Impact of climate change and socioeconomic factors on domestic energy consumption: the case of Hong Kong and Singapore

Abstract

Temperature and population growth are key drivers of energy consumption. However, the relative importance of climatic and socioeconomic factors driving energy consumption at different temporal scales is not well-understood. Therefore, we developed a time-series decomposition method to attribute the relative importance of climatic (heat index and monsoon index) and socioeconomic variables to domestic energy consumption in Hong Kong from 1981 – 2015. The same method was used for Singapore from 2005 – 2015 to test the transferability of our time-series method. Population growth and GDP were the primary drivers for domestic energy consumption in Hong Kong from 1981 – 2015, but the heat index became the primary driver from 2005 –2015 instead. The monsoon and heat indexes were the primary drivers of domestic energy consumption in Singapore from 2005 – 2015. Climate change will increase air temperatures by 2 – 5 °C for Hong Kong and Singapore by 2100. For RCP4.5 and RCP8.5 scenarios, Singapore shows a linear relationship between temperature and domestic energy consumption, whereas the relationship is non-linear in Hong Kong. Our findings highlight the importance of understanding the impact of climatic change on monsoon mechanism and heat index, which can predict future cooling demand and help achieve sustainable development goals.

Keywords

Energy consumption; climate change; heat index; monsoon index; population change; relative importance analysis

1 Introduction

Identifying the drivers of building energy consumption trends and the influence of climate change on this trend are crucial for sustainable development. Urban energy consumption increases rapidly because of population growth, urbanization, and technological change in indoor environment management, especially space conditioning (Allouhi et al., 2015). Understanding the relationship between climate change and building energy consumption is critical to achieving the Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action), both of which are interlinked (Bleischwitz et al., 2018; Fuso Nerini et al., 2019; Taylor et al., 2017). In particular, climate impact drivers would affect the ecosystem and socio-economic sectors and subsequently influences the achievement of various SDG targets (Fuldauer et al., 2022; Liu and Patricia, 2019). SDG 7 targets environmental and social sustainability (Bain et al., 2019), whereas SDG 13 involves the environmental and energy sectors (Pandey and Asif, 2022). Both synergies (Cohen et al., 2021; Zhang et al., 2022) and trade-offs (Griggs et al., 2014) exist between SDG 7 and SDG 13 (Fuso Nerini et al., 2018; Sachs et al., 2019; Yalew et al., 2020). Appropriate government policies would turn these trade-offs into synergies (Kroll et al., 2019), which can achieve environmental, social and economic sustainability (Danish et al., 2020).

Meeting the increasing cooling demand associated with climate change threatens the progress toward SDG 7 and SDG 13, which depends on the extent of urbanization, population growth and economic development (Khosla et al., 2021). Understanding the future energy demand would help society transit to a low-demand scenario (Grubler et al., 2018). Moreover, it is critical to understand the main drivers of energy use, which is key to achieving SDG 7 (Zaharia et al., 2019) and mitigating climate change impact (SDG 13) (Sarkodie, 2022). For example, the interaction between climate action (SDG 13) and energy use is affected by socioeconomic conditions, as well as demographic, societal and technological development (Liu et al., 2020a). In the SDG literature, other key drivers of energy consumption include population growth, GDP, energy price and climate variables (González-Torres et al., 2022; Martins et al., 2022). These drivers of energy consumption are the main variables examined in this study.

In terms of climatic variables, some studies used past climate change to indicate the impact of climate on energy use (Lam et al., 2004; Meng et al., 2018; Morakinyo et al., 2019; To and Lee, 2017; Zhang et al., 2019). Haines et al. (2006) reveal that there has been an increasing trend of heatwaves, which also have significant impacts on energy consumption (Añel et al., 2017). Urban heat islands and climate change contribute to high energy consumption in cities during summer, leading to urban overheating risks (Hamdy et al., 2017; Pisello et al., 2018; Santamouris, 2020). This unprecedented rise in energy consumption has important implications for global efforts to reduce greenhouse gas emissions (Gielen et al., 2016; Hoffert et al., 2002; Williams et al., 2012). This issue has become pressing in light of the 2015 Paris Agreement (Tollefson, 2019), SDG targets (Danish et al., 2020; Soergel et al., 2021), and ongoing urban population growth (Khosla et al., 2021).

Population, in terms of size and structure, is a key indicator of resource usage and energy consumption (Son and Kim, 2017). A larger population means atmospheric conditions have a greater influence on electricity demand (Auffhammer and Aroonruengsawat, 2011). Furthermore, higher population density could reduce energy use (Liu et al., 2015). The aging population can result in both an increase (Brounen et al., 2012; Yu et al., 2018) or a decrease in household energy consumption (Garau et al., 2013) due to variations in consumption patterns such as time spent on domestic energy service (Yu et al., 2018). Indeed, personal decisions on energy use and purchasing electrical appliances would likely affect household consumption patterns (Stern et al., 2016). The relationship between socioeconomic and climatic variables can explain past energy consumption trends, which vary in regions with different climate zones, populations and GDP levels (Duan et al., 2022).

Apart from changes in population structure, outdoor temperature shows the most direct relationship to energy consumption (Fung et al., 2006) because of the amount of energy spent in conditioning the indoor physical environment of buildings (Allouhi et al., 2015; Hekkenberg et al., 2009), including cooling in summer and heating in winter (Ihara et al., 2008). For example, cooling degree days increase with hot temperatures in Italy, but no significant trend is observed for heating degree days (Scapin et al., 2016). Unlike Italian cities, the response to changes in heating degree days differs between Northern and Southern China due to differences in energy consumption behaviour (Zhang et al., 2019). These results demonstrate that the interaction between economic factors and temperature in various climate zones can affect energy consumption patterns.

Apart from air temperature, energy consumption could be sensitive to changes in relative humidity due to dehumidification associated with air-conditioning (Ihara et al., 2008). Other meteorological variables are also shown to affect energy demand, such as wind speed, humidity, cloudiness, precipitation, and solar radiation (Apadula et al., 2012; Hor et al., 2005). Therefore, multiple climatic factors need to be considered when analyzing energy consumption patterns.

In Hong Kong, domestic energy consumption is shown to be modulated by climate (Ang et al., 2017; Fung et al., 2006). Residential buildings are accounted for about 27% of energy consumption in Hong Kong (Environment Bureau, 2015). Fung et al. (2006) reviewed energy consumption using different statistical models to establish the empirical relationships between energy consumption and temperature in Hong Kong. Using a potential weather stress index as a climate proxy, Yan (1998) investigated the roles of temperature, cloudiness, vapour pressure, and other climate variables on residential electricity consumption in Hong Kong. Due to the rapid developments in global climate models, climate projections for predicting future demand is an active energy research field. Lam et al. (2010d) developed statistical models related to dry-bulb temperature (DBT), wet-bulb temperature (WBT), global solar radiation, clearness index, and wind speed for projecting future energy consumption of commercial sectors in Hong Kong. The DBT affects indoor heating/cooling requirements, whereas WBT affects the need for humidification and dehumidification, and solar radiation affects the cooling load requirement (Wan et al., 2011a). Chan (2011) and Wan et al. (2011a) used Global Circulation Model (GCM) outputs to assess how changing climate may affect the energy performance of Hong Kong buildings. Tso and Yau (2007) explored energy consumption in Hong Kong using a bottom-up approach and suggested that the decision tree and the neural network models are viable alternatives to regression analysis. Cheung and Hart (2014) indicated a future increase in days experiencing heat stress in Hong Kong, which implies increased energy consumption during hot days.

In Singapore, household electricity consumption is positively related to temperature (Liu et al., 2017) and rainy days (Loi and Loo, 2016), as people tend to spend more time indoors during hot weather and rainy days (Loi and Loo, 2016). Ang et al. (2017) quantified the impacts of temperature increases on electricity consumption in Singapore and Hong Kong. They find that a 1°C rise in air temperature causes a 3-4% and 4-5% increase in electricity consumption in Singapore and Hong Kong, respectively. The response of energy consumption of Singaporean living in public households (publicly governed and more affordable) was also more sensitive to outdoor climatic variations compared with those living in private households (more expensive) (Li, 2018). This result indicates a possible impact of socioeconomic factors on domestic energy use. Moreover, increasing air pollution is shown to increase household electricity consumption in the long run in Singapore (You et al., 2017).

It is well-known for changing climate that energy consumption increases with rising outdoor temperature, but outdoor temperature can also be influenced by monsoon. The Asian monsoon system has long been considered one of the major regional climatic factors affecting the current climate in Asia (Turner and Annamalai, 2012). The summer monsoon brings moisture and cooler temperature from the ocean during summer from June to early September. As a result, the variation in climate (including temperature, humidity, and wind speed) has significant impact on energy consumption (Aldossary et al., 2014; Ang et al., 2017; Sailor and Muñoz, 1997; Yalew et al., 2020; Yetemen and Yalcin, 2009).

For future building energy consumption, the impact of climate change has been examined (Huang and Hwang, 2016; Perera et al., 2020; Qian et al., 2004), including Hong Kong (Chan, 2011; Li et al., 2012; Liu et al., 2020b; Spandagos and Ng, 2017; Wan et al., 2012; Wong et al., 2010) and Singapore (Li, 2018; Liu et al., 2017; Wong et al., 2013). Previous studies have used GCM (Dirks et al., 2015; Mei et al., 2020; Shourav et al., 2018; Zheng et al., 2020), statistical downscaling of GCM (Arima et al., 2016), and dynamic downscaling of GCM (Kikumoto et al., 2015) to model future energy use under climate change scenarios. Temperature has been commonly used to predict future energy consumption (Lam et al., 2004; Li, 2018). Other studies conducted principal component analysis (PCA) to combine dry-bulb temperature, wet-bulb temperature, and global solar radiation to estimate the impact of climate on future energy use (Lam et al., 2010c; Lam et al., 2010e; Wan et al., 2009; Wan et al., 2011b; Yang et al., 2011). Globally, increasing temperatures can reduce heating consumption by up to 47.5% (2080) and increase cooling consumption by up to 60.9% (2080), depending on the emission scenarios (Campagna and Fiorito, 2022). There is a wide consensus that climate change would increase the cooling load (e.g. cooling degrees days) and decrease the heating load (e.g. heating degrees days) in various climate zones (Andric and Al-Ghamdi, 2020; Arima et al., 2016; Cao et al., 2017; Dino and Meral Akgül, 2019; Meng et al., 2018; Triana et al., 2018; Yalew et al., 2020; Yang et al., 2014). This phenomenon is also reported in several studies in Hong Kong (Chan et al., 2012; Lam et al., 2010a; Lam et al., 2010b; Lim and Yun, 2017). However, the decrease in heating load demand could be negligible in cold climates (Andrić et al., 2017).

