Thesis for the Degree of Master of Science

# The development of Accumulated Heat stress Index based on time-weighted function

by


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# 시간가중함수를 이용한 열 스트레스 누적지수 개발

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By

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A dissertation

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# CONTENTS

**List of Figures** ······ ii

**List of Tables** ······ iv

**Abstract (Korean)** ······ 1

**1. Introduction** ······ 2

**2. Data and Methodology** ······ 7
2.1 Data ······ 7
2.2 Excess mortality by IH ······ 7
2.3 Mortality by DH ······ 8
2.4 Definition of the day of death by heat wave ······ 8

**3. Development of Accumulated Heat Stress Index** ······ 11
3.1 Calculation of accumulated heat stress ······ 11
3.2 Standardization of accumulated heat stress ······ 11
3.3 Monthly characteristics of the Accumulated Heat Stress Index ······ 18
3.4 Setting the AHI danger criterion ······ 18

**4. Comparison and Verification of AHI against Humidex, HI, and WBGT** ······ 22
4.1 Comparison of the rates of heat wave alert ······ 22
4.2 Comparison of the rate of sensing danger due to IH ······ 24
4.3 Comparison of the rates of sensing danger due to DH ······ 26
4.4 Comparison of the rates of sensing danger due to simultaneous IH and DH ······ 27

**5. Conclusions and Discussion** ······ 29

**REFERENCES** ······ 32

# List of Figures

**Fig. 1.** Hourly variation of the mortality by DH over 71 stations in Korea during JJAS in 2000-2008. ........ 10

**Fig. 2.** Variation of the weight for accumulated heat-stress along time pass, which is taken 72 hours. ........ 12

**Fig. 3.** Example of an equiprobability transformation from a fitted 3-parameters weibull distribution to the standard normal distribution. ........ 14

**Fig. 4.** Histogram of the daily maximum accumulated heat-stress and fitted 3-parameter Weibull distribution in (a)Seoul, (b) Gangneung, (c)Daejeon, (d) Daegu, (e)Gwangju, and (f)Busan during JJAS in 1999-2008 (histogram: empirical data, solid line: fitted 3-parameter Weibull distribution). ........ 15

**Fig. 5.** Monthly distribution of AHI when DH days were occurred on JJAS from 2000 to 2008. In the box plots, solid lines denote median value. The low and high inner fences extending from the box represent 10th and 90th percentile. 'o' signs imply AHI when heat wave was occurred by DH. 'x' signs imply monthly mean of AHI from 2000 to 2008. ........ 20

**Fig. 6.** (a) Scatter diagram shows relation between the AHI and the excess mortality by IH when the excess mortality is above 2 at 71 stations for JA in 2000-2008 (n=3370). The left scale shows the excess mortality and the bottom scale shows the AHI. Box-plot represents distribution of the AHI when the excess mortality is more than 2 and the vertical axis is not used. (b)Box-plot means distribution of AHI during DH days. (Each outer: outside of the 10th and 90th percentiles). ........ 21

**Fig. 7.** Scatter diagrams showing the relation between the daily maximum AHI and the thermal indices ((a)Humidex, (b)HI, (c)WBGT). The left scale shows the AHI values. The bottom scale shows the index (unit: ℃). The coefficients of determination (Rsqr) and regression equations are shown in the top of the panels. The horizontal dashed-lines denote alert threshold of AHI. ........ 22

**Fig. 8.** Same as in Fig. 6a but for the (a)AHI, (b)Humidex, (c)HI, (d)WBGT during IH days (n = 17257). The areas drawn diagonal lines represent range of warning for each indices. ········ 25

**Fig. 9.** Same as in Fig. 6b but for the (a)AHI, (b)Humidex, (c)HI, (d)WBGT during DH days (n = 107). In addition, light-grey box-plots showed distribution of the indices over Korea (71 stations) during JJAS from 2000 to 2008 are added. The areas drawn diagonal lines represent range of warning for each index. ········ 26

**Fig. 10.** Same as Fig. 8. but for the (a)AHI, (b)Humidex, (c)HI, (d)WBGT when IH day and DH day are occurred simultaneously (n = 77). ········ 28

**Fig. 11.** Scatter diagrams showing the relation between the daily maximum temperature and the thermal indices ((a)AHI, (b)Humidex, (c)HI, (d)WBGT) when IH day and DH day are occurred simultaneously (n = 77). The left scale shows the temperature values(unit: ℃). The bottom scale shows the index. The vertical dashed-lines denote alert threshold of each thermal indices. The horizontal dashed-lines represent temperature boundary of 33℃. ········ 31

# List of Tables

**Table 1.** Alert criteria for heat-wave warning in each country. ······ 3

**Table 2.** Thermal indices which evaluate heat stress. ······ 4

**Table 3.** Category of the deaths by IH in KCD. ······ 9

**Table 4.** Category of the deaths by DH in KCD. ······ 9

**Table 5.** Goodness-of-fit of parametric probability distributions for Anderson Darling tests (Total number of distribution: 30). ······ 16

**Table 6.** For each thermal indices, (a) criteria values of heat-wave warning, 1σ and 2 σ of distribution for JJAS in 2000-2008, (b) rate of sensing danger during IH days, (c) rate of sensing danger during DH day and (d) Rate of sensing danger when IH day and DH day are occurred simultaneously in the range of (a) and above. ······ 23

시간가중함수를 이용한 열 스트레스 누적지수 개발

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## 요 약

고온환경이 지속될 경우 인체는 순화되지 못한 열 스트레스를 체내에 누적시킨다. 이 점에 착안하여, 발생 시간에 따라 가중치를 조절해 주는 시간가중함수를 이용하여 열 스트레스를 72시간 동안 누적하였다. 누적된 열 스트레스는 equiprobability transformation method (열 스트레스 누적량의 확률분포를 이론적 확률분포인 weibull 분포로 변환하고, 이를 역 표준정규분포에 대입하는 방법)를 이용하여 표준화 한 다음, 이를 AHI (Accumulated Heat stress Index)로 정의하였다.

지수검증을 위해, AHI를 현재 통용되고 있는 폭염지수들 (Humidex, Heat Index, Wet-Bulb Globe Temperature)과 비교하였다. 그 결과, 여름 동안 AHI에 따른 폭염경보일 수는 다른 지수들과 유사한 수준이면서도, 실제로 폭염에 의해 사망자가 발생한 날에 대한 경보적중률은 다른 지수들 보다 더 높았다. 특히 moderately hot days (28~32℃ of daily maximum temperature)가 지속되어 폭염 피해가 발생하는 경우, 다른 지수들은 이를 대부분 감지하지 못하는데 반해, AHI는 잘 감지함을 보였다.

**Key words**: Heat wave, Thermal index, Heat stress, Humidex, Heat index, WBGT

## 1. Introduction

On July 23rd and 24th, 1994 in Seoul, Korea, the daily maximum temperature record (38°C) was broken consecutively and the daily mortality increased every day. On July 25th, the daily maximum temperature dropped, but the daily mortality continuously increased, and the excess mortality for annual mean value (1999-2003) reached 77 people (Lee 2006; Park et al. 2007). In this summer in Japan, 589 people also died of heatstroke by heat wave (Nakai et al. 1999; Heo et al. 2009). In the summer of 2003 in Europe, as hot weather approaching 40°C continued for over 10 days, over 35,000 people died and economic losses amounted to over 13 billion dollars (WMO 2004; Trigo et al. 2005; Diaz et al. 2006). It is estimated that these increasing damages from heat wave have been caused by global warming and its effects will become more severe in the future (Confalonieri et al. 2007).

Countries that experience frequent damages from heat wave are operating a heat wave warning system to reduce these damages. The methods for diagnosing heat wave are classified into three categories (Table 1) (WMO 2004; Park et al. 2008); a) a method that only considers the daily maximum temperature (China, UK, Portugal, Czech Republic), b) a method that considers both the daily maximum temperature and the duration of high temperature (Greece, France, Southern Australia), and c) a method that considers the thermal index in addition to the aforementioned two conditions (Canada, Korea, USA, Singapore).

Recently, countries that use the method c) are gradually increasing. The thermal indexes used here are subdivided again to non-accumulated indexes (Table 2-1) and accumulated indexes (Table 2-2). Between these two, the non-accumulated indexes are generally well-known. These indexes are classified again to three types depending on the meteorological elements for diagnosing heat wave. The first type of indexes uses the four elements of temperature, humidity, wind, and solar radiation. Apparent Temperature (AT, Steadman 1979, 1984) which belongs to this category turned measure of relative discomfort into an index by testing the evaporation and cooling on skin when people are involved in light activities.

