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Simulating the Urban Heat Island Augmented with a Heat Wave Episode Using ICTP RegCM4.7 in a Mega-Urban Structure of Karachi, Pakistan

B. Ahmad[1*], Sh. Ali[2,3], T. Khan[4], Sh. Hasson[5], S.A.A. Bukhari[6]

1. Computational Meteorologist, Numerical Weather Prediction Center, Pakistan Meteorological Department, Islamabad, Pakistan
2. Senior Scientist, Earth System Physics, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy
3. Global Change Impact Studies Centre (GCISC), Ministry of Climate Change, Pakistan
4. Senior Meteorologist, Numerical Weather Prediction Center, Pakistan Meteorological Department, Islamabad, Pakistan
5. Post Doc Researcher, CEN, Institute of Geography, University of Hamburg, Hamburg, Germany
6. Electronic Engineer, Numerical Weather Prediction Center, Pakistan Meteorological Department, Islamabad, Pakistan

Corresponding author: *burhanahmadkhan@gmail.com*

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ABSTRACT

The metropolis of Karachi, with a density of around 4000 persons/km^2 at present, is going through unprecedented urbanization and population growth, which can augment Urban Heat Island (UHI) triggered heat wave impacts on life and living. Here, we investigate skill of Regional Climate Model version 4.7 (RegCM4.7) in simulating 2015 heat wave episode in southern Pakistan by dynamically downscaling ERA-Interim reanalysis at 10km resolution and switching on the urban parameterization in the employed land surface scheme. Our results suggest that the RegCM4.7 has successfully reproduced the overall conditions of the 2015 heat wave. For instance simulated surface temperature maxima is seen well above 50°C for at least three consecutive days along the austere heat wave duration. Also, extended sustenance of a ridge in locality of the Karachi, as well as a low pressure system in adjacent Arabian Sea is seen to restrain normal drift of sea-breeze to the coastal city, in the simulated output. The National Weather Service (NWS) based heat index derived from the simulation is seen to remain well above 124°F during the whole heat wave period, placing the city in an "Extreme Danger" class of discomfort and high vulnerability to heat stroke. The UHI integrated RegCM4.7 is hence recommended for use in modelling to help in adaptation strategies against occurrences of such heat wave events in future.

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1. Introduction

Extreme weather events, particularly the heat waves over the urban areas can lead to disasters, causing severe damages to life and living of mostly less resilient vulnerable poor communities. Heat wave is a climate related hazard that affects human comfort and in severe cases can result into "mortality". Further, heat wave accompanies by warm (humid or dry) weather conditions that prevail three to five consecutive days, and exacerbate production of heat by anthropogenic activities, increasing the intensity of the urban heat island [1]. The UHI implies that temperatures in the urban interiors soar relative to those of the suburban vicinities owing to diverse thermal, radiative, anthropogenic, hydrological and mechanical features of the urban infrastructure [2,3]. Normal warmer climatic conditions over the metropolitan areas as compared to their adjacent countryside when combined with the heat wave gives rise to human discomfort, exacerbate the daily life problems and can cause mortality. The United Nations Department of Economic and Social Affairs declared in 2014 that above half of the social residents dwell in cities and that the figure is still escalating. In view of such urbanization and its rapid increase, exploration for the effect of urbanized zones on nature, particularly on surface and atmospheric settings, turns out to be of vital significance [4].

Meteorological surveillance and modelling studies establish that besides altered temperatures, winds also vary considerably ([5–10]). City facades effect the organization as well as the height of the boundary layer, which is especially imperative for air quality perception [11]. Huszar et al. [9] describes that metropolitans are vulnerable to distress by urban meteorological impacts, and the scale of temperatures upsurge can match to an extent triggered by climate change. Owing to projected warming and rising urbanization, urban communities will be exposed to extra rigorous, recurrent and elongated heat waves [12]. To simulate the UHI in global climate models, various parameterizations are introduced, besides their typical systematic biases are yet a great concern after long history of extensive development in terms of resolution and incorporation of physical processes. Lately, numerical weather prediction and/or regional climate models are coupled to a range of urban canopy models (UCMs; e.g., Chen et al., [13]; Lee et al., [8]; Liao et al., [14]) so as to apprehend diverse urban courses on limited area resolution with an attempt to illustrate particularly the UHI more precisely. Due to incorporation of extensive land-surface schemes, the RCMs represent atmosphere-surface energy exchanges at fine resolutions, designating them as a suitable tool to study the heatwave and UHI assessment for urban centres.

