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Recent Climatic Trends and Analysis of Monthly Heating and Cooling Degree Hours in Sydney

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Abstract: Recent climatic trends of two nearby stations in Sydney were examined in terms of hourly ambient air temperature and wind direction for the time period 1999–2019. A reference was set for the monthly number of cooling (CDH) and heating (HDH) degree hours and the number of monthly hours that temperatures exceeded 24 °C (T24) or were below 14 °C (T14), parameters affecting not only the energy demands but also the quality of life. The degree hours were linked to the dominant synoptic conditions and the local phenomena: sea breeze and inland winds. The results indicated that both areas had higher mean monthly number of HDH (980–1421) than CDH (397–748), thus higher heating demands. The results also showed a higher mean monthly number of T14 (34–471) than T24 (40–320). A complete spatiotemporal profile of the climatic variations was given through the analysis of their dynamic progress and correlation. In order to estimate the daily values of CDH and HDH, T24 and T14 empirical models were calculated per month based on the maximum and minimum daily air temperatures. The use of forecasted weather conditions and the created empirical models may later be used in the energy planning scenarios.

Keywords: regression analysis; empirical models; forecasting; energy demands; sea breeze



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1. Introduction

Cities are the core settlements humans live, consume and develop. They expand up to hundreds of kilometers and future projections show that by 2050 at least 65% of the earth's population will live in cities. Cities include all the necessities for living a comfortable life and people move to urban areas to have more opportunities and to live a “better” life with all the amenities [1]. The urban expansion has resulted in a number of climatic and environmental fallouts such as air pollution, noise, temperature increase and thermal stress. Higher urban temperatures are observed and are attributed to the increased sensible heat release by buildings and pavements, the higher anthropogenic heat, the increased heat storage by the urban structures and the lower evaporative cooling.

High urban temperatures and extreme events in Europe, the USA and in Australia have resulted in an increase in electricity demand, particularly for cooling purposes, raising CO₂ emissions and the urban ecological footprint [1–3]. Previous studies have shown that an increase in air temperature by 1 °C may result in an increase in electricity demand up to 0.45%–4.6%. The significant increase of energy demand to maintain thermal comfort in large cities has been explored, forecasting a 275–750% rise in energy demand by the year 2050 [4]. Even though higher temperatures with climate change could decrease the demand for heating in the winter, they could increase demand for cooling in the summer [5] and amplify peak loads leading to outages.

A measure of the changing climate in a region, and consequently the needs of electrical energy, can be obtained with the use of heating and cooling degree days or hours that characterize how energy demand depends on temperature. Heating degree hours (HDH) are calculated as the number of degrees that an hour is below a base temperature and cooling degree hours (CDH) are calculated as the number of degrees that an hour is above a base temperature. Electricity demand is assumed to increase linearly as the temperature increases above or decreases below the base temperature for CDHs and HDHs, respectively. Therefore, the degree hours' approach could be used to project energy demand and load in forecast studies. Moreover, HDH and CDH are used for forecasting temperature extremes to inform, in particular, the vulnerable population for whom these could result in heat/cold stress and mortality [6–12].

The forecasting degree hours' approach may be limited in forecasting energy load due to the hourly lags of the response of electricity load to temperature, the effect of relative humidity resulting in more or less comfortable conditions and the effect of wind speed [5]. Wang and Bielicki (2018) found evidence that electricity load varies at both decreasing and increasing relative humidity at a threshold temperature, but generally it depends more on the temperature variations.

The aim of the present paper is to present the trend of temperatures in the urban area of Sydney and particularly observe the variations in HDH and CDH over the course of twenty years, 1999–2018. The first part of the article presents a critical review of existing weather conditions in Sydney in terms of ambient air temperature and wind direction. The second part of the article presents the calculated HDH and CDH for the investigated years, as well as the number of hours per month the air temperatures were over 24 °C (T24) or below 14 °C (T14) in order to study the duration of heating and cooling conditions. Recent studies on building simulations directly calculate the energy needs of the buildings by using weather files' external weather conditions [13–16] and the user modifies the efficiency of heating and cooling systems and the desired comfort levels [17–20]. The concept of HDHs and CDHs has been well established over the years, usually using 14 °C and 24 °C as threshold temperatures, respectively, to determine upon them the requirements in heating and cooling. With greater application of building simulation programs, the subjective comfort levels and the different coefficient of performance (COP) and seasonal energy efficiency ratio (SEER) of the heating and cooling systems make recent studies harder to compare. This study uses the degree hours' concept to obtain a complete spatiotemporal profile of the climatic variations through the analysis of their dynamic progress and correlation. This is also the first study that evaluates degree hours in the city of Sydney using temperature values for this century. Furthermore, empirical equations are created based on regression models of the HDH, CDH, T24 and T14 and then validated using the temperature conditions in 2019. These empirical equations could forecast the next days' energy requirements. Finally, in the discussion we criticize the advantages of using such equations to estimate the increased or decreased energy demands for the following days' energy planning and to prevent energy waste at energy plants.

2. Materials and Methods

2.1. Study Area and Dataset

The investigated area was the city of Sydney with a population of 5.25 million, located at the southeastern coast of Australia extending up to 70 km to the West. Sydney has a humid, subtropical climate (Köppen-Geiger: Cfa) [21,22], changing from mild and cool winters to warm summers with average annual temperature around 18.0 °C and annual precipitation about 912 mm.

Hourly ambient air temperature values of years 1999–2019 were examined from two meteorological stations: the Observatory Hill station (33.8590° S, 151.2048° E, altitude 39 m) and the Sydney airport station (33.5677° S, 151.1063° E, altitude 6 m), which is located about 10 km south of the Central Business District of the city of Sydney (Figure 1).