The second type of index is the Wet-Bulb Globe Temperature (WBGT, Yaglou and

**Table 1.** Alert criteria for heat-wave warning in each country.

| Variables of heat-wave warning | Country | Range of criteria | |
|---|---|---|---|
| (a) Temperature | China | $T_{max} \geq 35℃$ | |
| | England | $T_{max} \geq 32℃$, $T_{min(night)} \geq 18℃$ (London) | |
| | Portugal | $T_{max} \geq 32℃$ (Lisbon) | |
| | Czech Rep. | $T_{max} \geq 33℃$ | |
| (b) Temperature, Consecutive days | Greece | $T_{max} \geq 38℃$, 3 Consecutive days | |
| | France | $T_{max} \geq 36℃$, 3 Consecutive days | |
| | Australia (south) | $T_{max} \geq 35℃$, 5 Consecutive days or $T_{max} \geq 40℃$, 3 Consecutive days | |
| (c) Thermal index, Consecutive days or none, Temperature or none | Canada | Humidex $\geq 40℃$ 2 Consecutive days | [Advisory] |
| | | Humidex $\geq 40℃$ 4 Consecutive days , or Humidex $\geq 45℃$ | [Warning] |
| | Rep. Korea | $T_{max} \geq 33℃$, $HI_{max} \geq 32℃$ 2 Consecutive days | [Advisory] |
| | | $T_{max} \geq 35℃$, $HI_{max} \geq 41℃$ 2 Consecutive days | [Warning] |
| | U.S. Navy | WBGT $\geq 31℃$ | [Advisory] |
| | | WBGT $\geq 32℃$ | [Warning] |
| | Singapore (WSH council) | WBGT $\geq 31℃$ | [Advisory] |
| | | WBGT $\geq 32℃$ | [Warning] |

**Table 2.** Thermal indices which evaluate heat stress.

| **1.** Non-accumulated Index | Formula | Country using index | Creator |
|---|---|---|---|
| Discomfort Index (DI) | $DI = 0.4(Ta_1+Tw)+15$ | Israel | Thom (1957, 1959) |
| Wet-Bulb Globe Temperature (WBGT) | $WBGT = 0.7NWT+0.2GT+0.1DT$ | Japan, Army of U.S.A. | Yaglou and Minard (1957) Burr (1991) |
| Approximation to the WBGT | $WBGT = 0.567Ta_2+0.393P+3.94$ | Australia | ACSM (1984) |
| Humiture or Humidex | $Humidex = Ta_2+0.5555(P-10)$ | Canada | Lally and Watson (1960) Masterton and Richardson (1979) |
| Apparent Temperature (AT) | $AT_i = 0.92Ta_2+22P-1.3$<br>$AT_{sh} = 1.04Ta_2+20P-0.65V-2.7$<br>$AT_s = 1.07Ta_2+24P-0.92V+0.044Q-1.8$ | Australia | Steadman (1979, 1984) |
| Heat Index (HI) | $HI = c_1+c_2Ta_1+c_3RH +c_4Ta_1RH+c_5Ta_1^2+c_6RH^2 +c_7Ta_1^2RH+c_8Ta_1RH^2+c_9Ta_1^2RH^2$ | U.S.A., Korea, Rumania | Rothfusz (1990) |
| **2.** Accumulated Index | Meteorological factors used | Accumulation period | Creator |
| Heat Stress Index | Max·Min AT,<br>mean cloud cover,<br>cooling degree days(CDD)<br>consecutive day(CONS) | CDD: $AT(hr) \geq 18.3$℃ over 24 hour<br>CONS: Max $AT \geq \sigma$ over 10 day | Watts and Kalkstein (2004) |

($Ta_1$: air temperature(˚F), $Ta_2$: air temperature(℃), Tw: Wet-bulb temperature(˚F), NWT: Natural wet-bulb temperature(℃), GT: Globe thermometer temperature(℃), DT: Dry-bulb temperature(℃), P: vapour pressure(hPa), $AT_i$: AT in indoor, $AT_{sh}$: AT in the shade outdoor, $AT_s$: AT in the sun outdoor, V: wind speed at 10 m height(m $s^{-1}$), Q: solar radiation(W $m^{-2}$), RH: relative humidity(%), $c_x$: constants)

Minard 1957) which considers the three elements of temperature, humidity, and solar radiation. WBGT is often used in military organizations and industrial sites, but since the globe temperature cannot be easily measured, WBGT-approximate formulas omitting it are also researched (ACSM 1984; Sparling 1997; Hunter 2001; Kang et al. 2001). However, they are insufficient to fully reproduce WBGT (Budd 2008).

The third type of indexes use the two elements of temperature and humidity, and include Discomfort Index (DI, Thom 1957, 1959), Humidex (Masterton and Richardson 1979), and Heat Index (HI, Rothfusz 1990). DI is the most widely known thermal index. As it was developed in the USA, it is similar to the summer temperature range of the USA (Giles et al. 1990). Humidex is a modification of Humiture (Lally and Watson 1960) and is sensitive to humidity change. HI is a modification of AT (Steadman 1979), which is calculated with various meteorological parameters, into a multiple regression equation of temperature and relative humidity. The calculation of HI is simple and fast, and the expected error is small.

Although the aforementioned non-accumulated thermal indexes are used in the field, they have a few disadvantages. First of all, they do not reflect the fact that the longer the duration of heat wave is, the higher the mortality by thermal diseases becomes. Even though people may be killed by the effect of heat wave only for one day, the mortality increases as the duration of heat wave is lengthened (Nakai et al. 1999). Thus, the accumulated effect of heat stress cannot be ignored. The non-accumulated indexes, however, diagnoses heat wave only by the atmospheric condition at one point of time, so they recognize the heat wave of the day well, without considering the accumulated effect of heat stress. To complement this problem, some countries (e.g., Korea, Canada) define the warning criterion as continuation of the index higher than the critical value for 2 or 3 days or longer. This is inconvenient, however, because heat wave cannot be diagnosed only by the index. Furthermore, it cannot consider the difference in the level of damage which varies by how many hours the high temperature continued. Secondly, they do not reflect the regional climatic characteristics and the acclimatization of the residents. Turks who live in the middle latitude are exposed to high temperature for more time than Russians who live in the high latitude. Thus, Turks have a high level of immunity to high temperature because they have improved circulatory system and perspiration function (Lyashko et al. 1994; Moseley 1997; Bouchama and Knochel 2002). This means that acclimation to high temperature occurs depending on regional climate, and thermal index needs to provide a relative heat stress value by considering this.

The accumulated index that was developed to address this problem was Heat Stress Index (HSI, Watts and Kalkstein 2004) (Table 2-2). HSI considered the accumulated effect of heat wave using an AT value of over 18.3°C that was accumulated for one day and the number of days of continued heat wave. In addition, HSI considered the daily maximum and minimum ATs and the mean daytime cloud cover to calculate heat stress with five parameters in total. Furthermore, this value is represented as a percentile of the 30 year data of each region to reflect climatic adaptation level.

This index, however, has a shortcoming as well. HSI has a high possibility of heat wave prediction error because there are more climatic parameters than other generally used thermal indexes. Moreover, when the high-temperature-related parameters were accumulated, the difference in effects by the duration of the parameters was not considered. For example, even at the same high temperature of 40°C, the heat stress of 72 hours ago has a different effect on human body than the present heat stress, because the heat stress of 72 hours ago would have become weakened through adaptation process over time. Therefore, it is unreasonable to accumulate heat stress with the same weight regardless of the time.

Thus, this study developed Accumulated Heat Stress Index (AHI) which accumulates heat stress with a time-weighted function, and compared this index was with other existing indexes to determine its excellence. Among thermal indexes, there is the total degrees-days of exceedance index (DD index, Diaz et al. 2006) which measures the intensity of heat wave by year, and this will be examined in a follow-up study because it is a little beside the focus of this study.

## 2. Data and Methodology

### 2.1 Data

The hourly weather data (temperature, relative humidity) and hourly mortality of all stations (71) at which consecutive data exist for the analysis period were used. The weather data were received from the Korea Meteorological Administration, and the mortality data were received from the Micro Data Service System that is affiliated with Statistics Korea. The analysis period was set to summer (June to September) from 2000 to 2008 for which hourly mortality data are available. For temperature and relative humidity, the data of the entire period (from 1999 to 2008) for which hourly data are available for climate analysis of each station.

The mortality data include the address, sex, age of death, time of death, place of death, and cause of death according to the Korean Standard Classification of Disease (KCD). In this study, the KCD code was used to classify mortality into mortality by the indirect effect of heat wave (IH) and mortality by the direct effect of heat wave (DH)

### 2.2 Excess mortality by IH

Causes of death by IH include heart diseases, nervous diseases, and mental diseases (Table 3) which can be aggravated by heat wave (Donoghue et al. 1997; Naughton et al. 2002; Kim et al. 2006). However, since these diseases can cause death even without the effect of heat wave, most previous studies did not use the mortality directly but converted it to excess mortality (Whitman et al. 1997; Guest et al. 1999; Smoyer et al. 2000; Kysely 2004; Lee 2006; Lee 2007). In this study, the excess mortality conversion method proposed by Kysely (2004) was used (Eq. 1).

$$Excess\ mortality(y,d) = M_{obs}(y,d) - M_{\exp}(d) \quad (y = 2000,\cdots,2008,\ \mathrm{d} = 1,\cdots,365) \qquad (1)$$

$$M_{\exp}(d) = M_{mean}(d) \cdot w$$

Excess mortality is calculated by the difference of $M_{obs}$ and $M_{exp}$ (y is year and d is Julian day). $M_{obs}$ is the daily mortality by IH and $M_{exp}$ is the expected daily mortality by IH. For $M_{exp,}$ the intra annual cycle (Lerchl 1998) and weekly cycle (Wang et al. 2002) of variations of mortality were considered. $M_{mean}$ is the 7-day moving average of the daily average mortality for each date of 9 years, and w is the day of the week weight which is 1.005 for weekday and 0.995 for weekend.

