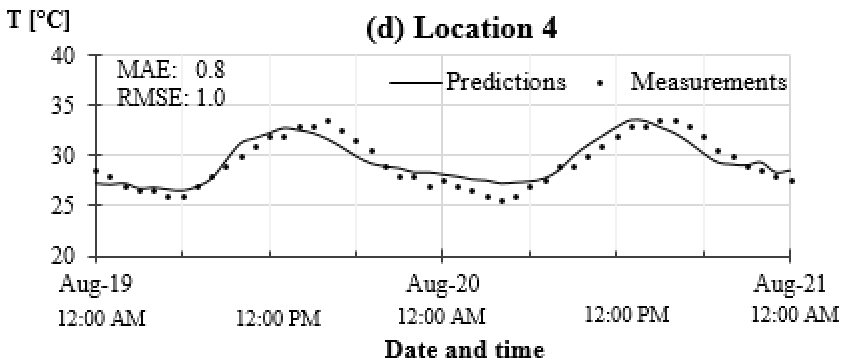
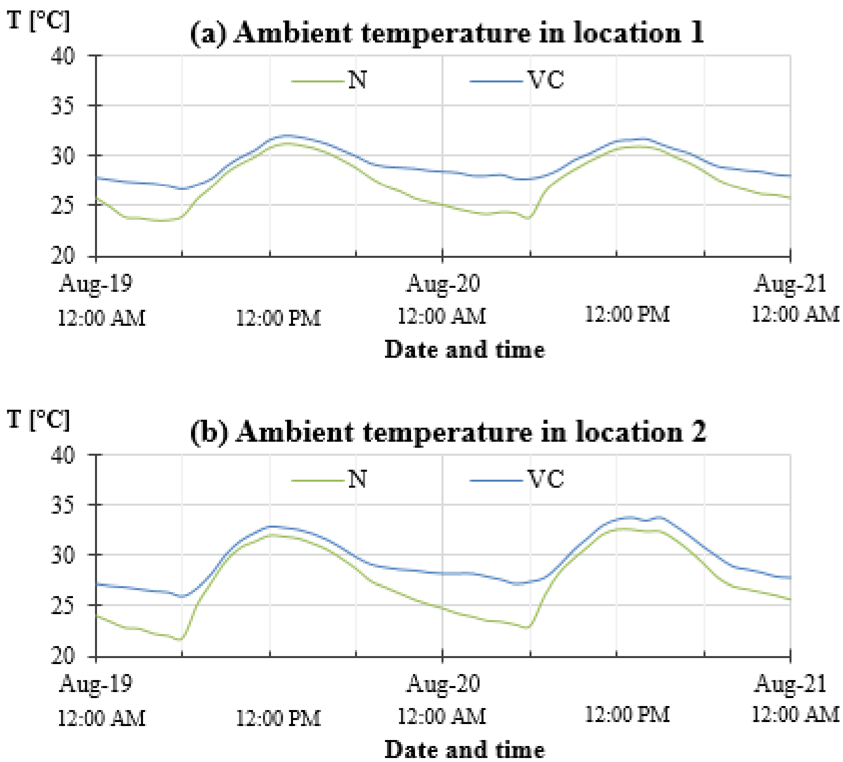


Figure 9 - Predicted and measured ambient temperatures in (a) location 1, (b) location 2, (c) location 3, and (d) location 4, presented in the validation section.

It is observed that the computed results from the model reproduce fairly well the ambient temperature during the period of simulation. The correlation between the predicted and measured ambient temperature is characterized by a Mean Absolute Error (MAE) of about 0.7 °C and a Root Mean Square Error (RMSE) of about 0.9 °C in the four locations, indicating a statically significant correlation and a good performance of the model. The MAE and RMSE values (MAE, RMSE) were (0.7 °C, 0.8 °C), (0.6 °C, 0.8 °C), (0.7 °C, 0.9 °C), and (0.8 °C, 1.0 °C) for locations 1, 2, 3, and 4 respectively (Figure 8). These values were close to values found in other studies, such as 1.5 °C and 1.17 °C in Phoenix [58], and 1.5 °C and 0.2 °C in Paris [16] respectively. The MAE and RMSE are slightly higher for locations 3 and 4 situated in the suburbs of Beirut city, indicating that the results are more accurate for locations 1 and 2 situated in Beirut governorate.

4.2 Impact of conventional VC systems on UHI of Beirut City

In order to evaluate the impact of the conventional AC systems on the urban ambient temperature in day-time and night-time, Figure 10 shows the predicted ambient temperature in (a) location 1, (b) location 2, (c) location 3, and (d) location 4 presented in the validation section for both cases when conventional VC systems are used and when they are not used during the simulation period of August 19 and 20, 2016.



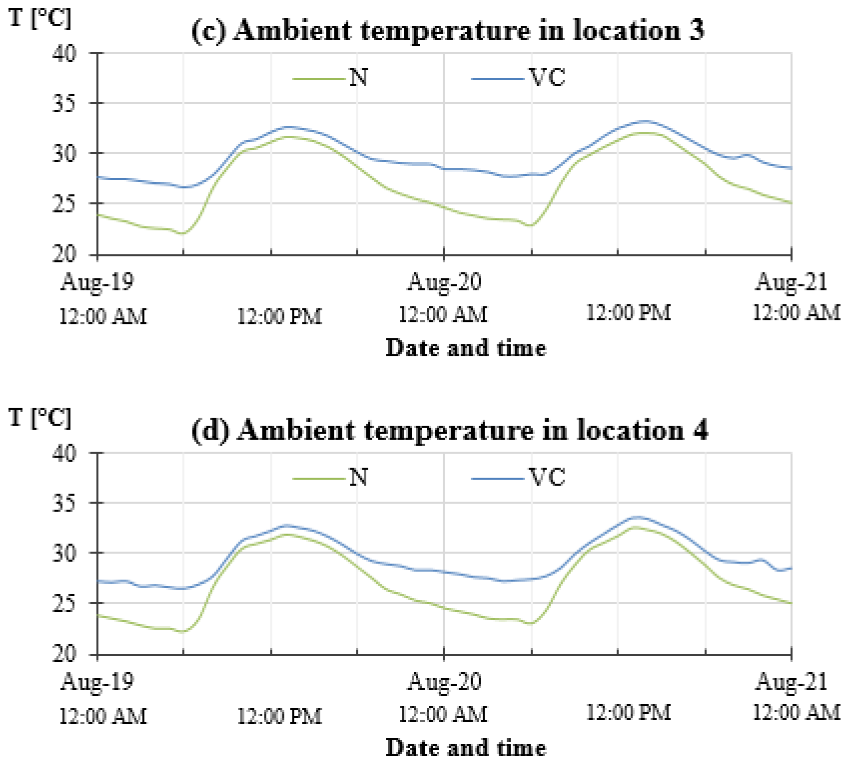
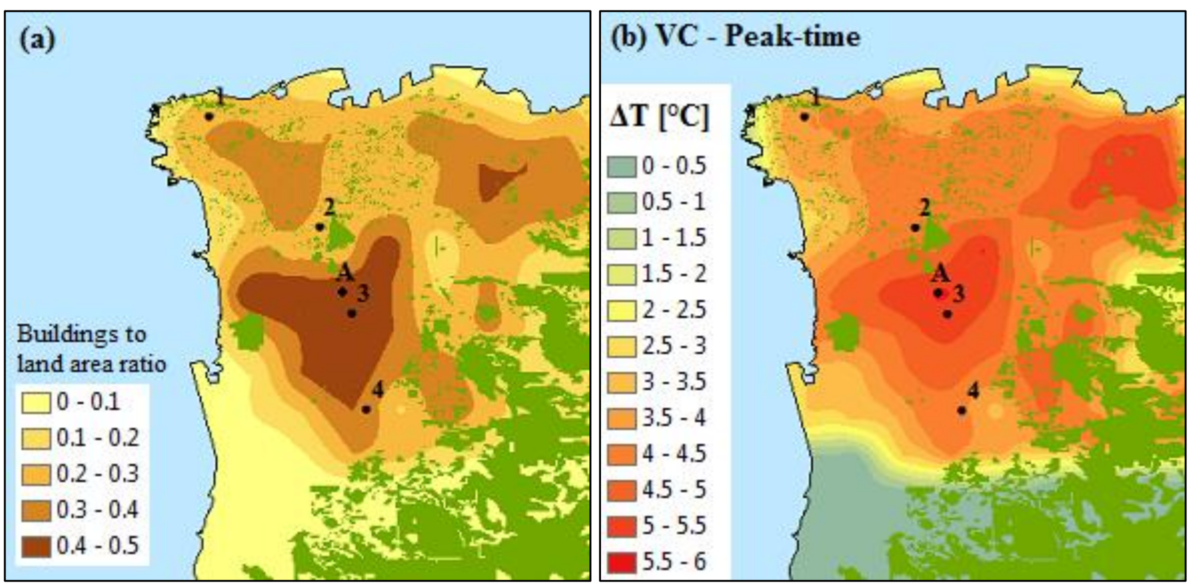


Figure 10 - Predicted ambient temperature for the cases where AC systems are not used (N) and where the conventional VC systems (VC) are used during the simulation period in (a) location 1, (b) location 2, (c) location 3, and (d) location 4 presented in the validation section.

