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Abstract

In subtropical Hong Kong, energy is consumed for cooling in summer and heating in winter for human comfort. This study attempts to identify the monthly variation of energy consumption and the correlation between energy consumption and climate factors in Hong Kong using the monthly energy consumption data and meteorological observations from 1970 to 2009. Two climatic indices, namely cooling degree-days (CDD) and heating degree-days (HDD), were used to correlate with the energy consumption in warm months (May to October) and cool months (December to February) respectively. The results revealed that there were significant monthly variations in the electricity consumption in the domestic and commercial sectors as well as in gas consumption in the domestic sector. In both sectors, CDD had a significant positive correlation with electricity consumption in warm months and the consumption per unit CDD increased from 1970s to 2000s, probably attributable to the higher living standard and the increased popularity of air-conditioning during this period. For cool months, electricity or gas consumption did not show significant positive correlation with HDD in both sectors. Looking into the future, the projected increase in the mean temperature implies a significant increase in CDD by the end of 21st century. This may have implications on the future energy demand if the current energy consumption pattern does not change.

1 Introduction

Climate has long been considered as one of the key factors influencing the energy consumption in a city. Amongst various climatic factors which may affect energy consumption (e.g. temperature, relative humidity, solar radiation, etc.), previous studies have reported that temperature is the most dominant one (Sailor and Munoz, 1997; Yan, 1998). In subtropical Hong Kong, the annual average temperature is 23.1^{o}C with hot and humid summer and relatively mild winter. In the warmer months, such as May to August, afternoon temperatures often exceed 31 °C whereas at night, temperatures generally remain around 26 °C with high humidity. The coldest months in Hong Kong are January and February. Occasionally, there are cold snaps with urban temperatures dropping below 10 °C (Lee *et al.*, 2006; HKO, 2009a).

Figure 1 shows the annual electricity and gas consumption per capita in Hong Kong in both the domestic and commercial sectors from 1970 to 2009. It also shows that electricity consumption was much higher than that of the gas consumption and the commercial sector consumed more than twice of the electricity consumed by the domestic sector. The fastest growth in the electricity consumption occurred during the period of 1980's and 1990's, which was the period of high economic growth in Hong Kong. Moreover, it is possible that the increase in service-oriented economic activities (e.g. financial services, retailing, etc) has contributed to the rise in commercial electricity beginning from 1980. Several studies have been conducted to investigate the climatic and economic influences on residential electricity consumption in Hong Kong in 1990s. Lam (1998) pointed out that steady economic growth and improvement in income per household could be related to the increase in energy consumption. Lam (1996) also indicated that the increase in the residential energy consumption in 1990s was mainly due to air-conditioning. According to the Electrical and Mechanical Services Department (EMSD) of HKSAR Government, over 80% of households rely on air-conditioners to maintain thermal comfort in summer. Air-conditioning on average accounts for about 34% of all electricity consumption in both domestic and commercial sectors in 2000-2007 in Hong Kong, which is the largest end-use in electricity (EMSD, 2009).

The impact of climate change on the energy consumption for heating and cooling is another major concern in recent years (Chen *et al.*, 2007; Parkpoom and Harrison, 2008; Liu and Sweeney, 2008). Locally, Fung *et al.* (2006) studied the temperature dependence of the monthly energy consumption in Hong Kong for the period from 1990 to 2004 and indicated that temperature rise resulted from global warming and local urbanization could have implications on the energy sector of Hong Kong.

Using the monthly energy consumption data and temperature data in Hong Kong for the past four decades (from 1970 to 2009), this study attempts to identify the monthly variation of energy consumption in Hong Kong and the correlation between energy consumption and climate indices, namely the cooling degree-day and heating degree-day. The data and analysis methods used in this study are described in Section 2. The analysis results are presented and discussed in Section 3. The potential implication of climate change on the future energy demand based on the current energy consumption pattern is also briefly discussed in Section 4.

2 Data and Methodology

2.1 Meteorological Data

The Hong Kong Observatory Headquarters (HKOHq), located at the urban area, has been conducting temperature measurements continuously since 1885 apart from a break during World War II from 1940 to 1946. In this study, the daily and monthly mean temperatures at HKOHq from 1970 to 2009 were used. Metadata related to the instruments and temperature measurement at HKOHq have been documented in the Observatory's publications (Lee *et al.*, 2006; HKO, 2009b).

2.2 Cooling Degree-Days and Heating Degree-Days

Two climatic indices, namely cooling degree-day (CDD) and heating degree-day (HDD), are adopted in this study. CDD has been used to assess the climate influence on cooling energy consumption in subtropical climate (Lam, 1995). Similarly, HDD has been commonly adopted to estimate space heating requirement in temperate and cold climates (Eto, 1988; Day and Karayiannis, 1999; Valor *et al.*, 2001).

CDD (HDD) indicates how often and to what extent cooling (heating) will be required during a particular period. Monthly CDD (HDD) is the monthly total of the differences between daily average air temperature and the base temperature. The larger the value of CDD (HDD), the more cooling (heating) is required.

Monthly CDD and HDD are calculated based on the following formula:

$$CDD = \sum_{i=1}^{M} (T_i - T_{base}) \qquad (\text{For } T_{base} > T_i,\ (T_i - T_{base}) = 0)$$

$$HDD = \sum_{i=1}^{M} (T_{base} - T_i) \qquad \text{(For } T_i > T_{base},\ (T_{base} - T_i) = 0\text{)}$$

where M is the number of days in a month, T_i is the mean daily temperature of day i and T_{base} is the base temperature.

Different climatic regions and different building types can have different base temperature (Ruth and Amato, 2005). In this study, the base temperatures follow those of the Ministry of Housing and Urban-Rural Development in China (2005), which defines the base temperatures as 26.0°C and 18.0°C for CDD and HDD respectively. Daily mean temperature data recorded at the HKOHq were used in the calculation of monthly CDD and HDD in Hong Kong.

2.3 Energy Consumption and Population Data

Monthly electricity consumption data from 1970 to 2009 and monthly gas consumption data from 1975 to 2009 from Census and Statistics Department (C&SD), HKSAR Government, were used in this study (CS&D, 2010). Annual population data in Hong Kong from C&SD was used to calculate the monthly consumption per capita.

2.4 Warm Months and Cool Months

The 30-year monthly normal temperature data (1971-2000) at the HKOHq is given in Table 1 (Lee *et al.*, 2006). In this study, May to October are regarded as the warm months in which space cooling would be required to achieve thermal comfort in Hong Kong. December to February are defined as cool months when space heating may be required instead.

