Abstract

This paper aims to clarify the effects of extreme weather conditions on the space thermal comfort and energy consumption, which depend on the thermal characteristics of buildings and HVAC systems. Various types of extreme weather days that occur in Tokyo were picked from Expanded AMeDAS weather data for the period 1981 to 1995. Computer simulations were performed for office spaces, using 15-year Tokyo weather data to obtain the hourly changes in the PMV and the load on each of the components in a HVAC system. The type of extreme weather day that created severe conditions from the standpoint of thermal comfort and equipment load was clarified.

Keywords: extreme weather day; thermal comfort; equipment load; expanded AMeDAS weather data; office space

1. Introduction

For the economical and correct sizing of heating, ventilating and air-conditioning (HVAC) equipment, designers popularly use design weather data that allows for the risk occurrence of the more extreme weather conditions. In this paper, we attempt to define the loads that are imposed on the HVAC equipment in order to keep the space or room temperature at the set point, and how the space thermal environment deteriorates on days where extreme weather is experienced. Various types of extreme weather were selected from actual events in Tokyo occurring during the years from 1981 to 1995, using Expanded AMeDAS weather data. Computer simulations were performed to obtain the space thermal environment and the equipment loads required to maintain set point space temperature throughout 15 years. The effect of the extreme weather on the space thermal comfort and the equipment load may be dependent upon the kind of HVAC equipment, the space zoning, and the building thermal characteristics such as window orientation. The effect of extreme weather on the space thermal comfort and the equipment load was analyzed with respects to these points. The results obtained are valuable for the proposal of better design weather data to ensure adequate and economical sizing in future HVAC designs.

2. Selection of the Extreme Weather Days

Various types of extreme weather days were selected from weather data for the period from 1981 to 1995 based upon the daily weather indices. The following three types of winter extreme weather days selected occurred between December and March.

Type A: The day when the daily minimum of the outdoor air temperature was at the minimum for the 15-year period.

Type B: The day when the daily average of the outdoor air temperature was at the minimum for the 15-year period.

Type C: The day when the daily average of the outdoor air enthalpy was at the minimum for the 15-year period.

The Four types of the summer extreme weather days selected occurred during June and September.

Type A: The day when the daily maximum of the outdoor air temperature was at the maximum for the 15-year period.

Type B: The day when the daily average of the outdoor air temperature was at the maximum for the 15-year period.

Type C: The day when the daily average of the outdoor air enthalpy was at the maximum for the 15-year period.

Type D: The day when the daily total of solar radiation on a horizontal or vertical surface was at the maximum for the 15-year period.

Table 1. shows the dates and weather characteristics of the selected days. Each of the extreme weather days selected on the basis of one of the indices of outdoor air temperature or enthalpy, can also be regarded as a considerably extreme weather day based upon the other indices of outdoor air temperature or enthalpy. The day that occurred before the selected day also tends to show...
characteristics of considerably extreme weather.

3. Simulation Model
The simulation model is based on typical office space as shown in Figure 1. The space is conditioned by a single air-handling unit (AHU) that has temperature and humidity sensors in the interior zone, and fan coil units (FCU) that have a temperature sensor in the perimeter zone. The air temperature of the perimeter zone, the interior zone, and the ceiling space as well as 11 surface temperatures were obtained from solving convective and radiative heat balance equations. Operative temperature (OT) was used as a combined index of space air temperature and radiant environment, and predicted mean vote (PMV) was used as an index of thermal sensation. OT and PMV were calculated with the assumption that the individual is at the center of each perimeter and interior zone. The simulation conditions are given in Table 2. The operation of the HVAC system is as follows:

1) The equipment capacity is enough and the space air temperature is assumed not to rise or fall owing to its limitations. Although water spray in the AHU meets the space requirements for humidification, dehumidification by cooling coils in the AHU and the FCU are not con-

Table 1. The Extreme Weather Days in Tokyo Selected from Weather Data during the Years from 1981 - 1995

