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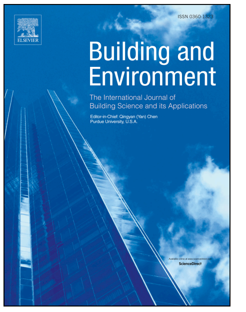

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Spatial Analytical Methods for Deriving a Historical Map of Physiological Equivalent Temperature of Hong Kong

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Abstract

Physiological Equivalent Temperature (PET) has been widely used as an indicator for impacts of climate change on thermal comfort of humans. The effects of thermal stress are often examined using longitudinal observational studies over many years. A major problem in retrospective versus prospective studies is that it is not feasible to go back in time to measure historical data not collected in the past. These data must be reconstructed for the baseline period to enable comparative analysis of change and its human impact. This paper describes a systematic method for constructing a PET map using spatial analytical procedures. The procedures involve estimating PET values (based on the RayMan model and four key parameters of temperature, relative humidity, wind velocity, and mean radiant temperature) at a spatially disaggregated level comprising of a grid of 100 m × 100 m cells. The method can be applied to other geographic locations pending availability of basic meteorological and morphological data of the locations.

Keywords

Physiological Equivalent Temperature; PET; thermal comfort; spatial analysis; RayMan model;

Hong Kong

1. Introduction

The world is warming up and there is increasing worldwide concern about the potential health effects of climate change. Thermal stress, or the conditions of cold and hot temperatures beyond the normal comfort range, has been the subject of much research due largely to more frequent occurrences of heat waves and cold spells in high-latitude regions [1]. Human response to the thermal environment is affected by local environmental variables (notably air temperature, radiant temperature, humidity, and air movement) as well as the clothing worn and activity engaged at the time [2, 3]. An environment that is too hot, too cold, or just right can affect human comfort and wellbeing because an individual must undergo thermoregulatory physiological changes to adapt to the environment and maintain an internal body temperature of around 37 °C [4]. Long-term exposure to heat or cold can lead to serious health risks or death when the body cannot sustain thermoregulatory function.

The Physiological Equivalent Temperature (PET) is a thermal index derived from the heat-balance model of a human body [5]. It is a personal and geographic event that does not remain constant over space and time. The RayMan model [6, 7] simulates short- and long-wave radiation fluxes from a three-dimensional surrounding in simple and complex environments that can be transferred into a synthetic parameter, also called the mean radiant temperature (Tmrt). By supplying air temperature (Ta), relative humidity (RH), wind velocity (WV) and Tmrt, PET derived from the RayMan model is considered the same as that calculated using the PET Fortran programme by Höppe [5, 8]. To facilitate studies of long-term health effects on thermal stress, spatially defined data must be available to record signs of prolonged heat stress (as reflected through time-series PET) and health responses of individuals (as measured by tracking subjects over time). To create a map of PET which can account for thermal comfort conditions over a geographic extent, spatial analysis is essential to assemble individual PET values at respective neighborhoods to create a generalized surface representation [9]. For example, a PET value can be assigned to a neighborhood measuring 100 m × 100 m. A map of PET over a geographic space will thus comprise of a collection of grid cells of a uniform size, each with a PET value.

To date, there have been numerous health effect studies on thermal stress but the majority has focused on short-term exposure [10]. It is difficult to assess effects of long-term exposure to thermal stress in a longitudinal cohort study partly because of confounding problems of acclimatization and also because it is not feasible to obtain historical data on environmental conditions to afford comparative analysis of changes. This paper presents a methodology to derive historical maps of PET distribution through retrospective space-time analysis by integrating time-sensitive environmental data and spatial analytical methods.

2. Study Area and Method

2.1. Study Area

The study area is the Hong Kong Special Administrative Region, which is situated east of the Pearl River Estuary. Hong Kong measures 1,104 square kilometers in size and had a population of over 7.2 million in mid-2014 [11]. A cohort of elderly people was first enrolled to the 18 elderly health centers of the Department of Health in 1998 – 2001 until the present time [12, 13]. The spatial distribution of this cohort of 66,820 persons (61,588 after data cleaning and taking account of geocoding errors, missing data, and repeat/overlapping addresses) spans across Hong Kong which dictates a spatial approach to health effect studies (Figure 1).