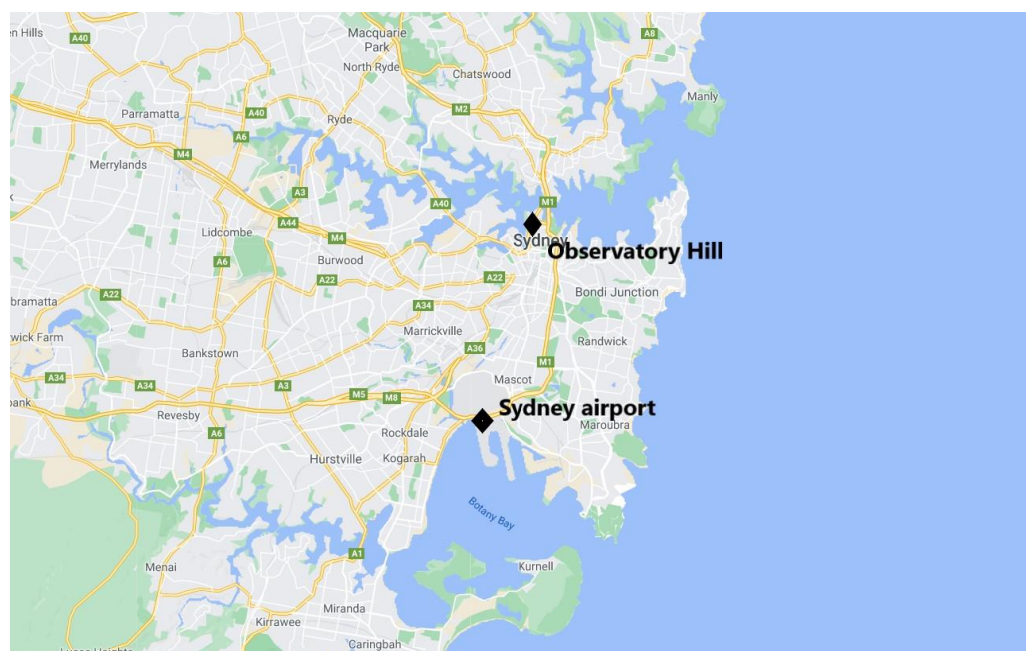


Figure 1. Map of two meteorological stations at the city of Sydney.

2.2. Local Climatic Trends

In order to investigate the energy demands for heating and cooling it is essential to investigate the current trend of the local climate during the past 21 years, years 1999–2019. The mean average, maximum and minimum ambient air temperatures were found, as well as the absolute maximum and minimum ambient air temperatures.

Then, using the average monthly values of the past 21 years, we decomposed the time series to observe the seasonality, the random effect and whether there was an increasing or decreasing trend using the decompose function of R Studio software [23].

2.3. Calculation of Degree Hours and Their Duration

The hourly ambient air temperatures of years 1999–2018 were used for the calculation of the cooling degree hours (CDH) and heating degree hours (HDH). Heating and cooling degree hours are defined as the sum of the differences between hourly average temperature and the base temperature. Monthly degree hours are the sum of daily degree hours over the number of days in the month. The number of cooling degree hours (CDH) in a day were defined as

$$CDH = \sum_{i=1}^N T_i - T_b \quad (1)$$

Similarly, daily heating degree hours (HDH) were defined as

$$HDH = \sum_{i=1}^N T_b - T_i \quad (2)$$

where N is the number of hours in the day ($N = 24$), T_b is the base temperature to which the degree hours are calculated, $T_b = 24^\circ\text{C}$ for CDH and $T_b = 14^\circ\text{C}$ for HDH, and T_i is the hourly air temperature. The base temperature was chosen considering the range of the mean monthly temperatures for the investigated years, 13.1 – 23.4°C for the Sydney airport station and 13.3 – 23.2°C for the Observatory Hill station. The number of hours within the day with high (over 24°C) or low (below 14°C) determined the duration of the required heating or cooling.

A new concept of the study was the use of T_{24} and T_{14} which are defined as the number of hours exceeding 24°C (T_{24}) or are below 14°C (T_{14}), thus revealing the number

of hours required for cooling and heating, respectively. The daily values of T24 and T14 were limited within the range of 0 to 24, while monthly values ranged between 0 to 744 (31 days $\times$ 24 h).

2.4. Empirical Models

The daily calculated heating and cooling degree hour values for the base of 14 °C and 24 °C, respectively, and the number of hours showing the duration of heating and cooling (T14 and T24) were further utilized for the creation of empirical models/equations that could forecast them. The daily empirical models were determined using regression analyses of the 1999–2018 time series where the independent variables were the daily $T_{\max}$ and $T_{\min}$, and then the best correlations were proposed. The same method was also employed to estimate daily number of hours with $T < 14$ °C and $T > 24$ °C. Later, the proposed empirical models were validated using the hourly ambient air temperatures of year 2019.

3. Results

3.1. Local Climatic Trends

3.1.1. Ambient Air Temperature

Figure 2 and Table 1 show the mean temperatures, absolute and average minimum temperatures and absolute and average maximum temperatures at the two investigated stations per month. The average monthly mean air temperatures recorded at the Observatory Hill and Sydney airport stations (Figure 2) ranged from 12.8 °C to 23.1 °C and 13.1 °C to 23.4 °C, respectively.