In other words, excess mortality is the daily mortality from which the average temporal variability was removed. It is negative if the mortality is lower than average and positive if the mortality is higher than average. In this study, the day when the excess mortality is positive was defined as IH day.

## 2.3 Mortality by DH

Unlike IH, mortality by DH is only caused by heat wave, and these data are indispensible for heat wave research. Diseases associated with mortality by DH include heatstroke and sunstroke (Table4). These diseases are classified as T67 group in the Korean Statistics data, but recognition of the S00-T98 group is low because it has not been revealed. Furthermore, it is very difficult to analyze the relationship between mortality by DH and thermal index because the mortality by DH on the same day and same region is rarely more than two. Thus, few studies have defined and verified the danger criterion of thermal indexes by mortality by DH. However, the danger diagnosis capability of a thermal index could be rationally verified if it is shown that the thermal index diagnoses as dangerous days the days on which there was mortality by DH regardless of the number of deaths. Therefore, in this study, the day when there was mortality by DH was defined as DH day, and it was used for verification of the index together with IH day.

## 2.4 Definition of the day of death by heat wave

People with thermal diseases die within about 24 hours after onset if their condition is not improved, the time of death after heat wave can be delayed by about one day (Ferris et al. 1938; Jones et al. 1982; Naughton et al. 2002). That is, people affected by heat wave in the afternoon could die in the morning of the next day. Therefore, to use IH day of DH day for verification of the index, the day of death by heat wave of the previous day must be

**Table 3.** Category of the deaths by IH in KCD.

| Code | Causes of the death |
|---|---|
| E00~99 | Endocrine, nutritional and metabolic disease |
| F00~99 | Mental and behavioral disorders |
| G00~99 | Diseases of the nervous system |
| I00~99 | Diseases of the circulatory system |
| J00~99 | Diseases of the respiratory system |
| R00~99 | Symptoms, signs and abnormal clinical and laboratory findings, NEC |

**Table 4.** Category of the deaths by DH in KCD.

| Code | Causes of the death |
|---|---|
| T67.0 | Heatstroke and sunstroke |
| T67.1 | Heat syncope |
| T67.2 | Heat cramp |
| T67.3 | Heat exhaustion, anhydrotic |
| T67.4 | Heat exhaustion due to salt depletion |
| T67.5 | Heat exhaustion, unspecified |
| T67.6 | Heat fatigue, transient |
| T67.7 | Heat oedema |
| T67.8 | Other effects of heat and light |
| T67.9 | Effect of heat and light, unspecified |

modified.

Fig. 1 shows the distribution of time of death by heatstroke during the analysis period. The mortality by heatstroke is very small between 19:00until 10:00the next day, but it increases rapidly from 11:00 and peaks at 16:00. This suggests that because accumulated heat stress gives greater damage than instantaneous heat stress, more deaths occurred in late afternoon than the time of the highest temperature in a day. Due to the differences in physical strength of individuals, small number of deaths occurred in the dawn or morning of the next day, and it is valid to regard these cases to be the effect of the heat wave on the previous day of the death. Thus, for excess mortality by IH (or by DH before 11:00 a.m., the previous day was defined as the IH day (or DH day).

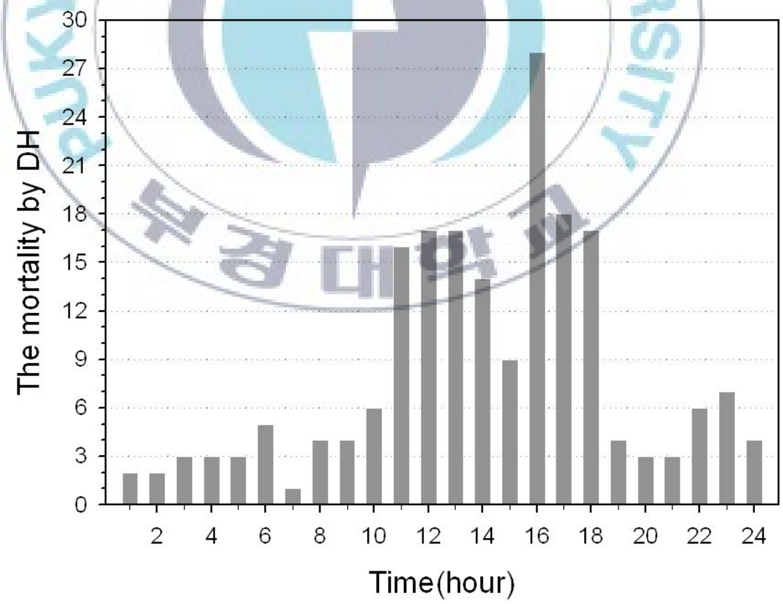


**Fig. 1.** Hourly variation of the mortality by DH over 71 stations in Korea during JJAS in 2000-2008.

# 3. Development of Accumulated Heat Stress Index

## 3.1 Calculation of accumulated heat stress

The accumulated heat stress includes all heat stresses which occurred in the past and still have effects at present. Different weights were applied to heat stresses depending on the occurrence time and they were accumulated for 72 hours (Eq. 2).

$$AH_{DS} = \sum_{i=1}^{DS} [H_i \cdot W_i] \qquad (i = 1,\ 2,\ \cdots,\ DS) \tag{2}$$

$$W_i = \sum_{m=i}^{DS} 1/m \tag{3}$$

Wherein DS is the duration of summation and $AH_{DS}$ is the accumulated heat stress for DS. In this study, DS was set to 72 hours. This is the time required for heat stress is weakened as the perspiration function is improved by the short-term heat adaptation of the body (Hori 1995). Furthermore, i is the time passed at the point of calculation, and $H_i$ is the heat stress received i hours ago. The $H_i$ at each hour was defined as Humidex. Humidex quantitatively indicates the current intensity of heat wave by considering the effect of humidity as well as temperature (Table 2). There are other thermal indexes such as HI and WBGT, but their heat wave danger sensing rates were lower than that of Humidex even after they were accumulated and standardized as Eq. 2. Therefore, this study used Humidex. More details about this will be given in Conclusions and Discussion. $W_i$ (Eq. 3) is the weight of heat stress according to the passing of the time i. This weight is greater for heat stresses that occurred more recently. $W_i$ decreases like a logarithmic function over time, and converges to almost 0 when i=DS (Fig. 2).

## 3.2 Standardization of accumulated heat stress

Standardized index can diagnose heat waves with the same danger criteria in regions with different climates because the climatic adaptation level for each region is applied. Thus, accumulated heat stress was standardized and the result was defined as thermal index. Since this study focused on the diagnose of the days of heat wave rather than the time of

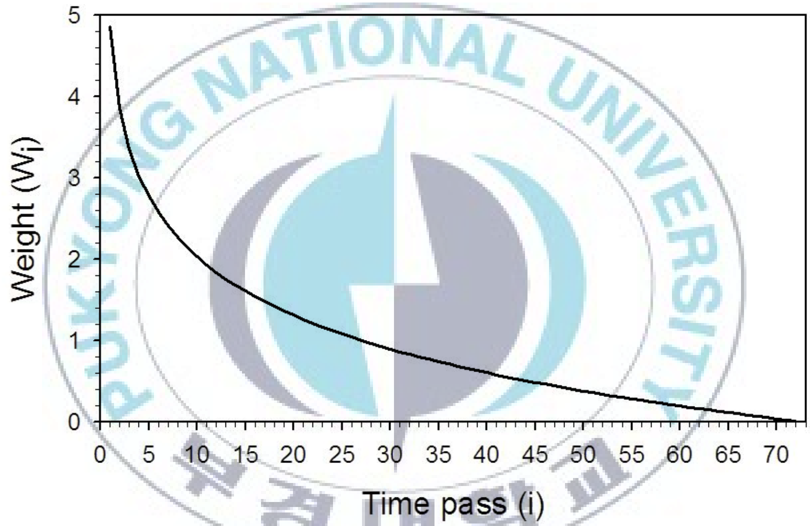


**Fig. 2.** Variation of the weight for accumulated heat-stress along time pass, which is taken 72 hours.

heat wave, only the daily maximum accumulated heat stresses were extracted from the hourly accumulated heat stresses. Furthermore, to standardize the accumulated heat stress for each station, the equiprobability transformation method proposed by Lloyd-Hughes and Saunders (2002) was used. This method can standardize observation values more ideally by representing the observed values which are the sample group with a theoretical probability distribution which is close to the population. This process can be described in more detail as follows. A probability distribution which can best estimate the probability estimation of accumulated heat stress is selected. The observation values are substituted in the fitted theoretical Cumulative Distribution Function CDF) to determine the probability value F (AH). Then F (AH) is substituted in the inverse standard normal CDF to ideally standardize the accumulated heat stress (Fig. 3).This value was defined as AHI.