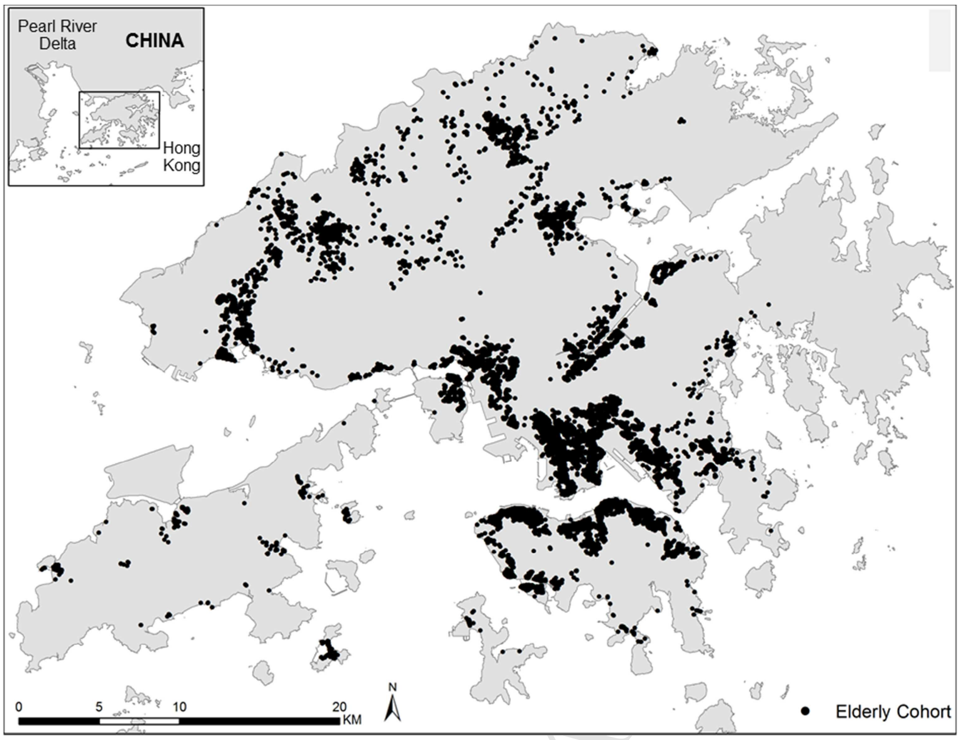

Figure 1: A map of Hong Kong showing the geographic distribution of the elderly cohort

2.2. Environmental Data

Various kinds of environmental data have been collected by the government of Hong Kong. The Hong Kong Observatory (HKO) has established meteorological monitoring stations to collect air temperature, relative humidity, wind, and cloud cover data for many years. The number of meteorological monitoring stations has increased from about 20 in early 1900s to over 40 in recent years. Each monitoring station has a coordinate to enable spatial interpolation of point-based readings into a surface map of continuous measurements with varied degrees of spatial accuracy. WV data at reference heights are available from the Institute for the Environment at the Hong Kong University of Science and Technology (http://envf.ust.hk/). The simulated WV data were processed at high resolution using the MM5/CALMET system [14]. Similarly, the Survey and Mapping Office of the Lands Department has maintained a series of digital land records of Hong Kong at various map scales (1:1000, 1:5000, 1:10000, and 1:20000) as well as digital ortho-photographs (1:5000). These digital data include building footprints with years of construction and height, contour elevation, road networks, coastlines, and other data.

