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Application of a weather stress index for alerting the public to stressful weather in Hong Kong

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An operational procedure for alerting the public of stressful weather (exceptionally hot and cold situations) in Hong Kong has been implemented since late 1997. From a 28-year (1968-1995) climatological database, criteria based on a weather stress index (WSI) was established to define stressful weather conditions. A special bulletin is issued to the public when exceptionally high (hot, i.e. ≥ 97.5%) or low (cold, i.e. ≤ 2.5%) WSI is forecast. The bulletin provides information on current or predicted stressful weather conditions as well as statements on precautionary action to take. A study was also carried out to examine the effects of WSI on mortality rates on days with extreme WSI. Preliminary results indicate that there was a relationship between low WSI and mortality rates in winter. In summer, however, the results were not conclusive.

1. Introduction

Climate and weather play important roles in the well-being of mankind. Of the various meteorological factors directly or indirectly affecting human health, extreme heat and cold conditions have been shown to be the most significant ones in terms of human morbidity and mortality (e.g. WHO/WMO/UNEP, 1996a, 1996b; Collier & Hardaker, 1995). Prolonged exposure to hot and humid weather can cause illnesses ranging from depression, hypotension, fatigue, hypothermia, tachycardia and inappetence, to fatal conditions such as heat stroke and acute heart failure. On the other hand, prolonged exposure in an extremely cold environment can lead to depression, indolence, asthma, respiratory infections, hyperthermia, hypertension, stroke, heart failure and even frostbite (WHO/WMO/UNEP, 1987).

To provide health-related weather services to the general public, many weather centres around the globe have developed various kinds of operational system for alerting the public to the danger of extreme weather conditions. The objectives of this study are to explore the methodologies available, to adopt an operational index suitable to Hong Kong and to implement a warning service based on the index.

Section 2 of this paper is a review of the more popular approaches to the problem. Section 3 presents the climatological results in terms of the net effective temperature (NET) computed for Hong Kong. Section 4 reports on how weather stress index (WSI) is derived and the criteria chosen. The relationship between WSI and local mortality rates and the warning system since implemented are summarized in sections 5 and 6 respectively. Some concluding remarks are given in section 7.

2. Background

Most of the operational systems currently in use can be broadly divided into three categories: (a) simple physical indices or comfort indices, (b) the human energy balance approach, and (c) the synoptic climatological classification approach.

For the physical type, the most common wintertime indices are the Siple-Passel wind-chill index and its variants (WMO, 1972), which measure the quantity of heat that the atmosphere is capable of absorbing from an exposed surface. Taking it one step further, the US National Weather Service (NWS) employs the Steadman wind-chill formula (Steadman, 1984) to measure the net heat loss of a healthy adult with an appropriate amount of outdoor clothing in winter. For extreme heat, the NWS, on the basis of the apparent temperature (Steadman, 1979), uses a heat stress index (HSI) to alert the public to excessively hot weather. The apparent temperature measures human perception to heat by adjusting the ambient temperature with relative humidity. Corrections due to the effects of moisture and wind can also be included in the calculations of the Steadman wind-chill formula and HSI respectively.

In Germany, the Deutscher Wetterdienst adopts the human balance approach and runs a more sophisticated model, called the Klima-Michel Model, to take into account virtually all aspects of heat exchange processes between a human body and the environment. The heat exchanges considered include human heat production, sensible heat flux, latent heat flux, moisture heat flux, and respiration heat flux, as well as direct/diffuse/reflected solar radiation entering and re-emitting from human surfaces. This model is considered to be a valuable tool in bioclimatic assessments, providing additional comprehensive information not given by simple comfort indices.

Climatic and synoptic classifications are done mainly by analysing a number of meteorological elements, including temperature, dew point, atmospheric pressure, cloud cover and wind. The approach was adopted, for example, in Philadelphia, Pennsylvania, USA in the form of a Hot Weather-Health Watch/Warning System to alert local residents of oppressive weather situations potentially harmful to human health. Kalkstein *et al.* (1996) defined 11 airmass categories and correlated them with mean daily mortality rate so as to identify the most oppressive conditions. On the basis of weather forecasts from NWS, the Philadelphia Department of Public Health, in cooperation with other government departments, issues alerts or even warnings via the media whenever oppressive weather is expected.