Past studies have investigated different climate impacts and energy consumption aspects (Auffhammer and Mansur, 2014; Ciscar and Dowling, 2014; Pilli-Sihvola et al., 2010). Population growth and conditioning of the physical environment are well-known factors affecting urban energy consumption trends (Cao et al., 2016). An increase in the frequency and intensity of peak events would likely require greater demand for future cooling demands, such as in cities in the US (Auffhammer et al., 2017). The extent of air-conditioning use would also depend on the technology adoption in the long run (Auffhammer and Mansur, 2014; Waite et al., 2017) and the affordability of such technologies (Santamouris, 2020). However, past studies have seldom decomposed the complex relationships between climatic factors and population change to understand their relative importance.

This study is significant for three reasons. First, we fill the gap by quantifying the relative importance and complex relationships of socioeconomic factors to domestic energy consumption instead of the narrow focus on climatic variables only. Second, we develop a time-series decomposition method to quantify such relative importance using the Lindeman Merenda and Gold (LMG) Method (Lindeman et al., 1980) and the Proportional Marginal Variance Decomposition (PMVD) Method (Feldman, 2005). Third, we discuss the extent to which social factors should be highlighted in future energy consumption studies.

Therefore, this study aims to fill the gap and understand the relative importance of climatic variables and population growth at different temporal scales, and predict the impact of climate change on future domestic energy consumption in Hong Kong and Singapore. We used a population time series, a monsoon index, a heat index, gross domestic product (GDP), and energy prices to investigate their relative importance to Hong Kong and Singapore's energy consumption. Following the relative importance analysis, we used GCM to simulate the future climate and domestic energy use in these two cities. This study answers the following research questions:

1) What are the most important drivers of past domestic energy consumption in Hong Kong and Singapore?
2) What are the effects of climate change on future domestic energy consumption in Hong Kong and Singapore?

2 Case study

Hong Kong and Singapore share similar socioeconomic factors but differ in climate conditions. They are worthwhile for case studies for at least three reasons. First, both Hong Kong and Singapore have comparable populations and economic sizes. In 2019, Hong Kong had a population of 7.5 million, a density of 6,757 persons/km^2 and a gross domestic product (GDP) of US$370 billion (Census and Statistics Department, 2020a). In comparison, Singapore had a population of 5.7 million, a density of 7,866 persons/km^2 and a GDP of US$380 billion in 2019 (Department of Statistics Singapore, 2020). The high population densities and high level of GDP of the two Asian cities are attributable to the rising energy consumption trends.

Second, Hong Kong and Singapore have comparable per capita electricity consumption. The two Asian cities had high energy consumption levels, ranking 17th and 32nd in per capita electricity consumption in the world respectively (International Energy Agency, 2014). In 2015, the total and domestic electricity consumption for Hong Kong were 43.91 terawatt-hours (TWh) and 11.77 TWh (Census and Statistics Department, 2015), while the corresponding values for

Singapore were 48 TWh and 7.2 TWh, respectively (Energy Market Authority, 2015). Domestic energy consumption increased by 1.46% in Hong Kong between 2005-and 2015 (Census and Statistics Department, 2015) and 1.58% in Singapore during the same period (Energy Market Authority, 2015). Domestic energy consumption has risen sharply during the past few decades in Hong Kong (Jia and Lee, 2016; Lai et al., 2014; Ma and Wang, 2009) due to rapid urbanization and electrification (To et al., 2015). In Hong Kong, the most remarkable change in domestic energy consumption started after the 1980s. This change may be attributed to the wider adoption of domestic electrical appliances and better living standards (Lee et al., 2010; To et al., 2015). In Singapore, domestic energy consumption has also increased since 1990 (Ang et al., 2017) due to population growth and increasing ownership of electrical appliances in households (Li, 2018). The two cities are thus valuable cases for examining whether socioeconomic factors are significant determinants to the rise in energy consumption.

Third, Hong Kong and Singapore are both fossil fuel-dependent and face similar challenges in energy security and decarbonization. Coal and natural gas contributed about 50% and 25% to the Hong Kong fuel mix for electricity generation in 2019 (The Government of Hong Kong, 2019). Natural gas, coal, and petroleum products constituted about 96%, 1%, and 0.2% respectively of the Singapore fuel mix for electricity generation in the same year (Energy Market Authority, 2020a). Hong Kong thus lags behind Singapore in its pathway to phase-out coal in the fuel mix.

Yet, climate difference is one of the major factors affecting energy consumption in Hong Kong and Singapore. Hong Kong is located at 22.4°N latitude in the subtropical region. Under the Köppen climate classification (Peel et al., 2007), Hong Kong's climate is identified as humid subtropical (Cwa). Typically, January is the coolest month in Hong Kong with an average temperature below 10°C. The hot summers from May to September have made air-conditioning a large part of domestic energy consumption (Lam et al., 2008). In contrast, Singapore is located at 1.35°N latitude in the tropical region. Under the Köppen climate classification (Peel et al., 2007), Singapore's climate is identified as a tropical rainforest climate (Af). It is fully humid (with an average monthly precipitation of at least 60 mm) in the equatorial region. The seasonal variation in domestic energy consumption is smaller in Singapore than in Hong Kong since the energy demand for water heating is greater in Hong Kong during winter (Ang et al., 2017).

3 Material and methods

3.1 Data description

Monthly mean outdoor temperature and relative humidity data of Hong Kong were extracted from the Hong Kong Observatory (Hong Kong Observatory, 2019) between 1981 and 2015. For Singapore, the outdoor temperature and relative humidity data from 2005 to 2015 were provided by Meteorological Service Singapore (Meteorological Service Singapore, 2018). Fig. 1 shows the monthly characteristics of air temperature and relative humidity in Hong Kong and Singapore. The time series of monthly energy consumption in Hong Kong from 1981 to 2015 were derived from the Census and Statistics Department of Hong Kong (Census and Statistics Department, 2019). Meanwhile, the energy consumption data for Singapore was obtained from the Energy Market Authority (EMA) (Energy Market Authority, 2018), but available in a shorter period (2005 to 2015). To investigate how population size affects energy consumption in Hong Kong and Singapore, the population time series of both cities were derived from the World Bank website (World Bank, 2020c). The GDP (World Bank, 2020b) and inflation data (World Bank, 2020a) of Hong Kong and Singapore were also downloaded from the World Bank website. The domestic energy price data of Hong Kong from 1981 to 2015 were extracted from Hong Kong Energy Statistics Annual Report (Census and

Statistics Department, 2020b), whereas Singapore domestic energy price data from 2005 to 2015 were obtained from EMA (Energy Market Authority, 2020b). Fig. 2 shows the time series of the energy price data in Hong Kong and Singapore. Energy price data were adjusted for inflation.

The causal relationship between population and GDP is complicated. On the one hand, population growth directly increases the supply of human resources which is an important factor of economic growth. However, it has been argued that in the short-term, population growth may have a negative impact on economic growth (Barlow, 1994). On the other hand, economic growth, especially in highly developed economies, may contribute to slower population growth or even population decline (Luci-Greulich and Thévenon, 2014). Both Hong Kong and Singapore have experienced a very modest population growth but significant GDP growth. Therefore, it is more suitable to treat population and GDP as separate predictor variables. For more information about the population, GDP and per capital energy consumption and energy intensity in Hong Kong and Singapore, please refer to appendix A.

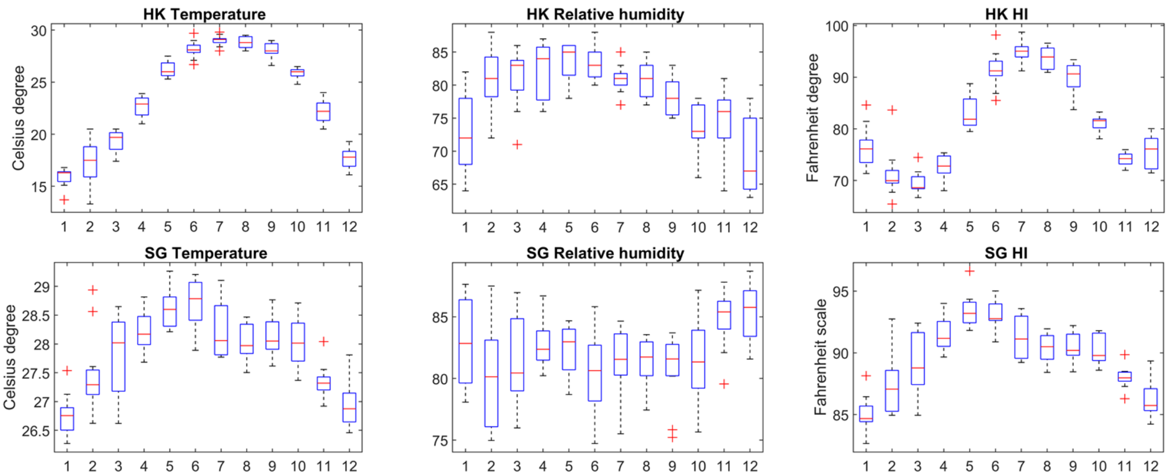

Fig. 1 The seasonality of temperature, relative humidity and HI in both Hong Kong (HK) and Singapore (SG).