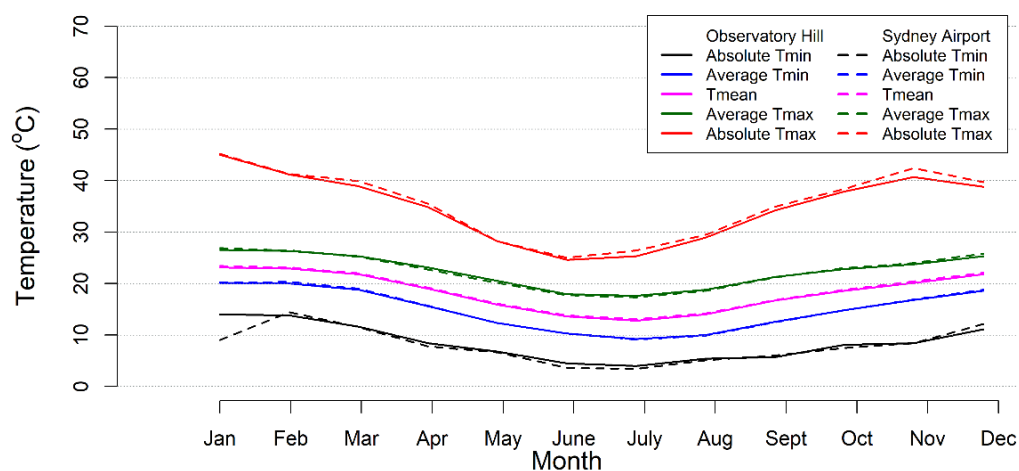


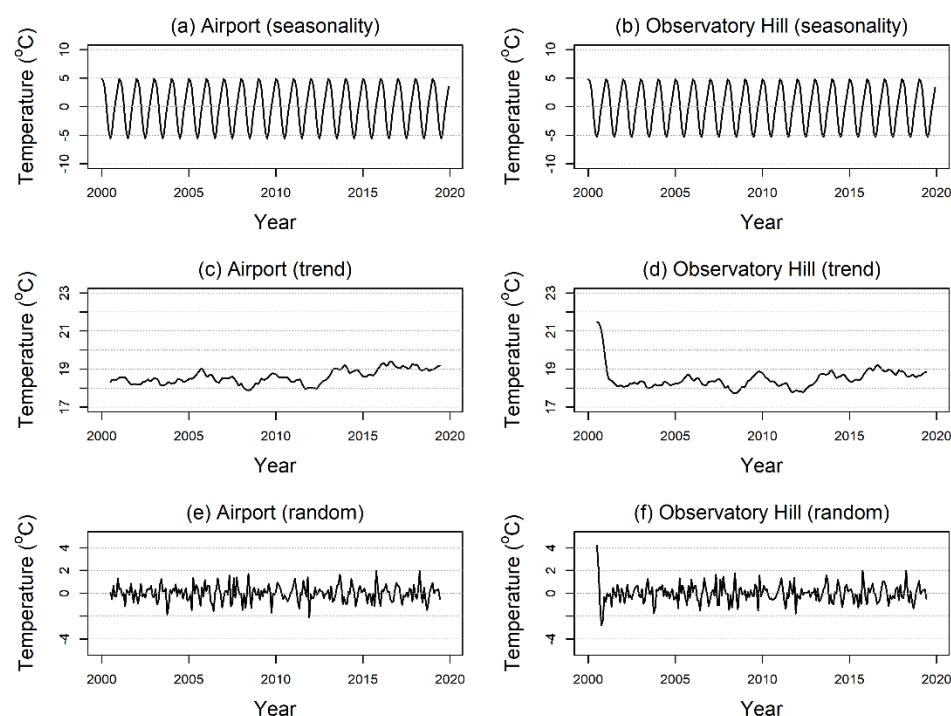
Figure 2. Monthly values of absolute maximum and absolute minimum temperatures, average maximum and minimum temperatures and mean temperatures at the Observatory Hill station (solid lines) and the Sydney airport station (dotted lines).

At the Sydney airport station, the monthly mean maximum and minimum air temperatures varied between 26.9 °C in January (with absolute maximum value of 45.2 °C) and 9.1 °C in July (with absolute minimum value of 3.4 °C). For the Observatory Hill station, the monthly mean maximum and minimum air temperatures varied between 26.5 °C in January (with absolute maximum value of 45.0 °C) and 9.2 °C in July (with absolute minimum value of 4.0 °C). Based on the average monthly temperatures and the monthly values of HDH and CDH the year was divided into a warm period (October–April) and a cold period (April–October).

Table 1. Average monthly maximum ($T_{\max}$), minimum ($T_{\min}$) and mean (T_{mean}) air temperatures [absolute minimum–maximum monthly temperatures] for years 2000–2019 for the Observatory Hill and Sydney airport stations.

	$T_{\max}$ (°C)		$T_{\min}$ (°C)		T_{mean} (°C)	
	Observatory Hill	Sydney Airport	Observatory Hill	Sydney Airport	Observatory Hill	Sydney Airport
January	26.8 [18.8–44.6]	27.0 [18.5–45.3]	20.2 [13.9–25.1]	20.3 [14.1–24.6]	23.2 [17.4–32.5]	23.4 [17.6–33.3]
February	26.7 [19.3–41.2]	26.5 [18.8–41.3]	20.1 [13.8–26.9]	20.2 [7.0–27.2]	23.1 [16.8–32.3]	23.1 [14.6–33.0]
March	25.7 [18.7–39.0]	25.2 [19.2–39.9]	18.8 [12.2–23.7]	19.0 [8.5–23.8]	21.9 [16.2–29.1]	22.0 [16.3–30.0]
April	23.6 [15.9–34.9]	22.9 [16.3–35.4]	15.8 [8.4–23.3]	15.8 [7.8–23.9]	19.3 [12.9–27.2]	19.3 [12.6–28.6]
May	21.0 [14.1–28.5]	20.2 [12.8–28.5]	12.5 [7.3–19.7]	12.3 [6.7–19.9]	16.2 [11.3–22.6]	16.1 [9.5–22.1]
June	18.3 [11.5–26.4]	17.7 [11.2–24.8]	10.7 [4.6–16.5]	10.2 [3.5–16.0]	14.0 [8.9–21.7]	13.8 [8.9–19.3]
July	18.1 [11.9–25.9]	17.4 [10.7–26.3]	9.5 [4.0–16.0]	9.1 [3.5–15.2]	13.3 [8.6–20.8]	13.1 [9.0–19.7]
August	19.1 [11.9–28.9]	18.4 [10.5–29.5]	10.1 [5.3–17.6]	9.9 [5.2–24.0]	14.3 [9.6–21.5]	14.1 [9.7–24.0]
September	21.5 [13.2–34.2]	21.1 [11.7–35.3]	12.5 [5.6–22.6]	12.6 [5.6–27.3]	16.8 [11.0–26.3]	16.8 [11.0–27.6]
October	22.9 [14.8–38.0]	22.9 [13.6–38.4]	14.8 [8.0–23.0]	14.9 [7.5–23.5]	18.6 [11.8–30.1]	18.8 [11.7–30.3]
November	23.9 [15.2–40.7]	24.1 [15.3–42.2]	16.9 [8.4–23.1]	17.1 [8.6–24.9]	20.2 [12.4–29.7]	20.4 [12.4–29.5]
December	25.5 [18.0–38.8]	26.0 [16.4–41.0]	18.6 [12.0–24.5]	18.8 [12.1–23.8]	21.8 [15.0–29.4]	22.1 [14.8–30.1]

According to the Australian Bureau of Meteorology for years 1859–2016, the monthly mean maximum and minimum air temperatures varied between 25.9 °C in January (with an absolute maximum value of 45.8 °C) and 8.1 °C in July (with an absolute minimum value of 2.2 °C), revealing an increase in mean, mean maximum and mean minimum air temperature values in recent years [24]. The seasonality, trend and random factors were investigated for the 21 years using the decompose function of R Studio software [23] and we verified a small increasing trend of the moving average of about 0.5–1.0 °C at both stations (Figure 3c,d). A seasonal yearly trend was also observed with roughly similar peaks of temperature per year. This decomposition provided a clean way to understand the yearly patterns of the data sets, and that there was a small but important increasing trend of the moving average.

**Figure 3.** Decomposition of mean monthly temperatures of Sydney airport and Observatory Hill stations, into seasonality (a,b), trend (c,d) and random (e,f).

3.1.2. Wind Direction

This study focused on temperatures below 14 °C and over 24 °C so the wind direction was examined for temperatures below 14 °C, between 14 °C and 24 °C and over 24 °C. The results (Figure 4a,b) showed that temperatures below 14 °C were associated with western wind direction at both stations (blue color), whereas temperatures over 24 °C were associated with north-eastern (Sydney airport) and eastern (Observatory Hill) wind direction (brown color). Several studies have shown that the sea breeze in Sydney is greatly influenced by the local temperature difference between the sea and land surfaces [25–27]. However, sea breeze, based on the location of the two investigated stations, did not affect the diurnal variation of the examined temperatures.