These operational systems often assume some sort of standard adult human model which is obviously not applicable to people of different ages and different physical conditions. They generally require input of a host of meteorological variables. Some of them even require input parameters, such as radiation values, which are difficult to forecast. Whether the output warrants further action would normally depend on certain criteria, such as HSI greater than 80 in NWS's system, or a cold stress index below -3 in the Klima-Michel Model. It is, however, accepted that such criteria should be 'relative' rather than 'absolute', as a result of acclimatization. In other words, to what extent a weather condition should be treated as stressful at a particular locale is not universal. For instance, a temperature of 10 °C may be quite pleasant to people living in mid-latitudes but rather uncomfortable for those used to tropical heat. In contrast, a warm day of 30 °C will be quite acceptable to people living in the tropics but intolerable to people from high latitudes.

To take into account the acclimatization effect, Kalkstein *et al.* (1986) advocated the use of a relative climatological index. The index so derived is called the weather stress index (WSI). In his study, the WSI on a particular day is derived by calculating the apparent temperature and determining to what extent that apparent temperature deviates from the mean value for that locale. In other words, a WSI is defined as the proportion of days with apparent temperature lower than the day under consideration. While a WSI of 99% is considered to be stressful in Kalkstein's scheme, other studies such as WHO/WMO/UNEP (1996a) consider that a WSI of 95% at some locale would already pose a threat to human health. It should be noted that the relative climatological index approach is not confined to apparent temperature. Any other appropriate parameters can be used instead.

A similar relative climatological index approach was adopted in our effort to devise a scheme to alert the general public of Hong Kong of potentially stressful weather. The WSI parameter used was based on the calculation of the net effective temperature (NET). A distribution of NET from a 28-year database was prepared for the determination of WSI. To test the correlation of the WSI during extreme weather situations with human health, daily WSI figures during cold winter and hot summer were checked against the mortality rates from 1986 to 1995, the period when data were readily available.

3. Net effective temperature

Among a number of indices tested for use as the WSI parameter, NET is found to be the most suitable for operational purposes. Effective temperature, the predecessor of NET first introduced by Missenard in 1937 (Hentschel, 1987) to include the effect of relative humidity, was limited to hot weather situations. Modifications by Gregorczuk (WMO, 1972; Hentschel, 1987) to include the effect of winds extended its use to cold situations. The resulting formula for NET is:

$$NET = 37 - \frac{37 - T}{0.68 - 0.0014RH + 1/(1.76 + 1.4v^{0.75})} - 0.29T(1 - 0.01RH)$$

where T is the ambient temperature (in °C), v the wind speed (in m s^{-1}) and RH the relative humidity (in %).

The advantages of using NET are:

(a) It is relatively simple to compute and easy to interpret. A large positive value implies exceptionally high heat load, while a large negative value represents large heat loss.
(b) It is applicable in both hot and cold situations.
(c) It displays similar sensitivity as 'wind-chill' and 'apparent temperature', the two commonly used indices for cold and hot weather respectively.
(d) It has a predictive value since the meteorological inputs required are routinely forecast. Other indices involving solar radiation or cloud amount are more difficult to forecast.
(e) It is consistent with common human perception:
    (i) in hot weather, NET increases as temperature and/or RH increases, but decreases with increasing winds;
    (ii) in cold weather, NET decreases with temperature, and with increasing RH and winds.

Figure 1 shows the behaviour of NET as a function of wind and temperature. It can be seen that NET reflects the common observations that people tend to feel more stressful on calm, hot and humid days in summer and windy, cold and humid days in winter.