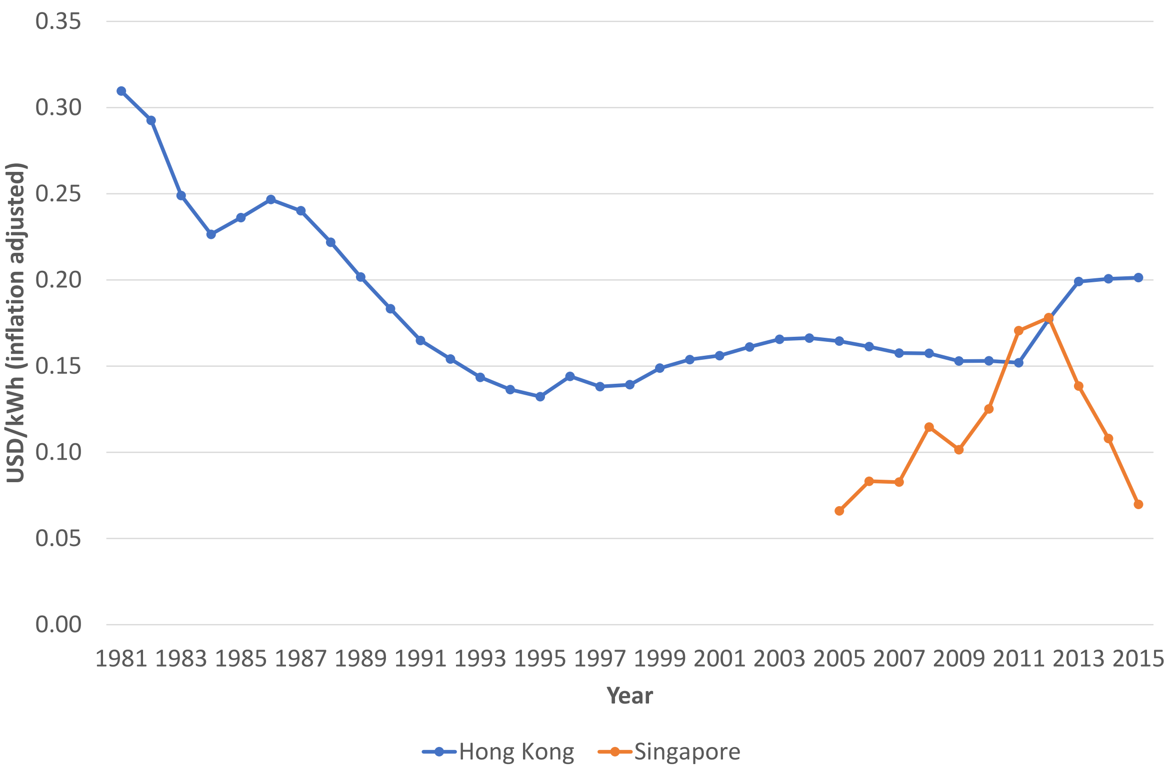

Fig. 2 Hong Kong and Singapore Electricity Price by Year (inflation adjusted with 2014 as base year).

3.2 Heat index and monsoon index

Rothfusz (1990) combined air temperature and relative humidity to calculate the heat index by conducting multiple regression analysis on the data from Steadman's table (Steadman, 1979) . We found that the heat index values vary by relative humidity (Fig. S.4 in the supplementary material). We used Eq. (1) to calculate the heat index (Rothfusz, 1990) (see also Fig. 1 for the monthly variations of the heat index in Hong Kong and Singapore):

$$HI = -42.379 + 2.04901523T + 10.1433127RH - 0.22475541(T)(RH) - 6.83783(10^{-3})(T^2) - 5.481717(10^{-2})(RH^2) + 1.22874(10^{-3})(T^2)(RH) + 8.5282(10^{-4})(T)(RH^2) - 1.99(10^{-6})(T^2)(RH^2) \quad [1]$$

where *HI* is the heat index, *T* is ambient dry bulb temperature, and *RH* is relative humidity.

Although there are 21 different heat index algorithms in the literature, Anderson et al. (2013) show that these algorithms generate values consistent with the apparent temperature. The heat index values generated by different algorithms are also closely correlated. Previously, we have used apparent temperature in our work in the Guangdong-Hong Kong-Macau Greater Bay Area (Fan et al., 2022). Furthermore, the heat index has been applied in different areas in Asia (Kotharkar and Ghosh, 2021), including Hong Kong (Liu and Jim, 2021) and Singapore (Zhou et al., 2020).

The influence of the heat index to the energy consumption is presented below (Eq. (2) to Eq. (5)).

$$\log(E_t) = \beta_{HI} HI_t + \beta_{Pop} Pop_t + \cdots + z_t \qquad [2]$$

$$E_t = e^{\beta_{HI} HI_t} \ldots e^{\beta_{Pop} Pop_t} \qquad [3]$$

where E_t, HI_t, Pop_t, and z_t represent the energy consumption, heat index, population, and random error at time t, respectively. And β_{HI} and β_{Pop} are the regression coefficients of the heat index and population, respectively.

If we assume that the population and all other predictor variables are zero, we get the influence of heat index on energy consumption (Eq. (4)).

$$E_t = e^{\beta_{HI} HI_t} \ldots e^{0} \qquad [4]$$

Therefore, domestic energy due to the heat index effect could be derived using Eq. (5).

$$E_t = e^{\beta_{HI} HI_t} \qquad \text{since } e^0 = 1 \qquad [5]$$

Since our β_{HI} is estimated using the 2005-2015 data, our base period is 2005-2015.

The monthly monsoon index ranging from 1970-2015 is defined by the spatial average of the vertical zonal wind shear between 850 and 200 hPa over the region of 100°E–130°E, 0°–10°N (Zhu et al., 2005). The meridional and zonal wind data for computing the index were derived from the US National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis II (Kanamitsu et al., 2002; NOAA/National Weather Service, 2015). The East Asian monsoon system involves global circulation systems in the tropics and midlatitudes that affects the climatic variability over East Asia (Zhao et al., 2015). It encompasses not just seasonal variations but also significant interannual variations in precipitation, air temperature, and humidity (Zhu et al., 2005). Therefore, air temperature and humidity in seasonal and interannual timescales are modulated by the variability in the monsoon index. In comparison to day-to-day variations in air temperature and humidity, the monsoon index is much more stable and relatively easier to forecast its mode. Hence, we included the monsoon index in our analysis. For more information, Fig. S.5 shows the relationships between energy consumption and heat index/monsoon index, as well as heat index and monsoon index.

3.3 Relative importance analysis

We used the relative importance analysis to investigate the impact of socioeconomic and climate variables on domestic energy consumption in Hong Kong and Singapore. Two different relative importance methods were adopted in this study, including the LMG Method (Lindeman et al., 1980) and the PMVD Method (Feldman, 2005). The relative importance analysis decomposes the coefficient of determination (R^2) into non-negative contributions attributable to every regressor in a linear regression model (Jian, 2012). We used these two methods to quantify the contributions of independent variables (i.e., population, GDP, energy price, the heat index, and the monsoon index) to domestic energy consumption. Subsequently, it could reveal the relationships between domestic energy consumption and explanatory variables in both Hong Kong and Singapore. Meteorological data can be obtained on a daily basis. However, the monsoon index and energy consumption data are only available on a monthly resolution. As a result, we run the model on a monthly basis.

According to the literature, additive model depicts the absolute changes in a variable, whereas the multiplicative model allows for indicating the relative (proportional) changes in a variable (Bechhofer, 1960; Menzefricke, 1979). In this case, the variance in domestic energy consumption in response to the heat index has increased (Fig S.2 and Fig S.3 in the supplementary material). It means that the relative importance of the heat index in energy consumption over years had to be considered. Therefore, the multiplicative model is superior to the additive model here.

The LMG method uses simple unweighted averages (Lindeman et al., 1980). The LMG method decomposes into non-negative contributions attributable to each regressor based on averaging over all possible permutations for p regressors (p!). This method can be used when the number of regressor variables is smaller than that of observations. It can be written as Eq. (6):

$$\mathrm{LMG}(x_k) = \frac{1}{p!}\sum_{r\,\mathrm{permutation}} \mathrm{seq}R^2\big((x_k|r)\big) \qquad [6]$$

where r indicates r-permutation, r = 1,2,…, p!; $\mathrm{seq}R^2\big((x_k|r)\big)$ indicates the sequential R^2 for the regressor x_k in the ordering of the regressors in the r^{th} permutation. p equals to 5 in the study, and then there are total 120 (5!=120) different permutations. The relative importance of each variable calculated by LMG is the average of 120 sequential R^2 estimations.

The PMVD method is a weighted analogue of the LMG method with data-dependent weights (Feldman, 2005). The constructions of PMVD allocate a share of zero to any regressor with coefficient of zero (Bi, 2012). It can be written as Eq. (7):

$$\mathrm{PMVD}(x_k) = \frac{1}{p!}\sum_{\mathrm{rpermutation}} w(r)\mathrm{seq}R^2\big((x_k|r)\big) \quad [7]$$

where w(r) indicates the data dependent PMVD weight in the r-permutation. However, LMG's property of allowing correlated regressions to benefit from regressors' shares has a plausible background when focusing more on causal than predictive importance (Grömping, 2006). Therefore, LMG and PMVD have their advantages for a different purpose.

3.4 Climate model dataset

We analyzed monthly surface air temperature and relative humidity simulated by Coupled Model Intercomparison Project Phase 5 (CMIP5) models in the historical experiment (1971-2000), Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 scenarios (2071-2100). The CMIP5 models generally have coarse spatial resolution with a median horizontal grid resolution of 2.8° × 2.8° (about 250km x 250km) and a median number of vertical levels of 17. We have chosen six CMIP5 climate models and considered multi-model ensembles of future climate projections to account for model uncertainty (Table 1). Navarro-Racines et al. (2020) provided more details of different CMIP5 climate models. The CMIP5 climate models have been extensively evaluated (Sillmann et al., 2013a; Sillmann et al., 2013b), including China (Yang et al., 2020) and peninsula Malaysia (with Singapore) (Noor et al., 2019).