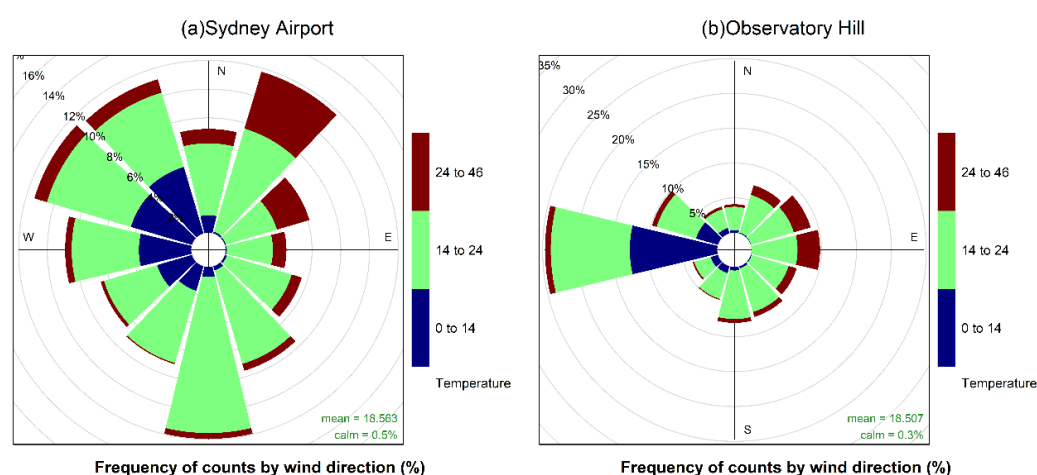


Figure 4. Distribution of wind directions for different air temperatures at the (a) Sydney airport and (b) Observatory Hill stations.

3.2. Calculating Heating and Cooling Degree Hours, T14 and T24 Hours

Figure 5 shows the mean, mean maximum and mean minimum number of hours (T14 and T24) for years 1999–2018 for the two investigated stations. The mean monthly number of T24 ranged from 40 in April to 244 in January at the Observatory Hill station, whereas for the Sydney airport station this ranged from 54 in April to 320 in January. The mean monthly number of T14 ranged from 38 in April to 471 in July at the Observatory Hill station, whereas for the Sydney airport station this ranged from 34 in April to 449 in July. The Observatory Hill station had a slightly higher mean monthly number of T14 and slightly lower mean monthly number of T24 compared to the Sydney airport station. The absolute maximum monthly number of hours appeared for the Observatory Hill station with 356 of T24 in January and 546 of T14 in July. A paired t-test analysis indicated that the differences between the two meteorological stations were non-statistically significant ($t = 0.591 < t_{\alpha} = 2.20$ for $\alpha = 0.05$).

Figure 6 shows the monthly heating and cooling degree hour (mean, maximum and minimum) values for the years 1999–2018 at the Observatory Hill and Sydney airport stations. The mean values of HDH reached a maximum in July, 1501 and 1411 for the Observatory Hill and Sydney airport stations, respectively, and was also significantly high for June (1010 and 980) and August (1099 and 1052). The mean values of HDH were 49 in April and 109 in October for the Observatory Hill station, while the mean values of HDH were 46 in April and 98 in October for the Sydney airport station.

During the warm period, the mean values of CDH reached a maximum in January, 597 and 750 for the Observatory Hill and Sydney airport stations, respectively, and were also significantly high for December and February. The mean values of CDH were 84 in April and 190 in October for the Observatory Hill station. The mean values of CDH were 114 in April and 257 in October for the Sydney airport station. Overall, the results showed

relatively higher values of HDH in the cool period, compared to the values of CDH in the warm period.

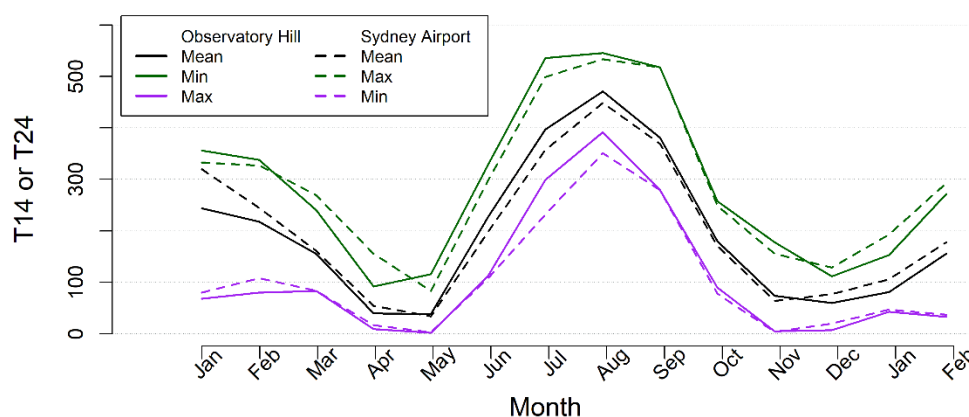


Figure 5. Combined monthly mean, maximum and minimum values of T14 and T24 at both stations.

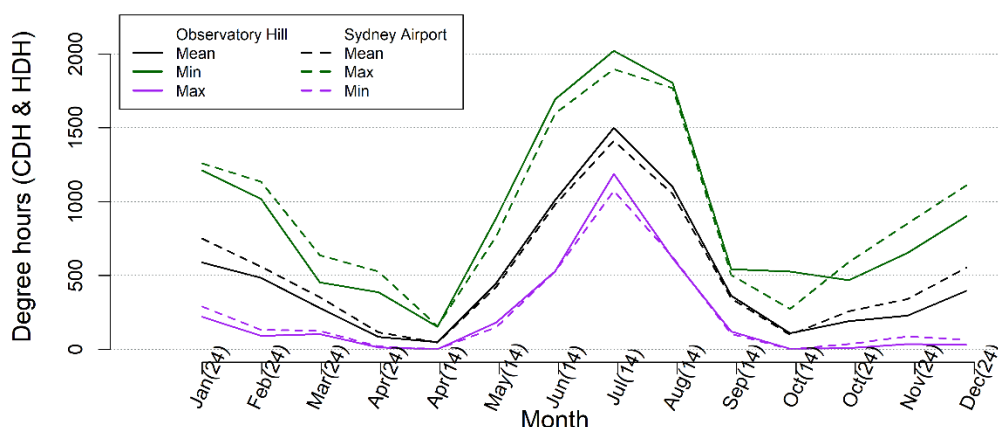


Figure 6. Mean, maximum and minimum monthly values of CDH and HDH at the Observatory Hill and Sydney airport stations for the period 1999–2018.

The time series of cooling degree hours (CDH), with a base temperature of 24 °C, and the number of hours exceeding 24 °C (T24) for the period 1999–2018 appeared to have a statistically significant increasing trend ($\alpha = 0.05$) using linear regression, whereas the time series of heating degree hours (HDH), with a base temperature of 14 °C, and the number of hours below 14 °C (T14) appeared to have decreasing trends, statistically significant only for the HDH time series.