NET values were computed based on Hong Kong Observatory (HKO) hourly readings from 1968 to

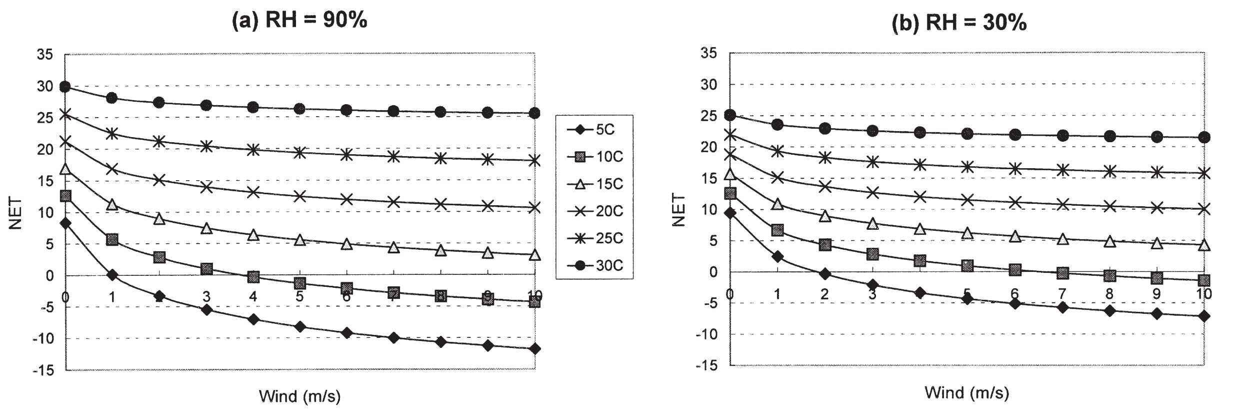

Figure 1. *Behaviour of NET as a function of wind and temperature, for (a) wet conditions (RH = 90%) and (b) dry conditions (RH = 30%). Lines with diamond, square, triangle, cross, star, and circle are evaluated at air temperatures of 5 °C, 10 °C, 15 °C, 20 °C, 25 °C , and 30 °C, respectively.*

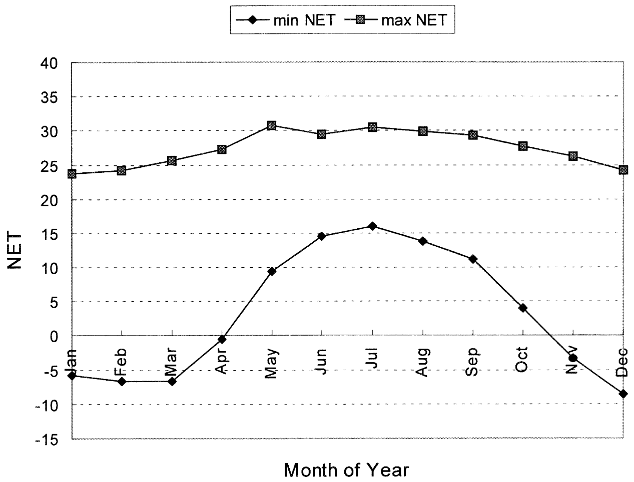

Figure 2. *Monthly distribution of absolute daily maximum NET and daily minimum NET for 1986-1995.*

1995. The resultant monthly distribution of absolute daily maximum and minimum NETs over the 28-year period is plotted in Figure 2. Significant negative minima occur between November and March and large positive maxima occur between May and September. The absolute minimum was -8.6 °C on 14 December 1975. The temperature, relative humidity and wind speed recorded at the time of absolute minimum NET were 4.4 °C, 91% and 4.5 m s^{-1} respectively. The absolute maximum NET was 30.7 °C on 26 May 1976. The temperature, relative humidity and wind speed recorded at the time of absolute maximum NET occurred were 34.6 °C, 62% and 0.5 m s^{-1} respectively. On the basis of the observed seasonal trends, winter months for the purpose of this paper are defined as November to March while summer months are May to September.