As observed in Figure 10(a-d), the predicted ambient temperature in the actual case of usage of conventional VC systems is higher at all times of the day than the predicted temperature when no AC is used. Even though AC systems are intensively used during the day, it is noticed that the difference in ambient temperature between with and without AC cases is higher at night. The difference in temperature in locations 1, 2, 3, and 4 varied during the day between a minimum of 0.6 °C, 1 °C, 1 °C, 0.8 °C in day-time (7:00 AM until 8:00 PM), while it reached a maximum up to 3.9 °C, 4.3 °C, 5.2 °C, 4.3 °C in night-time (9:00 PM until 6:00 AM of the next day), respectively. The time-averaged increase in temperature in day-time hours during the two-days simulation period was 1 °C, 1.1 °C, 1.5 °C, 1.3 °C, and in night-time hours it was 1.8 °C, 2.1 °C, 2.6 °C, 2.2 °C, in locations 1, 2, 3, and 4, respectively. The time-averaged increase in temperature computed for Beirut metropolitan area was 1.3 °C in day-time hours and 2.2 °C in night-time hours. This phenomenon was also reported in the published study of Paris city, where the average increase in temperature due to AC during the heat wave in August 2003 was higher in night-time compared to day-time [17]. The higher increase in night-time temperature is due the high heat storage capacity of the urban construction materials such as concrete and asphalt that absorb heat during the day and re-emit it during the night [16, 58]. Researchers also explained this by the higher turbulence during day-time than during night-time which reduces the impact of anthropogenic heat on increasing the ambient temperature [13, 16].



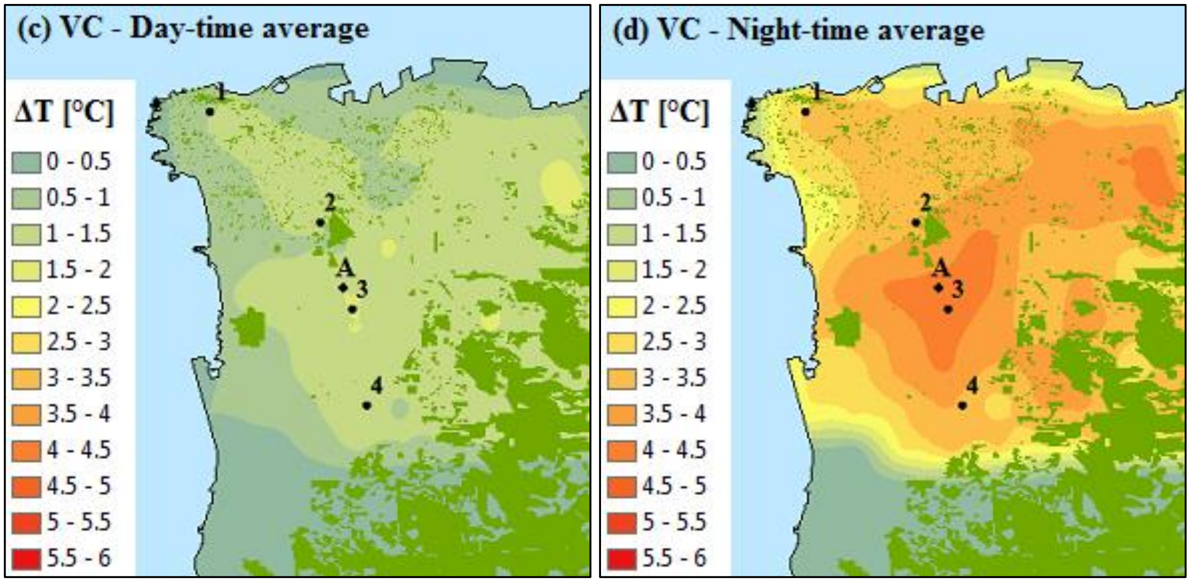


Figure 11 - (a) Buildings to land area ratio in Beirut metropolitan area, and the increase in ambient temperature in [°C] due to conventional VC systems (b) at the peak-time (time of maximum increase in temperature), (c) in day-time average (7:00 AM - 8:00 PM), and (d) in night-time average (9:00 PM - 6:00 AM next day).

The extensive use of AC systems in the city causes an increase in the ambient temperature and intensifies the UHI. In order to evaluate the impact of conventional VC on Beirut's UHI, Figure 11(a) shows the distribution map of the buildings to land area ratio in Beirut metropolitan area, while the spatial map of the increase in ambient temperature in [°C] due to use of conventional VC systems compared to no AC case is shown in Figure 11(b) at the peak-time (time of maximum increase in temperature, see Figure 10). In addition, the time-averaged temperature difference between base case and the case of no AC is shown in Figure 11(c) for the day-time period, and in Figure 11(d) for the night-time period. On the same maps, the four studied location 1, 2, 3, and 4 are shown in addition to location A that has the maximum buildings to land area ratio of 0.5. The increase in temperature is computed as the difference between the temperatures predicted from the simulation cases (1) and (2) (see section 2.3). Figure 11(b-d) demonstrated the influence of the VC systems in increasing the ambient temperature in Beirut city, especially in the regions having higher buildings to land area ratio. For example, location A has the highest increase in the ambient temperature due to VC systems reaching 5.6 °C, and thus contributing to significant intensification of the UHI. The highest increase in temperature in locations 1, 2, 3, and 4 were 3.9 °C, 4.3 °C, 5.3 °C, and 4 °C corresponding to buildings to land area ratios of 0.26, 0.25, 0.49, and 0.35 respectively. Among these four locations, location 3 had the highest increase in temperature due to AC since it had the highest building concentration. However, location 2, which had the lowest buildings to land area ratio resulted in a larger increase in temperature due to AC compared to locations 1 and 4. This indicates that even though the concentrations of buildings is a major influencing factor on the impact of AC in a region in a city, it is not the only contributing factor. Despite the approximately similar concentration of buildings in locations 1 and 2, location 1 had lower increase in microclimate temperature compared to location 2 due to the proximity to the sea. Coastal region has higher humidity which also produces denser clouds and reduces the solar radiation reaching the ground [59]. Location 4 is situated in the suburb of the city, which is less urbanized than other location, and hence resulted in lower increase in temperature compared to location 2. In fact, urban heat islands are characterized by the higher influence of the most urbanized regions in the center of the city on the temperatures than from suburbs [16].

4.3 Power consumption and waste heat of conventional and hybrid AC systems

In order to evaluate the effect of proposed interventions using hybrid AC systems, the electricity consumption and waste heat of the studied AC system types are compared.