Of particular interest to this study is the Urban Climate Analysis Map (UC-AnMap) of Hong Kong from the Hong Kong Planning Department. The UC-AnMap was established in 2009 and has a spatial resolution of 100 m × 100 m. It measures outdoor microclimatic conditions considering the combined effects of buildings, open spaces, natural landscape, topography, and wind conditions to imply the comfort sensation of people in outdoor spaces. This UC-AnMap (Figure 2) conveys typical climate conditions in the hot and humid summer months of Hong Kong (June, July and August 2008) and can serve as an "accepted" representation of summer PET conditions in Hong Kong as verified from field measurements indicating a strong relationship ($R^2 \approx 0.74$) between the UC-AnMap classes and PET values [15].

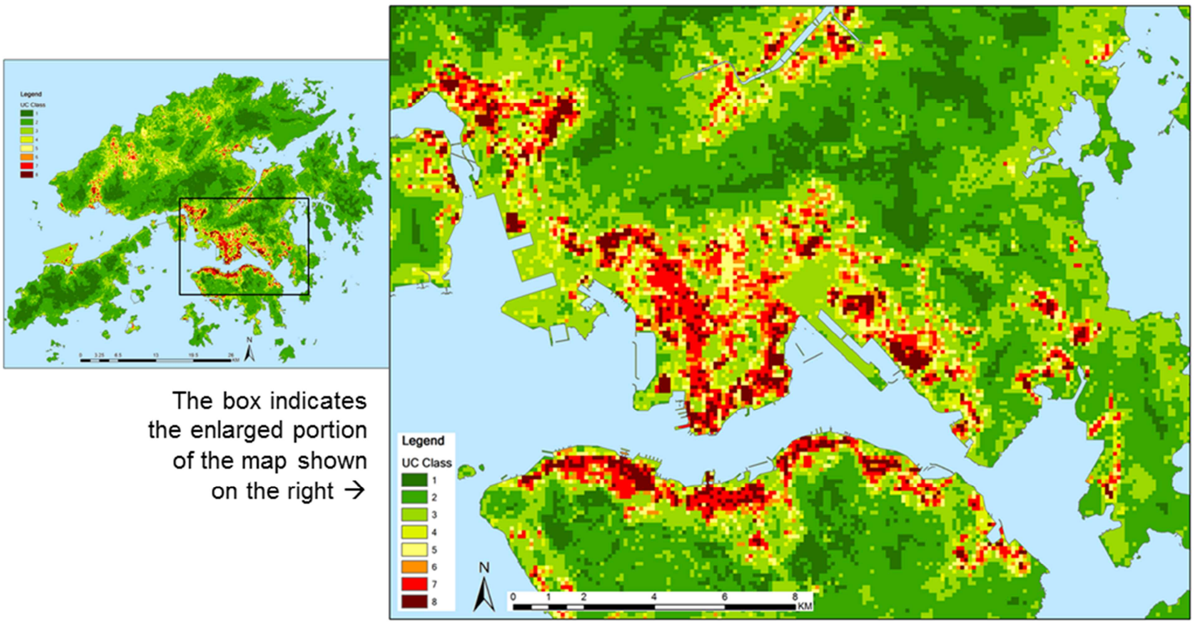

Figure 2: UC-AnMap showing climate zones of Hong Kong. Source: Hong Kong Planning Department.

Moreover, satellite images of Hong Kong can be sourced from international organizations. For example, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imagery is available from the U.S. National Aeronautics and Space Administration Terra satellite since 2000 and current Landsat 5, 7, 8 satellite imageries can be acquired from the U.S. Geological Survey.

2.3. Computing Physiological Equivalent Temperature (PET)

The RayMan Pro model [6, 7] was used to calculate PET values. Although the average height of males in Hong Kong is 1.72 m [16], a recent study based on Chinese adults [2] on the effects of height on mean skin temperature showed a difference of less than 0.2 °C between men measuring 1.72 m and 1.75 m in height. This slight difference in skin temperature should not pose significant impact on human thermoregulation. Therefore, this study adopted the default personal values used in a recent study on thermal comfort in Hong Kong [3]: male, 35 years old, 1.75 m in height, 75 kg in weight, indoor clothing (0.9 clo), light activity (80 W), and in a standing position (Figure 3). Here, "0.9 clo" represents heat resistance of clothing in a typical indoor setting and "80 W" represents a human body with work metabolism of light activity added to basic metabolism. Locational and personal factors aside, it can be seen from Figure 3 that PET is influenced by sun paths and local environmental conditions that include microclimate factors in a complex urban structure. By supplying different values for Ta, RH, WV, and Tmrt while keeping the rest of the parameters the same, PET values for all neighborhoods in Hong Kong can be derived. The procedures to derive input parameters of Ta, RH, WV, and Tmrt by spatial analysis method are described in the next section.