2. Research significance

Karachi, at 3780 Km^2 of area, is a thickly populated city hosting 10% of Pakistan's total inhabitants, 22% of its urban inhabitants, and 60% of country's annual return [15]. It is located on coastline of Sindh province in southern Pakistan, along a natural harbour on Arabian Sea. Urban growth tendency in Karachi undermine resilience to heat. The megacity established under several phases without any master plan attributed to abundant areas of uneven land use and urban stretch [16]. Sixty one percent of the population subsists in slums, which have existed and unforeseeably expanded since mid-20th century [17]. The rambling, unanticipated, characteristics of the metropolitan has not aided for green spaces that would encourage mitigation from heat islands and from the effects of heat wave events. Rapid population growth is a challenge to deliver basic and urgent health services to residents. Under a reasonable tolerance, the city has grown with sheer changes in population by 5% on annual basis. Migration from rural localities and from other cities of the country contributed to the accelerated and haphazard urbanization and expansion that Karachi has incurred. With a population density of over 4000 people/km^2, Karachi is declared as the largest city in Pakistan [18].

Found on the Arabian Sea shore, Karachi hosts semi-arid environment. May to July are warmest months with long term mean of historical temperature stretching from 30.3°C to 31.4°C. Spring to summer transition is usually dry, however summers get wet as soon as monsoon rains start off in July and August. Relative humidity of the city in summer season has high variability. Long term historical mean of maximum temperature for June is 34.8°C. Historic maxima of temperatures ever recorded in May and June are found to be as high as 47.8°C in 1938 and 47°C in 1979 (Climatic Normals of Pakistan, Pakistan Meteorological Department). Attributable to some record high temperatures in the history, an ascending trend in the frequency of heat waves is seen in Southern regions (including Karachi city) of Pakistan[19]. Moreover, under a high emission scenario, future projections derived from Regional Climate Models (RCMs) forecast a persistent growth in the frequency of heat waves by the end of century [20].

Risks evolving via extreme heat are emerging concerns. In June 2015, Karachi underwent most fatal heat wave conditions ever recorded in over 50 years [21]. Meteorological metrics driving the June 2015 heat wave recorded a strong depression over the Arabian Sea that obstructed incoming sea breeze rendering stable atmospheric conditions prevailing in the city for several days [22]. Along the heat wave episode, the maximum temperature reached 44.8°C on June 20, 2015. What was staggering during the 2015 event was that the temperatures in Karachi were not as high as they were in other zones of Pakistan and that the temperatures in Karachi did not break records for that city, yet the heat wave event had proven fatal claiming more than 1200 human lives in Karachi. This calls for inclusion of the UHI being an alleged attribute to the severity of heat wave events. Therefore it is imperative to analyse the skill of RCM integrated with the UHI to analyse subsequent surface and atmospheric conditions.

Hence, we investigate the skill of the Regional Climate Model version 4.7 (RegCM4.7) in simulating the 2015 heat wave episode in southern Pakistan and subsequently the UHI intensity over the Karachi metropolis by dynamically downscaling the ERA-Interim reanalysis at 10km resolution and switching on the urban parameterization in the employed land surface scheme. Our rationale of engaging the UHI is based on the fact that even though heat wave struck major parts of southern Pakistan, yet the urban canopy of the densely populated metropolis Karachi aggravated the targeted impact on already severed heat wave struck city that primarily suffered the effects as a consequence of anomalies in atmospheric dynamics.

3. Methods

3.1. Urban parameterizations

We have employed a mesoscale, non-hydrostatic regional climate model of the Regional Climate Model version 4.7 (RegCM4.7), which has been developed at the Abdus Salam International Centre for Theoretical Physics (AS-ICTP) and described in detail by Giorgi et al., [23]. The RegCM4.7 was run with the land surface scheme of the Community Land Model version 4.5 (CLM4.5), which incorporates the parameterizations for the urban canopy heat and air-conditioning [24,25]. The urban parameterization of the CLM4.5 (CLMU4.5) is based on a canyon like design of the city zones and is theoretically analogous to a single layer urban canopy model of the SLUCM [26]. The SLUCM's urban structure is presumed to be an interminably extended road channel with diverse prearranged assimilations that aids to encompass shadowing, reflections and trapping of radiation [27,28]. The city parameterization of the CLM4.5 is adapted to replicate impacts of the urban surfaces with parameters representing surface characteristics such as air temperature, building roof temperature, building wall temperature, road temperature, sensible heat exchange at reference height, sensible heat flux from the canyon to the atmosphere, sensible heat flux from the wall to the canyon space, sensible heat flux from the road to the canyon space and sensible heat flux from the roof to the atmosphere. Under this parameterization the urban geometry emulates infinitely-long street canyons where shadowing, reflections, and trapping of radiation are considered. The deployed urban parameterization discriminates temperatures of the roofs, walls and roads, and shapes within these structures while adopts an exponential sketch for the winds. Prognostic variables in the parameterization include surface skin temperatures at the roof, wall, and road; that are calculated from the surface energy budget, and temperature profiles within roof, wall and road layers; that are calculated from the thermal conduction equation. Monin-Obuchov similarity theory is deployed for all the surface heat fluxes in the urban canopy model. Moreover a canyon drag coefficient and friction velocity is computed using a similarity stability function for momentum.