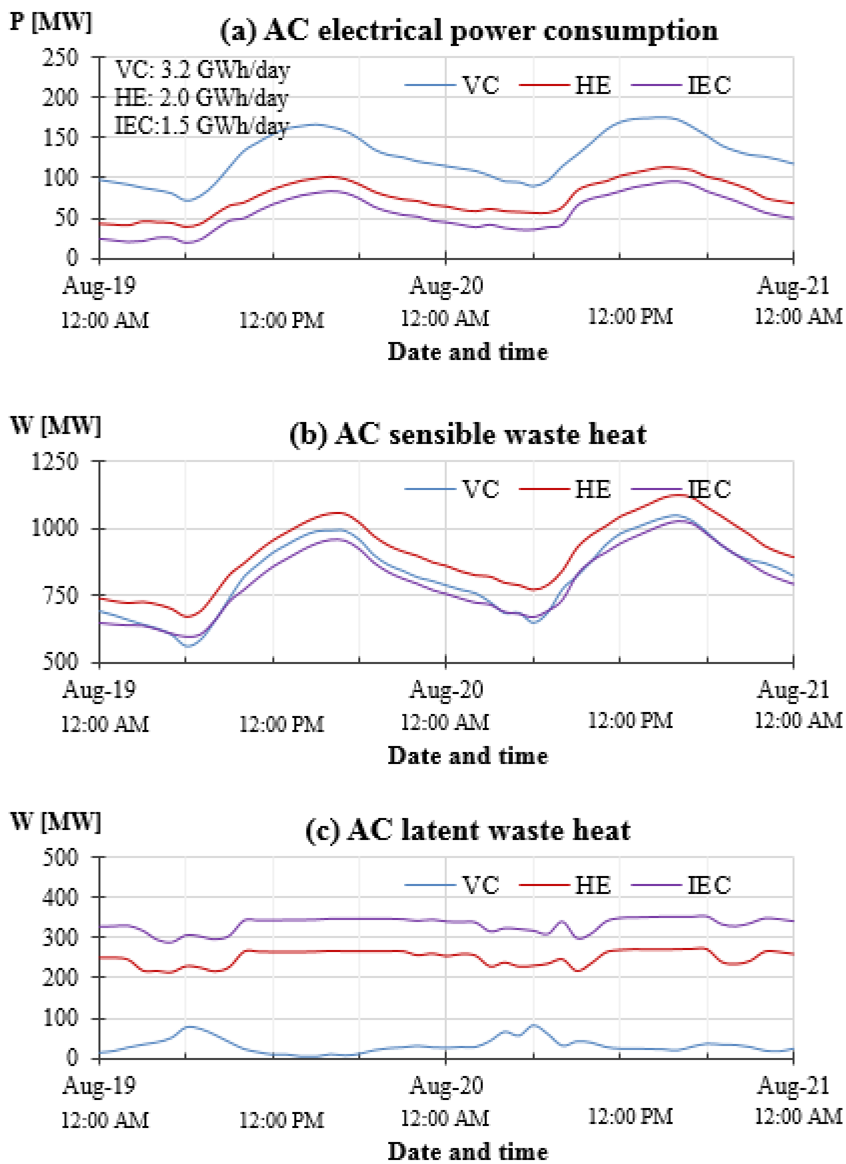


Figure 12 - (a) Electrical power consumption, (b) sensible waste heat, and (c) latent waste heat releases from the different AC types in Beirut metropolitan area over the simulation period.

Figure 12 shows the amount of (a) electrical power consumption, (b) sensible and (c) latent waste heat release to the outdoor in [MW] from the conventional VC system, the hybrid system with HE, and the hybrid system with IEC in Beirut metropolitan area over the 2-days simulation period. These values were computed by summing the predicted values per unit area in the grid cells of domain D3 multiplied by the area of cells. This computation was made for each hour of the simulation period. In addition, the total electrical energy consumption per day in [GWh/day] in Beirut metropolitan area was computed by summing the values of the predicted electrical energy consumed in that area in each hour in the day August 20 of the simulation period.

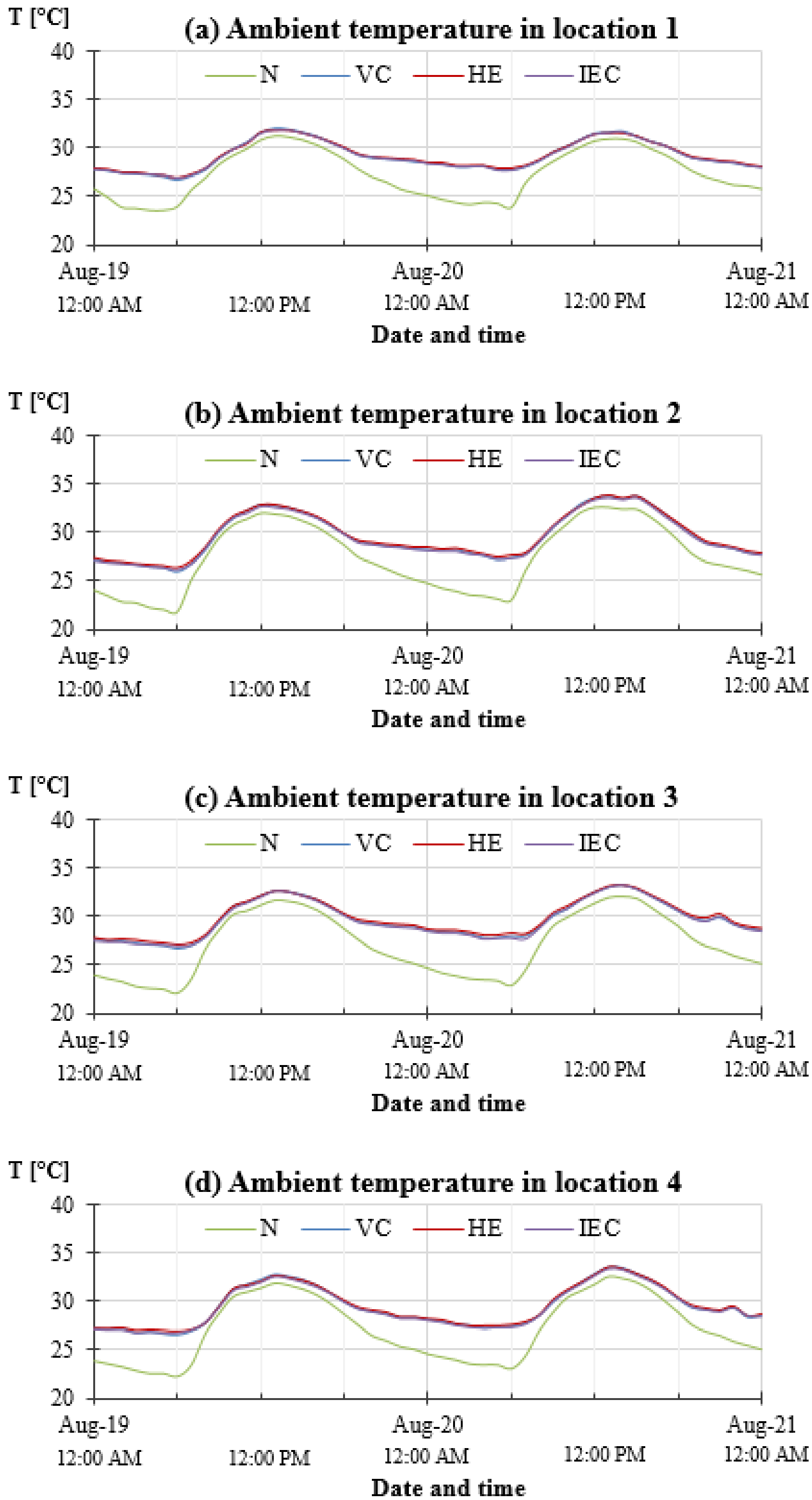
The electrical power consumed by the conventional VC systems in Beirut metropolitan area varied during the day where the minimum was 71 MW in night-time and the maximum was 175 MW in day-time (Figure 12(a)). The higher electricity consumption in day-time over night-time is attributed to the higher use of AC systems since a higher absolute outdoor temperature occurs during day-time. The associated amount of sensible waste heat released by the conventional VC systems varied during the day where the minimum was 559 MW in night-time, and the maximum was 1040 MW in day-time (Figure 12(b)). Similar to the electrical power consumption, the sensible waste heat is found to be proportional to the intensity of the AC systems usage. The latent heat released by the conventional VC systems varied during the day where the minimum was 5 MW in day-time and the maximum was 78 MW in night-time (Figure 12(c)). Unlike the sensible waste heat, the latent waste heat was inversely proportional to the intensity of AC usage because the indoor air exhausted to the outdoor had lower humidity content than the outdoor air when AC systems are operating since they dehumidify the indoor air.

The electrical power consumed by the hybrid AC system with HE in Beirut city varied during the day where the minimum was 38 MW and the maximum was 114 MW (Figure 12(a)). The predicted total electrical energy consumption by hybrid system with HE during the day in August 20 was 2 GWh/day. Compared to the conventional VC system, the electricity consumption was less by 38%, similar to the reduction of 35% found by Ghali [5]. The reason for this reduction is that the dehumidified fresh air is cooled by the return air from the building in the heat exchanger (see Figure 6), which alleviates the load on the evaporator of the VC unit. The associated amount of sensible waste heat varied during the day where the minimum was 671 MW and the maximum was 1127 MW (Figure 12(b)). Compared to the conventional VC system, the sensible waste heat is higher by 10% due to the regeneration process. The latent heat varied during the day between 213 MW and 271 MW (Figure 12(c)). It was higher by 5.7 times than the latent waste of the conventional VC system, and it was released mainly from the regeneration of the desiccant wheel. These results show that while the hybrid system with HE reduces the electricity consumption, it slightly increases the sensible waste heat and significantly increases the latent waste heat.

