The vertical component of urban bioclimate – The Taipei 101 Tower

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Abstract

An urban climate investigation is processed based on two stations at different levels (150 m and 350 m) at Taipei 101 Tower and a ground station at National Taiwan University (NTU). The study delivers the vertical gradients of urban bioclimatic components.

Physiologically Equivalent Temperature (PET) varies from -0.6 ℃ to 48.9 ℃ depending on altitudinal and seasonal changes in Taipei. Comparison of PET between ground level and height of 150 m shows that there are similar thermal conditions at the two layers.

Frequency analysis of PET shows that the probability of hot days is approx. 35 % at ground level and is reduced by 5 % to 10 % between each level according to increasing height during summer. Additionally, the probability of occurrence of cold days between the measuring levels increases by 5 % to 10 % along increasing height in winter, while it is close to 90 % at ground level.

Occurrence of heat stress was measured at all levels during winter on February 27th and 28th 2011.

Keywords: Physiologically Equivalent Temperature, RayMan, Taipei 101 Tower, Taiwan, urban climate

1. Introduction

Urban climate and thermal bioclimate are important issues for human beings in urban areas, because most inhabitants live in cities. Urban areas have not only expanded horizontally in past decades but also grew in altitude. Therefore, vertical thermal conditions are also an important issue in human-biometeorology in cities. Thermal bioclimate at ground level was already discussed and analysed widely with different factors, like height-width ratio [1] and shading effect [2]. Physiologically Equivalent Temperature (PET) [3, 4] is approved to be useful for evaluating thermal bioclimate. However, vertical thermal bioclimate in urban areas was not discussed in recent years.

There are more and more skyscrapers in Asia because of lack of living space. The rising height of urban buildings leads to issues of vertical human-biometeorology and urban climate. For those reasons, an investigation of thermal bioclimate conditions at skyscrapers is necessary to quantify vertical urban climate and bioclimate conditions. For this purpose, measurement stations are set up at Taipei 101 Tower to investigate human-biometeorolgical parameters since January 2011.

2. Data and method.

2.1 Measurement locations

Two measurement sites are situated in a distance of about 3 km to each other in Taipei (25° 2'0" N, 121° 32'0" E) (Fig.1). Since it is impossible to set up measurement stations at ground level near Taipei 101 Tower (TP 101 in Fig. 1), ground level station is located at the campus in National Taiwan University (NTU in Fig. 1). The other two stations (Vaisala WXT510) were set up at the north-western corner of Taipei 101 Tower at the heights of 150 m and 350 m. Fig. 2 illustrates the two different altitudes of the measurement stations at Taipei 101 Tower.

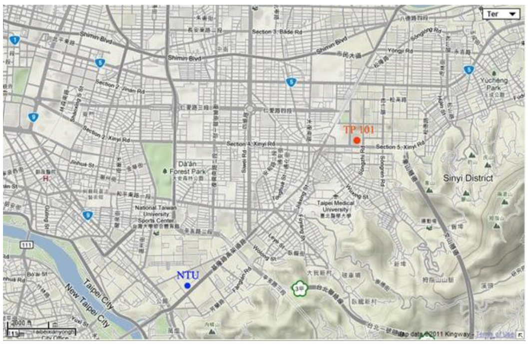

Fig 1. Location of measurement stations in Taipei

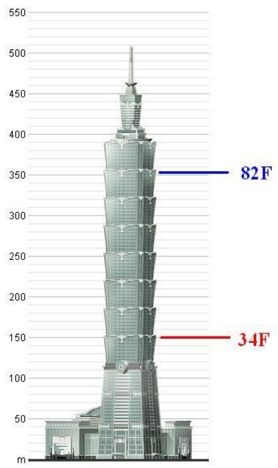

Fig 2. Measurement heights on Taipei 101 Tower (34th and 82nd floor)

2.2 Measurement instrument and data analysis

In order to estimate PET, air temperature, air humidity, wind speed and global radiation are necessary parameters. Additional urban climate analysis requires data on precipitation and wind direction. However, the instruments at Taipei 101 Tower measured only the following data (per minute): air temperature, air humidity, barometric pressure, precipitation, wind speed and wind direction. Fig 3 shows the station at the 34th floor of Taipei 101 Tower. Unfortunately it is impossible to set up pryanometers to measure global radiation there. For this reason, global radiation at ground station is applied to evaluate PET on Taipei 101 Tower. The ground station measures also air temperature, air humidity, barometric pressure, precipitation, wind speed and wind direction (in 1 minute resolution). The instrument accuracy for those stations is listed in Table 1.