Figure 7 illustrates the mean monthly values of CDH, with a base temperature of 24 °C, with T24, and HDH, with a base temperature of 14 °C, with T14 for the period 1999–2018 and for the year 2019 at the Observatory Hill station (Figure 7a) and the Sydney airport station (Figure 7b). The mean annual values of 1999–2018 appeared similar to the 2019 data, with higher HDH and T14 in the cool period and lower CDH and T24 in the cold period, especially for the monthly CDH values.

The probability of the cooling and heating degree hours exceeding the 85th percentile for years 2000–2019 was calculated using the distribution of exceedances, which revealed a sample size $I = 54.75 \sim 55$ for each year. Table 2 shows the results of the goodness of fit (Kolmogorov–Smirnov test) for the observed and estimated frequencies, with maximum $D = \sup(cF_{\text{obs}(i-1)} - cF_{\text{est}(i)})$. There was an acceptable null-hypothesis for all years.

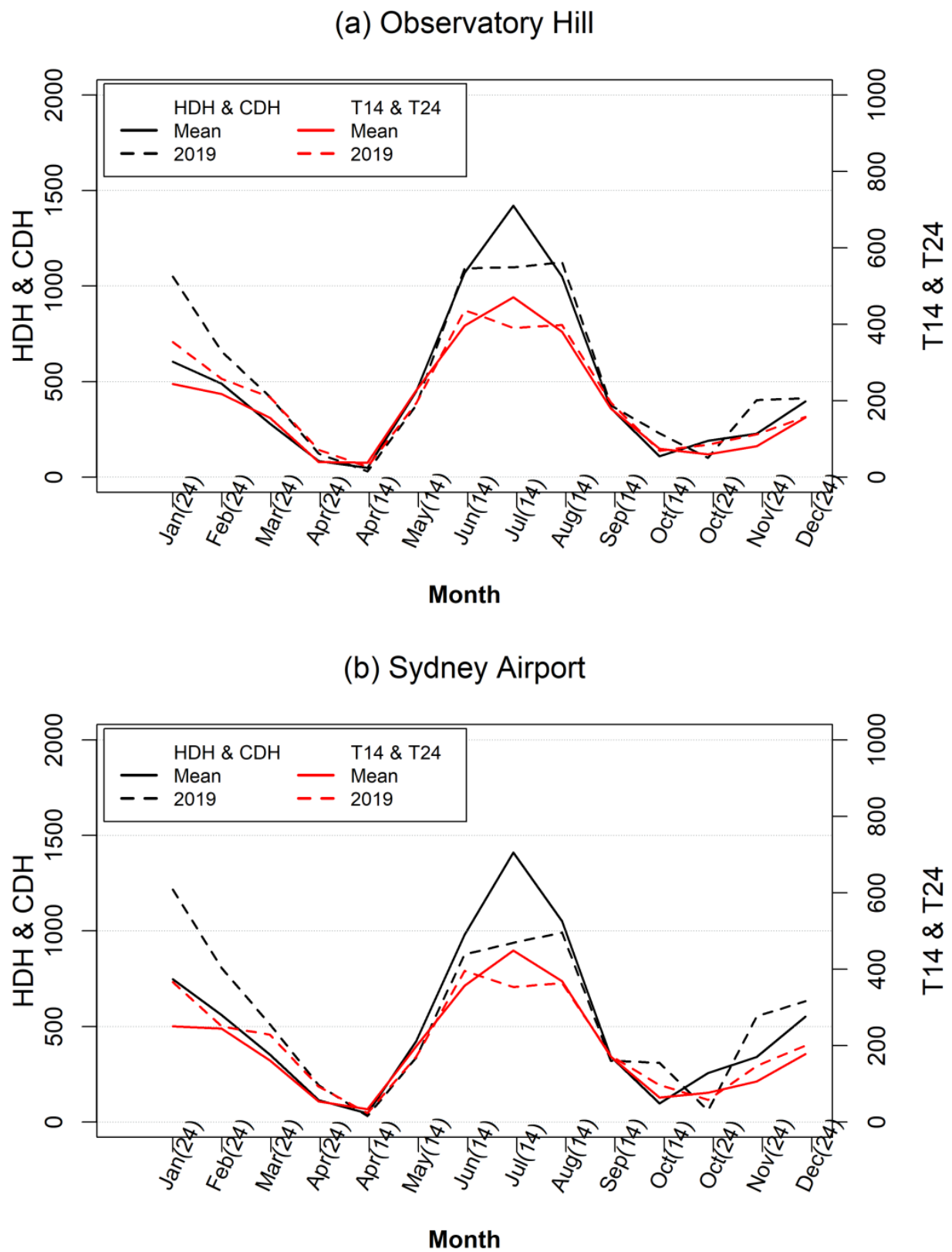


Figure 7. Mean monthly values of CDH, HDH, T24 and T14 for period 1999–2018 and 2019 at (a) Observatory Hill and (b) Sydney airport stations.

Table 2. D values (Kolmogorov–Smirnov test) for testing the goodness of fit between observed and estimated cumulative frequencies of the exceedances.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
CDH	0.010	0.010	0.006	0.004	0.003	0.007	0.004	0.009	0.001	0.012
HDH	0.120	0.107	0.117	0.117	0.074	0.121	0.155	0.147	0.139	0.091
Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CDH	0.009	0.010	0.012	0.004	0.001	0.016	0.008	0.004	0.017	0.015
HDH	0.080	0.189	0.123	0.219	0.175	0.163	0.168	0.117	0.079	0.171

The estimated frequencies were analyzed for a repetition period of $T = 10$ days in order to show a continuous variation for the investigated years. The estimated frequency of heating degree hour values at least once in every 10 days was statistically significant with t -test $t_b = 2.90$ ($> t_{(\alpha = 0.05)} = 2.11$) signifying a statistically significant increase in the hourly ambient air temperatures during the cool period. For the cooling degree hour values the estimated frequency was not statistically significant, with t -test $t_b = 0.834$ ($< t_{(\alpha = 0.05)} = 2.11$).