3.2. Experimental setup

The experimental setup adopted a single domain centred at 25°N and 68°E and stretched over 110 grid cells of 10km×10km horizontal resolution in each direction (Fig. 1). Although a finer resolution more realistically resolves the atmospheric processes and fine scale features that are associated with terrain, land cover and urban structures, however, adopted 10km resolution for resolving core urban zone of Karachi was deemed satisfactory since for a correct description of circulation impact on moist-thermal conditions of the city located in close proximity to a coastline requires minimal model resolution of at least 6 to 8 grid points within the domain (more than 10 grid points in current adoption (Fig. 2)). Within the framework of such approach, heating effect of the city due to inclusion sources of the heat and other heat physical characteristics of the surface can be simulated with robustness. Vertical resolution of the model was set to 18 levels up to the model's top, which was set at 100 hPa. The static geophysical dataset were based on the United States Geological Survey datasets.

The urban scheme was switched on in the CLM4.5 land-surface scheme of the RegCM4.7. The total friction velocity was aggregated from urban and non-urban surfaces and passed to RegCM's boundary layer scheme. Urban parameters (street canyon width, average building height, roof area, artificial heat) from within the CLM4.5 were then ingested in the RegCM4.7. The CLMU4.5 uses the urban land-use fraction, which is drawn from the 0.05° resolution LandScan2004 data, offering urban ravine factors and surface features [29].