All measurement data were averaged in hourly resolution, then applied in the RayMan model [5, 6] and finally analysed month by month. In order to quantify thermal condition frequencies, thermal bioclimate classification [7, 8] has been applied. Scales of both of the thermal bioclimate classifications are summarized in Table 2. Thermal bioclimate classification of Taiwan [7] is applied in this study.

Table 1: Accuracy of measurement instruments: barometric pressure (Pa), air temperature (Ta), relative humidity (RH), precipitation (RR), wind speed (WS), wind direction (WD) and global radiation (G)

Accuracy	**WXT510**	**Ground station**
Pa	0.5 hpa	0.5 hpa
Ta	0.3 ℃	0.2 ℃
RH	3 %	3 %
RR	0.1mm	0.1mm
WS	0.3 m/s	0.3 m/s
WD	3 °	3 °
G	-	5 w/m^2

Table 2: Thermal sensations and PET classes for south Taiwan and Western/Middle Eurpean classes

Thermal sensation	**PET range for Taiwan[1] (℃)**	**PET range for Western/Middle European[2] (℃)**
Very cold	< 14	< 4
Cold	14 – 18	4 - 8
Cool	18 – 22	8 - 13
Slightly cool	22 – 26	13 - 18
Neutral	26 – 30	18 - 23
Slightly warm	30 – 34	23 - 29
Warm	34 – 38	29 - 35
Hot	38 – 42	35 - 41
Very hot	42 <	41 <

Source: [[1]7, [2]8]

Fig 3. Photo of the instruments at 34th floor of Taipei 101 Tower

3. Results

3.1 Analysis of meteorological parameters

Monthly mean air temperature varies from 12.6 ℃ to 15.4 ℃ depending on height above ground in January. In July, the monthly mean air temperature is 28.7 ℃ at ground level, 28.5 ℃ at the height of 150 m and 27.0 ℃ at the height of 350 m. The difference in air temperature is significantly small in summer between ground level and the height of 150 m.

Monthly mean vapour pressure is only nearly 12.0 hPa in winter at all three levels and increases to about 26.0 hPa in summer.

Monthly mean wind velocity analysis shows a small difference between the three levels in summer. However, wind velocity is significantly stronger in winter at the height of 150 m. The mean value was 4.3 m/s. Meanwhile, mean wind velocity at level 150 m is always the largest of the three levels in winter.

3.2 Analysis of PET

Monthly minima, mean values and maxima of PET are shown for different measurement levels in Table 1 (ground level), Table 2 (150 m) and Table 3 (350 m). It seems there is no difference of PET between height at 150 m and ground in summer. In winter, mean values of PET range from 7.2 ℃ to 11.0 ℃ at the heights of 150 m and 350 m. However, maxima of PET were 36.7 ℃ at the height of 350 m and 41.2 ℃ at ground level in February (Table 3 and Table 5). This means that vertical thermal conditions vary violently in Taipei during winter. The mean values of PET at the height of 150 m and 350 m are even lower in March than in February. It is due to more rainy days at Taipei in March.

Table 3: Monthly minima, mean values and maxima of PET at ground level in 2011.

Month	Min (℃)	Mean (℃)	Max (℃)
Jan	2.8	11.1	35.8
Feb	3.4	13.2	41.2
Mar	4.8	13.8	43.8
Apr	7.6	19.3	43.3
May	12.9	22.6	46.2
Jun	18.4	27.9	48.9
Jul	19.9	29.7	45.7
Aug	19.4	28.9	48.5
Sep	16.7	25.2	47.8
Oct	13.4	20.5	45.2
Nov	11.7	19.1	43.3
Dec	5.0	11.6	33.8

Table 4: Monthly minima, mean value and maxima of PET at the height of 150 m in 2011.

Month	Min (℃)	Mean (℃)	Max (℃)
Jan	0.4	8.7	32.1
Feb	0.3	11.0	35.9
Mar	2.1	9.6	40.5
Apr	5.8	17.9	42.6
May	10.7	21.0	44.4
Jun	16.8	27.3	46.6
Jul	20.7	29.7	45.5
Aug	18.9	28.2	48.8
Sep	15.2	23.4	45.9
Oct	11.4	18.6	40.4
Nov	9.5	16.8	42.0
Dec	3.3	8.9	27.8

Table 5: Monthly minima, mean values and maxima of PET at the height of 350 m in 2011.