2.5 Correlation analysis

Monthly energy consumption, CDD and HDD data were normalized to 30-day values in all months to account for the difference in the number of days in calendar months. In order to investigate the possible changes in the consumption profile in different decades, the data of energy consumption were stratified into four 10-year periods, namely 1970-1979 (1970s), 1980-1989 (1980s), 1990-1999 (1990s) and 2000-2009 (2000s).

Energy consumption per capita in warm months and cool months for both domestic and commercial sectors were analyzed. For warm months, only electricity consumption data was considered. In cool months, both electricity and gas consumptions were examined as water heating was one of the main sources of energy consumption.

Correlation analysis was made using linear regression and t-test (Karl *et al.*, 1993; Easterling *et al.*, 1997; Storch and Zwiers, 1999). Linear regression lines were fitted to the parameters by least squares. The sensitivity of energy consumption was then taken as the slope of the fitted straight line. Two tailed t-test was applied to test the statistical significance of the trend at 5% significance level. The test statistics *t* used is:

$$t = r\sqrt{\frac{n-2}{1-r^2}}$$

where *r* is the correlation coefficient, following a t-distribution with *n*-2 degrees of freedom.

3 Results and Discussions

3.1 Observed Trends in HDD and CDD

Variations of the total CDD in the six warm months and total HDD in the three cool months from 1885 to 2009 are shown in Figure 2a and 2b respectively. They show that there was an increasing trend in the total CDD and a decreasing trend in total HDD. Both trends were statistically significant at 5% level. The trends were in line with the increasing trend of the mean temperature in Hong Kong observed over the same period under the combined effect of global warming and local urbanization (Lee *et al.*, 2006; Ginn *et al.*, 2010).

3.2 Energy Consumption in Warm and Cold Months

Figure 3 shows the 40-year (1970-2009) average of the (a) domestic electricity, (b) commercial electricity, (c) domestic gas and (d) commercial gas consumptions per capita in different months. Electricity consumption in Hong Kong appeared to have a significant monthly variation with higher electricity consumption from May to October in both domestic and commercial sectors (Figures 3a and 3b). This is likely due to the large electricity demand for air-conditioning in warm months (Lam, 1998). On average, the domestic electricity consumption per capita peaks in August and falls to a minimum in December. The peak consumption in August was more than the twice of that of December. Similar monthly variation in the electricity consumption was also observed in the commercial sector with the maximum and minimum consumption in September and January respectively.

For gas consumption, monthly variation was also observed in domestic sector as

depicted in Figure 3c. The gas consumption is higher during cool months, possibly due to the gas demand for water heating (Fung *et al.*, 2006). However, there is no obvious monthly variation in commercial gas consumption (Figure 3d). This may be due to the fact that weather-induced gas consumption is less significant in the commercial sector.

To analyze the change of the monthly variation in energy consumption in Hong Kong over the 40-year period, the energy consumption variation (ΔE) in each year is defined as follows:

$$\Delta E = E_{\text{peak}} - E_{\text{base}}$$

where the peak energy consumption (E_{peak}) and the base energy (E_{base}) are taken respectively as the maximum monthly and minimum monthly consumption in a year. E_{base} in general represents the base load which is the amount of energy consumed without air-conditioning or heating requirement (i.e. independent of weather). ΔE, to a certain extent, reflects the possible range of energy consumption in a month due to weather.

Figure 4a illustrates that the domestic and commercial electricity consumptions in Hong Kong exhibited an annual cycle. As shown in Figure 4b, ΔE for electricity consumption in Hong Kong increased significantly in the last 4 decades in both the domestic and commercial sectors.

The time series of monthly gas consumption variation is illustrated in Figure 5a. Similar to monthly electricity consumption, the annual cycle of domestic gas consumption was prominent. The ΔE for domestic gas consumption showed a long-term increasing trend from 1975-2009 (Figure 5b) and was much larger than that of the commercial sector.

3.3 Correlation Analysis

3.3.1 Domestic Sector

To explore the dependence of electricity consumption per capita on CDD in the recent four decades, the scatter diagrams of monthly electricity consumptions per capita were plotted against the corresponding monthly CDD in Figure 6. During warm months (from May to October), there was a statistically significant (at 5% level) positive correlation between monthly CDD and monthly electricity consumption per capita in the domestic sector for all the four decades (1970s, 1980s, 1990s and 2000s). The results also revealed that the electricity consumption per CDD (slope) was increasing from 1970s to 2000s (Table 2a). This suggests that the electricity consumption in domestic sector has become more and more sensitive to changes in CDD in the past 40 years. In other words, for each degree of CDD

increase, more electricity was consumed per capita in 2000s than that of the previous three decades. During cool months (December - February), there was no statistically significant correlation between monthly HDD and monthly electricity or gas consumption per capita in all the 4 decades (Figures 7 and 8, Tables 2b and 2c).

3.3.2 Commercial Sector

Figure 9 and Table 3a summarize the correlation results of electricity consumption per capita in warm months in the commercial sector. During warm months, the monthly electricity consumption per capita in commercial sector exhibited a statistically significant positive correlation with monthly CDD in 1990s and 2000s while there was no significant correlation in 1970s and 1980s. Similar to the domestic sector, the consumption per CDD (slope) increased from 1990's to 2000's in the commercial sector.

The correlation results of electricity and gas consumptions with HDD in cool months are tabulated in Tables 3b and 3c. During cool months, both electricity and gas consumptions had no significant positive dependence on HDD in all 4 decades.

3.3.3 Discussion

With rising income and living standards in Hong Kong in recent decades, air conditioning in buildings is not considered as a luxury any more and has become a common need for both the residential and commercial sectors. This has led to a rapid increase in the number of air-conditioners used in Hong Kong in last two decades (Chow, 2001). A survey of some public residential buildings indicated that the saturation rate of air-conditioners was 51% in 1989 (Hills, 1994). A similar survey in 1998-1999 found that the saturation rates in public and private residential buildings increased significantly to 87.1% and 92.8% respectively (Wan and Yik, 2004). Moreover, the ownership level of air conditioners in public and private residential buildings were 1.67 and 2.66 units per household respectively (Wan and Yik, 2004). The observed increase in the sensitivity of electricity consumption to CDD changes in warm months is very likely attributable to the increased use of air conditioning in Hong Kong.

The lack of significant positive correlation between electricity consumption and HDD can be explained by the low electricity demand for space heating in Hong Kong in cool months (Tso and Yau, 2003; Wan and Yik, 2004). The winter in Hong Kong is relatively mild with an average temperature of about 16.7 ^{o}C. Space heating is often not required except for some of the cold days in winter (On average, there are about 19 days in each year with a daily minimum temperature below 12 ^{o}C (Lee *et al.*, 2006)). This probably explains

why the electricity consumption due to space heating in cool months is not significant when compared with the variations in electricity consumptions for other electrical appliances, such as lighting, washing machines and refrigerators.