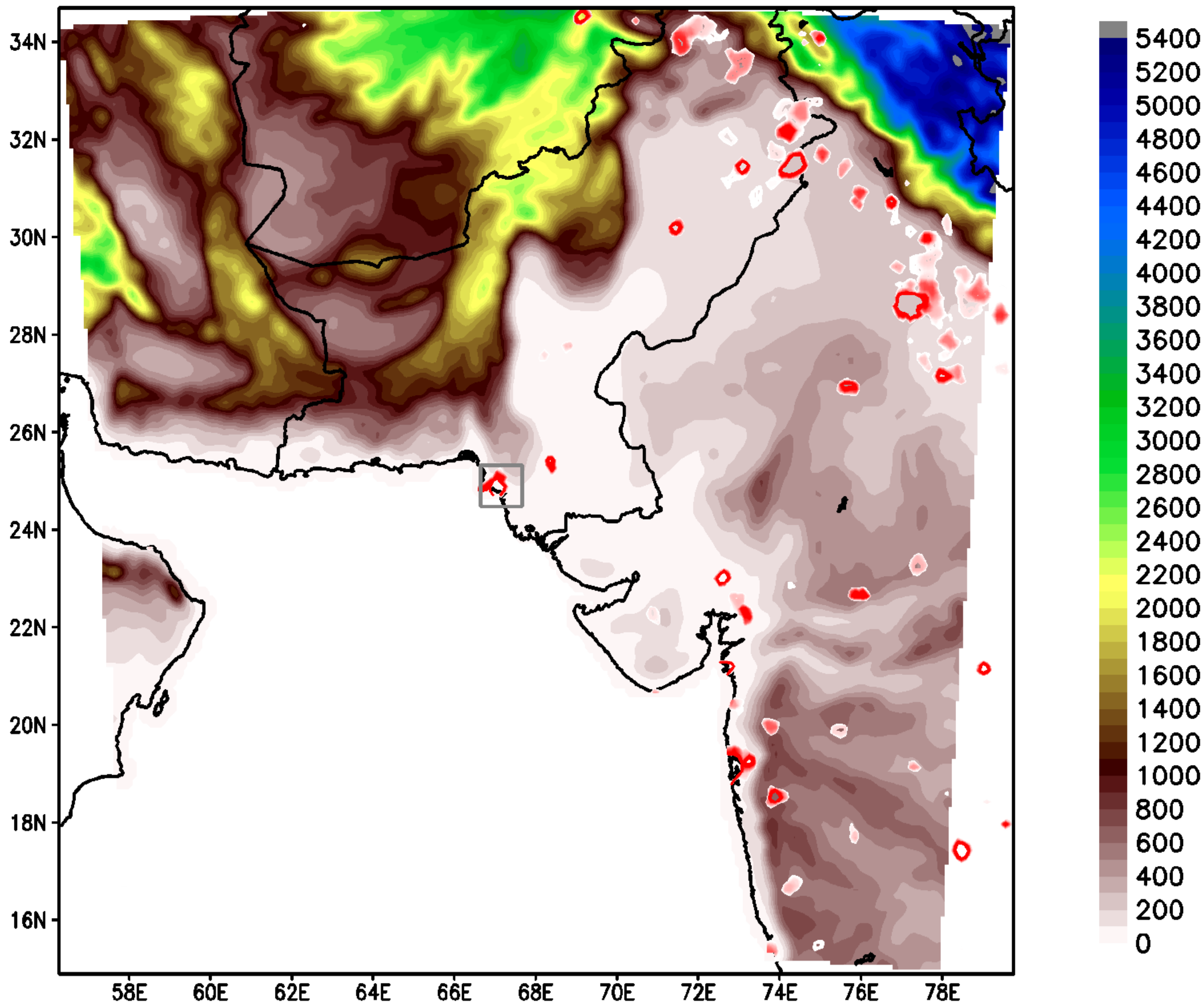

Fig. 1. Grid location in the model domain with model elevation (m) at 10 km resolution. The 2015 heat wave struck metropolitan "Karachi" is featured in grey hollow trapezoid. Below 0 m elevation is the Arabian Sea. Grid contours marked in red shades represent dominant urban land use with population density > 3500 persons/km^2 in the year 2015 (Population data source: Socioeconomic Data and Applications Center (SEDAC, NASA)).

The atmospheric boundary conditions were taken from the ERA-interim reanalysis dataset available at 0.75° resolution from the European Center for Medium Range Weather Forecast [30]. The length of the simulation spanned over 11 days, starting from June 15, 2015 and was performed without nudging. Since heat waves persist and progressively accumulate as a result of depletion in soil moisture (see e.g., Lorenz et al., [31] and Miralles et al., [32]), we used Sentinnel-2 satellite based soil moisture dataset for initialization of the model. The initial soil moisture conditions can modulate heat waves by sensitizing amplitudes, extents and intensities of heat waves [33].