Month	Min (℃)	Mean (℃)	Max (℃)
Jan	-0.6	7.2	33.4
Feb	-1.3	9.9	36.7
Mar	1.0	8.3	39.3
Apr	4.4	17.0	42.4
May	9.4	20.3	42.1
Jun	16.0	26.0	44.0
Jul	18.7	28.2	46.8
Aug	18.1	26.7	47.0
Sep	13.7	21.9	43.5
Oct	10.3	16.9	38.1
Nov	8.0	15.7	40.3
Dec	1.3	7.6	27.0

Frequency of PET shows that the probability of warm days at ground level and at the height of 150 m is greater than 30 % in summer 2011 (Fig. 4 and Fig. 5). There is no difference in the frequency of PET between the two levels in summer. However, the probability of warm days decreases to 20 % at the height of 350 m in summer (Fig. 6). From December to February, cool days occur more frequently at the heights of 150 m and 350 m than at ground level. The probability of cold days is 95 % at the both levels and 90 % at ground level. Additionally, heat stress even occurred on 27th and 28th of February 2011.

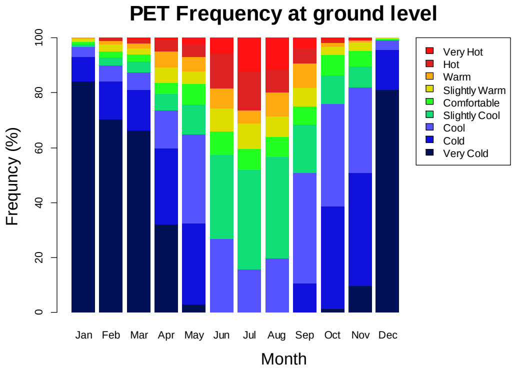

Fig 4. Frequency of PET at ground level in 2011.

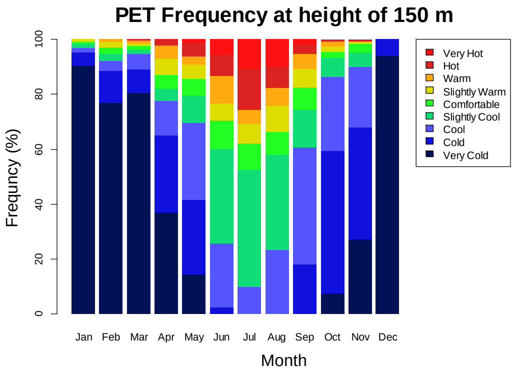

Fig 5. Frequency of PET at the height of 150 m of Taipei 101 Tower in 2011.

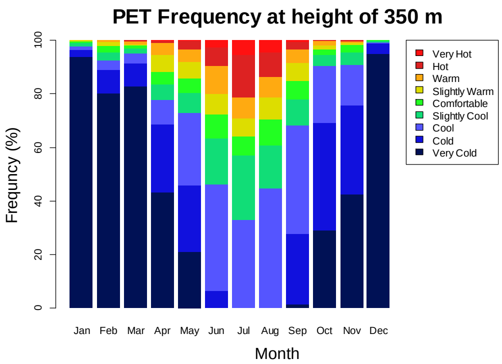

Fig 6. Frequency of PET at the height of 350 m of Taipei 101 Tower in 2011.

4. Discussion and conclusion

Vertical bioclimate analysis at Taipei 101 Tower shows that frequency of warm days (Fig. 4 and Fig. 5) and PET (Table 3 and Table 4) are very similar at ground level and height of 150 m during summer of 2011. That means that heat stress expands not only with horizontal urban expansion but also raises with vertical urban height in summer. Low wind speed and similar air temperature could cause little difference of thermal bioclimate between ground level and the height of 150 m in summer.

Due to seasonal monsoon, cold stress occurs often in Taipei in winter. Air temperature decreases to 10 ℃ to 15 ℃ during rainy days. Therefore, cold stress often occurs in Taipei in winter. However, also heat stress occurs sometimes during sunny days in winter. Variability of vertical bioclimate is driven by synoptic scale weather systems, especially by winter monsoon in Taipei. There is also significant difference in bioclimate from ground level to the height of 350 m due to summer and winter.