The electrical power consumed by the hybrid AC system with IEC in Beirut varied during the day where the minimum was 20 MW and the maximum was 95 MW (Figure 12(a)). The predicted total electrical energy consumption by hybrid system with IEC during the day in August 20 was 1.5 GWh/day. Compared to the conventional VC system, the electricity consumption was less by 53%, and it was further less than the reduction achieved by the hybrid system with HE. This value is in agreement with the values of 55% found in literature for similar outdoor conditions of Beirut city [6]. The reason is that the IEC cools furthermore more the dehumidified fresh air than the heat exchanger, which furthermore alleviates the load on the evaporator of the VC unit (see Figure 6). The associated amount of sensible waste heat released by the hybrid systems with IEC varied during the day where the minimum was 595 MW and the maximum was 1023 MW (Figure 12(b)). Compared to the conventional VC system, the sensible waste heat is less by 2%, due to the IEC causing a cooler air to be exhausted from the buildings to the outdoor. The latent heat released by the hybrid systems with IEC varied during the day between 288 MW and 351 MW, and it was higher by 7.9 times than the latent waste of the conventional system (Figure 12(c)). Besides the latent heat released from the regeneration process of the desiccant wheel, latent heat is also released from the evaporation in the IEC. These results show that while the hybrid system with IEC significantly reduces the electricity consumption, it maintained the same or less amount of sensible waste heat and produced more latent waste heat.

4.4 Impact of hybrid AC systems on UHI of Beirut City

In order to evaluate the impact of the hybrid AC systems in day-time and night-time, Figure 13 shows the predicted ambient temperature during the simulation period for each of the four studied simulation cases in (a) location 1, (b) location 2, (c) location 3, and (d) location 4 presented in the validation section, and in (e) location A where maximum influence of AC is found (see Figure 11). Similarly Figure 13 shows the predicted ambient humidity ratio in (a) location 1, (b) location 2, (c) location 3, (d) location 4, and (e) location A.


T [°C]
(a) Ambient temperature in location 1
N
VC
HE
IEC
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time
T [°C]
(b) Ambient temperature in location 2
N
VC
HE
IEC
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time
T [°C]
(c) Ambient temperature in location 3
N
VC
HE
IEC
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time
T [°C]
(d) Ambient temperature in location 4
N
VC
HE
IEC
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time

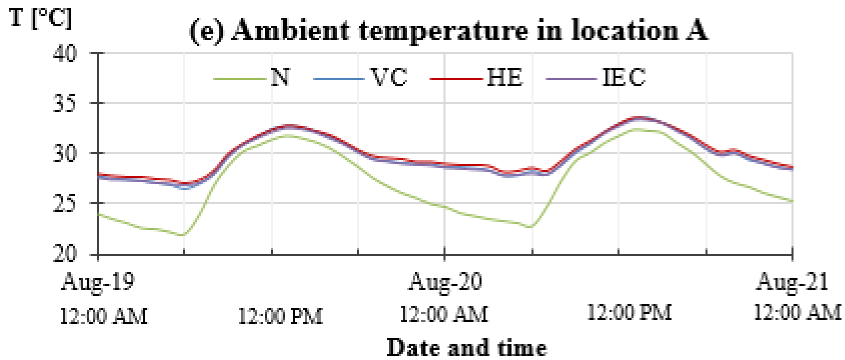
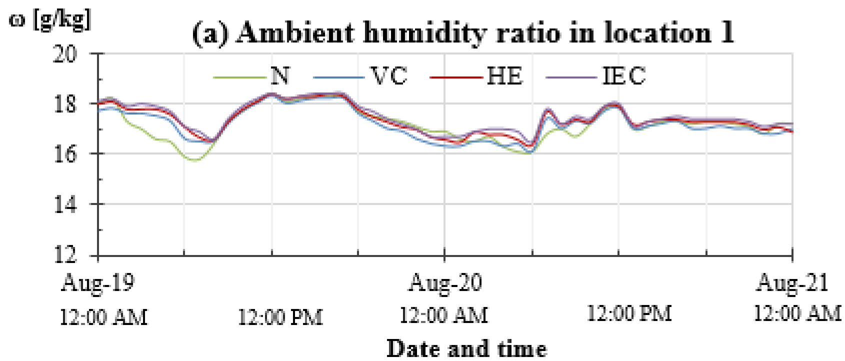
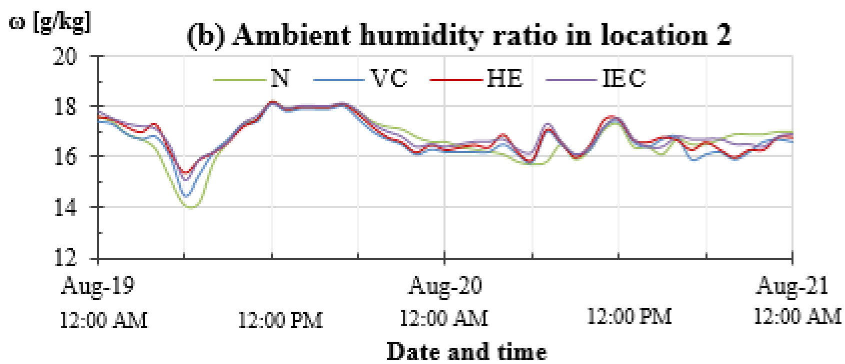


Figure 13 - Predicted ambient temperature for the cases where AC systems are not used (N), and where the different AC systems (VC), (HE), and (IEC) are used, in (a) location 1, (b) location 2, (c) location 3, and (d) location 4 presented in the validation section, and in (e) location A of maximum influence of AC.