The monthly temperature and relative humidity times series for Hong Kong and Singapore were extracted by using bilinear interpolation which interpolates the weighted average of the four nearest climate model grids to investigated location, i.e. Hong Kong and Singapore. Daily meteorological values of BNU-ESM outputs are averaged to generate monthly values to run the model on a monthly basis. Bias in the extracted time series was checked by comparing them with observed data from Hong Kong and Singapore. The quantile mapping method (Shukla et al., 2019) based on cumulative distribution function (CDF) was used for bias correction. Based on the comparison, we found that our six climate models have performed well in simulating the historical heat index (which incorporates temperature and relative humidity), and the monsoon index (see Appendix B for more detail). For our following analysis, we used the bias-corrected time series to compute the heat index and the monsoon index. Further information on the validation of the climate model with observed meteorological data is provided in the supplementary material.

Table 1 Details of the six CMIP5 climate models used in this study.

Model	Institution	Resolution (Lon × Lat)
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	1.875° × 1.25°
BNU-ESM	Beijing Normal University Earth System Model, China	Approximately 2.8° × 2.8°
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration, China	Approximately 2.8° × 2.8°
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancées en Calcul Scientifique, France	Approximately 1.4° × 1.4°
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France	3.75° × 1.875°
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	1.875° × 1.875°

4 Results

4.1 Results of variable importance for domestic energy use in Hong Kong and Singapore

Two relative importance analysis methods, LMG and PMVD, were used to investigate the relative importance of variables affecting the domestic energy consumption in Hong Kong and

Singapore (Fig. 3). By analyzing the multiple factors at the same time, the approach can be decomposed into the important controlling factors.

Based on energy price data from China Light and Power (CLP), the decomposition methods applied to domestic energy consumption in Hong Kong for 1981-2015. However, available energy price and consumption data are limited for Singapore for a shorter period 2005-2015 (from Uniform Singapore Energy Price). Hence, we had to use two different time frames 1981-2005 and 2005-2015 for Hong Kong to analyze the controlling factors in domestic energy consumption and to compare these factors with the ones of Singapore. Both LMG and PMVD methods for Hong Kong (1981-2015) showed comparable patterns but with different weightings. The energy consumption in Hong Kong could be mainly attributed to GDP and Population between 1981 and 2015 (Fig. 3a). In the simulations, we may assign importance to GDP and sometimes to population. PMVD has weightings to increase the contrast between variable compared to LMG. When interpreting Hong Kong data, monsoon and energy price were not important between 1981 - 2005 (Fig. 3a). When they are not important, a slight change can make one bigger than the other. Hence, it is cautioned that we should not over-interpret them.

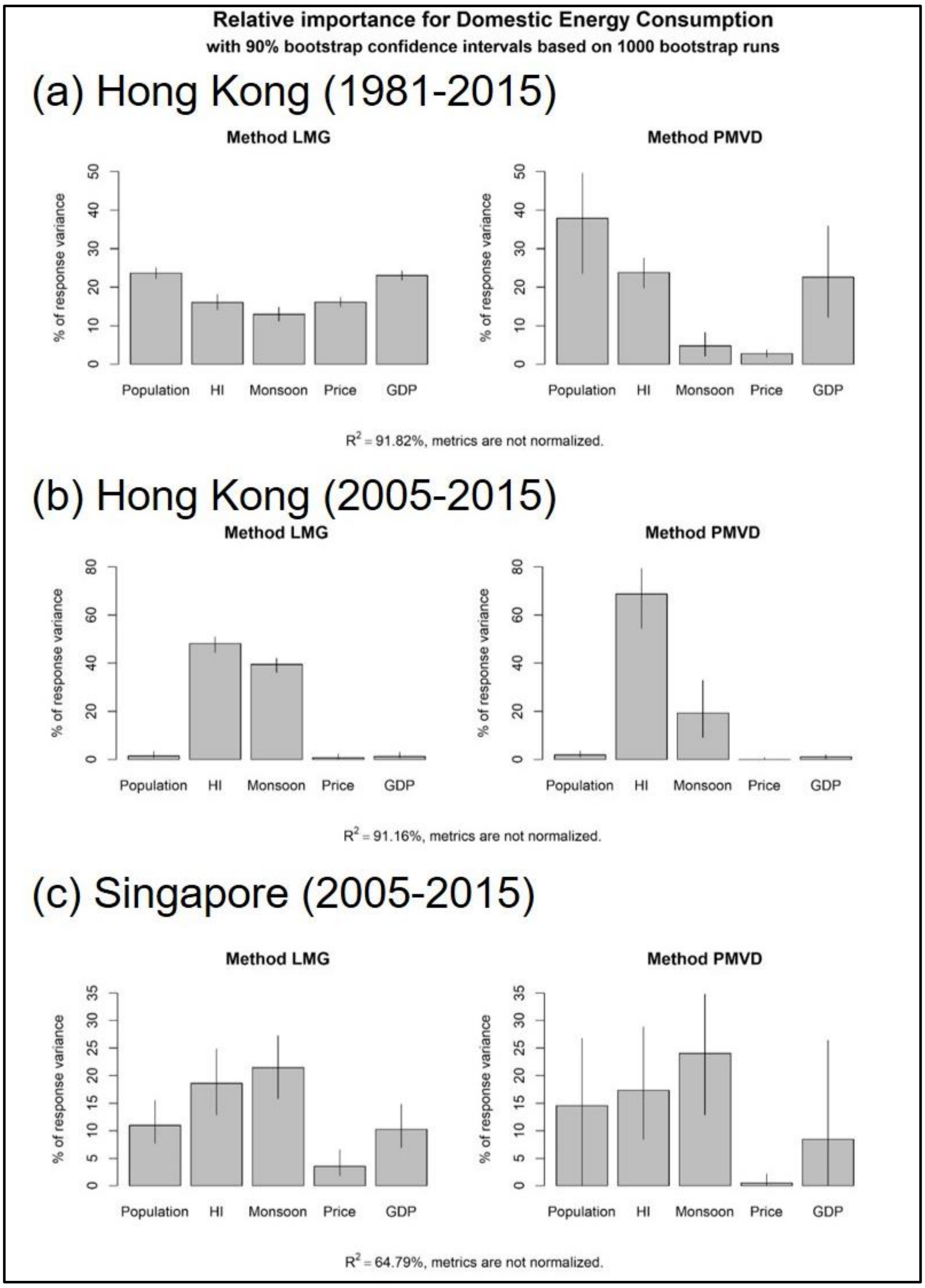

Fig. 3 The comparisons of the relative importance analysis for domestic energy consumption using LMG and PMVD methods for a) 1981-2015 and b) 2005-2015 for Hong Kong, and c) 2005-2015 for Singapore. Five variables were used in the analysis: population, the heat index (HI), the monsoon index, energy price, and GDP.

The results for Hong Kong were well within a high explanation variance R^2 of 91.82% (Fig. 3a). GDP and population were found the most important factors affecting the energy consumption in Hong Kong in two methods with different weightings. Similarly, as aforementioned, monsoon and price were the least important factors. For 2005-2015, the heat index was the most important factor among others in both methods (Fig. 3b). The heat index accounted for more than half of the response variance followed by the monsoon index (Fig. 3b). The response variances of the heat index and monsoon index are significantly higher than the rest. Even population growth was a primary driver for energy consumption from 1981 to 2015 (Fig. 3a), the population factor weakened in a shorter timescale (2005-2015) (Fig. 3b). This decline is probably due to a slower growth rate in population 0.64% per year for 2005-2015 compared with 1.83% per year for 1981-2015 (World Bank, 2020c). Subsequently, the decomposition analysis reveals the climatic factors (the heat index and the monsoon index) are the primary driving forces of energy consumption for Hong Kong at the decadal scale (2005-2015).

The analysis for Singapore revealed a different pattern. First, the explanation variance R^2 was 64.79% (Fig. 3c) which was lower than that of Hong Kong, 91.82% (Fig. 3a). Second, both methods result in a similar ranking in the response variance but with different percentages (Fig. 3c). Third, similar to Hong Kong, climatic factors were the most important factor affecting energy consumption for Singapore during 2005 and 2015 (Fig. 3c). In contrary to Hong Kong (Fig. 3b), the monsoon index was more important for Singapore than the heat index (Fig. 3c). Interestingly, population growth for Singapore was also found an important factor affecting energy consumption (Fig. 3c). For energy consumption in Hong Kong and Singapore, energy price was not important with or without adjusted for inflation. Electricity appears to be common good and relatively cheap in Hong Kong and Singapore. Therefore, electricity prices did not have a strong influence on domestic energy consumption. In summary, the relative importance analysis showed that the dominant variables driving domestic energy consumption depend on analysis period due to population growth and the spatial extent of the cities due to prevailing climate and ongoing climate warming.

4.2 Climate change scenarios for Hong Kong and Singapore

The regional map of Köppen climate classification for Southeast Asia is given in Fig. 4a (Rubel et al., 2017). As mentioned in section 2, the prevailing climate in Hong Kong and Singapore are categorized as Cwa and Af, respectively, based on Köppen's climate classification. Cwa refers to the warm temperate climate with dry winter, which is influenced by monsoon and has a dry winter-wet summer pattern (Kottek et al., 2006). In contrast, Af refers to the equatorial rainforest climate, where the driest month precipitation is ≥ 60 mm (Kottek et al., 2006). As shown in Appendix B, after bias-correction the 6 CMIP5 model results are similar. All the models give similar temperature and relative humidity projections. Therefore, we choose to present the climate model results from BNU in our subsequent analysis in sections 4.2 and 4.3. To examine the use of BNU model outputs for projections of future climate change, the generated Köppen climate map by the BNU model for a historical run (1970-2000) (Fig. 4b) was compared with the current Köppen climate map. There are discrepancies in the generated climate map with the prevailing climate for Northeast China. However, the model outcomes for Southeast China and the Indonesian archipelago are robust.