For gas consumption, although air temperature could affect the gas consumption for water heating in the domestic sector (Fung *et al.*, 2006), the monthly gas consumption in cool months did not exhibit a statistically significant correlation with HDD. Several factors complicate the issue. Apart from climatic factor, it is possible that the domestic gas consumption in Hong Kong during December to February might be affected by the vacation and dinning culture of Hong Kong people during the Christmas, New Year and Lunar New Year holidays, as hundred of thousands of Hong Kong residents dined out or left Hong Kong. Although there appears to be few studies on the behaviors of Hong Kong people, it might also be that they take hot water bath/shower year round.

In the commercial sector, the gas consumption has no significant annual cycle. The gas consumption in most commercial buildings in Hong Kong is not high except those for catering services of which gas consumption is not significantly affected by temperatures.

4 Implications on future energy demand

Results of this study reveal that, with electricity as the most dominant energy end use in Hong Kong, there is a positive correlation between CDD and the electricity consumption per capita in both domestic and commercial sectors, especially in the summer. Under the combined effect of global warming and local urbanization, the increasing trend of the mean temperature in Hong Kong is expected to continue in the 21st century (Figure 10) (Leung *et al.*, 2007). The projected increase in the mean temperature implies a significant increase in CDD in the 21st century and could possibly lengthen the period of warm months. Such an increase in CDD may have implications on the future energy demand for cooling if the current energy consumption pattern persists.

5 Conclusion

Climatic influence on the energy consumption in the domestic and commercial sectors was analyzed using monthly energy consumption data and temperature data in Hong Kong from 1970 to 2009. It was found that the electricity consumption per capita in both the domestic and commercial sectors as well as the gas consumption per capita in the domestic sector exhibited significant annual cycle. In warm months (from May to October),

there were statistically significant positive correlations between CDD and the electricity consumption per capita in both the domestic and commercial sectors. Moreover, the electricity consumption per unit CDD increased noticeably from 1970s to 2000s. In cool months, electricity and gas consumption per capita did not show significant positive correlation with HDD in both sectors. The projected increase in the mean temperature in the 21st century implies a significant increase in CDD by the end of 21st century in Hong Kong. This may have implications on the future energy demand if the current energy consumption pattern does not change.

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Figures and Tables

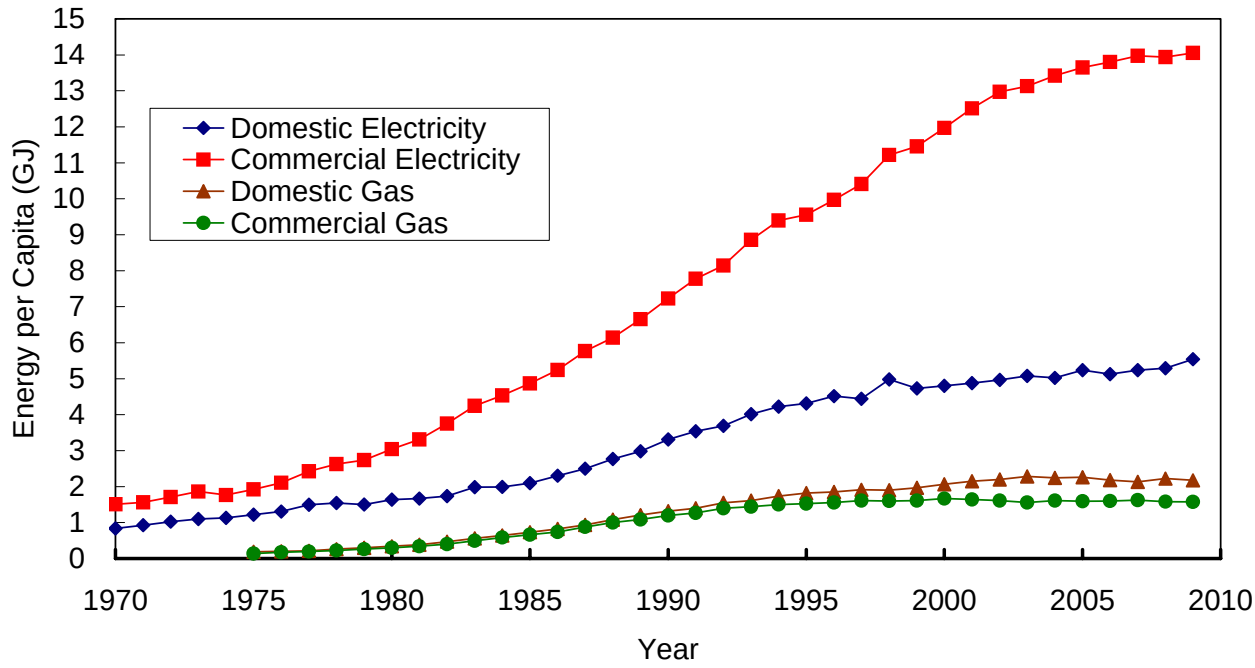

Figure 1. Annual electricity and gas consumption per capita in Hong Kong (1970-2009)

Table 1. Monthly mean temperature at the Hong Kong Observatory Headquarters (1971-2000). Months in pink and blue are defined as warm and cool months respectively.

Month	Daily Mean Temperature (°C)
Jan	16.1
Feb	16.3
Mar	18.9
Apr	22.5
May	25.8
Jun	27.9
Jul	28.7
Aug	28.4
Sep	27.6
Oct	25.3
Nov	21.4
Dec	17.8