3.3. Empirical Models of Daily CDH, HDH, T14 and T24

For the determination of the daily values of degree hours (CDH and HDH) empirical equations at both stations we utilised the daily maximum temperature ($T_{\max}$) and/or the daily minimum temperature ($T_{\min}$). The empirical equations had the form (Table 3)

$$(a) y = a + b \cdot T_{\max} \text{ (or } T_{\min}) \text{ or}$$

$$(b) y = a + b \cdot T_{\max} + c \cdot T_{\min}$$

The empirical heating and cooling degree hours' equations were found for both transiting months (April and October), with correlation coefficients for CDH ranging from 0.922–0.933 (statistically significant at $\alpha = 0.05$) and for HDH ranging from 0.926–0.952 (statistically significant at $\alpha = 0.05$). For the months November to March and May to October, for both CDH and HDH values, the 2nd degree polynomial equations were found with correlation coefficients ranging from 0.925 to 0.959 (statistically significant at $\alpha = 0.05$). The hourly HDH and CDH data for year 2019 were later used for the verification of the created empirical equations. Monthly empirical equations were preferred rather than daily as previous studies showed the dependency on past days' temperatures in the prediction of electricity loads [5,28].

Table 3. Monthly empirical equations for estimations of daily values of CDH and HDH, the corresponding correlation coefficients and the paired t -test values of goodness of fit with the observed daily values of 2019.

Month	Observatory Hill Station Empirical Model	R	t -Test	Sydney Airport Station Empirical Model	R	t -Test
October (CDH)	$CDH = -192.4 + 7.68 \cdot T_{\max}$	0.933	0.483	$CDH = -196.3 + 7.83 \cdot T_{\max}$	0.931	0.771
November	$CDH = -219.5 + 8.10 \cdot T_{\max} + 1.04 \cdot T_{\min}$	0.952	0.230	$CDH = -227.1 + 8.59 \cdot T_{\max} + 0.68 \cdot T_{\min}$	0.959	0.178
December	$CDH = -203.7 + 8.23 \cdot T_{\max}$	0.944	0.809	$CDH = -214.7 + 8.62 \cdot T_{\max}$	0.938	0.06
January	$CDH = -206.2 + 8.37 \cdot T_{\max}$	0.939	0.807	$CDH = -212.4 + 8.61 \cdot T_{\max}$	0.943	0.403
February	$CDH = -229.3 + 9.22 \cdot T_{\max}$	0.925	0.213	$CDH = -225.3 + 9.07 \cdot T_{\max}$	0.934	0.030
March	$CDH = -182.8 + 6.88 \cdot T_{\max} + 0.71 \cdot T_{\min}$	0.932	0.883	$CDH = -204.8 + 7.45 \cdot T_{\max} + 1.10 \cdot T_{\min}$	0.949	0.442
April (CDH)	$CDH = -148.1 + 6.01 \cdot T_{\max}$	0.933	0.611	$CDH = -178.1 + 7.19 \cdot T_{\max}$	0.922	0.410
April (HDH)	$HDH = 100.2 - 7.4 \cdot T_{\min}$	0.950	0.344	$HDH = 93.9 - 6.95 \cdot T_{\min}$	0.952	0.391
May	$HDH = 152.2 - 1.21 \cdot T_{\max} - 9.56 \cdot T_{\min}$	0.944	0.712	$HDH = 131.0 - 0.68 \cdot T_{\max} - 8.84 \cdot T_{\min}$	0.940	0.334
June	$HDH = 198.1 - 2.43 \cdot T_{\max} - 11.62 \cdot T_{\min}$	0.958	0.980	$HDH = 176.4 - 2.29 \cdot T_{\max} - 10.18 \cdot T_{\min}$	0.954	0.202
July	$HDH = 208.3 - 3.06 \cdot T_{\max} - 11.52 \cdot T_{\min}$	0.954	0.214	$HDH = 185.8 - 2.67 \cdot T_{\max} - 10.36 \cdot T_{\min}$	0.947	0.450
August	$HDH = 179.0 - 2.32 \cdot T_{\max} - 10.21 \cdot T_{\min}$	0.943	0.463	$HDH = 162.6 - 1.98 \cdot T_{\max} - 9.48 \cdot T_{\min}$	0.940	0.420
September	$HDH = 122.1 - 0.70 \cdot T_{\max} - 8.06 \cdot T_{\min}$	0.946	0.266	$HDH = 116.4 - 0.61 \cdot T_{\max} - 7.87 \cdot T_{\min}$	0.946	0.165
October (HDH)	$HDH = 102.2 - 7.61 \cdot T_{\min}$	0.942	0.119	$HDH = 93.0 - 6.91 \cdot T_{\min}$	0.926	0.428

The CDH and HDH values defined the intensity of the high or low temperatures. The number of hours within the day with high (over 24 °C) or low (below 14 °C) determined the duration of the required heating or cooling. As expected, the number of hours over 24 °C (T24) and the number of hours below 14 °C (T14) was directly correlated with the corresponding CDH and HDH values. Table 4 shows the empirical models of T24 and T14 hours, in the form $y = a \cdot \text{HDH}^b$ (or CDH^b), with their correlation coefficients ranging from 0.863–0.950 and with a statistical significance level of $\alpha = 0.05$. The parameters a and b were relatively similar, ranging from $a = 2.16$ – 3.24 and $b = 0.40$ – 0.46 . An effort to create seasonal empirical models did not give satisfactory results so monthly models were preferred.

Table 4. Daily number of hours with temperature over 24 °C (T24) or below 14 °C (T14) empirical models using cooling and heating degree hours (CDH and HDH), with their equivalent regression coefficients and paired t -test of goodness of fit with the observed daily values of 2019.

Month	Observatory Hill Station			Sydney Airport Station		
	Empirical Model	R	t -Test	Empirical Model	R	t -Test
January	$T24 = 2.99 \cdot \text{CDH}^{0.42}$	0.928	0.441	$T24 = 2.61 \cdot \text{CDH}^{0.45}$	0.931	0.940
February	$T24 = 2.73 \cdot \text{CDH}^{0.45}$	0.934	0.484	$T24 = 2.70 \cdot \text{CDH}^{0.45}$	0.938	0.335
March	$T24 = 2.59 \cdot \text{CDH}^{0.45}$	0.928	0.463	$T24 = 2.72 \cdot \text{CDH}^{0.43}$	0.941	0.087
April (24)	$T24 = 2.20 \cdot \text{CDH}^{0.44}$	0.913	0.181	$T24 = 2.35 \cdot \text{CDH}^{0.43}$	0.940	0.209
April (14)	$T14 = 2.80 \cdot \text{HDH}^{0.46}$	0.940	0.807	$T14 = 2.59 \cdot \text{HDH}^{0.45}$	0.934	0.190
May	$T14 = 2.75 \cdot \text{HDH}^{0.46}$	0.950	0.330	$T14 = 2.83 \cdot \text{HDH}^{0.42}$	0.941	0.117
June	$T14 = 3.24 \cdot \text{HDH}^{0.42}$	0.925	0.093	$T14 = 3.07 \cdot \text{HDH}^{0.42}$	0.907	0.056
July	$T14 = 3.15 \cdot \text{HDH}^{0.42}$	0.905	0.090	$T14 = 3.08 \cdot \text{HDH}^{0.42}$	0.874	0.673
August	$T14 = 2.59 \cdot \text{HDH}^{0.42}$	0.897	0.034	$T14 = 2.81 \cdot \text{HDH}^{0.43}$	0.863	0.609
September	$T14 = 2.70 \cdot \text{HDH}^{0.44}$	0.928	0.481	$T14 = 2.56 \cdot \text{HDH}^{0.45}$	0.924	0.907
October (14)	$T14 = 2.69 \cdot \text{HDH}^{0.45}$	0.930	0.818	$T14 = 2.53 \cdot \text{HDH}^{0.45}$	0.939	0.555
October (24)	$T24 = 2.00 \cdot \text{CDH}^{0.46}$	0.933	0.982	$T24 = 2.16 \cdot \text{CDH}^{0.43}$	0.930	0.407
November	$T24 = 2.50 \cdot \text{CDH}^{0.43}$	0.936	0.109	$T24 = 2.63 \cdot \text{CDH}^{0.40}$	0.924	0.223
December	$T24 = 2.78 \cdot \text{CDH}^{0.41}$	0.922	0.450	$T24 = 2.62 \cdot \text{CDH}^{0.42}$	0.931	0.140