After establishing confidence in the BNU model outputs, the generated Köppen climate maps for the future projections (the 2080s) by the BNU model for RCP4.5 and RCP8.5 scenarios were given in Fig. 4c and Fig. 4d, respectively. These RCP4.5 and RCP8.5 (representative concentration pathway) scenarios represent the level of radiative forcing by greenhouse emissions stabilizing at 4.5 W/m^2 or 8.5 W/m^2 by 2100. The enhanced greenhouse effect will lead to an increase in air temperatures between 2 °C – 5 °C for Hong Kong and Singapore (Fig. 5) and will increase the energy demand for air conditioning. Hong Kong will need air conditioning one or two more months for RCP4.5 and RCP8.5, respectively. Based on both scenarios, the projected climate at the end of the century in Hong Kong will be changed from Cwa to Cfa (Fig. 4c-d). Cfa refers to the warm temperate climate (fully humid), which is characterized by hot summers (mean temperature of the warmest month ≥ 22 °C) and the lack of a distinct dry season (Kottek et al., 2006). It indicates that the Hong Kong will be hotter and more humid. Moreover, the prevailing climate 'Af' in Singapore will extend towards the farther north and approach Hong Kong, especially in the RCP8.5 scenario (Fig. 4c-d). Hence, the current prevailing climate in Singapore will be prevailed at the end of the 21st century in Hong Kong because of ongoing climate change.

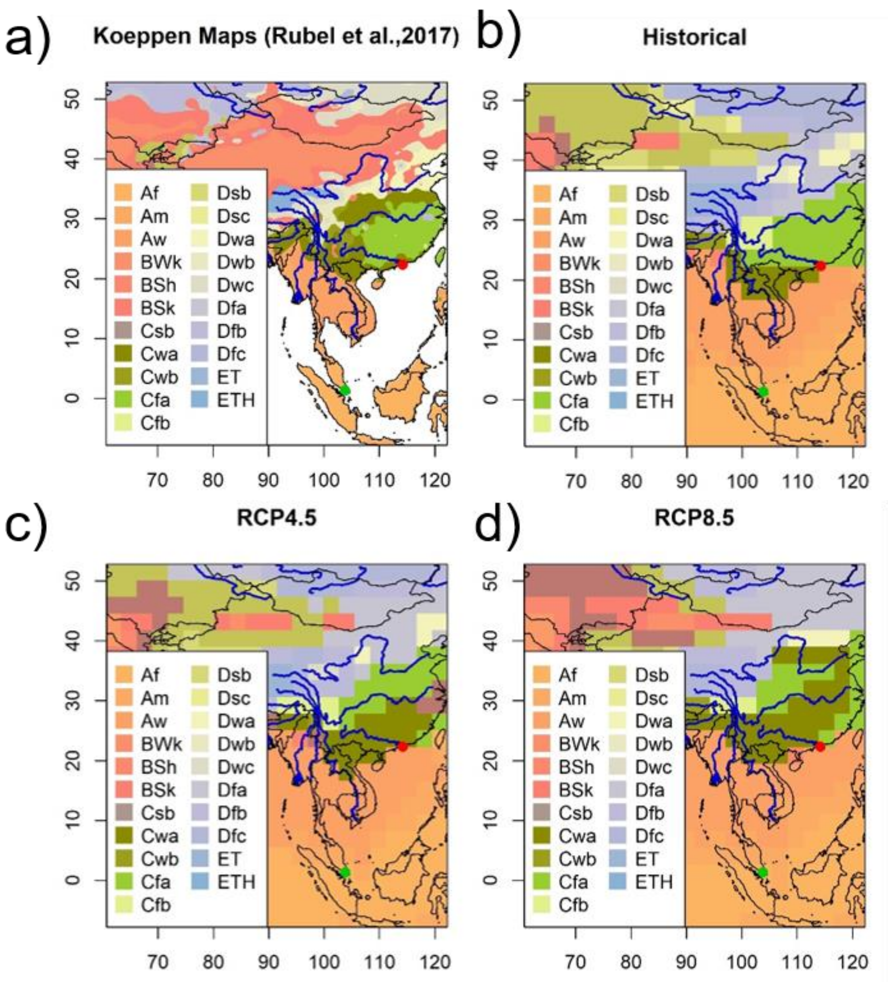

Fig. 4 Köppen map showing the Canonical Köppen map from a) WU-Wien (Rubel et al., 2017), b) historical, c) RCP 4.5 and d) RCP8.5 scenarios (BNU model) in Southeast China region. In the maps, red dots show Hong Kong and green dots show Singapore.

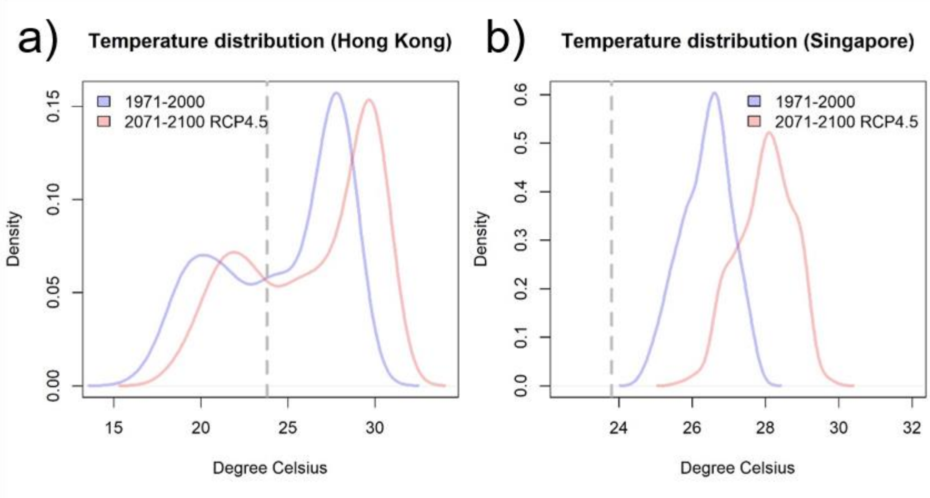

Fig. 5 The air temperature distribution during 1971–2000 and 2071–2100 (RCP 4.5) for a) Hong Kong and b) Singapore.

4.3 Effect of future climate change on domestic energy consumption in Hong Kong and Singapore

The BNU GCM simulates the shifts in the climate zones and warmer air temperatures than the present ones for both cities towards the end of the 21st century. It is intuitive to expect that elevated climate conditions will increase the heat index (Eq. 2) and the energy demand of both cities, especially for air conditioning. The heat index was the most and the second most important factor for Hong Kong and Singapore, respectively, among the five investigated factors. To respond to the second research question of this study - the effect of climate change on future domestic energy consumption - the influence of the heat index on the energy consumption was calculated (Eqs. 2-5) by using the BNU model outputs. Moreover, heat index is related to air temperature, relative humidity and monsoons. Therefore, the influence of the heat index as well as three related climate factors on the domestic energy consumption of both cities due to the increased air temperature as a result of global warming is shown in **Fig. 6** for both RCP scenarios (Fig. 6). Higher air temperatures will result in greater energy demand in both cities. At the end of the 21st century, expected temperatures in Hong Kong are lower than the tipping point and lower than it which requires heating (~18-20 °C) will preserve the non-linear behaviour in the energy demand in response to air temperatures (**Fig. 6**a). In contrary to Hong Kong, both elevated temperatures beyond the tipping point and all-year-round cooling demand will cause a linear increase in energy demand to air temperatures in Singapore (**Fig. 6**b). The relationships between heat index and energy consumption for both scenarios are similar to that between temperature and energy consumption (Fig. 6e-f). For relative humidity and monsoon, they do not have significant relationships with energy consumption for historical and both scenarios (Figure 6c-d. 6g-h). Therefore, as presented before, heat index (air temperature) could be the most important and most direct factors affecting energy consumption. The average consumption difference between RCP4.5 (RCP8.5) and the historical is 1.40 TWh (3.03TWh) for Hong Kong, the corresponding value for Singapore is 0.19 TWh (0.44TWh). Both cities will face to increase their current energy supply capacity to meet the increased demands at the end of the 21st century due to global warming.