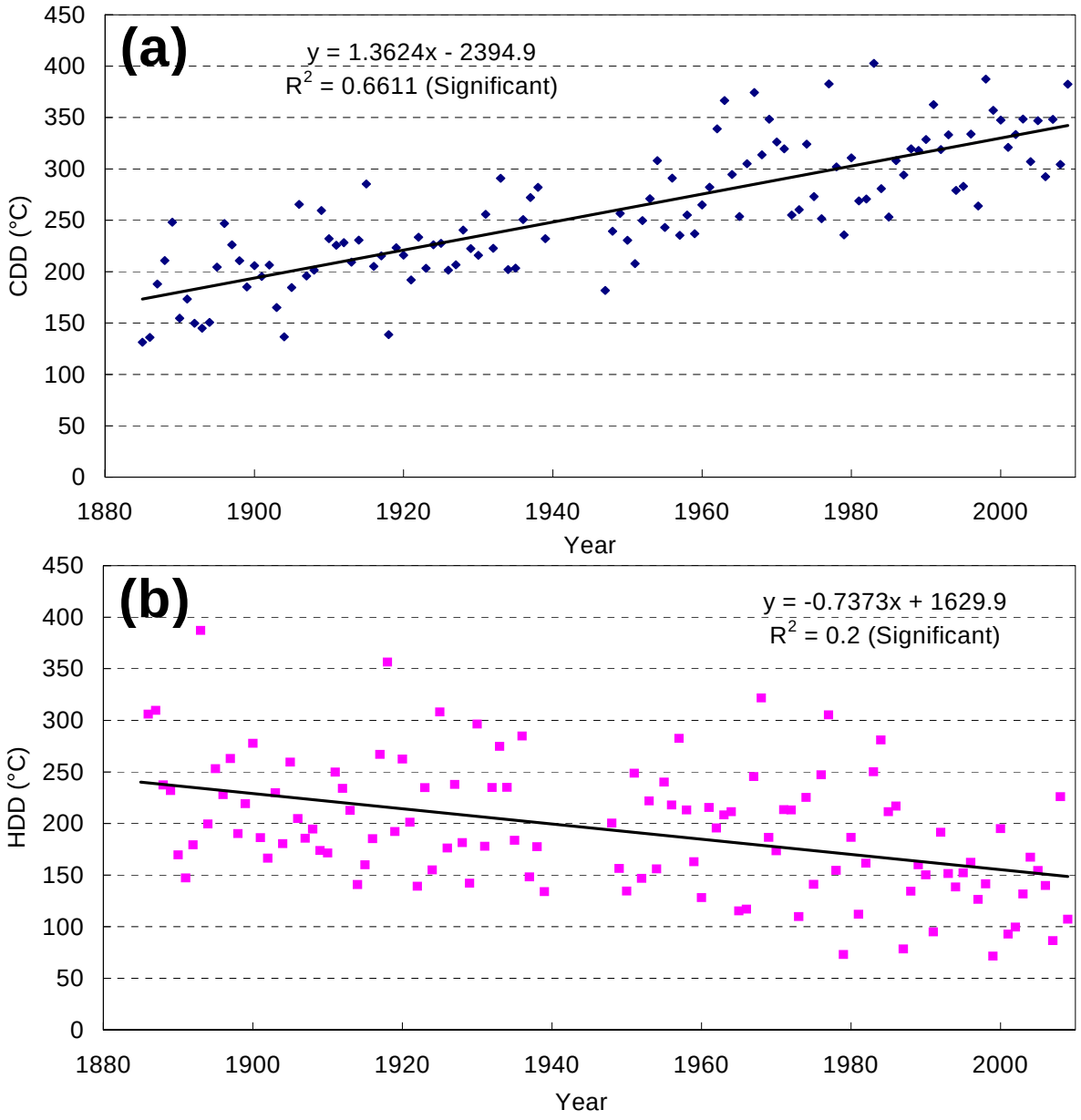

Figure 2. Time series of yearly degree-days in Hong Kong from 1885 to 2009 for (a) Cooling Degree-Day in warm months (May-Oct) and (b) Heating Degree-Day in cool months (Dec-Feb).

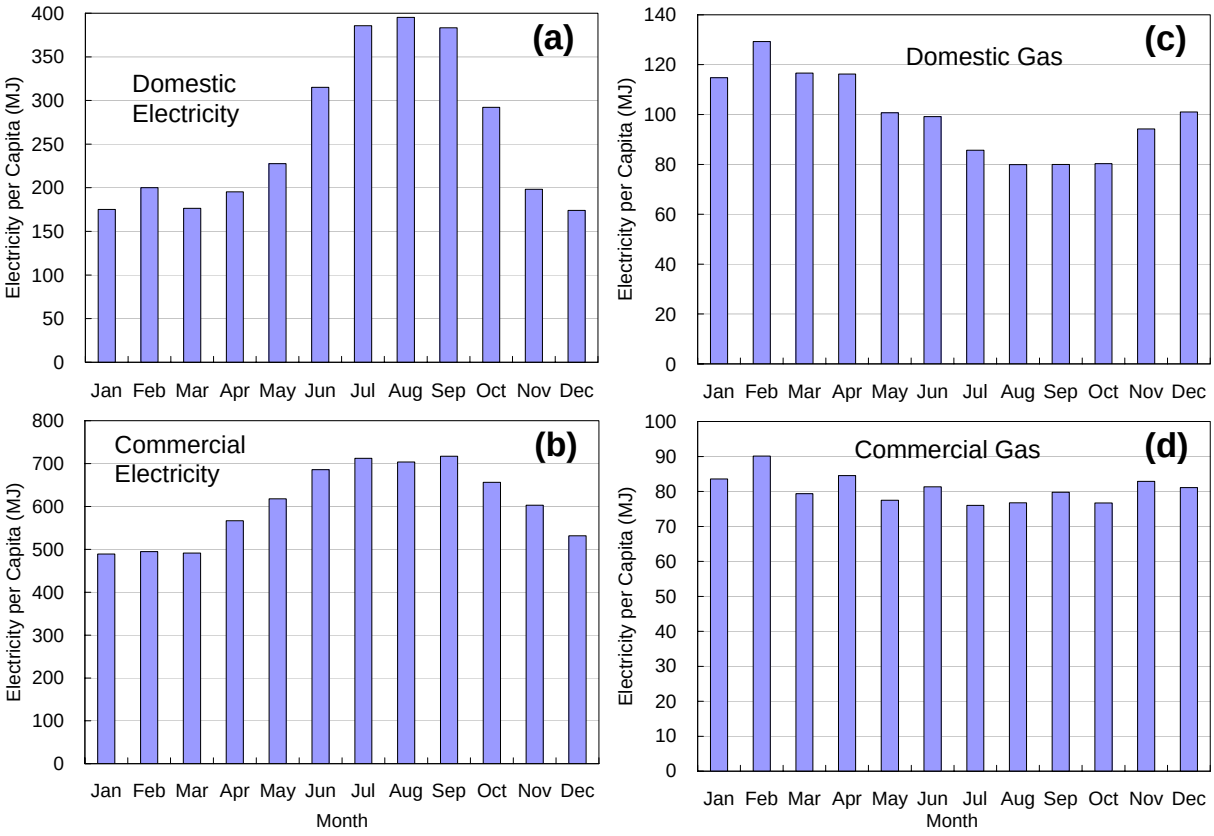

Figure 3. 1970-2009 average monthly energy consumption normalized to 30 days for each month in Hong Kong for (a) Domestic electricity, (b) Commercial electricity, (c) Domestic gas, and (d) Commercial gas.