The proposed empirical models for HDH, CDH, T14 and T24 were verified using the observed hourly data of 2019. The results are shown in Figures 8 and 9, suggesting in most days a goodness of fit of the empirical models on the observed data of 2019. Applying the paired t -test analysis on observed and estimated values, the calculated results of the goodness of fit are shown in Tables 3 and 4.

Two cases with underestimations of the estimated values were further investigated in terms of temperature and wind direction and speed:

- A. 12 February 2019 for cooling degree hour values (Figure 9a), and
- B. 29 August 2019 for daily number of hours below 14 °C values (Figure 9b,d).

In case A (12/2/2019), the reason that the estimated values of CDH were found to be smaller than the observed values was the extreme high temperature conditions with 16 consecutive hours when the temperature exceeded 24 °C, reaching a maximum of 36 °C and 36.8 °C at the Observatory Hill and Sydney airport stations, respectively. The wind direction during this day remained steady and westerly affecting the CDH values. However, the wind is not a reliable parameter to be used easily in empirical models.

In case B (29/8/2019) the air temperatures below 14 °C lasted for 23 hours so the empirical models could not be applied successfully. The temperature on that day remained low because of the south and south-western cold winds that kept the temperature low.

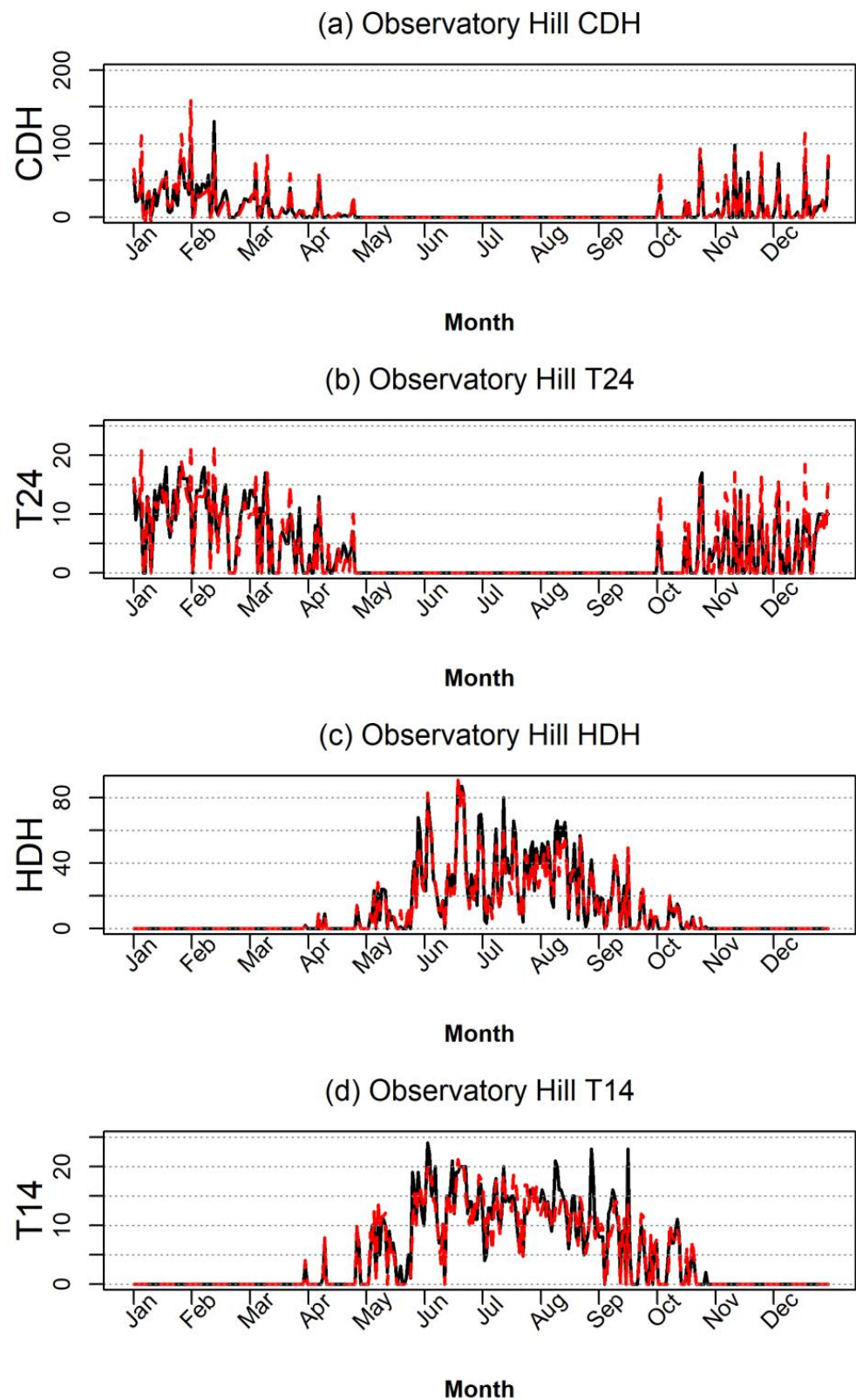


Figure 8. Observed (black solid) and estimated (red dotted) values from the empirical models for T24 and T14 values for the year 2019 at the Observatory Hill station.