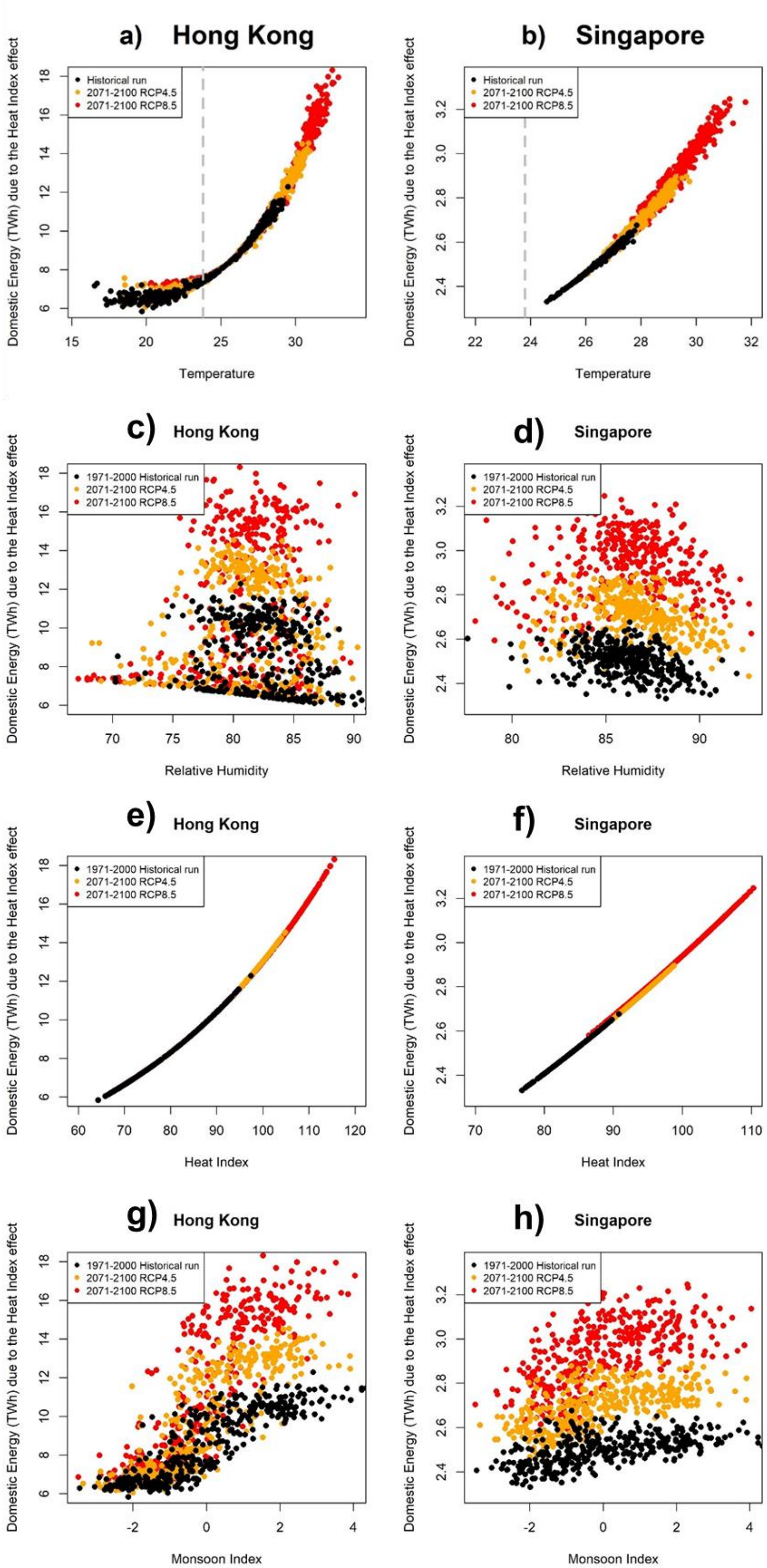

Fig. 6 Domestic energy consumptions related to temperature (a-b), relative humidity (c-d), HI (e-f), and monsoon index (g-h) derived from the RCP4.5 and RCP8.5 scenarios for a) Hong Kong and b) Singapore.

5 Discussion

5.1 The controlling factors of energy consumption in Hong Kong and Singapore at different temporal scales

The analysis period is an important factor in investigating the different drivers of energy consumption in case study research. Existing studies have found evidence that both socioeconomic factors shape household energy consumption (e.g., energy price, income, education, household size and structure, housing unit size, number of appliances) and climatic factors (Borozan, 2018; Karatasou and Santamouris, 2019; Yang et al., 2015). However, few studies have empirically examined the relative importance of these two classes of factors. This study investigates the interaction between study periods and the control factors on domestic energy consumption. Our results show that the population and GDP are the most important variable for Hong Kong's energy consumption between 1981 and 2015 (Fig. 3a), possibly due to baby boomers starting from the 1960s (i.e. increase in household numbers (Chung et al., 2011)). This result agrees with previous studies that highlight the importance of population (Auffhammer and Aroonruengsawat, 2011; González-Torres et al., 2022) and GDP (Kuo et al., 2014; Qian et al., 2004; Wang et al., 2016) as key domestic energy consumption drivers in the long-term.

At a shorter timescale, the heat index (which combines air temperature and relative humidity) is the most important variable for Hong Kong's energy consumption from 2005 to 2015 (Fig. 3b), when the population growth is more stable. Between 2005 and 2015, the population accounted for a low percentage of response variance for Hong Kong's domestic energy consumption. This result is probably due to the persistently low birth rate in Hong Kong and an increase in residents heading overseas in recent years. Between 2005 and 2015, the heat index explained more than 50% of the variance in Hong Kong's domestic energy consumption

(Fig. 3b). This result indicates that the role of high outdoor temperature would become more crucial regarding domestic energy consumption. Past studies also suggest higher temperatures would increase cooling demand (Khosla et al., 2021; Liu et al., 2020b; Wong et al., 2011). High outdoor temperature and heatwaves would be more likely to be correlated with Hong Kong's energy consumption behaviour in the future (Morakinyo et al., 2019). Furthermore, the average GDP growth rate in Hong Kong between 2005 and 2015 was 3.8% (World Bank, 2020b), which could affect domestic energy consumption patterns.

The same relative importance framework is applied to Singapore's energy consumption data between 2005 and 2015. The monsoon and heat indices each explain more than 20% of Singapore's domestic energy consumption variance. The monsoon index affects the city's regional precipitation, humidity, and temperature, whereas the heat index considers both air temperature and relative humidity. As Singapore does not experience winter, the monsoon index is the major driver of Singapore's domestic consumption during this period, followed by the heat index (Fig. 3c). Other studies also highlighted the role of monsoon-based domestic energy consumption in other climatic zones (Sheik Mohideen Shah and Meganathan, 2021). However, there is no clear association between relative humidity and energy consumption (**Fig. 6**), so it is inappropriate to use relative humidity alone as an independent predictor of domestic energy consumption. Heat index would be a more appropriate predictor, as indicated in other studies (Li et al., 2021; Maia-Silva et al., 2020).

For the overall models, the Hong Kong model (R^2=0.91) (Fig. 3b) performs better than the Singapore model (R^2=0.65) (Fig. 3c). By considering other variables driving energy consumption change related to the rapid economic growth of Singapore since the 2000s (World Bank, 2020b), it is likely to improve the Singapore model performance. Energy price was found to affect the energy consumption pattern in the literature (Aroonruengsawat and Auffhammer, 2011). However, the price effect is not found in Hong Kong and Singapore as these two cities have relatively low energy prices and energy prices keep constant for a period in Hong Kong. Overall, the importance of controlling factors of domestic energy consumption differs between various temporal scales.

5.2 Mitigation strategies to address increasing energy consumption under climate change

There has been a global increasing temperature trend since the early 20th century (Stocker et al., 2013). For the recent increasing global temperature, Hong Kong appears to have shorter winters and higher humidity (Leung et al., 2007). According to our GCM model output, the future climate in Hong Kong and Singapore will likely become 2 °C – 5 °C hotter (RCP4.5 in 2071-2100) and creates shifts in heat extremes (Fig. 5). This shift in temperature would lead to an increase in energy consumption in both Hong Kong and Singapore especially in RCP8.5 (Fig. 4), resulting in more demand for household cooling and lower demand for household heating (Wan et al., 2012). This increased residential cooling demand is consistent with previous findings in Hong Kong and Singapore (Ang et al., 2017). A non-linear increase in domestic energy consumption is found for Hong Kong, whereas a linear increase is found for Singapore in the future. Our results agree with studies in colder climatic regions (e.g. Quebec City, Toronto and Vancouver in Canada), which also indicate a decrease in heating loads and an increase in cooling loads under future climate change (Berardi and Jafarpur, 2020; Jafarpur and Berardi, 2021). However, unlike Hong Kong and these Canadian cities, Singapore has limited demand for heating at households in the future owing to its tropical climate.

Rising energy consumption can be related to social well-being and the fairness of distributing the burden associated with climate change and heatwave. Changes in outdoor temperature could lead to a behavioural change in energy consumption (Liu et al., 2020b). The monthly mean outdoor temperature in May 2018 was the highest on record for May in Hong

Kong (Hong Kong Observatory, 2018). As summer becomes hotter, the demand for household cooling will become more common (Nejat et al., 2015). Although some elderly people have air-conditioning at home, they face certain barriers to changing their behaviour and might be reluctant to use air-conditioning (Hansen et al., 2011). Community education (Loughnan et al., 2013) and opening cooling centres (Berisha et al., 2017) are some practical strategies to mitigate the impact of rising urban temperature.

With the potential increase in energy consumption, improving energy efficiency will become more crucial in the future (Meng et al., 2018; Reyna and Chester, 2017; Zhou et al., 2018). Some possible solutions include passive cooling (Santamouris and Kolokotsa, 2013; Yu et al., 2020) and increasing urban greenery (Wong et al., 2011), such as green roofs and green walls (Andric et al., 2020; Fahmy et al., 2020). Well-planned architectural design, carefully monitored air conditioning, and precise simulation technologies are possible solutions to reduce unnecessary energy consumption in a residential area (Nicol and Roaf, 2005; Wan et al., 2012). A well-adapted home would increase the resilience of vulnerable groups during the heatwave to prevent overheating (Hamdy et al., 2017). Overall, our study has highlighted the impact of socio-economic and climatic variables on domestic energy consumption. This information will help policymakers formulate energy policies to reduce the trade-offs between the energy system and climate vulnerability, which is crucial to achieving SDG 7 and SDG 13 targets (Chen et al., 2022; Sarkodie, 2022).

5.3 Limitations of this study and implications for future studies

In our study, there is a lack of long-term historical energy consumption data in Singapore. We acknowledge that the 10-year period (2005-2015) provides insufficient data to study the long-term energy consumption trend in Singapore. Considerable time was spent collecting different data and arranging them at the same resolution. This study has analyzed population grwoth, energy price, GDP, heat index, and monsoon’s influence on domestic energy consumption. In particular, we used the LMG and PMVD methods to examine the relative contribution of the above five variables, which incorporates the effect of climatic and socioeconomic factors. We acknowledge this study can only consider limited factors as our data is the accumulated monthly energy consumption data at a city scale. It is found that economic growth leads to an increase in energy consumption, and energy consumption could lead to economic growth without feedback (Belke et al., 2011; Costantini and Martini, 2010; Tsani, 2010).