Fig. 4 shows the probability distribution (histogram) of accumulated heat stress in large cities among the 71 stations and the 3-parameter Weibull distribution (solid line) fitted for this distribution. For the 3-parameter Weibull distribution here, one of the 30 unbounded non-negative probability distributions which was found to have high statistic ($A^2$) through the Anderson-Darling test. The 3-parameter Erlang distribution and the 4-parameter General Gamma distribution showed the highest $A^2$ for Daejeon and Daegu, respectively, but they showed low A2 in other regions. On the other hand, the 3-parameter Weibull distribution showed the highest $A^2$ in Gangneung, Seoul, Gwangju, and Busan and the second highest $A^2$ in Daejeon and Daegu (Table 5). Thus, the 3-parameter Weibull distribution which simulated well the probability distribution of accumulated heat stress for many regions was used as the theoretical CDF.

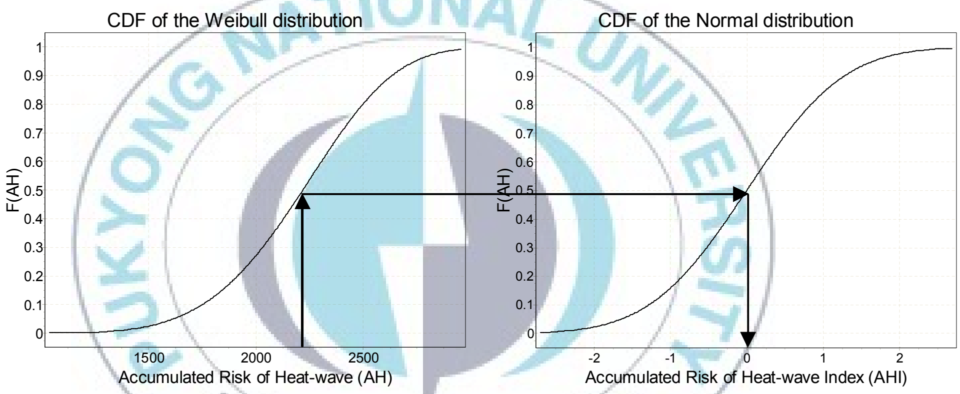


**Fig. 3.** Example of an equiprobability transformation from a fitted 3-parameters weibull distribution to the standard normal distribution.

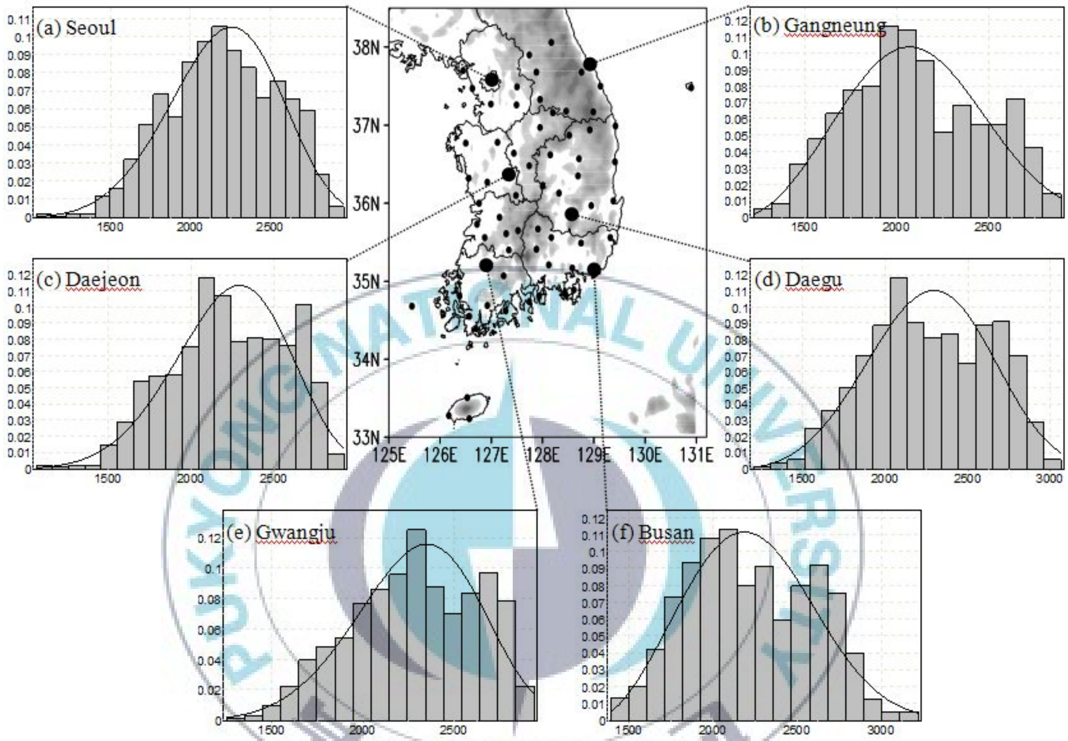


**Fig. 4.** Histogram of the daily maximum accumulated heat-stress and fitted 3-parameter Weibull distribution in (a)Seoul, (b) Gangneung, (c)Daejeon, (d) Daegu, (e)Gwangju, and (f)Busan during JJAS in 1999-2008 (histogram: empirical data, solid line: fitted 3-parameter Weibull distribution).

**Table 5.** Goodness-of-fit of parametric probability distributions for Anderson Darling tests (Total number of distribution: 30).