Since the objective was to establish a criterion for alerting the general public of exceptionally hot and cold situations, attention was focused on the extreme values of NET. Daily minimum NETs were analysed for the winter months and daily maximum NETs for the summer months. Figure 3 shows the occurrences of the lowest 1% NET in winter and the highest 1% NET in summer. The highest (lowest) 1% NET values occur most frequently in July (February). July is climatologically the most stressful summer month on the basis of its high temperature and humidity. Despite its slightly higher monthly mean temperatures, February rather than January is the most stressful winter month owing to more humid conditions in the former.

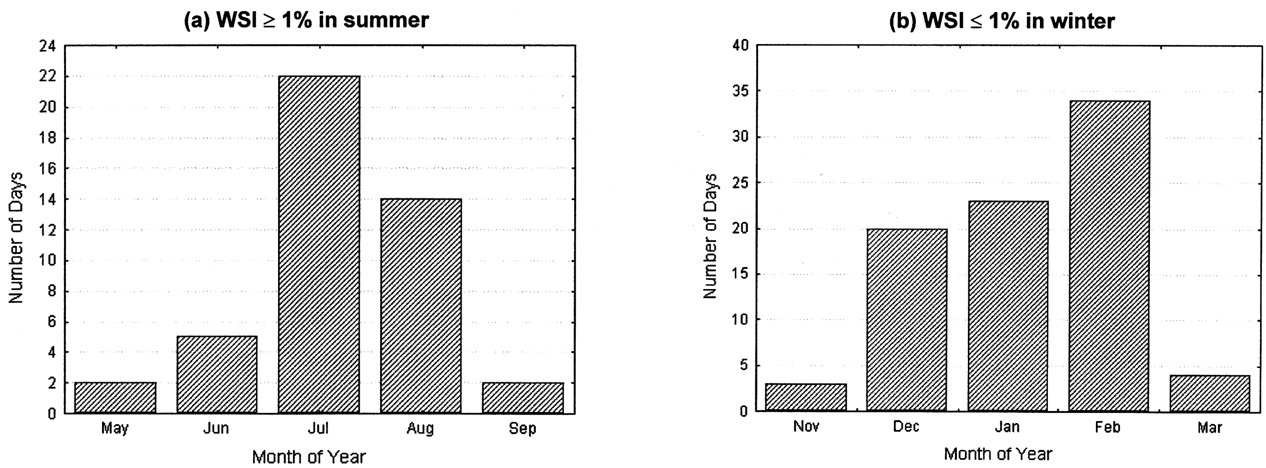

Figure 3. *Monthly distribution of the number of days for (a) WSI ≥ 1% in summer and (b) WSI ≤ 1% in winter.*