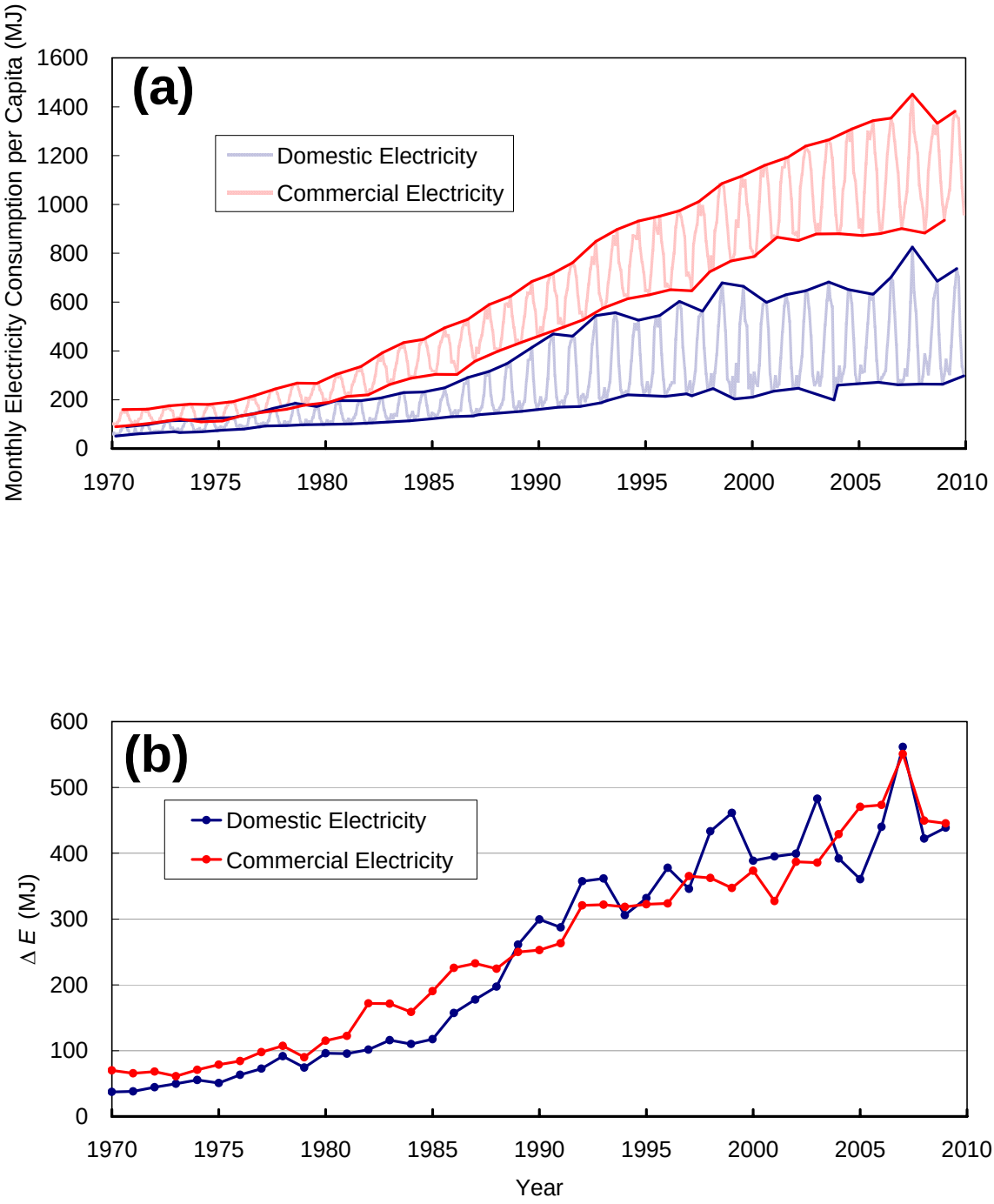

Figure 4. (a) 1970-2009 monthly domestic and commercial electricity consumption per capita (normalized to 30 days per month) in Hong Kong. The upper and lower solid lines are yearly values of E_{peak} and E_{base} respectively. (b) Energy consumption variation (ΔE) for electricity consumption.