| Type of extreme weather | Date       | tomin | tomax | toave | hoave | SRs or SRw | The ranking of other weather indices on the selected day | The ranking of the weather index used for selection on the previous day |
|-------------------------|------------|-------|-------|-------|-------|------------|------------------------------------------------------|---------------------------------------------------------------------|
| Winter                  | March 27 '81 | 3.6   | 4.9   | 0.8   | 4.0   | s 17.6     | toave 7th, hoave 4th                                 | toave 23rd                                                          |
| Type A: tomin was at the minimum | Jan 21 '84  | 2.2   | 0.7   | -0.6  | 6.4   | s 1.4      | tomin 8th, hoave 24th                               | toave 6th                                                           |
| Type B: toave was at the minimum | Feb 7 '84   | -3.1  | 2.7   | 0.1   | 2.8   | s 18.0     | tomin 3rd, toave 2nd                               | hoave 10th                                                         |
| Type C: hoave was at the minimum | Aug 3 '94   | 27.8  | 37.9  | 32.3  | 74.9  | s 7.6      | toave 2nd                                           | toave 5th                                                         |
| Type D: SRs was at the maximum | Aug 4 '94   | 29.5  | 36.2  | 32.4  | 76.8  | s 7.9      | toave 5th                                           | toave 11th                                                        |
| Type E: SRw was at the maximum | Aug 7 '94   | 28.1  | 34.5  | 30.7  | 81.5  | s 7.6      | toave 8th, toave 30th                              | hoave 26th                                                        |
| Type F: SRw was at the maximum | Aug 9 '84   | 20.9  | 27.3  | 23.5  | 47.6  | s 13.7     | SRs 5th                                             |                                                                     |
| Type G: SRw was at the maximum | Jun 24 '87  | 19.4  | 27.9  | 23.7  | 50.8  | w 13.4     | SRw 14th                                            |                                                                     |

*1 tomin, toave and tomax: daily minimum, daily average and daily maximum of outdoor air temp. (deg C), hoave: daily average of outdoor air enthalpy (J/g), SRs and SRw: solar radiation on a south-facing surface and on a west-facing surface (MJ/m2)

*2 The ranking of the weather indices among 1830 cooling days or 1818 heating days during the years from 1981 to 1995. The ranking within 50th is written in the table.

Table 2. The Conditions of the Building and the HVAC System for Simulations

| Building | Structure: Curtain wall, Glazing: Clear single glass | Blind operation: Closing blind is determined by the sunlit floor depth and the intensity of transmitted solar radiation | Occupancy: 0.2 person/m2, Lighting and equipment: 30W/m2 |
|----------|------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|
| HVAC system | Set point space air temperature and humidity: 25deg C for cooling and 23deg C RH50% for heating | Heating and cooling hours: 8:00 - 18:00 (warm-up or pull-down 8:00 - 9:00) | Heating season: December to March, Cooling season: June to September |
| Fresh air rate: 1.1 l/min/m2sec, supply airflow rate: AHU 5.0 l/min/m2sec, FCU 43 l/min/msec |
| Human | Clothing and metabolism: 0.6clo and 1.1 Met in cooling season and 0.9 clo and 1.2 Met in heating season, Air velocity: 0.2m/sec |

Fig.1. An Office Space on a Typical Floor
trolled and the dehumidification rate depends on the sensible cooling rate.

2) The HVAC system operates every day during the cooling season from June to September and during the heating season from December to March. The AHU can meet the interior zone demands of heating and cooling between December and March, but only cooling between June and September.

3) During the warming-up or pulling-down hours (from 0800 to 0900), each value of AHU load and FCU load is assumed to be constant and the space air temperature is also assumed to reach set point at 0900.

4. The Space Thermal Environment and the Equipment Load during the Extreme Weather Days in a South-facing Office Space

4.1 Changes of Space Temperature, Humidity and Thermal Loads

The simulation was performed for a south-facing office space, using 15-year Tokyo weather data. Figure 2
illustrates the hourly changes in the space thermal environment and the equipment load during the winter extreme weather days of type A and B. To give a comparison for the average weather day, the average values of the weather, the thermal environment, and the thermal load at each hour in February for 15 years are also included. During the extreme weather days of type A, the space air temperatures declined considerably till approximately 0600, and a large heating rate was required by the AHU to warm-up. Alternatively, a relatively high amount of solar radiation meant that the perimeter zone did not require heating until 1700. During the extreme weather day of type B, the rate of the thermal load on the AHU and the FCU is large, and OT in both the interior and perimeter zones is low during the space heating hours on that date.

Figure 3 illustrates the results of the summer extreme weather days of type A, C and D. On the extreme weather day of type A, the outdoor air temperature almost reached 38°C and the OT became higher than space air temperature by approximately 1.5K in the interior zone, and by approximately 2.5K in the perimeter zone. On the extreme weather day of type C, AHU loads became larger due to the increase in the latent load of humid fresh air. On the extreme weather day of type D, FCU loads became larger in order to remove the large amounts of solar heat gained. However, the OT did not become higher as found in the case of other extreme weather days.

![Figure 3](image-url)

Fig.3. The Changes in the Space Environment and the Equipment Load during the Summer Extreme Weather Days (in a south facing space)
4.2 Evaluation by Ranking the PMV and Equipment Load

Using the hourly PMV and the hourly equipment load calculated for 15 years, the ranking of the PMV and the equipment load was obtained to quantify how much the space thermal environment deteriorates, and how much heating or cooling is required to the HVAC equipment on the extreme weather days in comparison with the normal days. For example, Figure 4 shows the ranking of the warm space environment during cooling hours for 15 years using the PMV as an index. The ranking among 18300 cooling hours is taken as the variable of the X-axis in the left-hand figure. In the right-hand figure, the ranking is converted to the percentage of the total number of cooling hours and is expressed on a logarithmic scale. This percentage means the probability of occurrence of the warmer space environment than that corresponding to this percentage. The first ranking of the PMV can be regarded as the warmest and the worst space environment during the cooling hours for 15 years and its probability of occurrence is 0.005%.