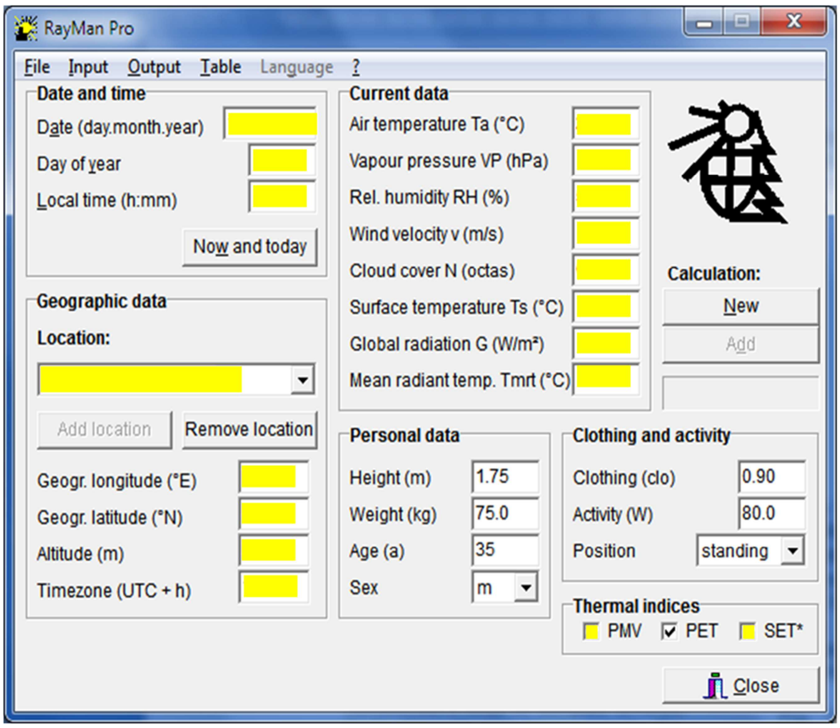

Figure 3: RayMan Pro and its controlling parameters. Source: http://www.mif.uni-freiburg.de/rayman/intro.htm

2.4. Spatial Analytics

Past meteorological data from the HKO are not of sufficient detail to account for the complex terrain and dense urban morphology of Hong Kong. We propose a spatial approach that integrates geographic information system (GIS) and remote sensing (RS) processing to derive the needed parameters (Figure 4). It can be seen that the calculation of PET requires Ta, RH, WV, Tmrt, and cloud cover. As HKO reports only the mean cloud cover percentage for each day, PET will be computed by assuming the same cloud cover value for all locations. The Ta surface is estimated from ASTER nighttime images [17] while the RH surface is generated by means of spatial interpolation. WV near the ground level and Tmrt needs more computational efforts as described below. The next section describes ways to estimate values of Ta, RH, WV, and Tmrt at 100m spatial resolution [see also 18] using spatial analysis methods. For illustrative purposes, we will demonstrate a typical PET map for the warm season in 2008.