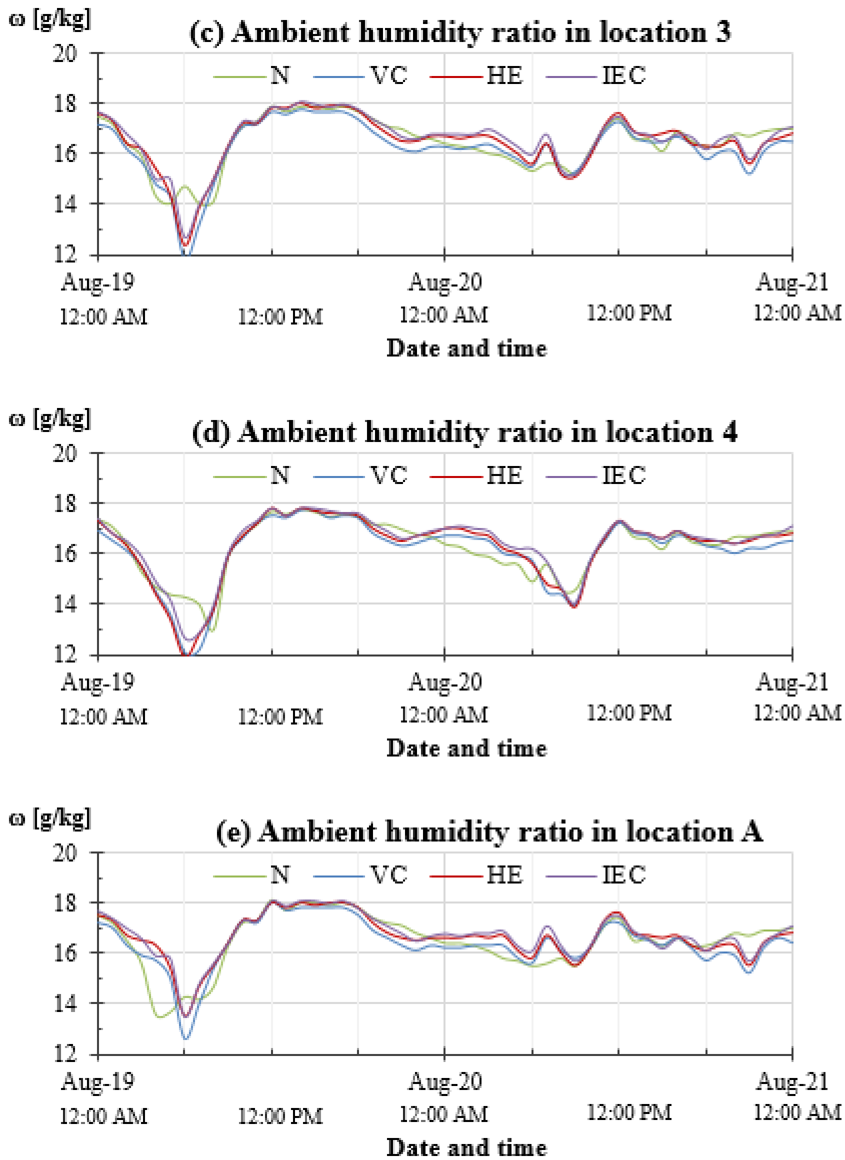
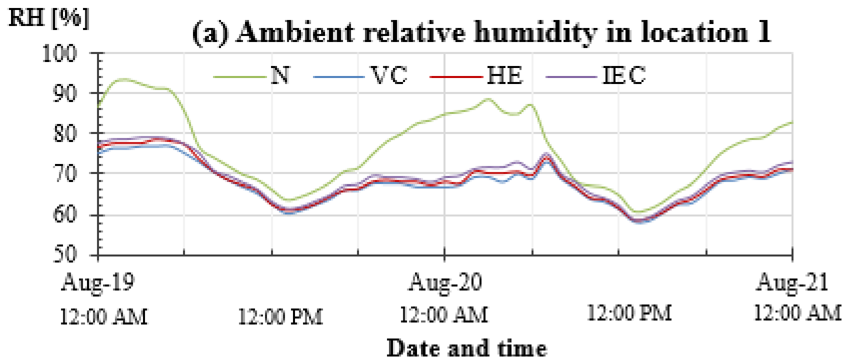
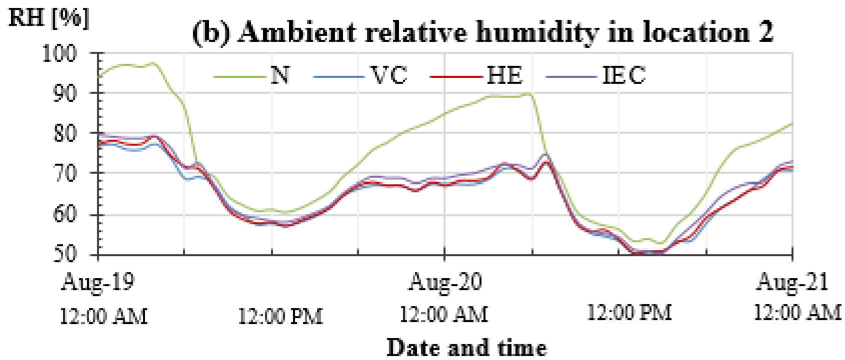
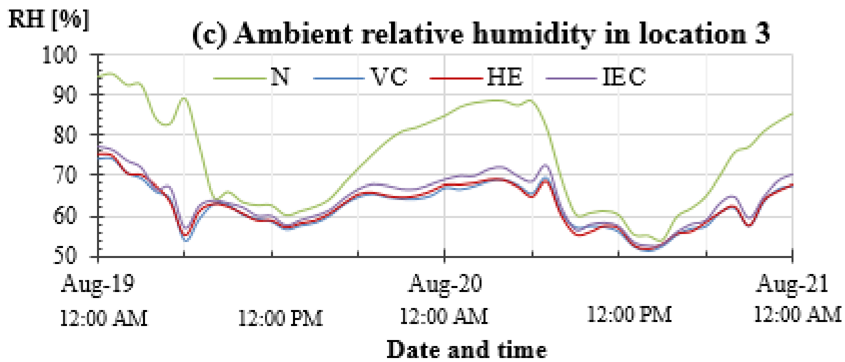
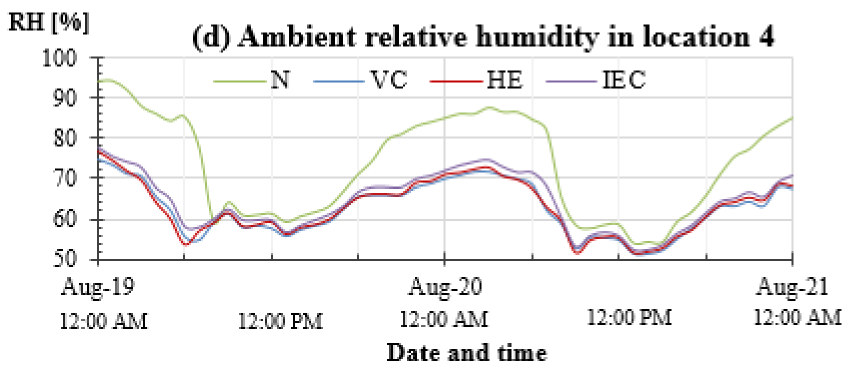


Figure 14 - Predicted ambient humidity ratio for the cases where AC systems are not used (N), and where the different AC systems (VC), (HE), and (IEC) are used, in (a) location 1, (b) location 2, (c) location 3, and (d) location 4 presented in the validation section, and in (e) location A of maximum influence of AC.


RH [%]
(a) Ambient relative humidity in location 1
N
VC
HE
IEC
100
90
80
70
60
50
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time


RH [%]
(b) Ambient relative humidity in location 2
N
VC
HE
IEC
100
90
80
70
60
50
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time


RH [%]
(c) Ambient relative humidity in location 3
N
VC
HE
IEC
100
90
80
70
60
50
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time


RH [%]
(d) Ambient relative humidity in location 4
N
VC
HE
IEC
100
90
80
70
60
50
Aug-19 12:00 AM
12:00 PM
Aug-20 12:00 AM
12:00 PM
Aug-21 12:00 AM
Date and time

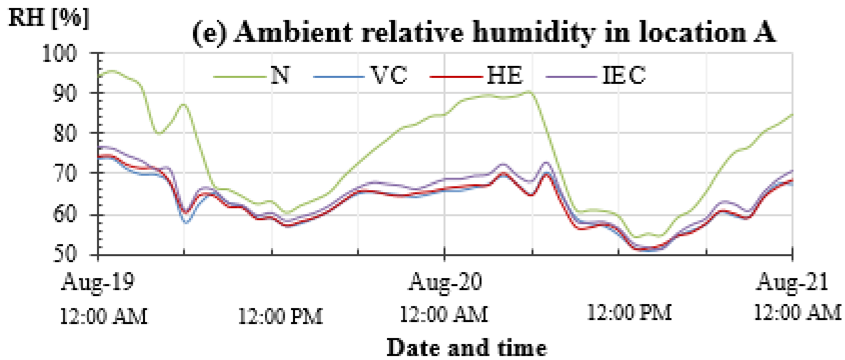
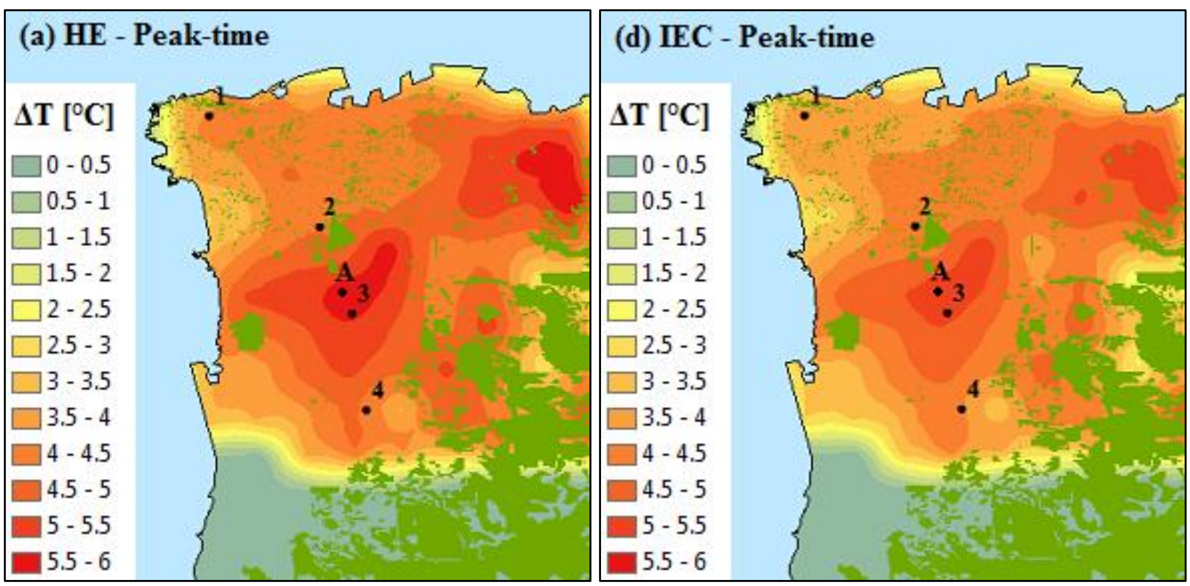


Figure 15 - Predicted ambient relative humidity for the cases where AC systems are not used (N), and where the different AC systems (VC), (HE), and (IEC) are used, in (a) location 1, (b) location 2, (c) location 3, and (d) location 4 presented in the validation section, and in (e) location A of maximum influence of AC.