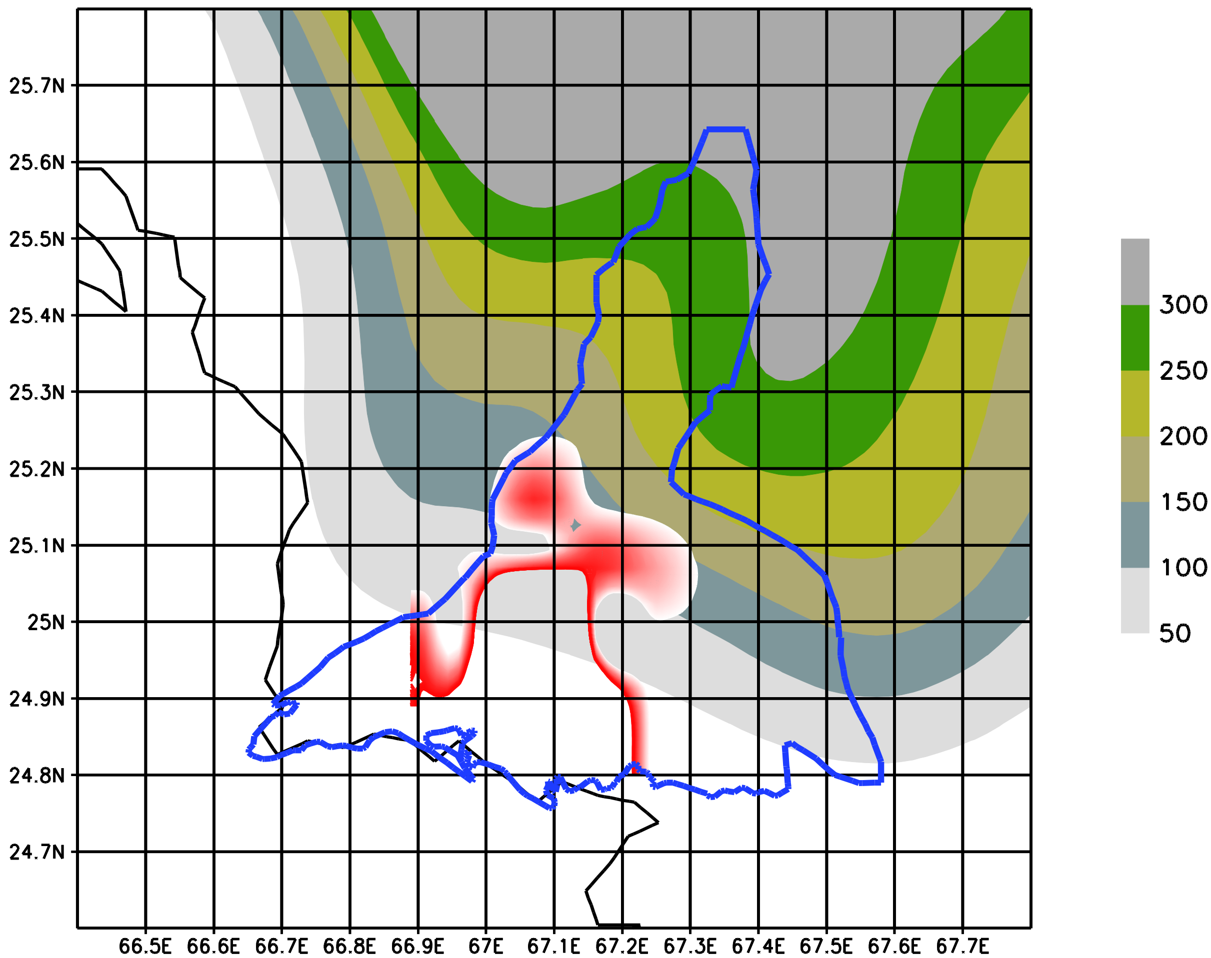

Fig. 2. Karachi city (blue shapefile) located in close proximity to a coastline (black shapefile) satisfying minimal encompassing of at least 6 to 8 grid points within the urbanized domain (shades of red) at 10 kms × 10 kms horizontal resolution (black grid lines). Relief is shown in meters.

3.3. Heat index

Heat index, also identified as the apparent temperature measures degree of heat which is actually sensed when relative humidity is augmented with the actual air temperature. It has significant contemplations for comfort of human body. When the body gets overheated, it prompts perspiration to cool itself off. The body dismisses to control its temperature if the perspiration is unable to evaporate. Evaporation of sweat is a cooling process which effectively decreases the body's temperature. High magnitudes of relative humidity tend to decrease rate of perspiration from the body. In particular sense, the human body senses virtually broiling in humid settings. The contrary holds when the relative humidity drops, since the amount of perspiration escalates. As a matter of fact, the body essentially experiences serener in arid environments.

Through a multiple regression analysis, the air temperature, the relative humidity and the heat index are directly related – the heat index increases (decreases) as the air temperature and the relative humidity increases (decreases). In current settings the heat index temperature is calculated using multiple regression analysis carried out by Lans P. Rothfusz and described in a 1990 National Weather Service (NWS) Technical Attachment (SR 90–23). The regression equation with a ±1.3° Fahrenheit error given by Rothfusz is

$$HI = -42.379 + 2.04901523F + 10.14333127P - 0.22475541FP - 0.00683783F^2 \\ - 0.05481717P^2 + 0.00122874F^2P + 0.00085282FP^2 - 0.00000199F^2P^2$$

where F is temperature in degrees Fahrenheit, P is relative humidity in percent and HI is the heat index expressed as an apparent temperature in degrees Fahrenheit. A full heat index chart derived from the HI for a range of temperatures and relative humidity values may be seen in Table 1.

The chart is interpreted by means of classifying colour coded heat index ranges for their severity in affecting human body. An 80°F–90°F range of heat index is classified as "cautionary" which may fatigue the body under prolonged exposure or physical activity. A class of "Extreme Caution" has a heat index range of 90°F–103°F that can affect the body with heat stroke, heat cramps, or heat exhaustion under prolonged exposure or physical activity. The heat index range of 103°F–124°F is classified as in "Danger Zone" owing to its probable effect of the heat cramps or the heat exhaustion with possibility of the heat stroke under prolonged exposure or physical activity. The heat stroke is highly likely for a heat index value greater than 124°F and is classed as "Extreme Danger" in the NWS proposed ranking.

Table 1
The NWS heat index (°F) chart. (Reproduced from source https://www.weather.gov/safety/heat-index).

	Relative Humidity (%)												
Temperature	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
110	136												
108	130	137											
106	124	130	137										
104	119	124	131	137									
102	114	119	124	130	137								
100	109	114	118	124	129	136							
98	105	109	113	117	123	128	134						
96	101	104	108	112	116	121	126	132					
94	97	100	103	106	110	114	119	124	129	135			
92	94	96	99	101	105	108	112	116	121	126	131		
90	91	93	95	97	100	103	106	109	113	117	122	127	132
88	88	89	91	93	95	98	100	103	106	110	113	117	121
86	85	87	88	89	91	93	95	97	100	102	105	108	112
84	83	84	85	86	88	89	90	92	94	96	98	100	103
82	81	82	83	84	84	85	86	88	89	90	91	93	95
80	80	80	81	81	82	82	83	84	84	85	86	86	87