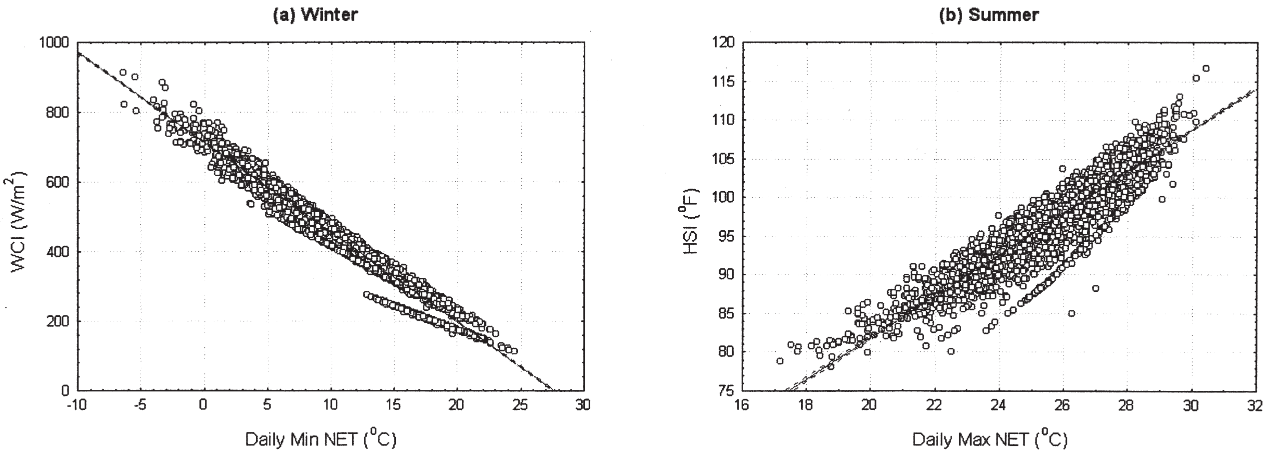

Figure 4. *Correlation of NET with* (a) *wind-chill index (WCI) and* (b) *apparent temperature (HSI) in the 1968-1995 winters and summers, respectively.*

To test whether NET behaves consistently in comparison with other well-known indices, Figure 4 shows the scatter plots of NET versus the Siple wind-chill index for winter and the Steadman apparent temperatures for summer. The correlations are quite good, with absolute correlation coefficient values as high as 0.98 in winter and 0.92 in summer.

4. Weather stress index

To calculate the WSI, the NET at a particular time on a particular day was checked against the distributions of maximum or minimum NET derived from the 28-year database. The percentage of days with a NET lower than the day under consideration was taken as the WSI. For example, WSI > 97.5% in summer means that less than 2.5% of summer days have NETs higher than the day in question and hence implies that the heat experienced was rather extreme and could be stressful. Climatologically, a criterion of 2.5% corresponds to about three occurrences every year on average. Similarly, WSI < 2.5% in winter means that less than 2.5% of winter days have NETs lower than the day in question and hence implies that the cold experienced was rather extreme and could be stressful. Again, a WSI of 2.5% corresponds roughly to three occurrences every year on average. For reference, WSIs of 2.5% and 97.5% according to 1968-1995 data correspond to NETs of -0.4 °C and 29.0 °C respectively.

The diurnal variations of extreme WSI, (i.e., lowest 2.5% in winter and 97.5% in summer) under different combinations of temperature, relative humidity and wind speed are shown in Figure 5. In winter, the most stressful time occurs in the latter part of the night and around dawn. Typical weather conditions are temperatures of about 6-10 °C, winds of 3-5 m s^{-1} and relative humidities of 70-90% (figures not shown). In summer, the most stressful time occurs in the early afternoon. Typical weather conditions are temperatures of 32-33 °C, light winds and relative humidity of 60-75% (figures not shown).

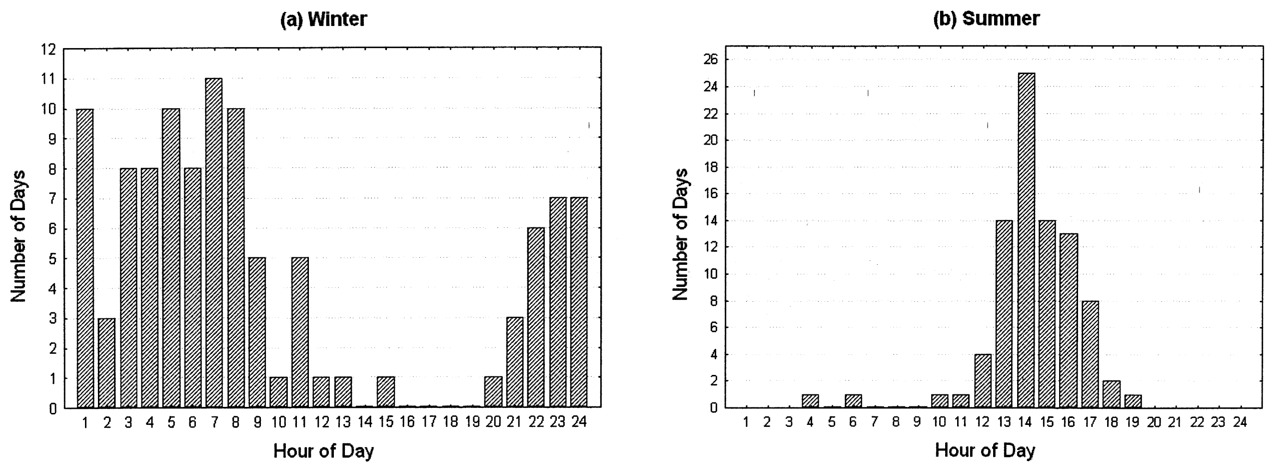

Figure 5. *Diurnal variations of the occurrences of extreme WSI from the 1968-1995 HKO data for* (a) *WSI ≤ 2.5% in winter and* (b) *WSI ≥ 97.5% in summer.*