The hourly changes in the PMV and the equipment load, as well as their ranking during the winter extreme weather days, are shown in Figure 5. PMV values during the extreme weather day of type A are similar to those on the extreme weather day of type C. During the extreme weather day of type B, the PMV has a constantly low value, and the PMV at 0900 in each of the interior zone and perimeter zone, ranks second (0.01% as a percentage expression) as the coldest environment during heating hours for 15 years. On any of these three days, the AHU load at 0900 becomes considerably larger. In particular, the AHU load at 0900 on the extreme weather day of type B ranks first in magnitude during heating hours. The FCU load on the extreme weather day of type B maintains a high value, and its ranking percentage is within 1% throughout the day.

Figure 6 demonstrates the hourly changes of the PMV and the equipment load, as well as their ranking during the summer extreme weather days. On the extreme weather day of type A, the ranking of the warm space environment at 1400 in each of the interior and perimeter zones is the highest of four days. However, the PMV decreases after 1500 due to the sudden decrease of solar radiation. On the extreme weather day of type B, the hours during which the ranking percentage of the warm environment is within 1% are considerably longer when compared with the other three days. The extreme weather days of type A and B can be regarded as the most severe conditions for thermal comfort during the cooling season. The ranking of the cooling AHU load becomes higher on the extreme weather day of type C. Although the ranking of the cooling FCU load becomes high on the extreme weather day of type D, the ranking percentage does not fall within 1%. The FCU load becomes much larger on those days with a high level of air humidity, as well as intense solar radiation on the window surface. On such days the FCU removes not only sensible heat but also latent heat from the conditioned space.

5. The Space Thermal Environment and the Equipment Load during the Extreme Weather Days in a North or West-facing Office Space

The effect of extreme weather on the space thermal environment and the equipment load depends largely upon the buildings thermal characteristics. During the simulations, the effects of different window orientation on each case were analyzed. Figure 7 illustrates the PMV and the equipment load, as well as their ranking in a north-facing office space during the winter extreme weather days. The ranking of the cold environment and the equipment load both become high during the extreme weather day of type B. This trend is similarly evident in the case of a south-facing office space. Figure 8 shows the PMV and the equipment load, as well as their ranking in a west-facing office space during the summer extreme weather days. On the extreme weather days of type A and C, the PMV ceases to increase at around 1600, and its changes are similar to those in a south-facing office. This is due to the decrease in solar radiation after 1500. As a result, the extreme weather day of type
A demonstrates severe conditions for thermal comfort, and the extreme weather day of type C demonstrates severe conditions for the AHU load. The extreme weather day of type D demonstrates severe conditions for the FCU load, however the thermal environment in the perimeter zone does not deteriorate as much. These results are the same as those obtained from the analysis performed for a south-facing office space. Further analysis for other location may be needed in order to validate these results for the summer extreme weather.

6. Conclusions
1) By selecting the most extreme weather day based upon one of the indices of outdoor air temperature or enthalpy, it can then also be regarded as a considerably extreme weather day based upon the other indices of outdoor air temperature or enthalpy. The day that occurred before the selected day also tends to show characteristics of the considerably extreme weather.

2) During the heating season, the extreme weather day of type B can be regarded as creating severe conditions from the standpoint of thermal comfort, AHU load, and FCU load when the daily average of the outdoor air temperature is at the minimum for 15 years. This result was obtained from the analysis of the case with a south-facing surface, as well as in the case with a north-facing space.
3) During the cooling season, the extreme weather days of type A and B can be regarded as creating severe conditions for thermal comfort only. The extreme weather day of type A is that when the maximum of the daily outdoor temperatures is at a maximum for 15 years. The extreme weather day of type B is likewise that when the average of the outdoor air temperatures is at a maximum for 15 years. The extreme weather day of type C, when the average of the outdoor air enthalpy is at the maximum, causes severe conditions for the AHU load. The extreme weather day of type D, when the daily total of solar radiation on the window surface is at its maximum, creates severe conditions for FCU load, although the thermal environment on this day can be expected not to deteriorate so much. These results were obtained from the analysis of those cases involving a south and a west-facing space.

In this paper, the effects of extreme weather were analyzed in south-facing, north-facing and west-facing office spaces. Further study is planned in various cases to clarify the effects of extreme weather dependent upon the building factors such as window ratio, glazing, insulation and space depth as well as the system factors such as zoning and method of cooling and heating.
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