Difference of PET at the three levels is summarized in Table 6. Vertical variability of PET does not show continuously linear decreasing either in summer or during the other seasons. In summer, PET is almost equal at the two lower levels and decreases significantly above the height of 150 m. During the other seasons, vertical variability of PET is similar to logarithmic decreasing. However, monthly mean values of PET are lower at the height of 150 m and 350 m in March. Additionally, probability of PET greater than 38 ℃ (heat stress) is summarized in Table 7 and probability of PET greater than 35 ℃ (heat stress after thermal bioclimate classification of western/middle Europe) is summarized in Table 8.

Results of the study provide thermal conditions of vertical bioclimate and urban climate. Further studies are necessary and planned.

Table 6: Monthly mean of PET at ground level, difference of monthly mean value of PET in 2011 between height of 150 m and ground level (150 m - GR) and height of 350 m and ground level (350 m - GR)

Month	**GR (℃)**	**150 m - GR (℃)**	**350 m - GR (℃)**
Jan	11.1	-2.4	-3.9
Feb	13.2	-2.2	-3.3
Mar	13.8	-4.2	-5.5
Apr	19.3	-1.4	-2.3
May	22.6	-1.6	-2.3
Jun	27.9	-0.6	-1.9
Jul	29.7	0.0	-1.5
Aug	28.9	-0.6	-2.2
Sep	25.2	-1.8	-3.3
Oct	20.5	-1.9	-3.6
Nov	19.1	-2.3	-3.4
Dec	11.6	-2.7	-4.0

Table 7: Probability of PET greater than 38 ℃

Month	**Ground (%)**	**150 m (%)**	**350 m (%)**
Jan	0.5	0.0	0.0
Feb	2.3	0.9	0.6
Mar	3.8	1.4	1.3
Apr	10.8	7.3	5.4
May	12.1	9.1	8.2
Jun	25.6	23.4	20.0
Jul	31.3	30.7	29.1
Aug	28.6	24.3	21.3
Sep	18.2	10.8	8.3
Oct	3.3	2.5	1.9
Nov	1.7	0.8	0.8
Dec	0.0	0.0	0.0
annual	8.4	7.3	5.7

Table 8: Probability of PET greater than 35 ℃

Month	**Ground (%)**	**150 m (%)**	**350 m (%)**
Jan	1.6	1.1	0.6
Feb	5.4	3.4	2.6
Mar	6.8	2.5	2.4
Apr	16.9	14.2	13.1
May	19.0	15.3	15.2
Jun	35.1	32.8	29.0
Jul	41.3	40.8	36.3
Aug	37.1	35.0	32.7
Sep	26.9	20.0	17.2
Oct	7.7	4.9	4.2
Nov	6.0	2.7	2.2
Dec	0.6	0.0	0.0
annual	13.1	11.9	10.0

5. References

1. Ali-Toudert F., H. Mayer, (2007). Thermal comfort in an east-west oriented street canyon in Freiburg (Germany) under hot summer conditions. Theoretical and Applied Climatology 87, pp. 223 - 237.

2. Lin, T.P., A. Matzarakis, R.L. Hwand, (2010). Shading effect on long-term thermal comfort. Build. Environ. 45, pp. 213 - 211.

3. Höppe P., (1999). The physiological equivalent temperature - a universal index for the bioclimatological assessment of the thermal environment. International Journal of Biometeorology 43, pp. 71 – 75.

4. Mayer, H., P. Höppe, (1987). Thermal comfort of man in different urban environments. Theor. Appl. Climatol. 38, pp. 43 - 49.

5. Matzarakis A., F. Rutz, H. Mayer, (2007). Modelling radiation fluxes in simple and complex environments – Application of the RayMan model. Int J Biometeorol 51, pp. 323 - 334.

6. Matzarakis, A., F. Rutz, H. Mayer, (2010). Modelling Radiation fluxes in simple and complex environments – Basics of the RayMan model.International Journal of Biometeorology 54, pp. 131 – 139.

7. Lin, T.P., A. Matzarakis, (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. Int J Biometeorol 52, pp. 281 – 290.

8. Matzarakis A., H. Mayer, (1996). Another kind of environmental stress: thermal stress. WHO News 18, pp. 7 – 10.