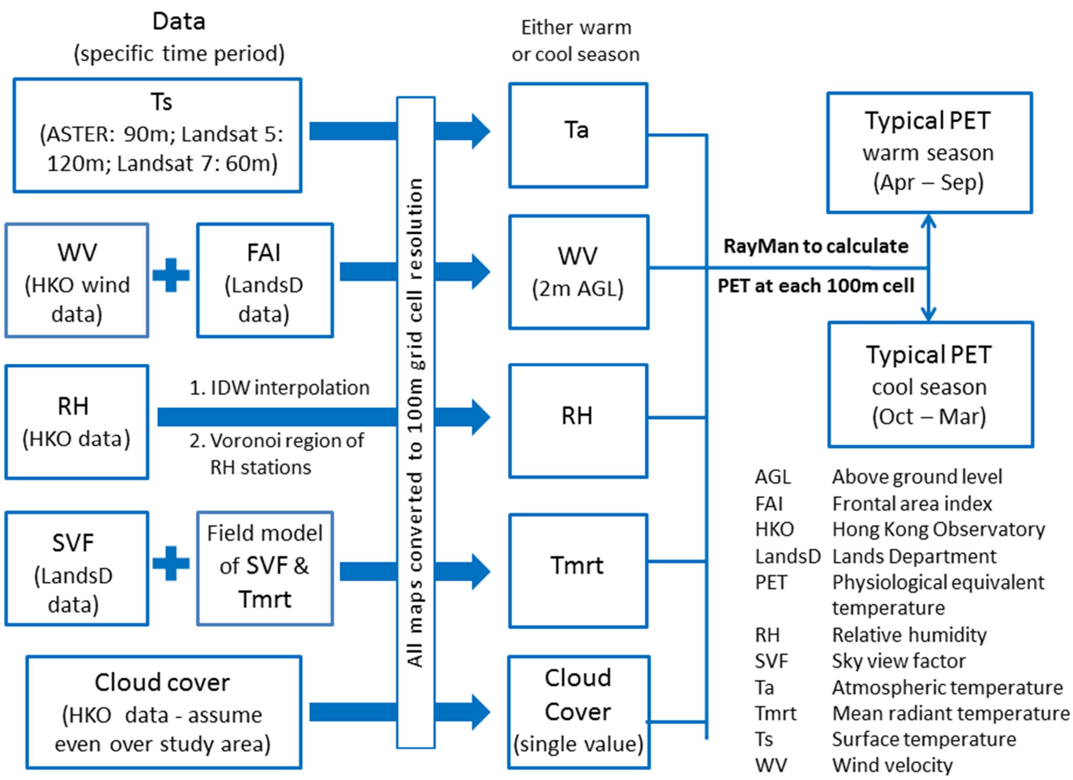

Figure 4: Spatial processing steps to deriving a map of thermal stress exposure

2.4.1. Air Temperature (Ta)

The Ta surface can be estimated from ASTER or LANDSAT images for a selected time period, pending availability, and adjusted using the hourly Ta data from the HKO following the method described in Nichol & To [19]. Noting that daily meteorological data do vary spatially and temporally, it is important to select a typical day in the summer/warm (April – September) or winter/cool (October – March) months and compute the daily averages to represent typical readings in different seasons [20, 21]. Moreover, it is also difficult to get a satellite image that is totally cloud free for each season [22, 23]. It may also be necessary to merge adjacent images from different days to provide a complete coverage of the study area.

2.4.2. Relative Humidity (RH)

RH values are monitored by weather monitoring stations managed by the HKO (http://www.hko.gov.hk/cis/annex/hkwxstn_e.htm). The average RH values at each monitoring station for a selected time period can be transformed into a continuous surface representation through spatial interpolation. Given the interrupted landscape of Hong Kong comprising of islands, the inverse distance weighted method is selected for the spatial interpolation [24]. Moreover, the extent of the interpolated surface is constrained within the Voronoi region [25] and excluding the peripheral regions of Hong Kong. This constraint has little effect on our cohort study (Figure 1) as the majority of subjects lie within the Voronoi region.

2.4.3. Wind Velocity (WV)

It has been noticed that low horizontal wind speeds are usually associated with high surface roughness caused by a high density of built structures [26]. The WV surface at 2 m above the ground level can be estimated by a map of Ground Coverage Ratio (GCR) derived from building footprints. GCR is highly correlated with the WV ratio which is defined as the ratio of mean WV at the pedestrian level to a reference height [27, 28]. It has been suggested as a good indicator for the 3D roughness of an urban area, and can be further adjusted using the hourly wind data available from the HKO. The estimation can be done at 100m spatial resolution using building data of a selected time period available from the Lands Department and applying the method proposed by Wong & Nichol [29].

