5B.2 THE DEVELOPMENT OF A WARM WEATHER RELATIVE COMFORT INDEX FOR ENVIRONMENTAL ANALYSIS

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1. INTRODUCTION

Numerous indices have been developed that give a measure of how comfortable a person feels based on the interaction of several weather variables (Hevener, 1959; Höppe, 1999; Jendritzky et al., 2000; Masterton and Richardson, 1979; NWS, 1992; Steadman, 1984; Thom, 1959). However, virtually all of these indices are based on absolute conditions and do not consider the importance of relative stress and adaptation based on location and time of season.

Kalkstein and Valimont (1986, 1987) developed a relative index called the Weather Stress Index (WSI), which accounts for hourly apparent temperature values, but excludes other important meteorological parameters related to heat stress. The WSI was never officially adapted, and there is no evidence of any other relative indices being previously developed.

A summer *relative comfort index*, known as the **Heat Stress Index (HSI)**, has been developed, which improves upon the limitations of the current, widely-used indices, as well as the shortcomings of the WSI, and can be useful in numerous environmental applications. The index has the ability to evaluate daily mean relative stress values for each first-order weather station in the United States. It includes variables not used in previous indices, such as a factor that considers consecutive days of stressful weather, cloud cover, and accumulation of heat through the day. In addition, the index has been designed to fit seamlessly into NWS forecasts, permitting daily values to be calculated for time periods up to 48 hours in advance.

2. INDEX DEVELOPMENT

The index was created based on 30 years of data (1971-2000) for over 225 first-order weather stations across the continental United States and Canada. An overview of the steps necessary to create the HSI for each location and 10-day period (May 1-10, May 11-20, May 21-31, etc.) from May through September is summarized below.

The **first step** is to run the 30 years of hourly data through the Steadman apparent temperature (AT) algorithm for each 10-day period and location.

The **second step** is to derive daily maximum and minimum apparent temperature values (ATMAX and ATMIN), cooling degree days (CDD), mean cloud cover (CCMEAN), and the number of consecutive days of extreme heat (CONS) based on the Steadman's AT model output.

- ATMAX (ATMIN) is the highest (lowest) hourly AT value recorded over a 24-hour period. ATMIN is just as important as ATMAX because high daily ATMINs add stress to the day.
- CDD accounts for temperature fluctuations such as those often associated with a temperature drop after the onset of a thunderstorm or passage of a cold front, which can bring relief to an otherwise stressful situation. The CDD variable is calculated by summing the number of degrees above an hourly apparent temperature of 18.3 °C (65 °F) over a 24-hour period.
- CCMEAN represents the average hourly cloud cover values from 1000-1800 LST. These hours were chosen because clear skies during the daytime generally raise temperatures and add stress due to an increased solar load (Kilbourne, 1997).
- CONS is included in the index because there is a negative human health impact of extreme weather that increases with each day that conditions persist (Kalkstein and Davis, 1989). A consecutive day is counted when the ATMAX value is at least one standard deviation above the AT mean. The count increases with each consecutive day that ATMAX exceeds the threshold.

The **third step** involves fitting a statistical distribution to each of the variable frequencies. Variable frequency patterns for every 10-day interval and station are considered, and a distribution is chosen that is deemed the best overall fit. ATMAX, ATMIN, and CDD frequencies are approximated by beta distributions (Fig. 1). A negative binomial distribution is fit to the CONS frequencies, because it does the best job capturing the overwhelming number of zero consecutive days consistently present at every location each period. CCMEAN frequency patterns vary significantly from one station to another, so an "empirical fit" is its best option.

The **fourth** step is the determination of daily values for each variable based on their location under the distribution curves. The purpose of this step is to place all the variables into the same set of units. A cumulative distribution function (CDF) is used to calculate the area under the curve, up to the given daily value of the variable. Each cumulative probability value can be

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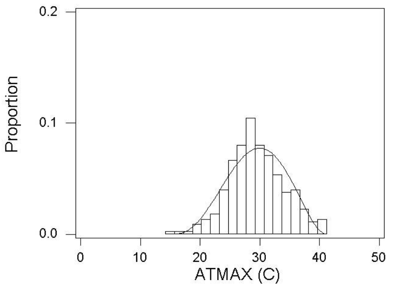

Figure 1. Example of a beta distribution fit to July 1-10 maximum apparent temperature frequencies for Philadelphia, PA.

expressed as a percentile. A value of 0.75 can be described as being in the 75th percentile, indicating that 75% of days, during that time period, are associated with a lower parameter value than that particular day's parameter. An example of the weather variables representing conditions on July 4, 1999 in Philadelphia, Pennsylvania, and their corresponding daily percentage values based on their location under the curves is given in Table 1.