As observed in Figure 13(a-e), the predicted ambient temperature in the proposed cases of usage of hybrid systems with HE was higher at all times of the day than the predicted temperature when no AC is used. The difference in temperature between these two cases varied during the day where the minimum was 0.7 °C, 1.1 °C, 1.1 °C, 0.9 °C, 1 °C in day-time (7:00 AM until 8:00 PM) and reached a maximum up to 4 °C, 4.5 °C, 5.5 °C, 4.5 °C, 5.8 °C in night-time (9:00 PM until 6:00 AM of the next day), in locations 1, 2, 3, 4, and A, respectively. The time-averaged increase in temperature in day-time hours during the two-days simulation period was 1.1 °C, 1.2 °C, 1.6 °C, 1.4 °C, 1.6 °C, and in night-time hours it was 1.9 °C, 2.2 °C, 2.8 °C, 2.4 °C, 2.8 °C, in locations 1, 2, 3, 4, and A, respectively. The time-averaged increase in temperature in Beirut metropolitan area was 1.4 °C in day-time hours and 2.3 °C in night-time hours. Compared to conventional systems, the hybrid systems with HE produced a higher increase in temperature by about 0.1 °C to 0.3 °C in day-time and night-time, due to the higher release of sensible waste heat (see section 4.3). However, when humidity is examined for hybrid systems with HE compared with conventional systems, the predicted ambient humidity ratio was higher by 0.1 to 0.4 g/kg at all times of the day in all locations (Figure 14(a-e)), due to the higher release of latent waste heat (see section 4.3). The predicted ambient relative humidity in the case of hybrid system with HE was approximately equal or slightly higher than the case of conventional VC system. In fact, the difference in relative humidity between the two cases of hybrid AC with HE and conventional AC varied between a minimum of -0.4 %, -1.6 %, -1.7 %, -2.4%, -2.1 %, and reached a maximum of 2 %, 3 %, 2 %, 2 %, 2.7 %, in locations 1, 2, 3, 4 and A, respectively (Figure 15(a-e)). This demonstrates that the use of hybrid systems with HE at a large scale in the city causes a slight increase in the outdoor temperature and humidity compared to conventional systems.

The predicted ambient temperature in the case of hybrid systems with IEC was approximately equal, or slightly lower at all times of the day than the predicted temperature in the case of conventional VC system (Figure 13(a-e)). The difference in temperature due to AC varied between a minimum of 0.5 °C, 1 °C, 0.9 °C, 0.7 °C, 1 °C, and reached a maximum up to 3.7 °C, 4.2 °C, 5 °C, 4.2 °C, 5.3 °C, in locations 1, 2, 3, 4 and A, respectively. The time-averaged increase in temperature in day-time hours during the two-days simulation period was 0.9 °C, 1.1 °C, 1.4 °C, 1.2 °C, 1.4 °C, and in night-time hours it was 1.7 °C, 2 °C, 2.6 °C, 2.2 °C, 2.6 °C, in locations 1, 2, 3, 4, and A, respectively. The time-averaged increase in temperature in Beirut metropolitan area was 1.2 °C in day-time hours and 2.1 °C in night-time hours. Compared to conventional systems, the hybrid systems with IEC produced a lower increase in temperature by about 0.1 °C to 0.3 °C in day-time and night-time, due to the lower release of sensible waste heat (see section 4.3). However, the predicted ambient humidity ratio was higher at all times of the day than the case of conventional AC, an increase of 0.1 to 0.8 g/kg in all locations (Figure 14(a-e)), due to the higher release of latent waste heat (see section 4.3). The predicted ambient relative humidity in the case of hybrid system with IEC was slightly higher than the case of conventional VC system and hybrid system with HE. In fact, the difference in relative humidity between the two cases of hybrid AC with IEC and conventional AC varied between a minimum of 0.4 %, -0.8 %, -0.7 %, 0 %, -0.7 %, and reached a maximum of 3.8 %, 3.3 %, 3.3 %, 5.6 %, 3.6 %, in locations 1, 2, 3, 4 and A, respectively (Figure 15(a-e)). This demonstrates that the use of hybrid systems with IEC at a large scale in the city causes a smaller increase in the outdoor temperature versus a higher increase in the outdoor humidity than both the conventional VC and hybrid systems with HE cases.



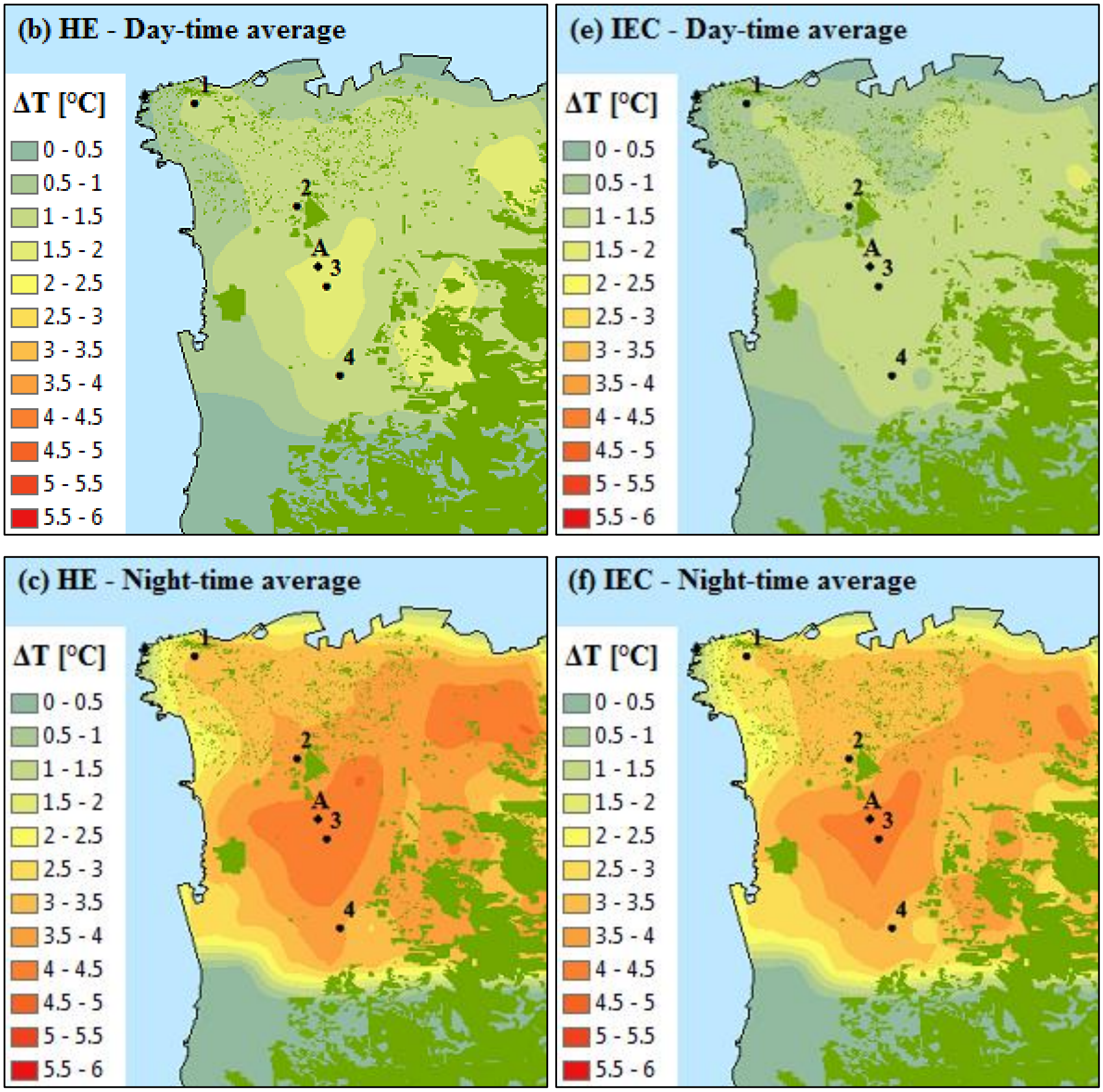


Figure 16 - Increase in ambient temperature in [°C] in Beirut metropolitan area for the (a) hybrid systems with HE at the peak-time (time of maximum increase in temperature due to AC), (b) hybrid systems with HE in day-time average (7:00 AM - 8:00 PM), (c) hybrid systems with HE in night-time average (9:00 PM - 6:00 AM next day), (d) hybrid systems with IEC at the peak-time, (e) hybrid systems with IEC in day-time average, and (f) hybrid systems with IEC in night-time average.