2.4.4. Mean Radiant Temperature (Tmrt)

Tmrt, defined as the "uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure" [30], is a complex variable which is affected by location, cloudiness and urban morphology. Tmrt has been investigated and measured by field methods mostly in high-latitude cities [31, 32]. It has been asserted that the spatial difference of Tmrt, which is highly correlated to urban morphology, can be estimated using the sky view factor (SVF) measured at the ground level [33, 34]. SVF is an indicator showing the relationship between built density, urban block typology, and sky exposure at a location. Tmrt can be measured using a black-globe thermometer to derive field measurements at representative locations over a specific time range [35]. These Tmrt measurements are correlated against the corresponding SVF to yield a generalized model calibrated to the local climate [15, 36] which can be used to derive the Tmrt surface.

3. Results

Figure 5 displays mapped surfaces of the above processes (with Kowloon enlarged to show detail). Each step yields a map surface of parameters needed for the PET calculation. The Ta map (Figure 5a) shows higher temperatures in urbanized Kowloon and built- up areas along the northern coast of the Hong Kong Island. Cooler areas colored in blue correspond to locations of country parks and open areas. This pattern agrees with the general understanding that natural surfaces tend to be cooler than artificial surfaces. The RH map (Figure 5b) is mechanistically looking because the surface was generated by automated means based on sparsely distributed weather monitoring stations. Even though the map looks simplistic, the general pattern does conform to our common understanding that vegetated areas have higher humidity compared to built-up areas. As for the WV map (Figure 5c), it suffices to say that wind speeds are slower in the densely urbanized parts of Kowloon and Hong Kong Island with many buildings. The Tmrt map (Figure 5d) shows higher Tmrt in open areas without buildings. Studies have indicated that Tmrt tends to be lowest in the densest urban environments due to shadowing [37].