Climate change could reduce electricity demand during the cold season and increase demand during the hot season (Yalew et al., 2020). This seasonal energy consumption pattern also varies with different income groups (Li et al., 2019). Unlike Hong Kong, Singapore does not experience the cold season, so it could be problematic to compare the seasonal energy consumption patterns of both cities directly. Moreover, we do not have access to the GDP data for Hong Kong and Singapore at the household level, both for the historical period (1981 - 2015) and the future forecast. Given the above factors, it is beyond the scope of this study to discuss the impact of past and future climate change on the seasonal pattern of domestic energy consumption.

Besides the long-term pattern, energy consumption also has a weekly cyclical pattern. For example, there is a different energy consumption pattern between working days and weekends in Italy (Scapin et al., 2016). However, only monthly domestic energy consumption data are available for Hong Kong and Singapore, so we cannot examine daily variability in their domestic energy consumption. Future studies can examine whether this weekly cyclical pattern occurs in Asian cities when daily energy consumption data becomes available.

Our study has analyzed the influence of climatic factors, population, energy price, and economic development on domestic energy consumption. However, other factors need to be considered. These factors include renewable energy potential and uptake (Markard, 2018), future building simulations and energy demand (Perera et al., 2020), policy intervention (Ng and Nathwani, 2010; Reyna and Chester, 2017; Zhou et al., 2018), user choices (Schot et al., 2016), lifestyle change caused by aging population (Yu et al., 2018) and household sizes (Cheung et al., 2015; Ellsworth-Krebs, 2020), and consumer reaction to temperature shift (Yau and Hasbi, 2013). Apart from normal population growth in a city, estimating the climate-related migration pattern (Labriet et al., 2015) and its impact on population size will also affect future energy use (Allen et al., 2016). Coupling models of different natures (climate, economy, energy, and environment) is often necessary to provide a more accurate simulation of future energy demand (Labriet et al., 2015; Stern et al., 2016; Yalew et al., 2020). However, linking these models is often challenging owing to the discrepancy between their temporal and spatial resolutions (Nik et al., 2020). Another difficulty is predicting extreme temperature changes from climate models, which can be considered an unpredicted outcome from energy modelling and scenarios (McCollum et al., 2020). Past studies have used a fixed threshold temperature to estimate future changes in heating and cooling. Future studies can choose a variable threshold temperature, which might better reflect heating and cooling demand (Labriet et al., 2015). The issue of model resolution and remaining biases over some model areas are other limitations of GCM. Addressing these factors is beyond the scope of our study.

6 Conclusions

We develop a framework to disaggregate the energy consumption time series of Hong Kong and Singapore. This framework uses the LMG and PMVD methods to quantify the relative importance of different variables affecting domestic energy consumption in both cities, including population, GDP, energy price, the heat index, and the monsoon index. We chose a monsoon index as a climate predictor in addition to the heat index, as large-scale synoptic patterns can affect regional temperature. Moreover, our study demonstrates that the factors of domestic energy consumption and variability are both climatic and non-climatic. Due to the rise in population and GPD, these two factors are more important in long-term energy consumption. In particular, the relative importance of socioeconomic and climatic factors in determining Hong Kong's domestic energy consumption differs for a longer (1981 – 2015) and shorter period (2005 – 2015). For Hong Kong, the population and GDP were the most important control variable for the domestic energy consumption time series between 1981 and 2015. In contrast, the heat index became the most important variable affecting Hong Kong's domestic energy consumption between 2005 and 2015. For Singapore, the monsoon index and the heat index were the major drivers of domestic energy consumption between 2005 and 2015, followed by population growth. Singapore's results reveal a different pattern compared with Hong Kong during the same period.

Our study highlights the socioeconomic factors, in addition to climate conditions, as significant determinants of domestic energy consumption trends. By demonstrating the relative importance of socioeconomic factors for Hong Kong and Singapore through the energy consumption time series, we show that climate conditions alone cannot completely explain the change in energy consumption. The combined effect of socioeconomic factors, as well as climate conditions, have to be considered simultaneously when estimating the energy consumption trend and formulating corresponding and effective climate and energy consumption solutions.

Certain conditions have to be held to apply our model to other cities. Hong Kong and Singapore are typical cities with shared features in other leading cities to some extent. The energy consumption of these two cities is highly sensitive to variations in climatic factors (e.g. temperature, heat index). As such, our model could be applied to cities in similar climate zones affected by hot weather (e.g. subtropical coastal and equatorial regions) and with a large population in a developed economy. Further studies can investigate whether our model can be used in cities outside Asia or developing countries. Factors regarding different geometric conditions and cultures can also be explored using sub-city scale data in future studies. Examining how different scales of climate factors interact with socioeconomic factors would improve the time series analysis of energy consumption and promote resilient cities.

Apart from changes in population structure, it is important to understand the implications of changing climate conditions in Hong Kong, which is likely to become hotter and have large humidity changes according to the 6 CMIP5 model results (Fig. S.6). Future increases in summertime outdoor temperature would likely increase overheating risks and the demand for air-conditioning in Hong Kong and Singapore. Climate change could affect regional atmospheric circulation patterns (e.g., shifting monsoon mechanisms), which in turn affects the local outdoor temperature conditions. How monsoon as a regional climate variable may affect future cities' energy consumption is worth further research. A hotter future with more heat extremes implies more frequent use of air-conditioning and higher domestic energy consumption in summer. In RCP 4.5 and 8.5 scenarios, there is a linear relationship between air temperature and domestic energy consumption related to the heat index effect in Singapore. In contrast, the relationship is non-linear in Hong Kong. Understanding future changes in domestic energy consumption trends will facilitate climate change mitigation and adaptation in urban environments.

7 Appendix A

We discover that energy consumption when taking population and GDP into account, are two very different indicators. Population and GDP in Hong Kong (1985 – 2015) and Singapore (2005 - 2015) per se are correlated (see Fig. A.1a and Fig. A.1b), showing a positive linear relationship in both cases. Nevertheless, per capita energy consumption (kWh per capital, Fig. A.1c) illustrates a very different pattern from energy intensity (kWh/US$, Fig. A.1d). Fig. A.1c shows that per capita energy consumption is stabilising in Hong Kong in 2005 – 2015 and gently climbing after a significant drop and comeback in Singapore in the same period. In contrast, Hong Kong's energy intensity moved gradually downwards in 2005 – 2015; Singapore intensity moved downwards from 2005 – 2013 and upwards again from 2013 – 2015 , Fig. A.1d). These results suggest that population and GDP in energy consumption present different patterns and may have different significances in energy consumption. Moreover, our PMVD models suggest that population and GDP can have different levels of impact.

Fig. A.1 Hong Kong Population vs. GDP from 1985 – 2015, b) Singapore Population vs. GDP from 2005 – 2015, c) per capita energy consumption of Hong Kong (1985 - 2015) and Singapore (2005 - 2015), d) energy intensity of Hong Kong (1985 - 2015) and Singapore (2005 - 2015).

8 Appendix B

We used CDF for bias correction for temperature and relative humidity and then got the bias-corrected HI (Fig. B.1 and Fig. B.2). The seasonality of the climate models generally matches well with observed HI, especially for Hong Kong (Fig. B.1). After bias correction, the model derived HI have a high consistency with observed HI at both Hong Kong and Singapore (all Diff values are less than 0.5; Fig. B.2). Moreover, we have compared the observed monsoon index and the climate model outputs. The seasonality of the climate models matches very well with observed monsoon indices (Fig B.3). Moreover, we have compared the biased corrected monsoon indices with climate model outputs. Results are also very consistent (Fig B.4).