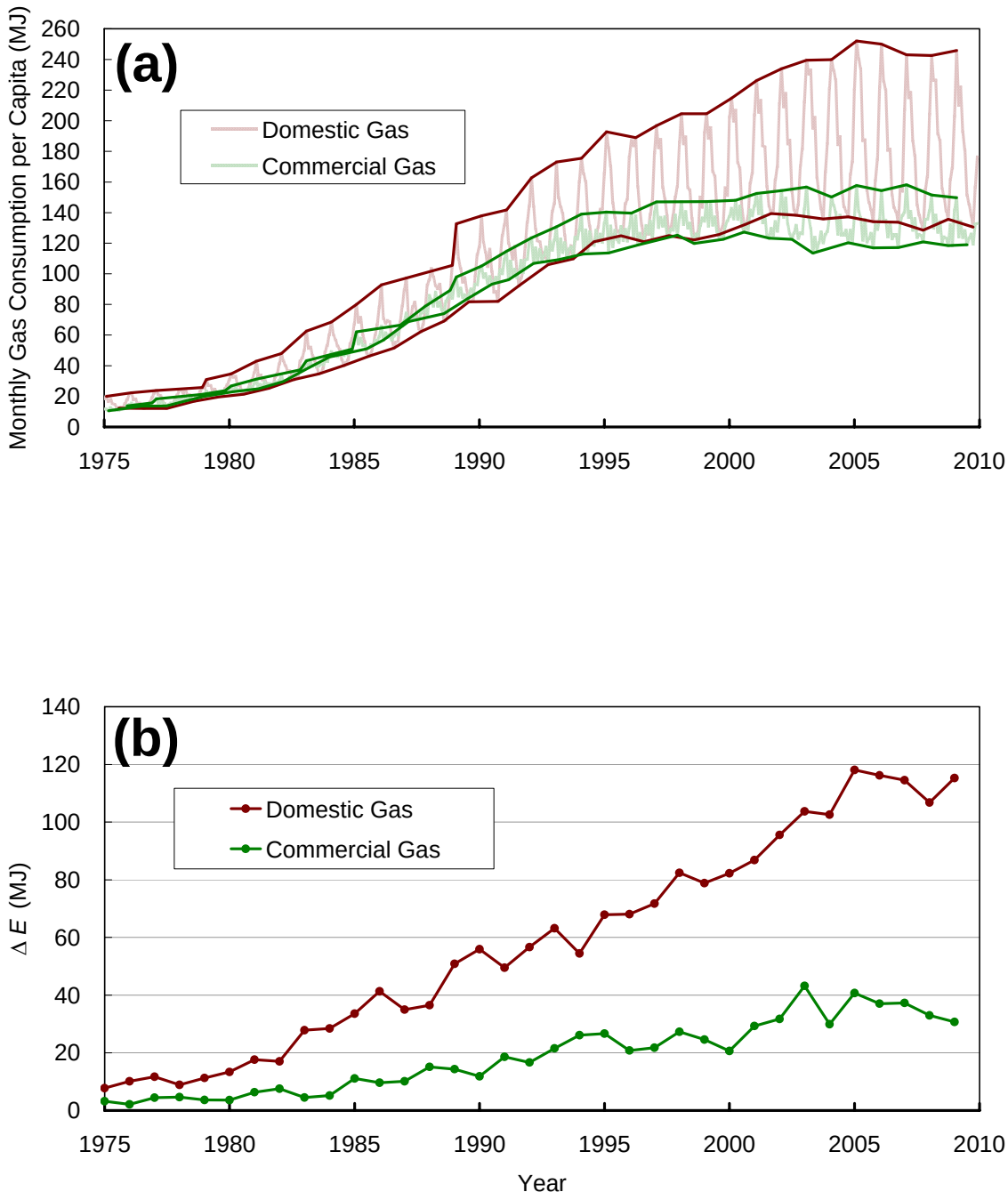

Figure 5. (a) 1975-2009 monthly domestic and commercial gas consumption per capita (normalized to 30 days per month) in Hong Kong. The upper and lower solid lines are yearly values of E_{peak} and E_{base} respectively. (b) Energy consumption variation (ΔE) for gas consumption.

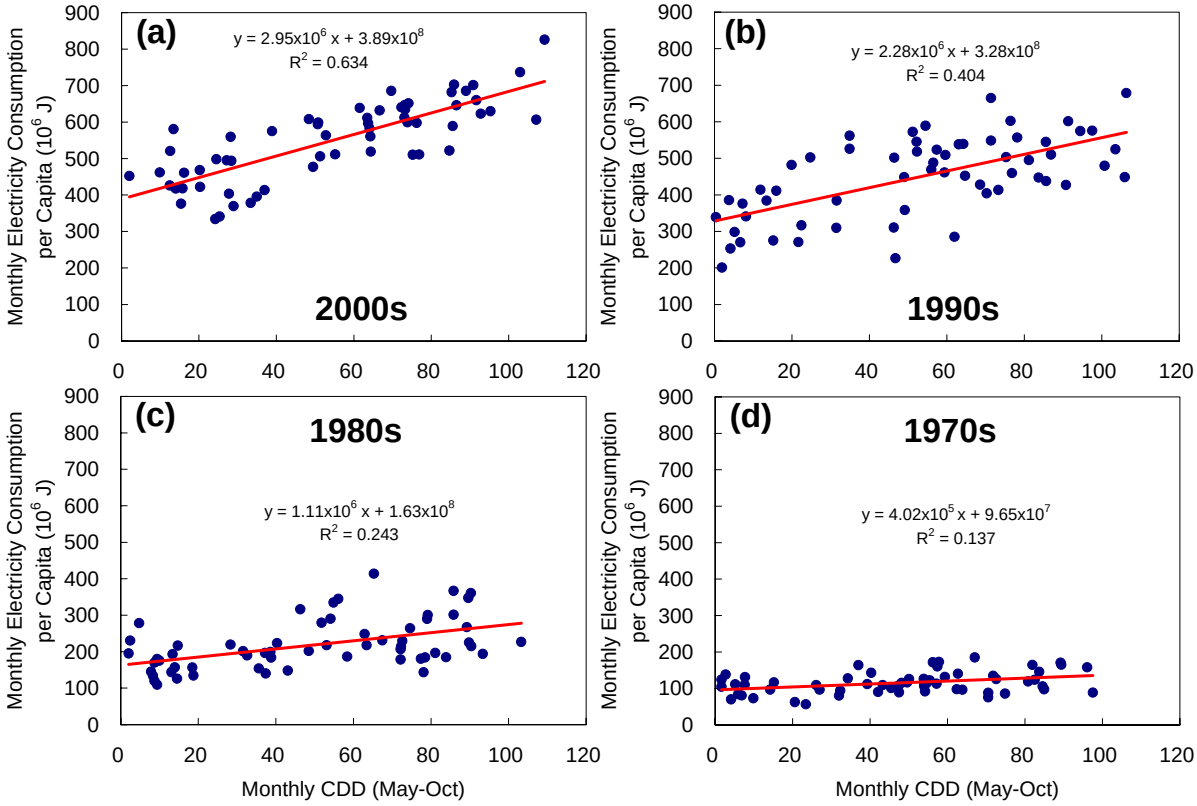

Figure 6. Monthly electricity consumption per capita in warm months against monthly CDD in (a) 2000's, (b) 1990's, (c) 1980's, and (d) 1970's, in domestic sector in Hong Kong.

Table 2a. Correlation results for electricity consumption per capita in warm months in domestic sectors in Hong Kong.

Decade	Slope (10^6 J/°C)	Correlation Coefficient (r)	Significant at 5%?
2000s	2.95	0.80	Yes
1990s	2.28	0.64	Yes
1980s	1.11	0.49	Yes
1970s	0.402	0.37	Yes