4. Results

4.1. Surface temperature, mean sea level pressure and winds analysis

As per Pakistan Meteorological Department (PMD) observations, the relentless 2015 heat wave continued for five successive days during 19–23 June-2015. Patterns of progressively increasing magnitude of temperature at 12Z hrs of the subject heat wave event is well captured by the RegCM4.7 as seen in the simulated results (Fig. 3). Owing to high resolution UHI attributes (building structures, roof tops, asphalt roads, air-conditioning, waste heat etc.), near to precise heat exchange from surface to near-surface atmosphere can be well seen in the post processed output of the RegCM4.7. According to the PMD records, the daily temperature anomalies for the episode were more than 5°C for five consecutive days and the departure of maximum temperature from the normal stretched amidst 5.3 to 11ºC for the duration of austere heat wave [34]. This incessant phase of very warm conditions was formed in extents of South Pakistan through the second fortnight of June-2015. Environment grew predominantly life-threatening in the course of 19–23 June-2015, once apex heat echelons became intolerable. On these specific days, in-situ measurements recorded air temperature greater than 44°C for two consecutive days [22]. Post processed output of the RegCM4.7 simulation has shown that the surface temperature maxima for the episode is well above 50°C for at least three consecutive days along the duration of the austere heat wave (surface temperature would overwhelm air temperature by a few degrees). Yasmeen et al., [1] also found that land surface temperature persisted between a range of 44 to 53°C along the 2015 heat wave episode and that the reason for such extremity was greater heat storage of urban surfaces during sunny and very warm summer days attributed to specific thermal properties (i.e. heat capacity and conductivity) of man-made materials. Post simulated results demonstrate the UHI effect on the peak heat wave days featuring surface temperature to get 9°C warmer than its rural surroundings.

What is seen phenomenal during the episode is that there is no relief in terms of drifting coastal winds during the period over which the afternoon temperatures are also high; rendering pattern of hot weather to persist for a number of days resulting in the heat wave. Post-simulated results show that 12Z in Karachi during 19–21 June-2015 display an atypical wind magnitude from Arabian Sea into the target region. Form 17 June-2015 onwards till 22 June-2015, moisture laden winds are seen to weaken from the Arabian Sea at 12Z local time. Overextended persistence of a moist ocean depression in vicinity of Karachi coast is further seen to reduce moisture transport in the simulated results. Owing to existence of the depression, ventilating winds towards Karachi are seen to get blocked during 19–21 June, 2015. Weather modalities driving the heat wave are seen to integrate an unremitting air depression over the Arabian Sea that allegedly halts the entering sea breeze to the metropolitan city with clear skies further aggravating the condition by getting the air warmer and stalled over the region for several days. Ultimate weakening of low pressure system at 12Z afternoon of June 24–25 is seen over the Arabian Sea rendering normal moisture flux over the coast.