| Rank | 47105 (Gangneung) | | 47108 (Seoul) | | 47133 (Daejeon) | | 47143 (Daegu) | | 47156 (Gwangju) | | 47159 (Busan) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Distribution | $A^2$ | Distribution | $A^2$ | Distribution | $A^2$ | Distribution | $A^2$ | Distribution | $A^2$ | Distribution | $A^2$ |
| 1 | Weibull (3P) | 3.96 | Weibull (3P) | 2.72 | Erlang (3P) | 6.03 | Gen. Gamma (4P) | 5.84 | Weibull (3P) | 5.79 | Weibull (3P) | 5.30 |
| 2 | Fatigue Life | 4.42 | Normal | 2.91 | Weibull (3P) | 6.13 | Weibull (3P) | 6.43 | Burr | 6.22 | Pearson 6 (4P) | 6.47 |
| 3 | Gen. Gamma | 4.43 | Fatigue Life (3P) | 2.92 | Fatigue Life (3P) | 6.25 | Inv. Gaussian (3P) | 6.63 | Fatigue Life (3P) | 6.33 | Fatigue Life | 6.63 |
| 4 | Lognormal | 4.47 | Chi-Squared (2P) | 2.94 | Normal | 6.30 | Lognormal (3P) | 6.82 | Inv. Gaussian (3P) | 6.33 | Pearson 5 (3P) | 6.64 |
| 5 | Gamma (3P) | 4.58 | Lognormal (3P) | 2.99 | Inv. Gaussian (3P) | 6.30 | Erlang (3P) | 6.98 | Normal | 6.44 | Gen. Gamma | 6.65 |
| 6 | Log-Gamma | 4.65 | Inv. Gaussian (3P) | 3.01 | Lognormal (3P) | 6.52 | Pearson 6 (4P) | 7.07 | Gen. Gamma (4P) | 6.68 | Gamma (3P) | 6.72 |
| 7 | Pearson 5 (3P) | 4.69 | Gamma (3P) | 3.23 | Gamma (3P) | 7.06 | Fatigue Life (3P) | 7.10 | Erlang (3P) | 6.96 | Lognormal | 6.73 |
| 8 | Gamma | 4.71 | Pearson 6 (4P) | 3.28 | Burr | 7.18 | Normal | 7.10 | Gamma (3P) | 6.97 | Gen. Gamma (4P) | 6.76 |
| 9 | Fatigue Life (3P) | 4.75 | Gen. Gamma (4P) | 3.36 | Pearson 5 (3P) | 7.19 | Pearson 5 (3P) | 7.11 | Lognormal (3P) | 7.16 | Rice | 6.84 |
| 10 | Erlang | 4.78 | Pearson 5 (3P) | 3.79 | Gen. Gamma (4P) | 7.26 | Gamma (3P) | 7.18 | Log-Logistic (3P) | 7.68 | Fatigue Life (3P) | 6.88 |
| 11 | Lognormal (3P) | 4.85 | Log-Logistic (3P) | 4.11 | Gen. Gamma | 7.77 | Gen. Gamma | 7.32 | Pearson 5 (3P) | 8.11 | Log-Gamma | 6.89 |
| 12 | Gen. Gamma (4P) | 4.89 | Gen. Gamma | 4.17 | Log-Logistic (3P) | 7.98 | Pearson 6 | 7.87 | Gen. Gamma | 8.65 | Gamma | 6.96 |
| 13 | Erlang (3P) | 4.93 | Nakagami | 4.37 | Nakagami | 8.64 | Gamma | 8.11 | Weibull | 8.73 | Lognormal (3P) | 6.98 |
| 14 | Pearson 6 (4P) | 5.03 | Burr | 4.40 | Gamma | 8.66 | Fatigue Life | 8.11 | Nakagami | 9.28 | Nakagami | 7.26 |
| 15 | Pearson 5 | 5.21 | Gamma | 4.73 | Erlang | 9.03 | Lognormal | 8.13 | Gamma | 9.56 | Pearson 5 | 7.31 |
| 16 | Nakagami | 5.25 | Erlang (3P) | 5.03 | Lognormal | 9.18 | Nakagami | 8.41 | Lognormal | 10.40 | Pearson 6 | 7.38 |
| 17 | Pearson 6 | 5.43 | Lognormal | 5.58 | Fatigue Life | 9.24 | Log-Gamma | 8.55 | Fatigue Life | 10.48 | Inv. Gaussian (3P) | 7.78 |
| 18 | Inv. Gaussian (3P) | 5.75 | Fatigue Life | 5.63 | Log-Gamma | 9.77 | Erlang | 8.66 | Log-Gamma | 11.08 | Chi-Squared (2P) | 7.87 |
| 19 | Log-Logistic (3P) | 6.06 | Log-Gamma | 6.12 | Weibull | 10.02 | Burr | 8.88 | Inv. Gaussian | 11.35 | Normal | 7.91 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Chi-Squared (2P) | 6.25 | Inv. Gaussian | 6.77 | Pearson 6 | 10.19 | Log-Logistic (3P) | 9.34 | Log-Logistic | 12.64 | Erlang (3P) | 7.94 |
| 21 | Normal | 6.34 | Pearson 5 | 7.68 | Inv. Gaussian | 10.50 | Pearson 5 | 9.56 | Logistic | 12.68 | Frechet (3P) | 8.51 |
| 22 | Rice | 7.00 | Pearson 6 | 7.72 | Pearson 5 | 11.28 | Inv. Gaussian | 10.47 | Pearson 6 | 12.70 | Log-Logistic (3P) | 9.21 |
| 23 | Frechet (3P) | 7.39 | Weibull | 7.99 | Log-Logistic | 11.73 | Log-Logistic | 12.03 | Pearson 5 | 12.83 | Burr | 9.68 |
| 24 | Log-Logistic | 7.72 | Log-Logistic | 8.06 | Pearson 6 (4P) | 11.85 | Frechet (3P) | 13.45 | Hypersecant | 18.28 | Inv. Gaussian | 10.12 |
| 25 | Inv. Gaussian | 8.02 | Logistic | 8.29 | Logistic | 12.87 | Weibull | 13.62 | Pearson 6 (4P) | 19.70 | Log-Logistic | 12.00 |
| 26 | Burr | 8.41 | Hypersecant | 13.44 | Hypersecant | 18.80 | Logistic | 15.25 | Frechet (3P) | 20.72 | Rayleigh (2P) | 13.80 |
| 27 | Logistic | 12.51 | Erlang | 13.77 | Cauchy | 23.65 | Hypersecant | 22.48 | Gumbel Min | 22.16 | Erlang | 15.02 |
| 28 | Gumbel Max | 17.67 | Cauchy | 20.53 | Gumbel Min | 25.19 | Cauchy | 27.25 | Cauchy | 22.58 | Logistic | 16.56 |
| 29 | Hypersecant | 18.04 | Laplace | 23.49 | Laplace | 29.85 | Gumbel Max | 28.48 | Erlang | 27.38 | Weibull | 18.15 |
| 30 | Weibull | 18.95 | Gumbel Min | 23.83 | Gumbel Max | 34.67 | Gumbel Min | 31.15 | Laplace | 28.35 | Gumbel Max | 20.54 |

## 3.3 Monthly characteristics of the Accumulated Heat Stress Index

Fig. 5 shows the monthly distribution of AHI for DH days in summer from 2000 to 2008. The total number of DH days by month were 18, 52, 55, and 7, respectively, and about 80% of all DH days were concentrated in July and August. The DH days in July to September mostly when the AHI was greater the mean of each month (monthly mean AHI of June, July, August and September: -0.71, 0.59, 0.78, -0.72).On the other hand, the DH days of June and September often occurred when the AHI was negative, indicating that AHI does not detect the heat waves in these two months well.

The cause of this seems to be that the heat waves in June and September have different characteristics than those in July and August. June and September are the time of changing seasons and heat waves occur temporarily sometimes, whereas heat waves that continue for more than 2 days occur frequently in July and August. Thus, AHI which reflects the effect of accumulated heat stress well can diagnose the heat waves in July and August than in June and September. Therefore, the diagnosis of heat waves in June and September was left as a subject of a future study, this study focused on diagnosing heat waves in July and August. In the following, the AHI was verified for DH and IH days in July and August from 2000 to 2008.

## 3.4 Setting the AHI danger criterion

Fig. 6a shows a scatter diagram of the relation between the AHI and the excess mortality by IH when the excess mortality is above 2 (1σ and a box-plot representing the distribution of AHI regardless of the excess mortality for the day. The vertical line in the box represents the media value and the left and right inner fences of the whiskers represent the $10^{th}$ and $90^{th}$ percentiles, respectively.

Since the excess mortality by IH is affected by other factors than heat wave, a positive value can occur even if there was no heat wave. However, the scatter diagram shows that the days when the excess mortality is more than 2 usually occurs when AHI is greater than 0 (IQR of AHI: 0.13~1.33).Therefore, in this study, the danger criterion of AHI by IH was defined not as the AHI value at the time when there is excess mortality, but as 0.83 which is the time when the number of days with more than 2 excess mortality reaches the $50^{th}$

percentile. An index that set a similar danger criterion is HI. Korea Meteorological Administration defined the danger criterion of HI as the time when the rate of IH days reaches the $50^{th}$ percentile according to the increasing HI (Park et al. 2007). Watts and Kalkstein (2004) also verified the index by analyzing the percentiles of top 20 IH days according to the increasing HSI.

For DH days, on the other hand, since they occur only by the effect of heat wave unlike IH days, the danger criterion of AHI by DH must be set in such a way that all the DH days will be included in the range of danger. As shown in Fig. 6b, however, since these values also have abnormal values, AHI 0.86 (low inner fence) excluding the low outlier was set as the danger criterion of AHI. This is similar to the danger criterion by IH. In this study, the danger criterion of AHI was set to 0.85 by combining and simplifying these two criteria.

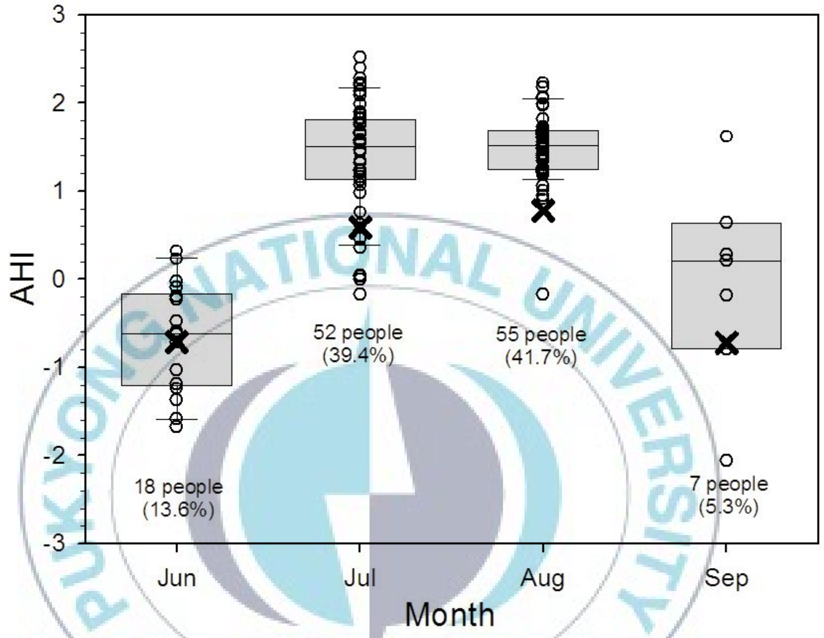


**Fig. 5.** Monthly distribution of AHI when DH days were occurred on JJAS from 2000 to 2008. In the box plots, solid lines denote median value. The low and high inner fences extending from the box represent 10th and 90th percentile. 'o' signs imply AHI when heat wave was occurred by DH. 'x' signs imply monthly mean of AHI from 2000 to 2008.