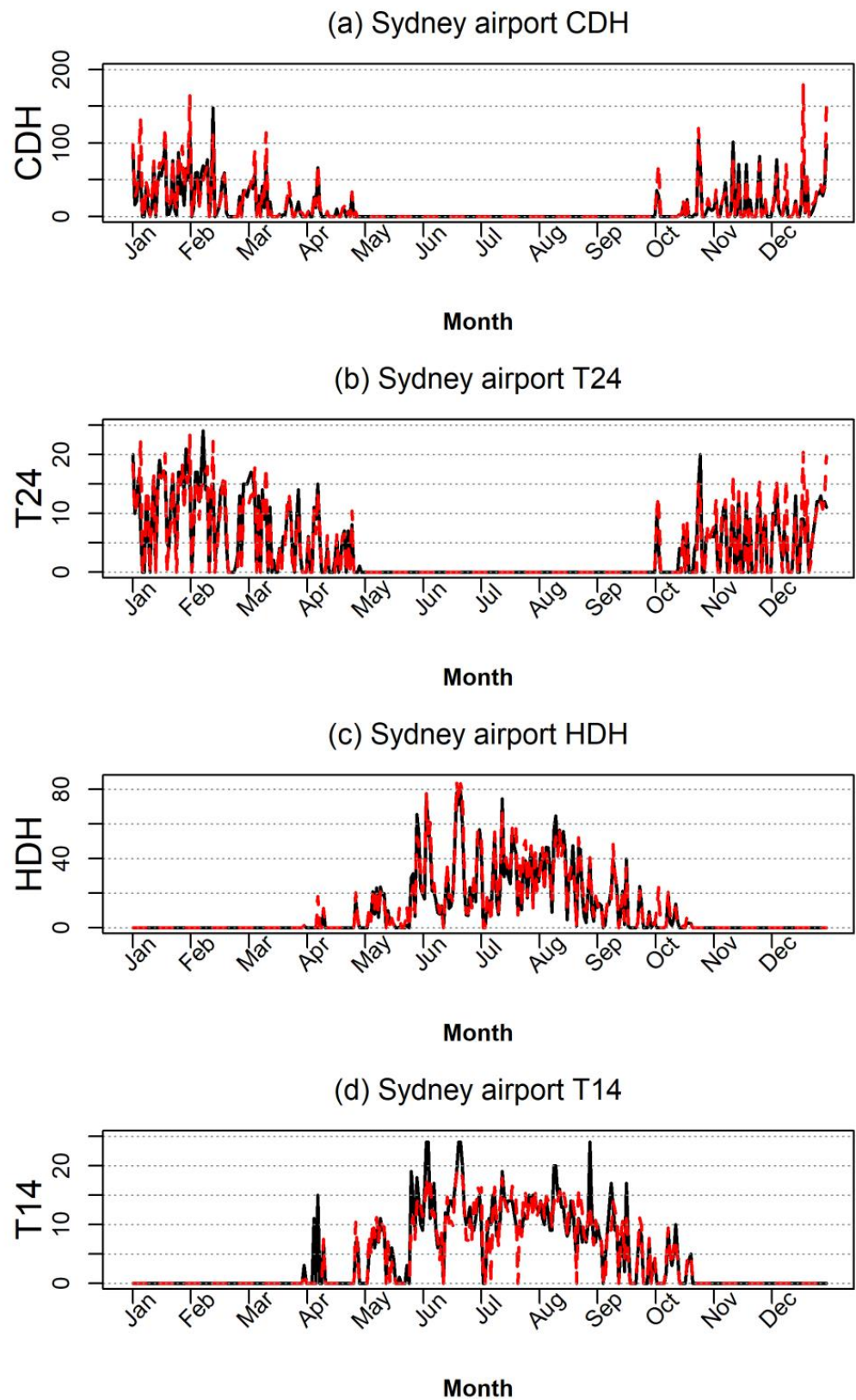


Figure 9. Observed (black solid) and estimated (red dotted line) from the empirical models CDH, T24, HDH and T14 values for the year 2019 at Sydney airport station.

4. Discussion and Conclusions

This study observed the air temperatures in the greater area of Sydney for the years 1999–2018, and calculated the cooling and heating degree hours, as well as the temperatures exceeding 24 °C or below 14 °C to show the intensity and duration of energy demands. Degree hours are a simplified representation of outside air temperature data usually using two threshold temperatures, 14 °C for heating degree hours and 24 °C for cooling degree hours. The degree hours were widely used in the preceding decades in the energy industry for calculation of the building energy consumption with regards to the effect of the outside air temperature. New building simulation software directly calculate the energy needs by defining just the indoor comfort temperature and by applying the coefficient of performance (COP) of a heat pump or the seasonal energy efficiency ratio (SEER) of an air-conditioning unit. However, the varying COP and SEER of the heating and cooling systems, as well as the subjective indoor thermal comfort air temperature, may provide inconclusive and incomparable values with other studies. Our research provided a spatiotemporal climatic profile using recent HDH and CDH values for the city of Sydney in order to understand the climatic changes over the years.

Empirical equations were proposed that could give an approximate of expected daily heating and cooling degree hours (HDH/CDH) per month and the daily number of temperatures exceeding 24 °C (T24) or below 14 °C (T14) per month. The empirical equations could use 24-hours of forecasting data of air temperature in order to estimate the energy demand of the following day.

We found that the need for heating (HDH) was almost double the need for cooling for the investigated period. The mean yearly values of CDH and HDH were 2250 and 4579, respectively, at the Observatory Hill station, and 2814 and 4467, respectively, at the Sydney airport station. The Sydney airport station was warmer in the warm period and colder in the cool period despite the fact that both stations had similar mean temperatures. The need for cooling and heating depends on daily maximum and minimum temperatures, but to accurately predict energy demands, a monthly variation of empirical models exists.

The mean and maximum monthly air temperature values for year 2019 were higher than the preceding years due to the increasing temperature trends in the area. However, by applying the empirical models, a goodness of fit was shown with only small deviations due to extreme and prolonged heat or cold weather conditions. The 24-hours forecasting of weather, for maximum and minimum temperatures, may also be used to estimate the heating and cooling degree hours of the next day, as well as the number of temperatures exceeding 24 °C (T24) or below 14 °C (T14), in order to forecast the energy demand of the next day for heating or cooling purposes. Moreover, the monthly cooling and heating degree hours of the selected weather station in the great area of Sydney showed that most of the energy in a building is consumed by heating systems rather than cooling systems due to the cool winters.

The developed models in this study may be used to predict annual degree hours in approximate areas within a region in case of the absence of temperature data in such areas. However, the relationship connecting the air temperatures in this approximate region with those at the Observatory Hill or Sydney airport stations needs to be defined in advance.

Extensions of this work could focus on estimating more thorough relationships between electricity loads and degree days or T14/T24. Such extensions could include the use of normalized electricity loads (e.g., per capita or for residential buildings only) or to consider other socioeconomic factors (e.g., population growth, electricity price, unemployment rate). With climate change posing a challenge in the electricity planning industry, our results could be further incorporated into the accuracy of prediction of electricity demands and loads.

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