5. Relationship between WSI and human health

An attempt was carried out to investigate any possible relationships between WSI and local mortality rates. Monthly mortality data during 1986-1995 were obtained from the Hong Kong Immigration Department. Deaths due to external causes were excluded. The monthly distribution of average daily mortality rates is shown in Figure 6. The distribution shows a skewed-U shape - the mortality rate in winter reaches its peak in February and declines gradually towards the summer months

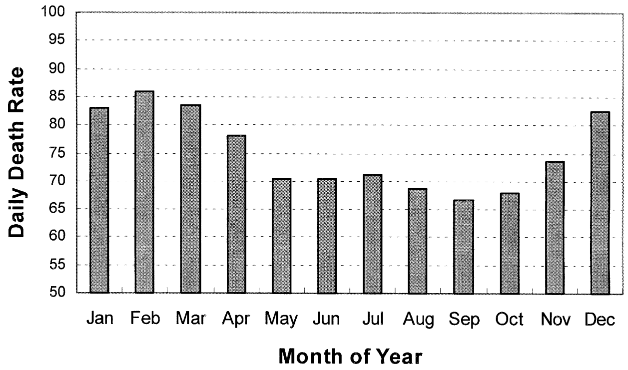

Figure 6. *Monthly distribution of average daily mortality rates (non-external causes) in 1986-1995.*

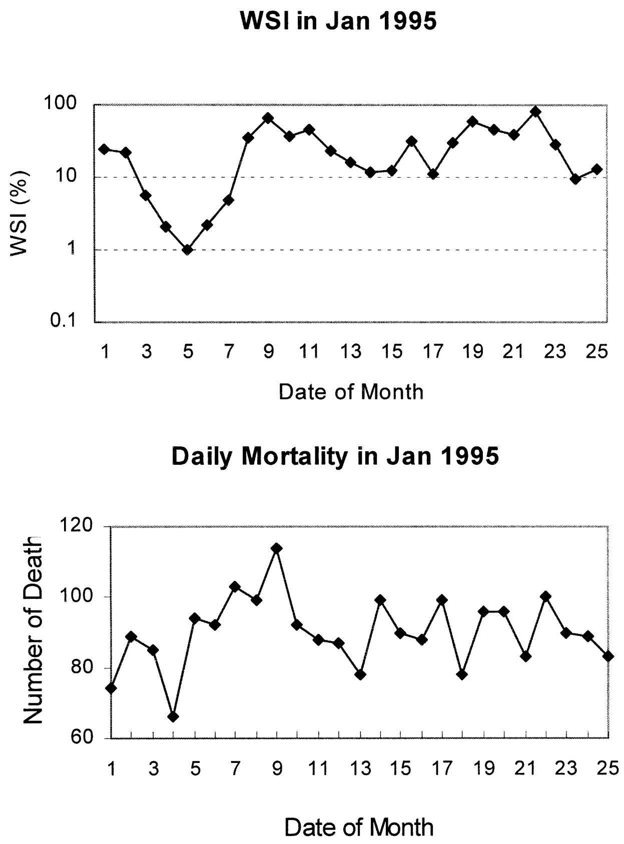

Figure 7. *Comparison between WSI and daily mortality rates during an intense winter monsoon event in early January 1995. WSI dropped below 2.5% on 4 January and mortality rate increased rapidly afterwards till 9 January.*

before climbing again after September. This U-shape distribution is observed in many other places (see, for example, Khaw, 1995). The highest mortality rate occurs in February, the month with the highest occurrences of extremely low WSI (<1%). There is a small relative maximum in July during the summer season. This is again coincident with the highest occurrences of extreme WSI (>99%) in summer. These observations seem to suggest that cold weather, in general, is more hazardous in terms of health and mortality, with February in particular being the most stressful month. The lower mortality rates during the summer months suggest that hot weather in Hong Kong is less fatally stressful.