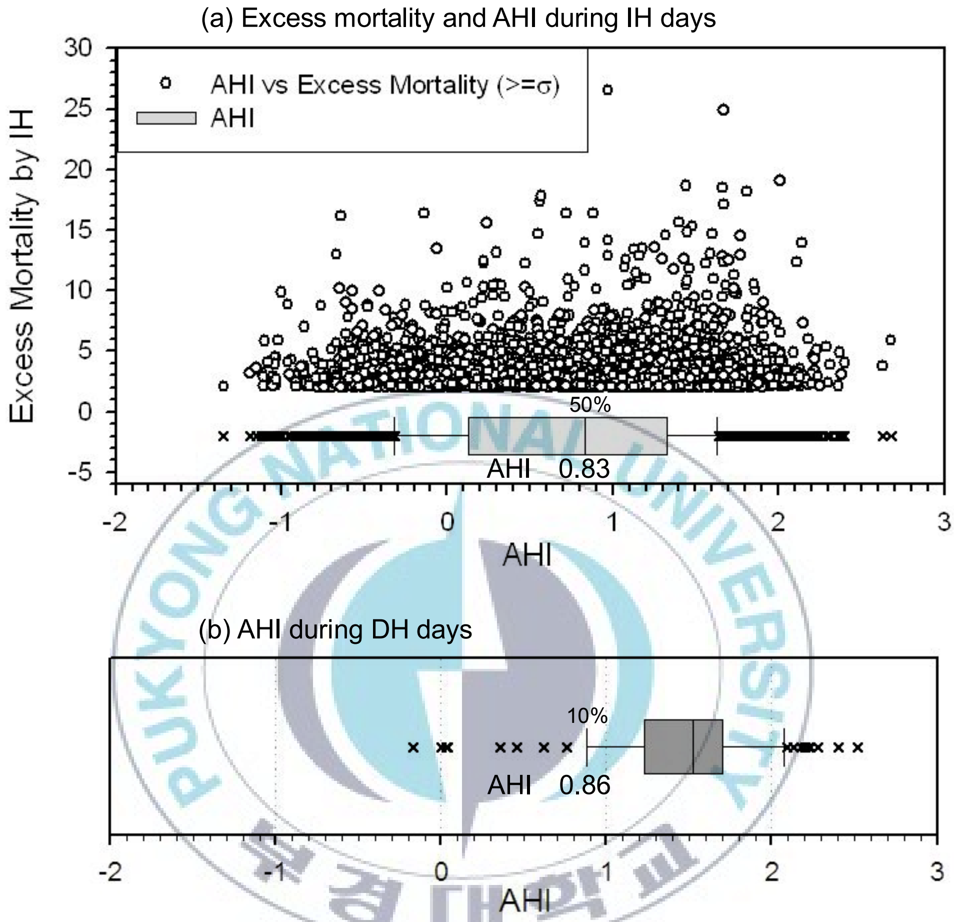


**Fig. 6.** (a) Scatter diagram shows relation between the AHI and the excess mortality by IH when the excess mortality is above 2 at 71 stations for JA in 2000-2008 (n=3370). The left scale shows the excess mortality and the bottom scale shows the AHI. Box-plot represents distribution of the AHI when the excess mortality is more than 2 and the vertical axis is not used. (b)Box-plot means distribution of AHI during DH days. (Each outer: outside of the 10th and 90th percentiles).

## 4. Comparison and Verification of AHI against Humidex, HI, and WBGT

AHI was compared with the commercialized thermal indexes (Humidex, HI, WBGT) regarding how well they detected danger from heat waves during IH and DH days. For WBGT, the approximate formula created by ACSM was used (Table 2).

### 4.1 Comparison of the rates of heat wave alert

Fig. 7 shows scatter diagrams of the relations of AHI vs. Humidex, HI, and WBGT for the entire nation during the analysis period. AHI has positive correlation with Humidex, HI, and WBGT, and the coefficient of determination ($R^2$) is 0.67, 0.59, and 0.68, respectively (sample size= 39618). To determine the values of the existing thermal indexes corresponding to the danger criterion of AHI using the regression equation between the two variables, they are 38.0°C for Humidex, 32.5°C for HI, and 30.7°C for WBGT when AHI is 0.85. These values are very close to the danger criteria (Table 6a) of the existing thermal indexes which are 40°C for Humidex, 32°C for HI, and 31°C for WBGT.

The percentages of days corresponding to the danger criterion of each index during summer were 24.2% for AHI, 15.4% for Humidex, 25.8% for HI, and 22.0% for WBGT. So they were similar except for Humidex. This result confirms that the danger criterion of AHI is not higher or lower than existing thermal indexes, but is appropriate.

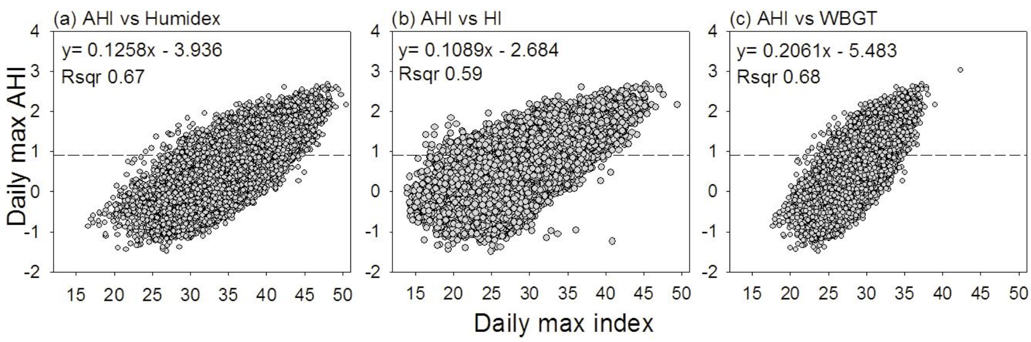


**Fig. 7.** Scatter diagrams showing the relation between the daily maximum AHI and the thermal indices ((a)Humidex, (b)HI, (c)WBGT). The left scale shows the AHI values. The bottom scale shows the index (unit: ℃). The coefficients of determination (Rsqr) and regression equations are shown in the top of the panels. The horizontal dashed-lines denote alert threshold of AHI.

**Table 6.** For each thermal indices, (a) criteria values of heat-wave warning, 1σ and 2 σ of distribution for JJAS in 2000-2008, (b) rate of sensing danger during IH days, (c) rate of sensing danger during DH day and (d) Rate of sensing danger when IH day and DH day are occurred simultaneously in the range of (a) and above.

| Index | (a) Criteria values | | | (b) Rate of sensing danger during IH day (n=17257) | | |
|---|---|---|---|---|---|---|
| | warning | 1σ | 2σ | warning | 1σ and above | 2σ and above |
| AHI | 0.85 | 1.17 | 1.79 | **46.5% | **31.7% | **4.9% |
| Humidex | 40℃ | 39.88 | 43.81 | 30.1% | 31.2% | **4.9% |
| *Acc_HI | - | 1.11 | 1.99 | - | 30.3% | 4.4% |
| HI | 32℃ | 34.40 | 39.36 | 45.3% | 29.6% | 4.2% |
| *Acc_WBGT | - | 1.17 | 1.78 | - | 31.6% | 4.8% |
| WBGT | 31℃ | 31.84 | 34.30 | 41.8% | 31.2% | **4.9% |
| **Index** | **(c) Rate of sensing danger during DH day (n=107)** | | | **(d) Rate of sensing danger when IH day and DH day are occurred simultaneously (n=77)** | | |
| | warning | 1σ and above | 2σ and above | warning | 1σ and above | 2σ and above |
| AHI | **90. | **82.2% | 20.6% | **92.2% | **85.7% | 27.3% |
| Humidex | 74.8 | 74.8% | **26.2% | 80.5% | 80.5% | **33.8% |
| *Acc_HI | - | 80.4% | 21.5% | - | 81.8% | 28.6% |
| HI | 85.0 | 76.6% | 23.4% | 87.0% | 84.4% | 29.9% |
| *Acc_WBGT | - | 80.4% | 21.5% | - | 83.1% | 28.6% |
| WBGT | 83.2 | 72.0% | 21.5% | 87.0% | 76.6% | 28.6% |

* 'Acc' is an abbreviation for 'accumulated'.

** The largest number in each column.

## 4.2 Comparison of the rate of sensing danger due to IH

Fig. 8 shows the distributions of (a) AHI, (b) Humidex, (c) HI, and (d) WBGT for IH days. The scatter diagram of each panel shows the relation between the excess mortality by IH and each index for IH days, and the box plot shows the distribution of each index for IH days regardless of the y-axis. The areas with diagonal lines represent the range of danger and the percentage of IH days corresponding to this area can be regarded as the rate of sensing danger due to IH.