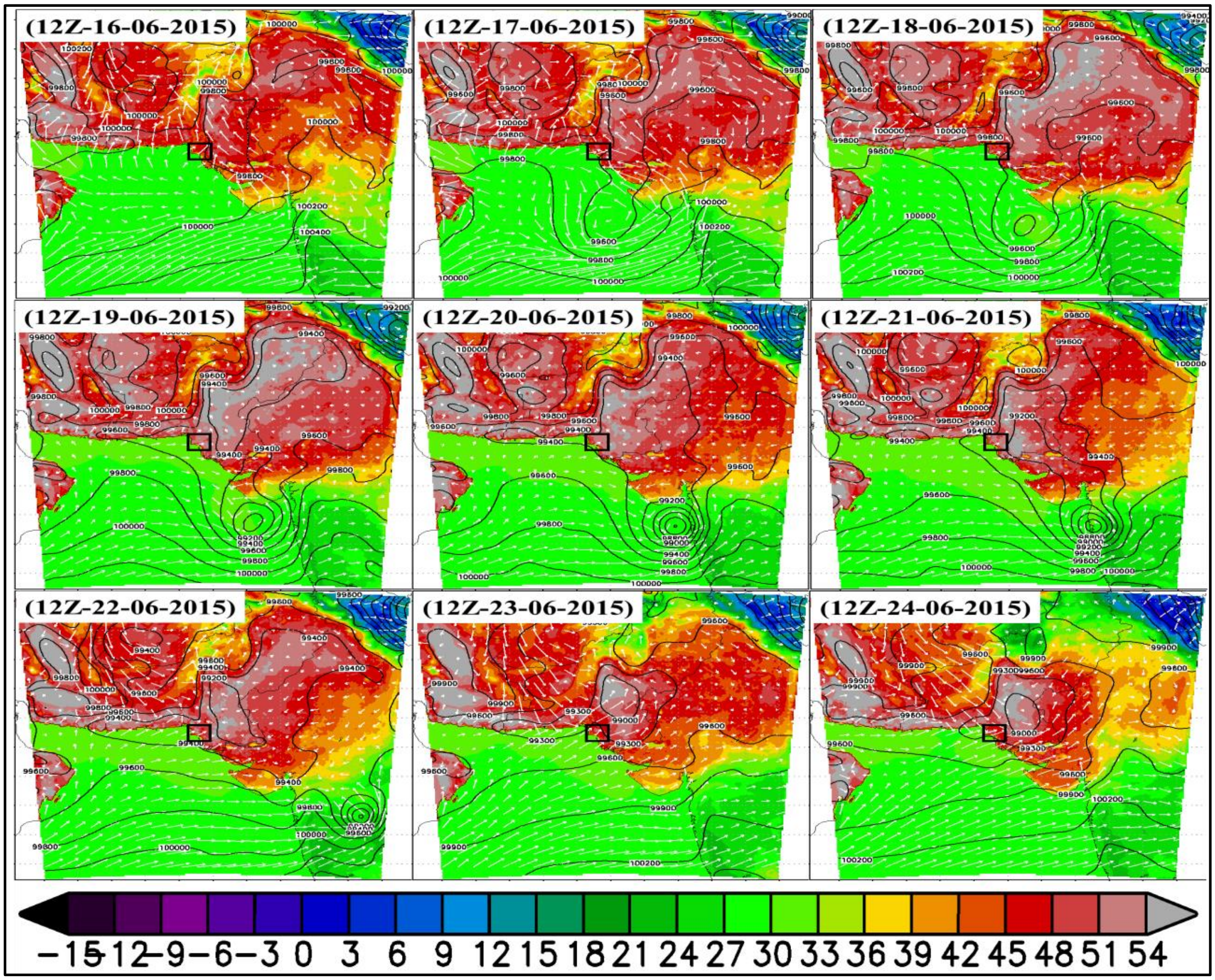

Fig. 3. Twenty four hour time-lapse analysis of UHI triggered surface temperature (°C), mean sea level pressure (hPa) and horizontal winds (m/s) in RegCM4.7. The 2015 heat wave conditions are reproduced for pre-heat wave conditions (top panels), amidst heat wave conditions (centre panels), and post-heat wave conditions (bottom panels).

4.2. Heat index analysis

Owing to dynamic effect of humidity it is seen that there is large spatial variability in heat index values across the city due to coastal influence of Karachi, which has led to a higher heat index in areas adjacent to coast than in inland areas (Fig 4). Moreover, owing to already assessed UHI triggered temperature field, heat index values are seen to be higher in the urban zones than in the suburban ones. It is significant to note that our calculated heat index is seen to remain well above 124°F during the whole heat wave period. It is further seen to aggravate by up to 151°F and to 137°F on 20th June-2015 and 22nd June-2015, respectively, that would have put Karachi in the "Extreme Danger" zone with high probability of heat stroke as per the NWS classification. Magnitude and extent of the heat index dropped on 23rd June-2015 and onwards which may be elucidated by regeneration of normal sea breeze which is presumed to significantly drop down magnitude of the actual temperature. Effect of the apparent temperature is eventually seen to subside on 24th of June-2015 in the target coastline. The magnitude and extent of the post processed heat index is thus seen in agreement with the observations analysed by Chaudhry et al.,[22], Zeenat et al., [1] and Hanif [34].