The impact of stressful cold weather on health and mortality is illustrated by a case study shown in Figure 7. An intense winter monsoon affected the south China coast on 3-8 January 1995. A minimum temperature of 9.8 °C was recorded at the Observatory on 5 January. On the same day, the WSI dropped to a value well below the threshold of 2.5%. Mortality rates rose and reached a maximum on 9 January, an increase of over 65% in just four days.

6. Implementaion of a WSI warning service

Based on NET and WSI studied in this paper, operational procedures to alert the public of the occurrence or likely occurrence of stressful extreme weather in Hong Kong have been established, starting with cold weather, since December 1997.

(a) The hourly WSI is computed using observed data of winds, temperatures and relative humidity. Forecasters also have the option of assessing the future trends of NET and WSI estimated from forecast winds, temperatures and relative humidity as given by the latest five-day forecast.

(b) Tables 1(*a*) and 1(*b*) show the combinations of temperatures, relative humidity and winds in summer and winter beyond which the WSI thresholds of 97.5% and 2.5% are exceeded respectively. Forecasters can refer to these look-up tables for a quick check in addition to the computed WSI outputs.

(c) If the actual or forecast WSI falls below (rises above) the adopted thresholds of 2.5% in winter (97.5% in summer), a bulletin giving special advice to the public will be issued to alert the public of stressful weather conditions. The messages of the press release will focus on: (i) warning of current or predicted extreme weather conditions (hot/cold); (ii) statements on precautionary actions to take under these stressful weather conditions. An example is given in the Appendix.

Table 1. *Look-up tables giving the temperatures (TT, °C) under different combinations of wind speed (FF, m s^{-1}) and relative humidity (RH, %) when (a) WSI > 97.5% for summer and (b) WSI < 2.5% for winter*

FF (m s^{-1})	RH (%)							
	30	40	50	60	70	80	90	100
(a) Critical Temperatures in summer (May-Sep) for WSI > 97.5%								
0	36.2	34.6	33.2	32.0	30.8	29.8	28.9	28.1
1	36.4	35.2	34.1	33.2	32.3	31.5	30.8	30.1
2	36.4	35.4	34.4	33.5	32.7	32.0	31.3	30.7
3	36.5	35.5	34.5	33.7	32.9	32.2	31.6	31.0
4	36.5	35.5	34.6	33.8	33.1	32.4	31.8	31.3
5	36.5	35.6	34.7	33.9	33.2	32.6	32.0	31.4
6	36.5	35.6	34.7	34.0	33.3	32.6	32.1	31.5
7	36.5	35.6	34.8	34.0	33.3	32.7	32.1	31.6
8	36.5	35.6	34.8	34.1	33.4	32.8	32.2	31.7
9	36.5	35.7	34.8	34.1	33.4	32.8	32.3	31.8
10	36.5	35.7	34.9	34.1	33.5	32.9	32.3	31.8
(b) Critical Temperatures in winter (Nov-Mar) for WSI < 2.5%								
0	-10.7	-9.5	-8.4	-7.5	-6.6	-5.8	-5.1	-4.4
1	1.7	2.2	2.8	3.3	3.7	4.2	4.6	5.0
2	5.0	5.4	5.9	6.3	6.7	7.0	7.4	7.8
3	6.8	7.2	7.6	7.9	8.3	8.6	9.0	9.3
4	8.0	8.3	8.7	9.0	9.3	9.7	10.0	10.3
5	8.8	9.1	9.5	9.8	10.1	10.4	10.7	11.0
6	9.4	9.7	10.1	10.4	10.7	11.0	11.3	11.6
7	9.9	10.2	10.5	10.9	11.2	11.4	11.7	12.0
8	10.3	10.6	10.9	11.2	11.5	11.8	12.1	12.4
9	10.7	11.0	11.3	11.6	11.8	12.1	12.4	12.7
10	10.9	11.2	11.5	11.8	12.1	12.4	12.7	13.0