This rate is 46.5% for AHI and 30.1% for Humidex. Thus, AHI which considers the accumulated effect of heat stress improved this rate by 16.4% compared to Humidex which is the heat stress value. Furthermore, since the danger criterion for AHI was only 50% of the number of days when the excess mortality by IH is more than 2, these values which are close to 50% signify a high sensing rate. Besides, this rate was 45.3% for HI and 41.8% for WBGT which are only slightly different from that of AHI. These two indexes are also non-accumulated indexes like Humidex, but their danger sensing rates were higher than that of Humidex and similar to that of AHI. However, this result cannot demonstrate by itself that among the four indices, AHI senses the danger by IH the best and Humidex is the weakest in sensing the danger by IH. The indices except for AHI are not standardized and their danger criteria have no flexibility according to the regional climate. This may be the reason for their lower sensing rates.

Hence, the values corresponding to 1σ and 2σ of the index distribution during summer were selected as the comparison criterion (Table 6a), and the percentage of IH days above this criterion was additionally compared (Table 6b). As a result, the danger sensing rates of the four indices were similar, but the danger sensing rate of AHI was still a little higher. Meanwhile, the danger sensing rate of HI which had showed the second highest danger sensing rate based on the alert criterion was the lowest and that of Humidex which had been the lowest was the second highest.

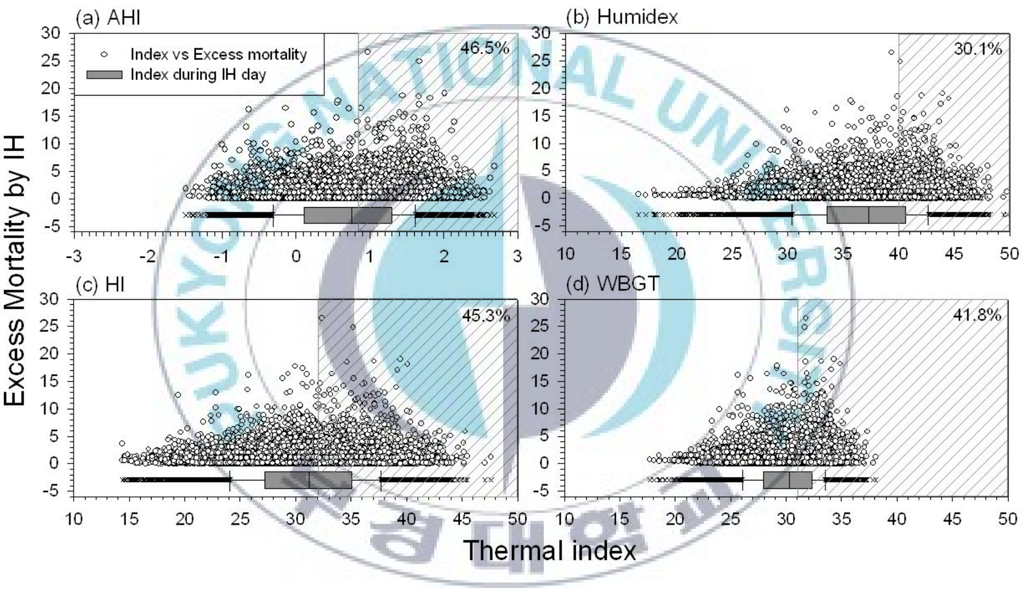


**Fig. 8.** Same as in Fig. 6a but for the (a)AHI, (b)Humidex, (c)HI, (d)WBGT during IH days (n = 17257). The areas drawn diagonal lines represent range of warning for each indices.

## 4.3 Comparison of the rates of sensing danger due to DH

Fig. 9 shows the box plots of the distributions of (a) AHI, (b) Humidex, (c) HI, and (d) WBGT for DH days (n=107) (dark grey) and the distributions of these indices in summer (light grey). The areas with diagonal lines represent the range of danger and the percentage of DH days corresponding to this area can be regarded as the rate of sensing danger due to DH. This rate was 90.7% for AHI and 74.8% for Humidex. So the danger sensing rate of AHI improved by 15.9% compared to that of Humidex. Besides, the danger sensing rates of HI and WBGT were 85.0% and 83.2%, respectively. They are higher than that of Humidex, but lower than that of AHI. Table 6c summarizes the danger sensing rate of each index (Fig. 9) based on the danger criterion (Fig. 9) and the danger sensing rates of the four indices which were calculated on the basis of the same criterion. The same criterion here is the values corresponding to 1σ and 2σ of each index distribution in summer (Table 6a). Above 1σ, the danger sensing rate of AHI was the highest at 82.2%, and the danger sensing rates of other indices were similar, ranging from 72.0 to 76.6%. Above 2σ, the danger sensing rate of Humidex was the highest and that of AHI was the lowest. The reason for this seems to be that because AHI has higher central concentration than other indices, the percentage of extreme values above 2σ is low.

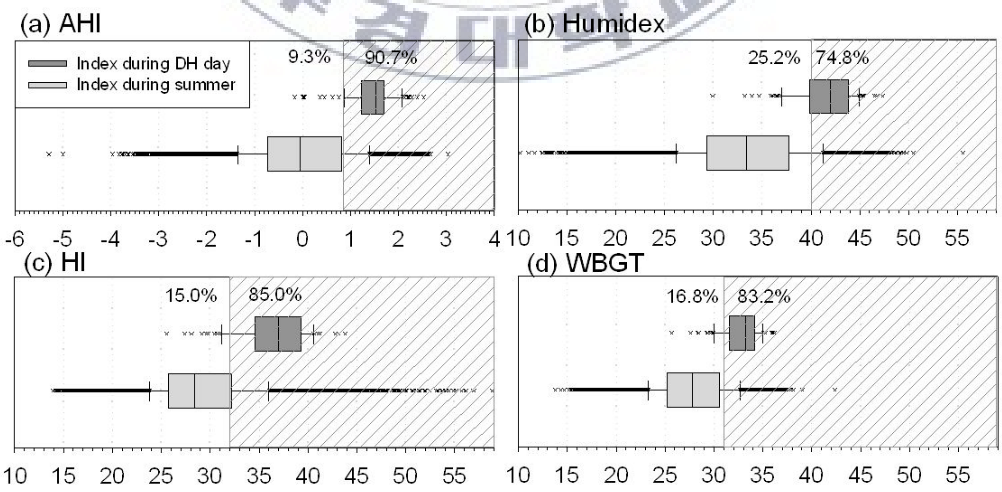


**Fig. 9.** Same as in Fig. 6b but for the (a)AHI, (b)Humidex, (c)HI, (d)WBGT during DH days (n = 107). In addition, light-grey box-plots showed distribution of the indices over Korea (71 stations) during JJAS from 2000 to 2008 are added. The areas drawn diagonal lines represent range of warning for each index.

## 4.4 Comparison of the rates of sensing danger due to simultaneous IH and DH

In the above sections, the danger sensing rates of thermal indices were analyzed by the danger due to IH and the danger due to DH, and the danger sensing rate of AHI was the highest in both of these two cases. Thus, it was examined whether AHI senses danger the best even when excess mortality by IH and mortality by DH occur simultaneously. Fig. 10 shows the distributions of (a) AHI, (b) Humidex, (c) HI, and (d) WBGT for simultaneous IH and DH days. The areas with diagonal lines in each panel represent the range of danger of each index, and the percentage of the days corresponding to this area can be regarded as the danger sensing rate of each index. This rate was 92.2% for AHI and 80.5% for Humidex. So the danger sensing rate of AHI improved by 11.7% compared to that of existing indices. Besides, this rate was 87.0% for HI and WBGT, so the danger sensing rate of AHI was a little higher than the other existing indices. Table 6d summarizes the danger sensing rate of each index (Fig. 10) based on the danger criterion (Fig. 10) and the danger sensing rates of the four indices which were calculated on the basis of the same criterion. Above 1σ, the danger sensing rate of AHI was the highest at 85.7% among the four indices like the above results. Furthermore, the danger sensing rate of HI was 84.4%, similar to that of AHI, and those of Humidex and WBGT were about 5-10% lower than these.