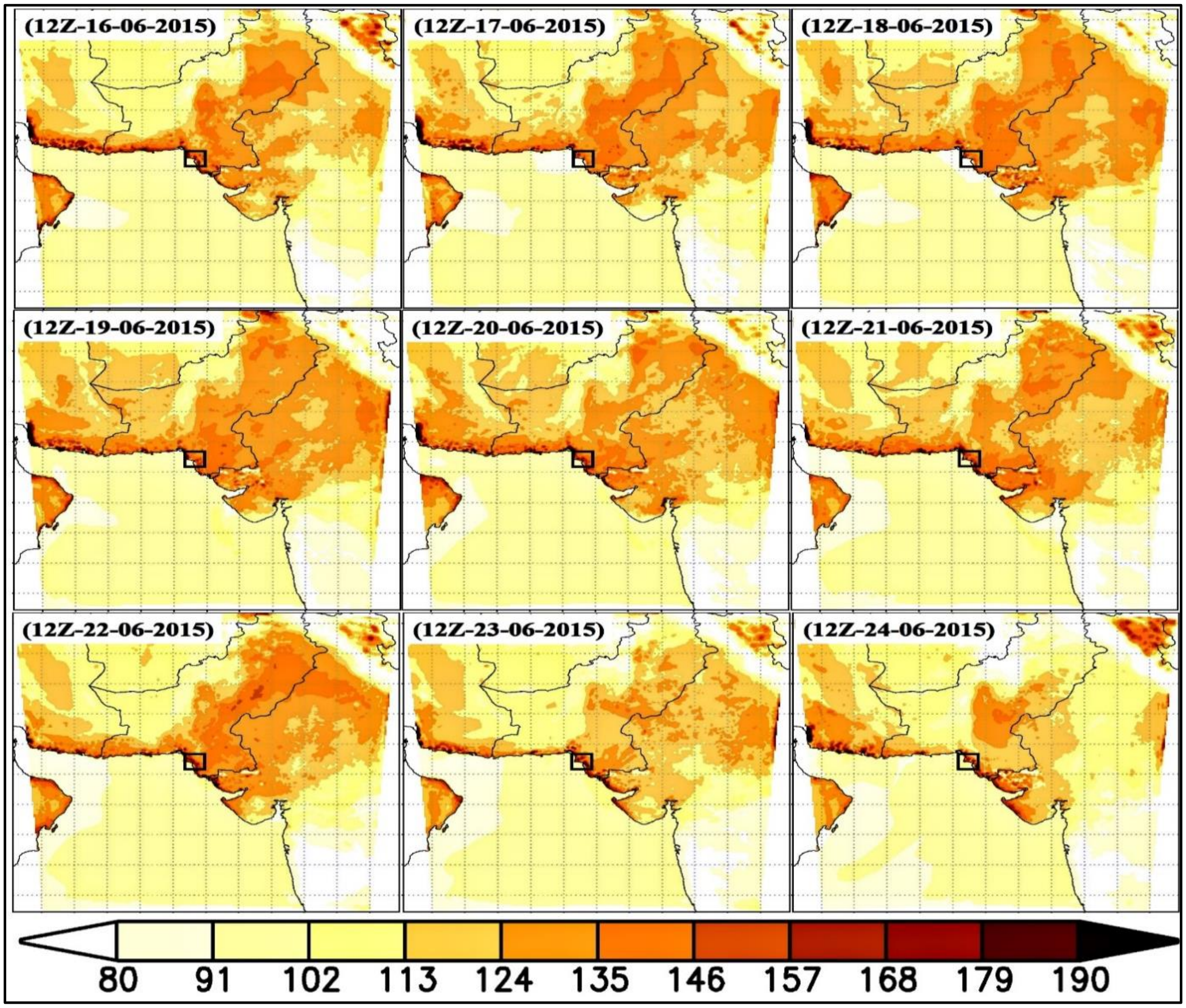

Fig. 4. Same as in Figure 3 but for the NWS based heat index (°F).

5. Discussion

As cited earlier in this paper, surrounding wind was varied considerably by urban tops. In the pre-heat wave conditions, simulated results presented near to normal wind patterns and magnitude over the coast from the Arabian Sea. Atmospheric settings were seen to go out of the ordinary as a ridge (extension of high pressure area) was seen to protract over Southwest coast and contiguous zones of the country embracing mega infra-structure of Karachi. The pattern of this ridge was seen to deplete sea breeze over the coast from the Arabian Sea. The ridge was seen to further galvanize and displace more into south and eastward extents of the coast in the following days. A cyclonic system was seen to advance over the eastern side of the Sea on June 18, 2015 which initially converged into a depression and afterwards weakened into a low pressure system. Extended subsistence of that low pressure system in the locality of the Karachi shoreline was seen to restrain normal drift of sea-breeze on to the coast. Replication of surface temperature, mean sea level pressure and winds by incorporating the UHI feature in the RegCM4.7 along the heat wave episode was thus seen exemplary in terms of precision.

6. Conclusions

The UHI effect is augmented in the RegCM4.7 for nearest possible emulation of the atmosphere for the 2015 heat wave event in mega-urban structure of Karachi, Pakistan. With a subtle horizontal resolution of 10 km × 10 km grids, the targeted terrain, the land cover and the urban structures are seen to resolve with ample attributes. The UHI forced anomalous surface and atmospheric conditions of the temperature and wind are seen to trigger the severe heat wave in the metropolitan city, Karachi. The NWS based heat index which augments the relative humidity with the actual air temperature and contemplates for comfort of human body left Karachi in the "Extreme Danger" zone with high probability of heat stroke. The simulation of the 2015 heat wave with the UHI augmented RegCM4.7 has provided intricacy in identification of subject atmospheric drivers, and is seen to emulate the heat wave episode with ample confidence.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution statement

Shaukat Ali, Shabehul Hasson and Tahir Khan: Conceptualization; Shabehul Hasson: Data curation; Burhan Ahmad: Formal analysis; Burhan Ahmad: Investigation; Shabehul Hasson: Methodology; Shaukat Ali: Project administration; Shaukat Ali: Resources; Shabehul Hasson: Software; Shaukat Ali: Supervision; Burhan Ahmad and Syed Ahsan Ali Bukhari: Validation; FA, Burhan Ahmad and Syed Ahsan Ali Bukhari: Visualization; Burhan Ahmad: Roles/Writing – original draft; Burhan Ahmad and Shabehul Hasson: Writing – review & editing.

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