7. Discussion and conclusion

In this study, the development of WSI through the use of NET is shown to be both climatologically and operationally applicable to the Hong Kong situation. The thresholds of stress chosen, 2.5% for winter and 97.5% for summer, correspond to about six occurrences throughout the year. This is consistent with the general perception, since cold or heat-related deaths are generally reported by the press no more than a few times each year. The meaningfulness of the adopted thresholds is also demonstrated by a case of pronounced increase in mortality figures during an intense outbreak of the winter monsoon in early January 1995.

A warning system based on the computed WSI and through the issue of special press releases was first implemented in the winter of 1997/98. While certain sectors of the community, such as the elderly, the homeless and the sick, are particularly vulnerable to cold stress, people in Hong Kong are generally more resistant to the effects of heat. The general availability of air-cooling systems in many public areas and also at home means that most people are well protected from heat impact. Heat-related deaths are mostly isolated incidents involving physical exertion in outdoor activities on a hot summer day. Therefore, unlike in winter when the people most at risk are the less fortunate who cannot help themselves, the most vulnerable group in summer is likely to be those who are young, fit and feeling confident in their own abilities. As such, even though the methodology and criteria adopted are very similar for both winter and summer, for the WSI warning service to be truly effective, there is a need for different emphases in the wording of warning messages given the contrasting nature and make-up of target groups between the hot and cold seasons. The medium through which such messages are conveyed may also be important, e.g. while the radio or TV is a popular companion for the old and the sick, paging messages could prove to be more effective for those working outdoors in summer.

The interpretation of WSI at the present stage is still rather simplistic, taking readings from one single station as representative of conditions over the territory. Obviously, countryside areas like the northern part of Hong Kong have much more extreme temperature variations than those in urban areas, both seasonally and diurnally. Ideally, studies should be extended to cover such regional differences. The way mortality rates relate to WSI should also be investigated further, for example the relative impact on health in the case of a cold snap with a sudden and drastic drop in temperatures compared with a cold spell with prolonged exposure to low temperatures.

Other more sophisticated approaches include the use of parameters such as water vapour pressure, turbidity, cloudiness and solar radiation. However, as these parameters are not readily measured or forecast, their potential for application in an operational warning service remains limited. Another alternative to pursue is the use of model-forecast parameters in predicting the trends of WSI. Based on the latest five-day forecasts, the computation of future WSI is currently confined to the use of forecast parameters averaged or generalized for the whole day. But incorporation of prognostic information from NWP products, such as those generated by the Regional Spectral Model (RSM) at the Hong Kong Observatory, will enhance the temporal resolution to include the all-important diurnal trends as well as other significant fluctuations in association with changing weather scenarios.

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Appendix. Press Releases

Press Release (Cold Stress)

Cold weather is expected in Hong Kong today/tomorrow/in the few days. Temperatures in the urban areas overnight/during the day will be in the region of 12 degrees or below. It will be a couple of/few degrees lower in the northern part of the New Territories/and on high grounds. Put on warm clothes. People are advised to be aware of low body temperature due to the cold weather.

If you must go out, please avoid prolonged exposure to wintry winds.

If you know of elderly persons or persons with chronic medical conditions living alone, call or visit them occasionally to check if they need any assistance.

Press Release (Hot Stress)

The Hong Kong Observatory is forecasting very hot weather in Hong Kong today/tomorrow/in the next few days. This will be coupled with high humidity and light winds, and people should beware the risk of heat stroke.

The Hong Kong Observatory advises the public to avoid prolonged exposure to sunlight. People engaged in outdoor activities should drink plenty of water and avoid overexertion. They should go into the shade or to cooler places to take a rest as soon as possible if they do not feel well.

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