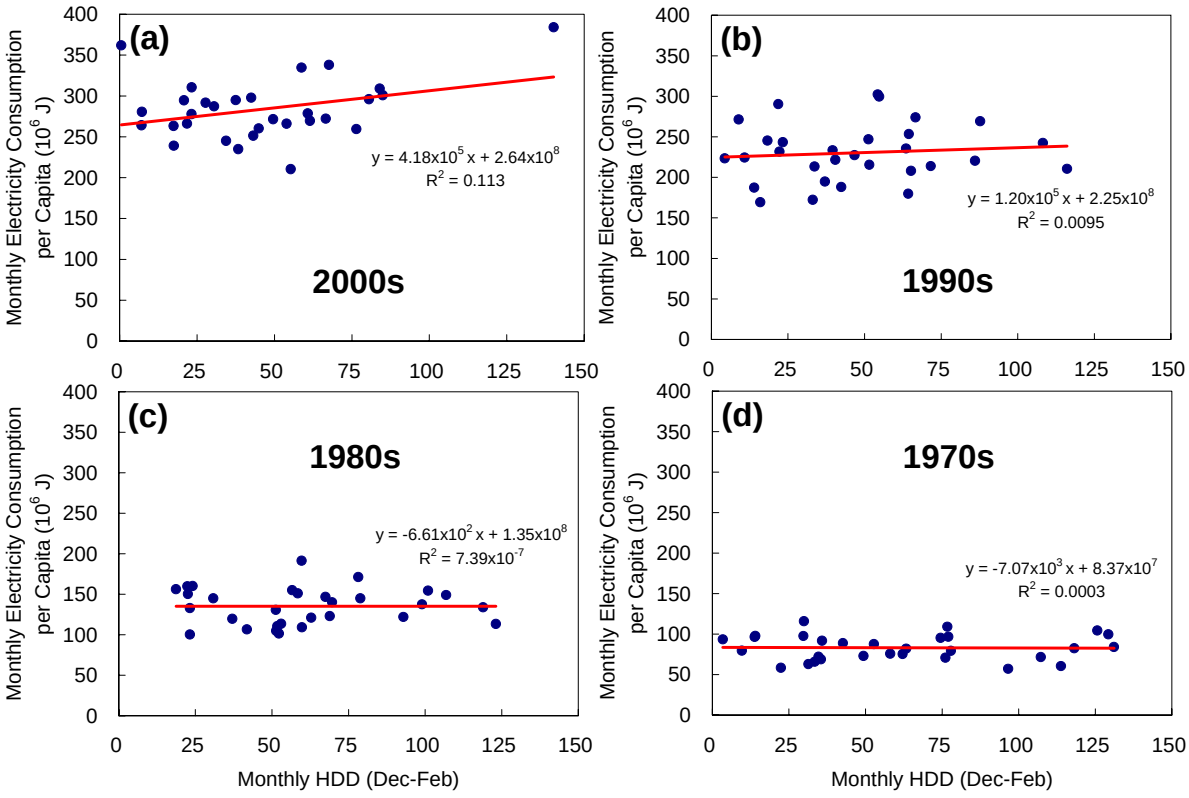

Figure 7. Monthly electricity consumption per capita in cool months against monthly HDD in (a) 2000's, (b) 1990's, (c) 1980's, and (d) 1970's, in domestic sector in Hong Kong.

Table 2b. Correlation results for electricity consumption per capita in cool months in domestic sectors in Hong Kong.

Decade	Slope (10^6 J/°C)	Correlation Coefficient (r)	Significant at 5%?
2000s	0.42	0.34	No
1990s	0.12	0.10	No
1980s	-0.000661	0.00	No
1970s	-0.00707	-0.02	No

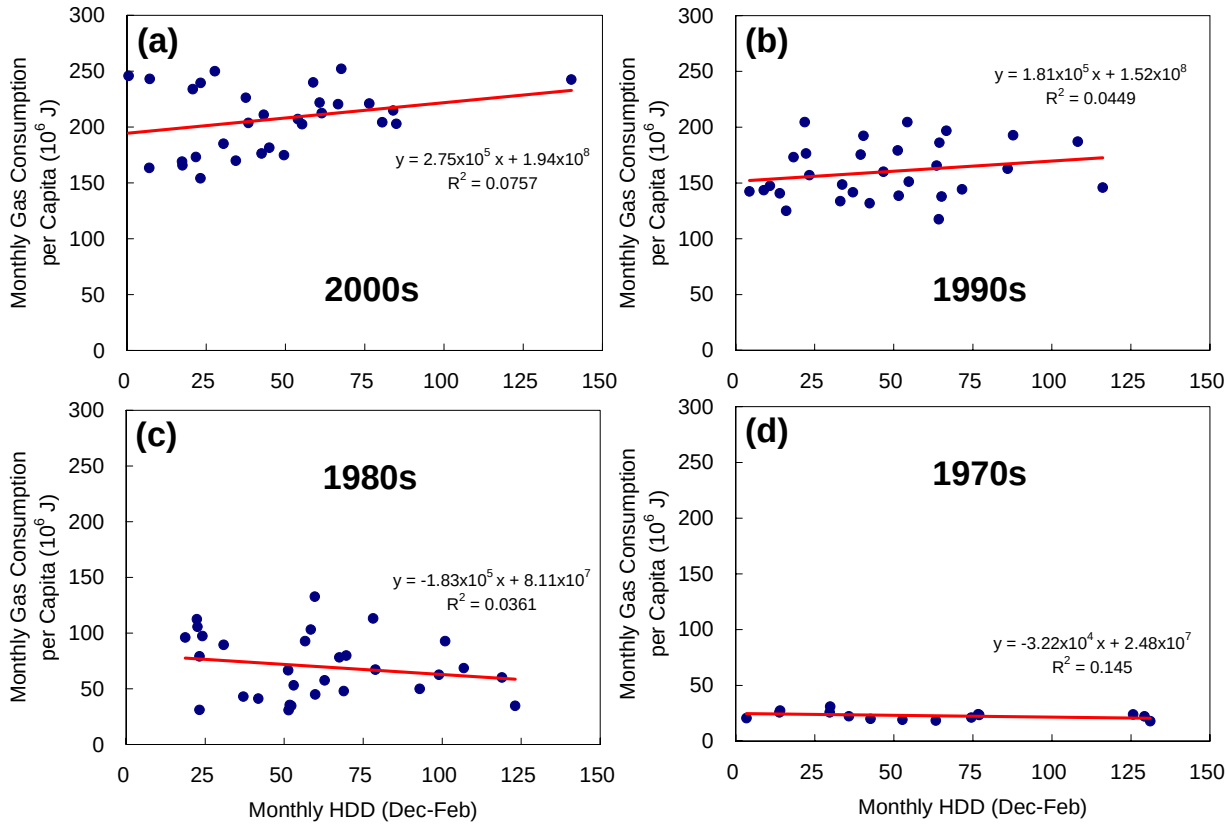

Figure 8. Monthly gas consumption per capita in cool months against monthly HDD in (a) 2000's, (b) 1990's, (c) 1980's, and (d) 1970's, in domestic sector in Hong Kong.

Table 2c. Correlation result for gas consumption per capita in cool months in domestic sectors in Hong Kong.