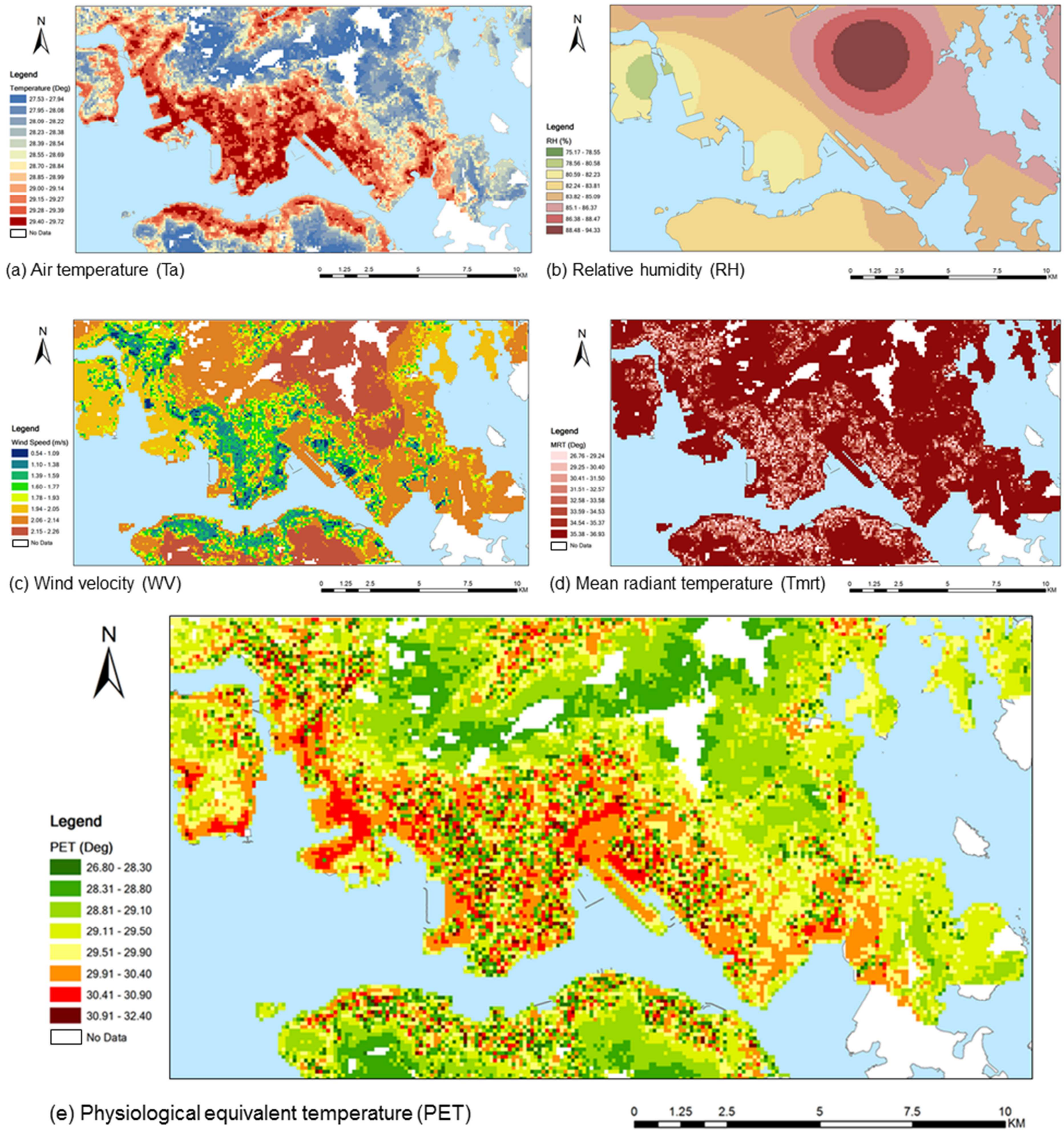

Figure 5: Results of interim maps and the final map of thermal stress exposure

The resultant PET map (Figure 5e) reveals an image that visually resembles the UC-AnMap (Figure 2) although more blotchy in appearance. This may be due to more detailed variables involved in the PET computation that amplifies differences between neighboring cells. Table 1 summarizes the relationship between the UC-AnMap and the resultant maps. Although not a strong positive relationship, the PET map is in general agreement with the UC-AnMap. The UC-AnMap is correlated with all four parameters, showing a strong positive relationship with Ta and negative relationships with the others (i.e., RH, WV, and Tmrt). Figure 6 is a plot of the PET values against field measurements taken on 15 May 2008 from the UC-AnMap study [15]. The plot suggests that the derived PET values, which were meant for the warm season in 2008, corresponded rather well with those measured in the field at select locations in Tsuen Wan, a small neighborhood in Hong Kong (R^2 = 0.5251). It is unfortunate that more extensive field verification is not possible because other field measurements reported in the study were not for the summer season [15].

Table 1 Correlation coefficients between UC-AnMap and PET-related variables

Correlation	Physiological equivalent temperature (PET)	Air temperature (Ta)	Relative humidity (RH)	Wind velocity (WV)	Mean radiant temperature (Tmrt)
UC-AnMap Urban Climate Analysis Map	0.23	0.70	-0.29	-0.90	-0.67