In order to evaluate the impact of the hybrid AC systems on Beirut's UHI, the increase in the ambient temperature compared to the no AC case in Beirut city due to the hybrid AC system types are compared obtained increase for the case of conventional VC systems. Figure 16 shows the map of the increase in ambient temperature [°C] over the reference case when no AC is used in Beirut metropolitan area for the (a) hybrid systems with HE at the peak-time (time of maximum increase in temperature due to AC), (b) hybrid systems with HE in day-time average, (c) hybrid systems with HE in night-time average, (d) hybrid systems with IEC at the peak-time, (e) hybrid systems with IEC in day-time average, and (f) hybrid systems with IEC in night-time average. Comparing Figure 10(b-d) and Figure 16(a-c), it is observed that the increase in the ambient temperature in Beirut city was higher in the case of hybrid systems with HE compared to the increase with conventional VC systems. In locations 1, 2, 3, and 4, the hybrid system with HE increase in temperature was 4 °C, 4.5 °C, 5.6 °C, and 4.3 °C respectively, higher than the conventional AC case in all studied locations. In location A, the increase in the ambient temperature due to hybrid systems with HE was highest and reached 5.8 °C, higher by 0.2 °C than the conventional AC case. This constitutes an increase of about 4%, indicating that the hybrid system with HE could cause a small intensification of the UHI. Figure 16(d-e) and 10(b-d) show that the increase in the predicted ambient temperature in the case of hybrid systems with IEC was slightly less than the case of conventional VC systems. In locations 1, 2, 3, and 4, the increase in temperature of hybrid system with IEC was 3.8 °C, 4.2 °C, 5.1 °C, and 4 °C respectively, lower than the conventional AC case in all locations. In location A, the increase in the predicted ambient temperature due to hybrid systems with IEC was highest and reached 5.3 °C, less by 0.3 °C than the conventional AC case. This constitutes a reduction of about 5%, indicating that the hybrid system with IEC could slightly mitigate the UHI.

CHAPTER 5

RECOMMENDATIONS

Table 5 - Summary of the results on electrical consumption, sensible and latent waste heat and the maximal temperature increase due to AC system compared to no AC, and increase in ambient humidity ratio and relative humidity compared to conventional AC. The value in parenthesis indicate the percentage change in electricity or waste heat compared to conventional VC system.

	Region / Location	Conventional VC	Hybrid AC (HE)	Hybrid AC (IEC)
Electrical Energy Consumption per day [GWh/day]	Beirut Metropolitan Area	3.2	2.0 (-38%)	1.5 (-53%)
Maximum Sensible Waste Heat in the day [MW]	Beirut Metropolitan Area	1040	1127 (+10%)	1023 (-2%)
Maximum Latent Waste Heat in the day [MW]	Beirut Metropolitan Area	78	271 (+570%)	351 (+790%)
ΔT_{max} due to AC compared to without AC proposed case [°C]	Location A	5.6	5.8	5.3
	Location 1	3.9	4.0	3.8
	Location 2	4.3	4.5	4.2
	Location 3	5.3	5.6	5.1
	Location 4	4.0	4.3	4.0
$\Delta T_{average}$ due to AC compared to without AC proposed case in day-time [°C]	Beirut Metropolitan Area	1.3	1.4	1.2
$\Delta T_{average}$ due to AC compared to without AC proposed case in night-time [°C]	Beirut Metropolitan Area	2.2	2.3	2.1
$\Delta\omega$ range due to AC [g/kg]	All locations	-	(+ 0.1 to 0.4)	(+ 0.1 to 0.8)

ΔRH due to AC [%]	Location A	-	(-2.1 to 2.7)	(-0.7 to 3.6)
	Location 1	-	(-0.4 to 2)	(0.4 to 3.8)
	Location 2	-	(-1.6 to 3)	(-0.8 to 3.3)
	Location 3	-	(-1.7 to 2)	(-0.7 to 3.3)
	Location 4	-	(-2.4 to 2)	(0 to 5.6)

The evaluation of the different configurations of AC systems, summarized in Table 5, showed that the hybrid desiccant system with integrated IEC has the highest saving in electrical energy compared to the hybrid system with HE and conventional VC system. In fact, hybrid systems with IEC save 53% of electricity consumption with respect to conventional AC, versus savings of 38% in the case of hybrid HE. On the other hand, its impact on Beirut's ambient temperature is approximately similar or slightly less than the impact of the conventional system. In fact, the ambient temperature is less by about 0.1 to 0.3 °C compared to the case of conventional systems. However, it slightly increases the ambient humidity ratio by 0.1 g/kg to 0.8 g/kg and the relative humidity by about 4% compared to the case of conventional systems. By considering the valuable advantages of energy savings versus the low-impact drawbacks on the urban microclimate compared to the conventional AC systems currently used, it is recommended to adopt the hybrid system with IEC in air-conditioning in Beirut as an alternative to the conventional VC system in order to solve the problem of the high electricity consumption due to AC in the summer.

CONCLUSION

The high cooling loads in buildings during the summer increase the demand on electricity. The hybrid desiccant vapor compression system used is proposed as an alternative for the conventional AC system in order to achieve electrical energy savings. However, the use of hybrid AC system collectively increases the urban anthropogenic heat, which may intensify the UHI. In this study, coupled atmospheric, urban, and building energy models were used to simulate the AC system operation and the outdoor climate in Beirut city. Actual data about the climatic conditions, the urban structure, AC systems parameters, and traffic heat were used as inputs. Conventional vapor compression AC systems, hybrid desiccant AC systems with HE, and with IEC were evaluated in terms of their impact on Beirut's UHI besides their energy consumption. It was found that among the studied AC systems, the hybrid AC system with IEC consumes less electrical energy by 53% than the conventional AC, while it don't have an additional impact on the UHI in Beirut with respect to conventional VC system, since the increase in the ambient temperature is less by 0.3 °C than the conventional AC case. Hence it could be recommended as an energy efficient alternative of the currently used VC system.

BIBLIOGRAPHY

[1] Landsberg H E. The Urban Climate. New York: Academic Press; 1981.

[2] Ghali K, Ghaddar N, Bizri M. The influence of wind on outdoor thermal comfort in the city of Beirut: A theoretical and field study. HVAC R Res 2011; 17: 813-828.

[3] Ghaddar N, Ghali K, Chehaitly S. Assessing thermal comfort of active people in transitional spaces in presence of air movement. Energy Build. 2011; 43: 2832-2842.

[4] Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A, et al. On the impact of urban climate on the energy consumption of building. Sol.Energy 2001; 70: 201-216.

[5] Ghali K. Energy savings potential of a hybrid desiccant dehumidification air conditioning system in Beirut. Energy Convers.Manage. 2008; 49: 3387-3390.

[6] Schelpp D and Schultz K. Analysis of advanced solar hybrid desiccant cooling systems for buildings. 1984.

[7] Howe R R, Beckman W A, Mitchell J W. Commercial applications for solar hybrid desiccant systems. Proc. Annu. Meet. - Am. Sect. Int. Sol. Energy Soc. 1983; 6.

[8] Howe R R, Beckmann W A, Mitchell J W. Factors influencing the performance of commercial hybrid desiccant air conditioning systems. Proc., Intersoc. Energy Convers. Eng. Conf. 1983; 4.

[9] Zhang H, Jianlei N. A two-stage desiccant cooling system using low-temperature heat. Building Services Engineering Research & Technology 1999; 20: 51-55.

[10] Jia C X, Dai Y J, Wu J Y, Wang R Z. Analysis on a hybrid desiccant air-conditioning system. Appl.Therm.Eng. 2006; 26: 2393-2400.

[11] Fong K F, Lee C K, Chow T T, Fong A M L. Investigation on solar hybrid desiccant cooling system for commercial premises with high latent cooling load in subtropical Hong Kong. Appl.Therm.Eng. 2011; 31: 3393-3401.