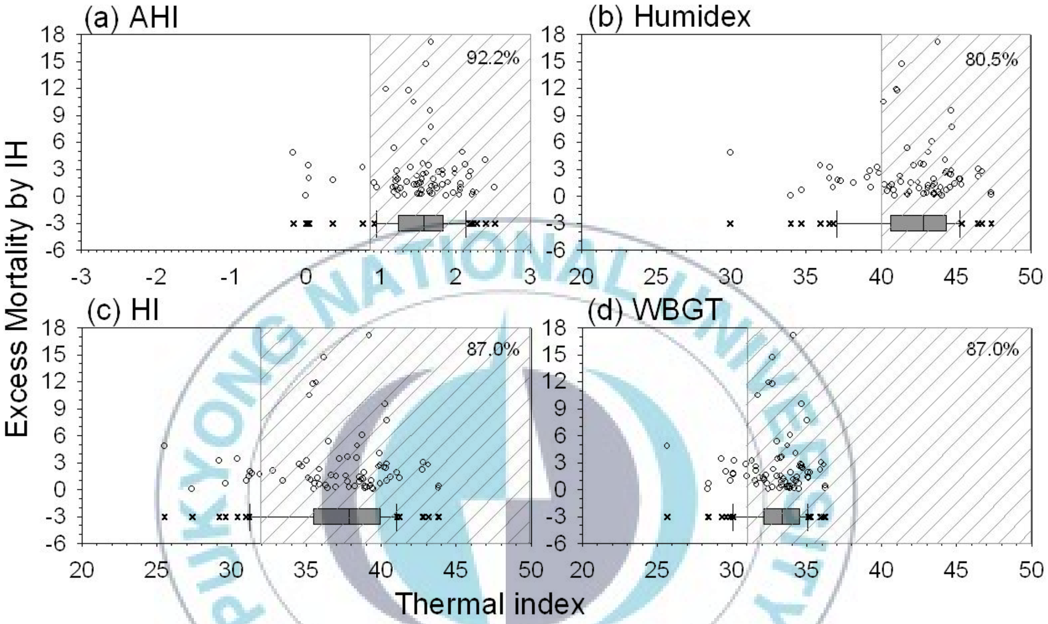


**Fig. 10.** Same as Fig. 8. but for the (a)AHI, (b)Humidex, (c)HI, (d)WBGT when IH day and DH day are occurred simultaneously (n = 77).

## 5. Conclusions and Discussion

AHI was developed to diagnose the danger due to accumulated heat stress in a continued heat wave. This index is different from other indices in that the changes and accumulated effects of heat stress over time are added up with a time-weighted function and then it is standardized for each station. Therefore, it has the advantage of diagnosing heat wave with the same criterion at various observation points.

For verification of AHI, the danger sensing rate of AHI was checked to determine how well it can diagnose the days when deaths by the effect of heat wave occur, and was compared with the danger sensing rates of the currently used thermal indices Humidex, HI, and WBGT. For the mortality days, not only the days of excessive mortality by the indirect effect of heat wave (IH days) which was used in previous studies, but the days of mortality by the direct effect of heat wave (DH days) and the days when these two occurred simultaneously were analyzed as well. As a result, AHI showed higher danger sensing rates than Humidex, HI, and WBGT in all of these three cases (improvement rate of the danger sensing rate of AHI for each case: about 1-16%, about 6-16%, about 5-12%). The difference was large for DH days, but the difference was very small at around 1% for IH days.

The basic reason that AHI can more effectively diagnose the days of mortality due to the effect of heat wave than other indices is that it considers not only the heat stress at specific times, but also the accumulated effects of heat stress over time. This is shown by the fact that the danger sensing rate of AHI which accumulated and standardized heat stresses was about 12-16% higher than Humidex which quantified the heat stress at a specific time. This is further proven by the fact that Acc_HI and Acc_WBGT which accumulated and quantified HI and WBGT, respectively showed improved danger sensing rate than the original indices (Table 6).

Moreover, AHI senses the mortality days even when the daily maximum temperature is not high because it considers the accumulated effect of heat stress. During the index verification period, there were 77 days when IH and DH occurred simultaneously, and 37.2% of them appeared at lower temperatures than 33°C. This suggests that if the Korea Meteorological Administration gives heat wave alerts only by the daily maximum temperature without using the number of days of continued heat wave and the criteria of HI, they can miss 37.2% of the days when IH and DH occur simultaneously. On the other hand, this percentage can be decreased to 7.7~16.7% by using such thermal indices as AHI, Humidex, HI, and WBGT, and to the minimum rate of 7.7% if AHI is used (Fig. 11).

Another advantage of AHI is that despite the fact that it only uses the two weather elements of temperature and relative humidity, it shows better performance than other thermal indices that consider more weather elements. Temperature and relative humidity are the basic weather elements that are observed by weather stations, and they have such advantages as ease of collection and high reliability. Therefore, it is expected that AHI will be able to provide highly reliable heat wave information in many regions.

On the other hand, since AHI was developed to sense the days of mortality due to continued heat wave, it does not detect well the days of mortality due to sudden heat waves (mainly in June and September). These days are not dangerous for people who are involved in general activities, but they can have adverse effect on the health of people involved in military training or intense exercises. Therefore, if AHI could be improved to even diagnose these heat waves, it could be used as a heat wave prediction index to further reduce the mortality due to heat waves.

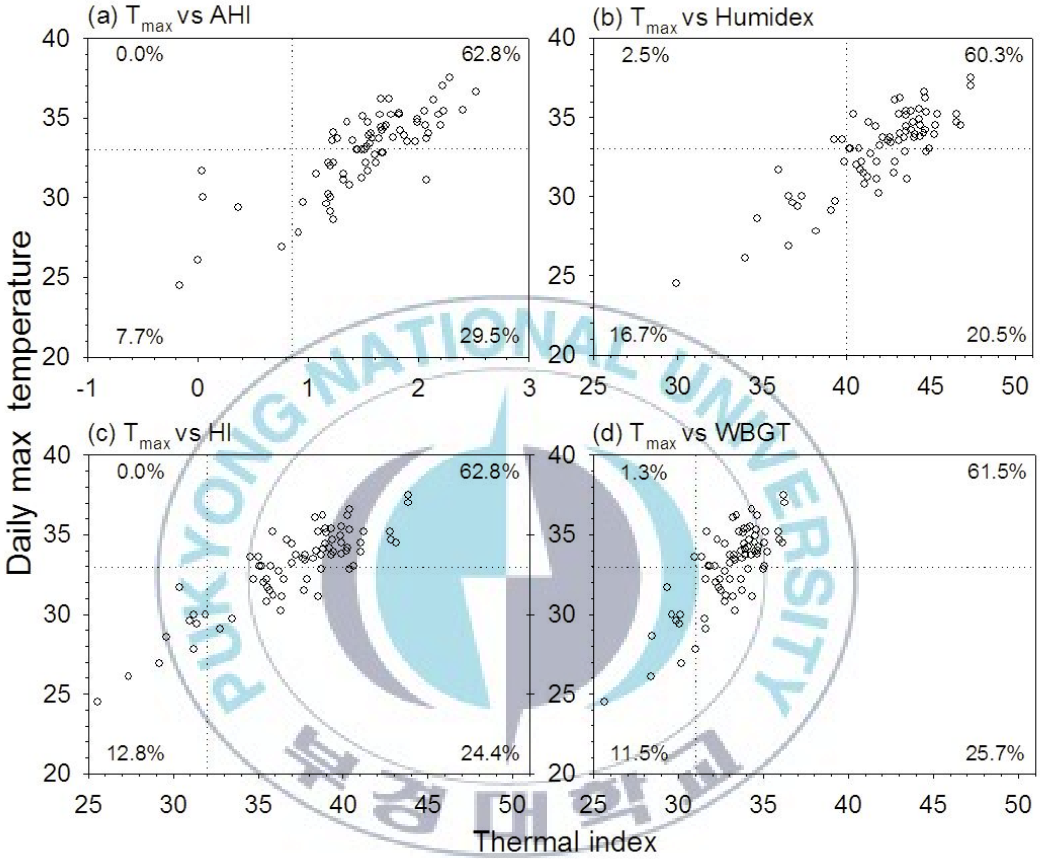


**Fig. 11.** Scatter diagrams showing the relation between the daily maximum temperature and the thermal indices ((a)AHI, (b)Humidex, (c)HI, (d)WBGT). The left scale shows the temperature values(unit: ℃). The bottom scale shows the index. The vertical dashed-lines denote alert threshold of each thermal indices. The horizontal dashed-lines represent temperature boundary of 33℃.

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## 감사의 글

처음에는 하늘이 보여주는 신비로움에 빠져 막연히 이 길을 걷게 되었습니다. 교수님들의 가르침을 통해, 사람은 날씨를 조절할 수는 없어도 그 원리를 깨우치면 이를 이용할 수 있다는 것을 배웠습니다. 그래서 많은 사람들이 날씨를 이용할 수 있게 도와주는 사람이 되고 싶어, 대학원이란 새로운 문턱을 넘었습니다. 석사를 마무리하는 단계에 오기까지 힘든 순간들도 많았는데 그때마다 저에게 도움을 주신 분들께 이 글로써 감사의 인사를 대신 전합니다.

먼저 저를 방재기상연구실의 가족으로 받아주시고 가르침을 주신 변희룡 교수님, 존경하는 마음으로 고개 숙여 깊은 감사의 말씀을 올립니다. 가끔씩 힘에 부쳐 주춤할 때마다 교수님께서 해주신 말씀과 칭찬들이 제겐 너무나도 큰 힘이 되었습니다. 몸이 건강해야 좋은 연구를 할 수 있다고 손수 저희들 건강까지 챙겨주신 것 또한 정말 감사 드립니다. 학자는 어떻게 생각하고 행동해야 하는지 몸소 보여주시던 교수님. 앞으로 교수님의 모습을 조금 더 닮을 수 있도록 노력하겠습니다.

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