The **fifth** step requires the summation of the five variable daily percentage values for each day and location. The summation is simply

$$SUM = ATMAX + ATMIN + CDD + CONS + (1 - CCMEAN) . \quad (1)$$

The higher the sum values, SUM, the more stressful the day since daily values closest to 1.0 (or 100%) indicate the worst conditions that can occur for that time of year at a given station. CCMEAN is subtracted from 1.0 to account for the fact that clear, rather than overcast, conditions add the most stress to a daytime situation. The summation value based on the Philadelphia, PA example (Table 1) is 3.95.

Variable	Data	Daily % Value
ATMAX	39 ºC	0.99
ATMIN	27 ºC	0.97
CDD	354 ºC	0.99
CONS	2	0.51
CCMEAN	5.11	0.49
	SUM	**3.95**

Table 1. Philadelphia, PA weather variables, their corresponding daily values, and SUM value for July 4, 1999.

The **sixth** step is to fit a distribution to the summed values (similar to third step). The beta distribution function is chosen based on the overall summation frequency patterns for each 10-day period and location (Fig. 2).

Last, the **seventh** step is the calculation of index values for every summer day within each station's 30-year dataset based on the location of the SUM variable under the beta distribution curve (similar to fourth step). For example, July 4, 1999 in Philadelphia, PA is a 97% day (Fig. 2).

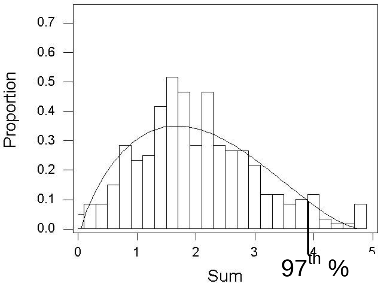

Figure 2. Example of a beta distribution fit to July 1-10 summation frequencies for Philadelphia, PA. July 4, 1999 is represented as the 97th percentile.

3. EVALUATION

To verify the relative and systematic nature of this index, the HSI results were thoroughly analyzed. The results were evaluated based on what was known about an individual station and how it compared with other stations. Here are some of the findings:

- Top ranking days had fairly clear sky conditions and occurred during a string of stressful days. The variable percentages associated with apparent temperatures also represented some of the most stressful conditions that could occur during that time of the year. Just the opposite was true of the lowest ranking days.
- Individual stations required much higher apparent temperatures in July and August to indicate a stressful day compared to those conditions that would report a similar index value in May and early June.
- Stations from various climate regimes had different criteria defining an excessive heat stress event.
- Generally, neighboring stations had similar HSI results, because they were located in the same climate region and were being affected by the same air mass.

The HSI has the ability to be incorporated into NWS forecasts. The index can be calculated 48 hours in advance using the AVN/MRF forecasts. During the past two summers, HSI forecasts have been disseminated as part of an experiment to determine the public's reaction to a relative index. HSI values were converted to a scale from 0.0–10.0, and descriptors were utilized such that: 0.0-3.0 was low, 4.0-6.0 indicated normal conditions, 7.0-8.9 represented a moderate day, 9.0-9.5 was severe, and 9.6-10.0 meant conditions were extreme. The overall results were positive with the vast majority saying use of the index should continue. The National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) will seriously consider using this index in their forecast products if this public response remains positive (NOAA, 2002).

4. FUTURE DEVELOPMENT

There are some important improvements that we suggest to enhance the HSI. One of these is to create daily, rather than 10-day, variable frequency distributions. The 10-day curves do not completely capture the transitional periods, such as May and September, where average conditions may vary greatly between the first and last days within a 10-day period.

An additional modification would be to utilize a better forecasting model other than the AVN/MRF. One shortcoming of the AVN/MRF is that it often forecasts slightly cooler temperatures than what actually occurs. This means that the forecasted HSI values may not accurately represent the stressfulness associated with the actual conditions. The goal is to use the new NWS Revised Digital Forecasts (RDF), which should become a national product in the next year.

5. CONCLUSIONS

The Heat Stress Index is clearly an improvement over other public-oriented indices, because it considers relative stress and adaptation based on spatial and temporal conditions. In addition, the relative index includes parameters that have never been incorporated into other indices, but are proven contributors to heat stress. The HSI could benefit both the operational and research fields with its ability to be used in numerous environmental applications.

6. ACKNOWLEDGMENTS

We would like to thank NOAA's National Climatic Data Center (NCDC) for funding the initial work on this project and for their continued involvement in its development. We also appreciate WCAU-TV in Philadelphia, WAFB-TV in Baton Rouge, and the NOAA/NWS for being involved in our public response experiment.

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