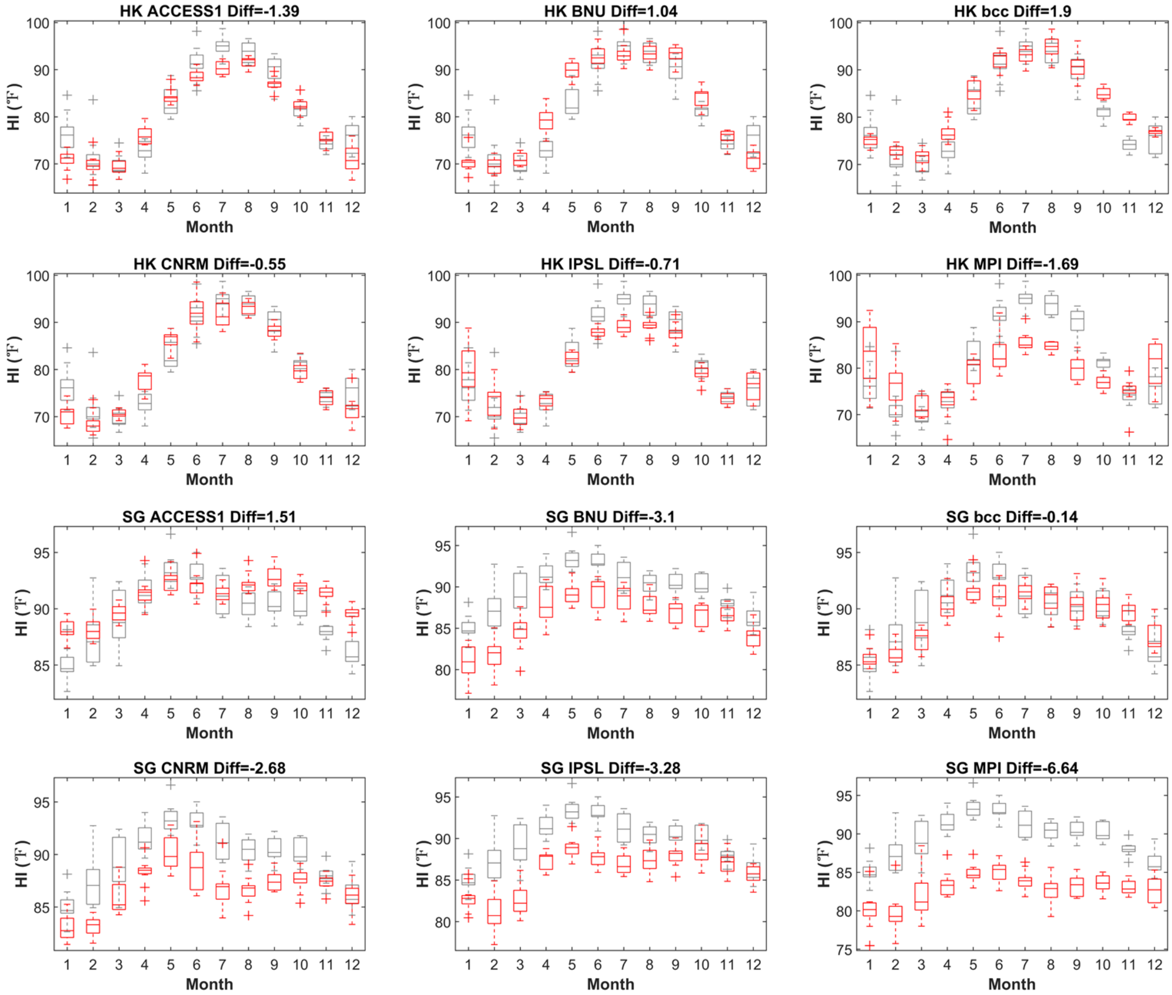

Fig. B.1 The comparison between observed HI (grey boxes) and climate model derived HI (red boxes) at Hong Kong (HK) and Singapore (SG). EAMI refers to the East Asian Monsoon Index. Diff refers to the median difference between observed monsoon index and (biased corrected) climate model derived monsoon index. The readers are referred to Table 1 for the acronym of different climate models.

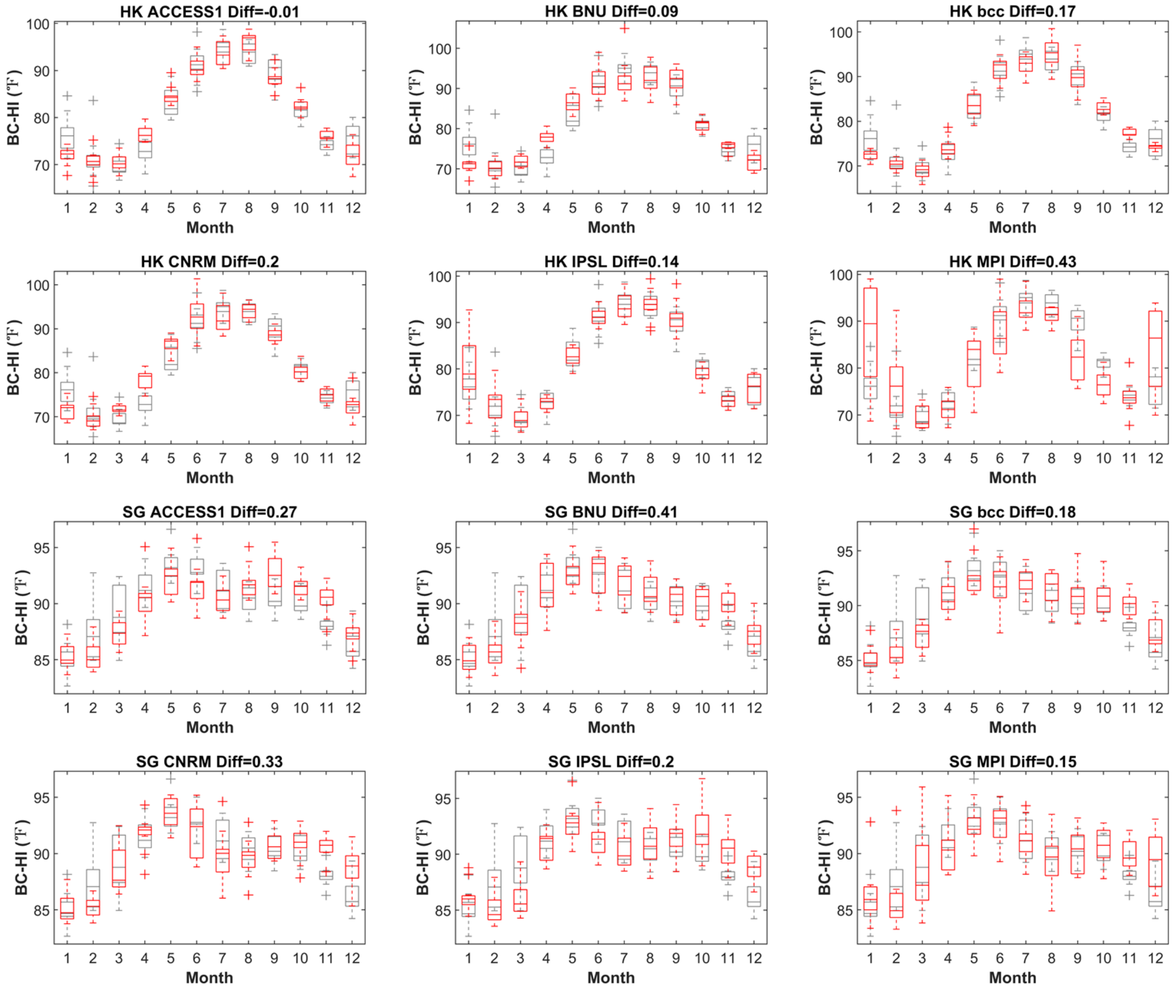

Fig. B.2 The comparison between observed HI (grey boxes) and biased corrected climate model derived HI (BC-HI; red boxes) at Hong Kong (HK) and Singapore. EAMI refers to the East Asian Monsoon Index. Diff refers to the median difference between observed monsoon index and biased corrected climate model derived monsoon index. The readers are referred to Table 1 for the acronym of different climate models.

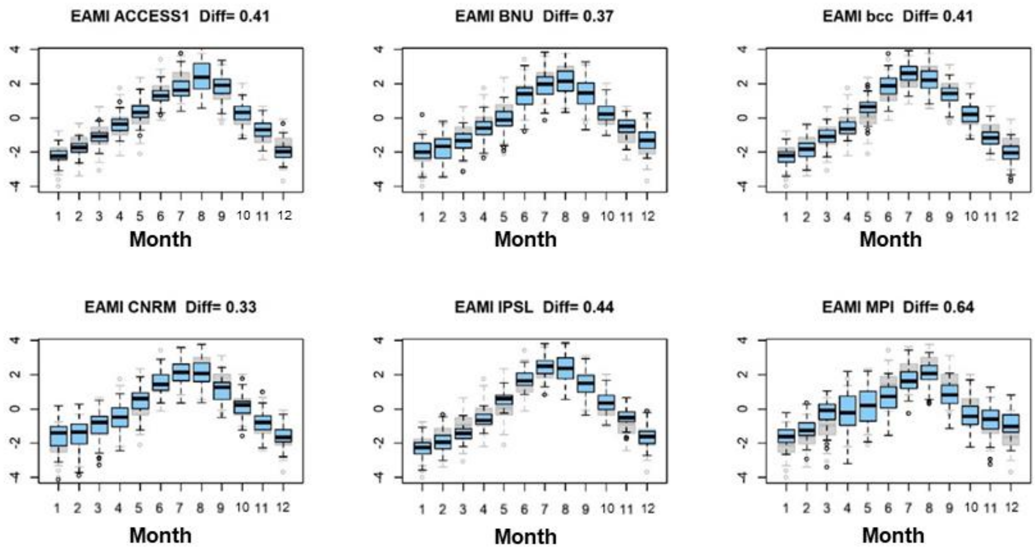

Fig. B.3 Comparison between observed monsoon indices (grey boxes) and climate model outputs (blue boxes). EAMI refers to the East Asian Monsoon Index. Diff refers to the median difference between observed monsoon index and (biased corrected) climate model derived monsoon index. The readers are referred to Table 1 for the acronym of different climate models.

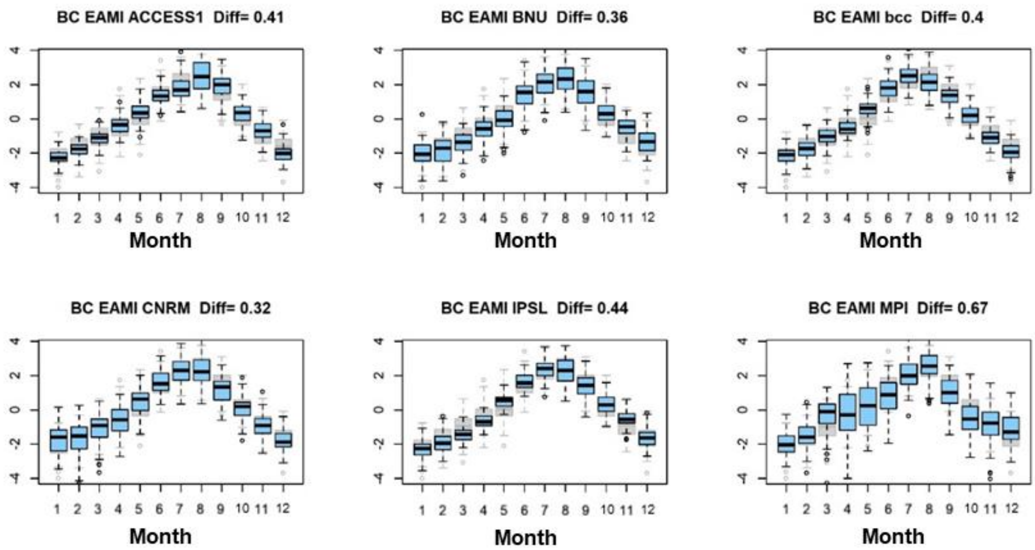

Fig. B.4 Comparison between observed monsoon indices (grey boxes) and biased corrected (BC) climate model outputs (blue boxes). EAMI refers to the East Asian Monsoon Index. Diff refers to the median difference between observed monsoon index and biased corrected climate model derived monsoon index. The readers are referred to Table 1 for the acronym of different climate models.

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