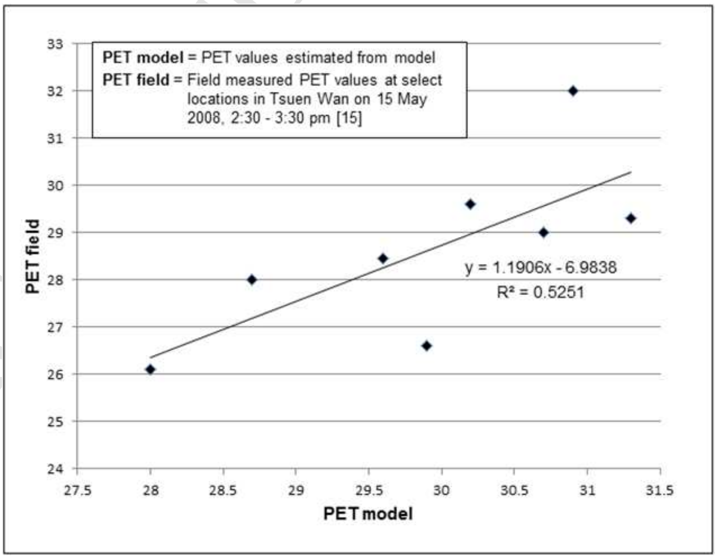

Figure 6: Correlation between computed versus field measured PET at select locations.

4. Discussion and Conclusion

The fact that PET and UC-AnMap are correlated, even though not highly, may indicate that they measure similar factors attributing to thermal stress. Results indicated in Table 1 above show that three of four factors (i.e., WV, Ta, Tmrt) have very strong correlation with the UC-AnMap. The three climatic analytical aspects for constructing the UC-AnMap included the followings: (i) wind ventilation capturing local air circulation patterns, (ii) thermal environment focusing on urban heat island effect, and (iii) areas of air pollution [15]. Although created based on objectively and empirically collected data, the UC-AnMap is a synthetic outcome for planning purposes because it also relies on expert and qualitative assessment of urban climatologists. In this regard, the whole procedure and evaluation methods are not truly standardized as they involved balancing and weighing many non-quantifiable aspects to arrive at a generalized view of the urban thermal environment. All things being equal, our PET map can discriminate thermal comfort conditions strictly from well-established mathematical procedures [5 – 8] without subjective manipulation.

It is difficult to justify whether the resultant PET map (Figure 5e) is truly reflective of the real thermal comfort conditions because the parameters were derivative from secondary procedures. The estimation of Tmrt, for example, can be further improved by establishing a stronger relationship between SVF and Tmrt through better choice of monitoring sites with specific morphological features [38, 39]. Unfortunately, the estimation of RH could not be improved given the limited and fixed number of meteorological stations in Hong Kong. It should also be noted that the resultant PET map is not continuous because the Ta map (Figure 5a) was derived from an ASTER image that was not totally cloud free. Here, the no-data cells did not affect subsequent health impact analysis because no cohort subjects lived in these locations. Thus, it is important that cohort locations must be accounted for in the selection of satellite images.

This paper presents a methodology to construct high-resolution maps representing thermal stress exposure in a city with complicated urban environment. It has demonstrated feasibility of the approach that is repeatable because satellite imagery is a ubiquitous resource accessible to all places on the Earth's surface and other data requirements can be satisfied easily. Provided that there is sufficient weather monitoring stations to cover a selected study area, PET maps can be created for different time periods based on local meteorological data on temperature, relative humidity, wind, and cloud cover. The method not only accounts for changes in local meteorological conditions but also the urban morphology as reflected through the building data. The changing patterns of urban constructs, if captured in digital representation, will enable the creation of PET surfaces of different time periods for comparative analysis.

A cohort study involving follow-up or longitudinal analysis is a research study for the detection of association between within-person change and the thermal stress exposure in this case in different geographic areas over a long period of time. It may not be possible to undertake certain exposure measurements, especially for the baseline period in the past and subsequent time in the future. This paper presents a methodology that makes use of available data and existing techniques to derive the data needed for the analysis. With increasingly dense built-up cities, planners and health practitioners are paying more attention to thermal comfort for urban residents. The proposed method can also model robust estimates of human thermal comfort in the future by considering consequences brought by global climate change and the more compact urban form.

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- Planners & health practitioners are paying more attention to human thermal comfort
- A method to construct a map of Physiological Equivalent Temperature was described
- Remote sensing and GIS were used to estimate parameters of PET
- PET map was validated against the Urban Climate Analysis Map of comfort sensation
- Proposed method can model long-term thermal exposure in a longitudinal cohort study