[12] Mirzaei P A, Haghighat F. Approaches to study Urban Heat Island - Abilities and limitations. Build.Environ. 2010; 45: 2192-2201.

[13] Oke T R. Boundary Layer Climates. 2nd ed. 1987.

[14] Lafore J P, Stein J, Asencio N, Bougeault P, Ducrocq V, Duron J, et al. The Meso-NH Atmospheric Simulation System. Part I: Adiabatic formulation and control simulations. Ann.Geophys. 1998; 16: 90-109.

[15] Stein J, Richard E, Lafore J, Pinty J, Asencio N, Cosma S. High -resolution non-hydrostatic simulations of flash-flood episodes with grid-nesting and ice-phase parametrization. Meteorology and Atmospheric Physics 2000; 72: 101–110.

[16] De Munck C, Pigeon G, Masson V, Meunier F, Bousquet P, Tréméac B, et al. How much can air conditioning increase air temperatures for a city like Paris, France?. Int.J.Climatol. 2013; 33: 210-227.

[17] Tremeac B, Bousquet P, de Munck C, Pigeon G, Masson V, Marchadier C, et al. Influence of air conditioning management on heat island in Paris air street temperatures. Appl.Energy 2012; 95: 102-110.

[18] Kikegawa Y, Genchi Y, Yoshikado H, Kondo H. Development of a numerical simulation system toward comprehensive assessments of urban warming countermeasures including their impacts upon the urban buildings' energy-demands. Appl.Energy 2003; 76: 449-466.

[19] Salamanca F, Martilli A. A study of the urban boundary layer using different urban parametrizations and high-resolution urban canopy parameters with WRF. Journal of applied meteorology and climatology 2010; 50: 1107-1128.

[20] Ibrahim O, Fardoun F, Younes R, Louahlia-Gualous H. Energy status in Lebanon and electricity generation reform plan based on cost and pollution optimization. Renewable Sustainable Energy Rev 2013; 20: 255-278.

[21] Haddad M, Mansour C, Stephan J. Unsustainability in emergent systems: A case study of road transport in the Greater Beirut Area. IEOM - Int. Conf. Ind. Eng. Oper. Manag., Proc. 2015.

[22] Masson V. A physically-based scheme for the urban energy budget in atmospheric models. Boundary-Layer Meteorol. 2000; 94: 357-397.

[23] Bueno B, Pigeon G, Norford L K, Zibouche K, Marchadier C. Development and evaluation of a building energy model integrated in the TEB scheme. Geoscientific Model Dev. 2012; 5: 433-448.

[24] Hidalgo J, Masson V, Pigeon G. Urban-breeze circulation during the CAPITOUL experiment: Numerical simulations. Meteorol.Atmos.Phys. 2008; 102: 243-262.

[25] Bougeault P, Bechtold P, Belair S, Carriere S, Cuxart J, Ducrocq V, et al. The MESO-NH atmospheric simulation system: scientific documentation,Part I: Dynamics. 9th ed. France: Meteo-France and CNRS; 2014.

[26] ECMWF. ERA interim database, http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/. 2017.

[27] Verstraete M. What does one mean by Model Spin Up Time? - ResearchGate, https://www.researchgate.net/post/What_does_one_mean_by_Model_Spin_Up_Time. 2016.

[28] Weather Spark. Average Weather in Beirut Lebanon, available at: https://weatherspark.com/y/99217/Average-Weather-in-Beirut-Lebanon. 2017.

[29] Daaboul J, Ghali K, Ghaddar N. Mixed-mode ventilation and air conditioning as alternative for energy savings: a case study in Beirut current and future climate. Energy Effic. 2017; 1-18.

[30] Masson V, Le Moigne P, Martin E, Faroux S, Alias A, Alkama R, et al. The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. Geoscientific Model Dev. 2013; 6: 929-960.

[31] Masson V, Champeaux J -, Chauvin F, Meriguet C, Lacaze R. A global database of land surface parameters at 1-km resolution in meteorological and climate models. J.Clim. 2003; 16: 1261-1282.

[32] Le Moigne P, Boone A, Belamari S, Brun E, Calvet J C, Decharme B, et al. Surfex Scientific Documentation. 2nd ed.Météo-France; 2012.

[33] Masson V, Grimmond C S B, Oke T R. Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. J.Appl.Meteorol. 2002; 41: 1011-1026.

[34] Lemonsu A, Grimmond C S B, Masson V. Modeling the surface energy balance of the core of an old Mediterranean City: Marseille. J.Appl.Meteorol. 2004; 43: 312-327.

[35] Pigeon G, Moscicki M A, Voogt J A, Masson V. Simulation of fall and winter surface energy balance over a dense urban area using the TEB scheme. Meteorology and Atmospheric Physics 2008; 102: 159-171.

[36] Hamdi R, Masson V. Inclusion of a Drag Approach in the Town Energy Balance (TEB) Scheme: Offline ID Evaluation in a Street Canyon. Journal of Applied Meteorology and Climatology 2008; 47: 2627-2637,2639-2644.

[37] CAS, Buildings and institutions census report. 2004.

[38] Annan G, Ghaddar N, Ghali K. Natural ventilation in Beirut residential buildings for extended comfort hours. Int.J.Sustainable Energy 2016; 35: 996-1013.

[39] Burian S J, Velugubantla S P, Brown M J. Morphological analyses using 3D building databases: Phoenix, Arizona. LA-UR-02-6726, Los Alamos National Laboratory 2002.

[40] Grimmond C S B, Oke T R. Aerodynamic properties of urban areas derived from analysis of surface form. J.Appl.Meteorol. 1999; 38: 1262-1292.

[41] Pigeon G, Zibouche K, Bueno B, Le Bras J, Masson V. Improving the capabilities of the Town Energy Balance model with up-to-date building energy simulation algorithms: An application to a set of representative buildings in Paris. Energy Build. 2014; 76: 1-14.

[42] MoPWT, Energy Analysis and Economic Feasibility. 2005.

[43] OEA, Thermal Standards for Buildings in Lebanon 2010. 2010.

[44] ASHRAE, ANSI/ASHRAE Addendum n to ANSI/ASHRAE Standard 62-2001. 2010.

[45] Kessey K O. Cooling coil selection using apparatus dewpoint charts. Int.J.Refrig. 1985; 8: 360-366.

[46] Payne W V, Domanski P A. A Comparison of an R22 and an R410A air conditioner operating at high ambient temperatures.2002.

[47] Henderson H, Huang Y J and Parker D. Residential equipment part load curves for use in DOE-2. 1999.

[48] Sailor D J. A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment. Int.J.Climatol. 2011; 31: 189-199.

[49] Sailor D J, Lu L. A top-down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas. Atmos.Environ. 2004; 38: 2737-2748.

[50] MoE/URC/GEF, Technology Needs Assessment Report for Climate Change, Chapter 5: Transport. 2012.

[51] MoE/UNDP, Mobility Cost: A case study for Lebanon. 2015.

[52] Pigeon G, Legain D, Durand P, Masson V. Anthropogenic heat release in an old European agglomeration (Toulouse, France). Int.J.Climatol. 2007; 27: 1969-1981.

[53] Ghali K, Othmani M, Ghaddar N. Energy consumption and feasibility study of a hybrid desiccant dehumidification air conditioning system in Beirut. Int.J.Green Energy 2008; 5: 360-372.

[54] Beccali M, Butera F, Guanella R, Adhikari R S. Simplified models for the performance evaluation of desiccant wheel dehumidification. Int.J.Energy Res. 2003; 27: 17-29.

[55] Sopian K, Dezfouli M S, Mat S, Ruslan M H. Solar assisted desiccant air conditioning system for hot and humid areas. International Journal of Environment and Sustainability 2014; 3: 23-32.

[56] Nakamura Y, Oke T R. Wind, temperature and stability conditions in an east-west oriented urban canyon. Atmos.Environ.Part A Gen.Top. 1988; 22: 2691-2700.

[57] Vachon G. Transferts des polluants des sources fixes et mobiles dans la canopée urbaine: Evaluation experimentale.2001.

[58] Salamanca F, Georgescu M, Mahalov A, Moustaoui M, Wang M, Svoma B M. Assessing summertime urban air conditioning consumption in a semiarid environment. Environ.Res.Lett. 2013; 8.

[59] Touchaei A G, Wang Y. Characterizing urban heat island in Montreal (Canada)—Effect of urban morphology. Sustainable Cities and Society 2015; 19: 395-402.