Decade	Slope (10^6 J/°C)	Correlation Coefficient (r)	Significant at 5%?
2000s	0.275	0.28	No
1990s	0.181	0.21	No
1980s	-0.183	-0.19	No
1970s	-0.0322	-0.38	No

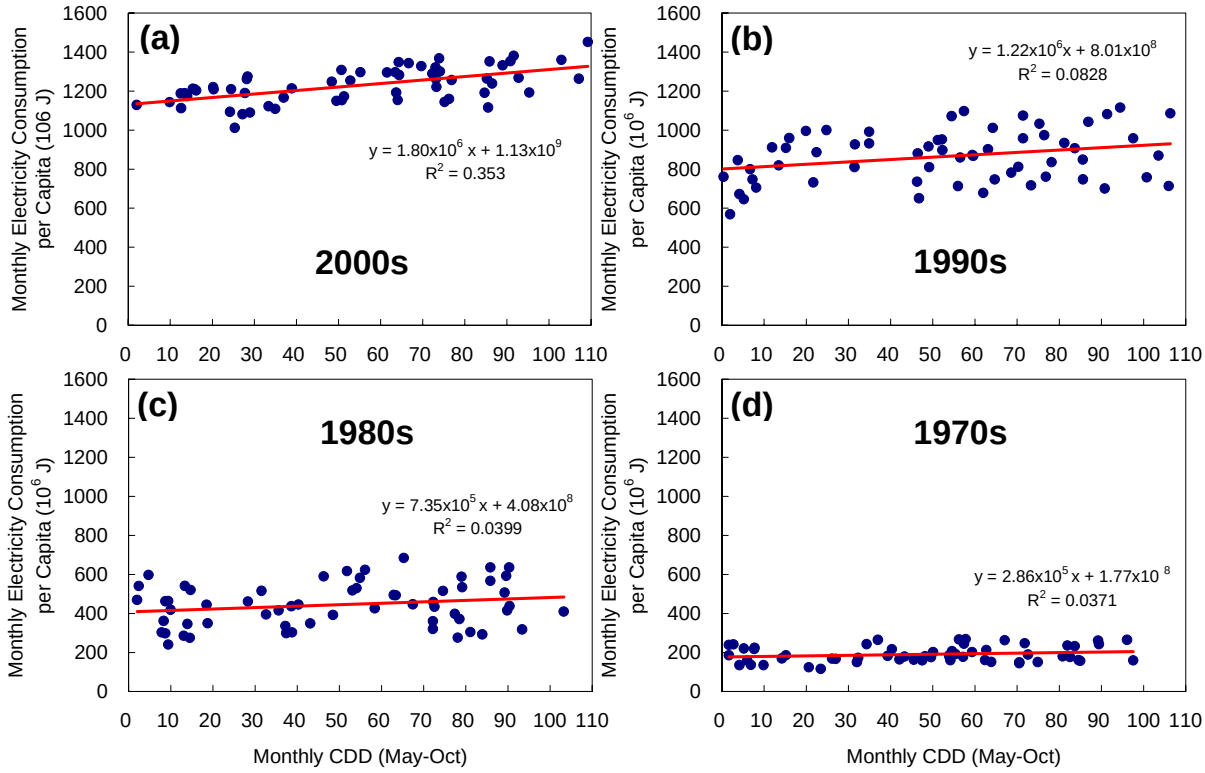

Figure 9. Monthly electricity consumption per capita in warm months against monthly CDD in (a) 2000's, (b) 1990's, (c) 1980's, and (d) 1970's, in commercial sector in Hong Kong.

Table 3a. Correlation result for electricity consumption per capita in warm months in commercial sector in Hong Kong.

Decade	Slope (10^6 J/°C)	Correlation Coefficient (r)	Significant at 5%?
2000s	1.80	0.59	Yes
1990s	1.22	0.29	Yes
1980s	0.735	0.20	No
1970s	0.286	0.19	No

Table 3b. Correlation result for electricity consumption per capita in cool months in commercial sector in Hong Kong.

Decade	Slope (10^6 J/°C)	Correlation Coefficient (r)	Significant at 5%?
2000s	-0.774	-0.40	Yes
1990s	-0.889	-0.25	No
1980s	-0.889	-0.32	No
1970s	-0.25	-0.31	No

Table 3c. Correlation result for gas consumption per capita in cool months in commercial sector in Hong Kong.

Decade	Slope (10^6 J/°C)	Correlation Coefficient (r)	Significant at 5%?
2000s	0.0372	0.10	No
1990s	0.0745	0.16	No
1980s	-0.203	-0.26	No
1970s	-0.0327	-0.38	No

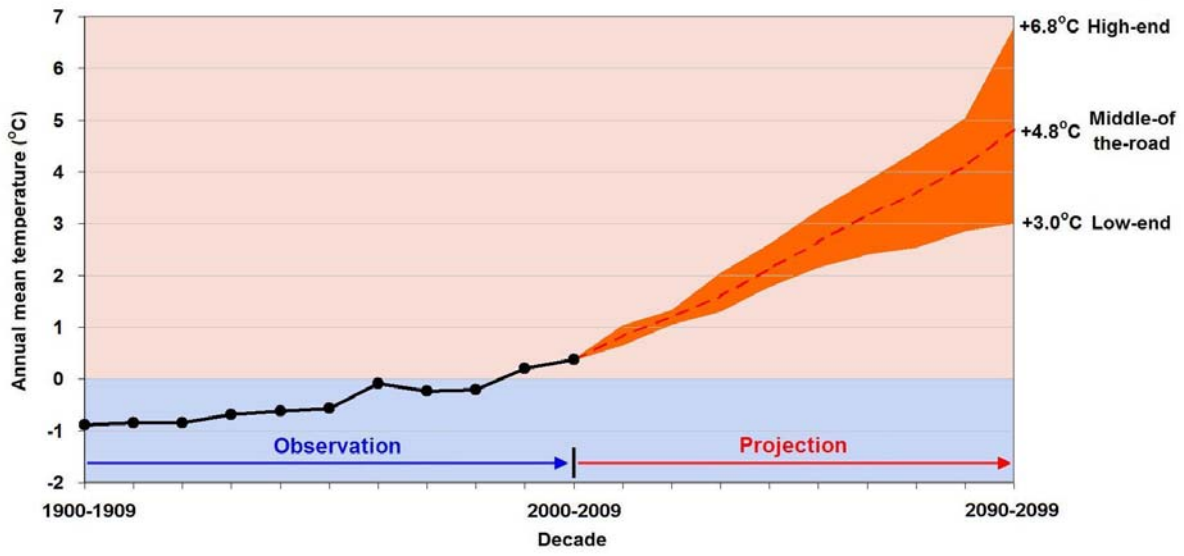

Figure 10. Past and projected annual mean temperature anomaly for Hong Kong Observatory (relative to the average from 1980 to 1999) based on IPCC AR4 annual mean projection data. (from Leung *et. al.*, (2007))