On the Definition of a Heat Wave

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ABSTRACT

Heat waves are a major cause of weather-related deaths. With the current concern for global warming it is reasonable to suppose that they may increase in frequency, severity, duration, or areal extent in the future. However, in the absence of an adequate definition of a heat wave, it is impossible to assess either changes in the past or possible consequences for the future. A set of definitions is proposed here, based on the criteria for heat stress forecasts developed by the National Weather Service (NWS). Watches or warnings are issued when thresholds of daytime high and nighttime low heat index (H_i) values are exceeded for at least two consecutive days. The heat index is a combination of ambient temperature and humidity that approximates the environmental aspect of the thermal regime of a human body, with the NWS thresholds representing a generalized estimate of the onset of physiological stress. These thresholds cannot be applied directly nationwide. In hot and humid regions, physical, social, and cultural adaptations will require that the thresholds be set higher to ensure that only those events perceived as stressful are identified. In other, cooler, areas the NWS criteria may never be reached even though unusually hot events may be perceived as heat waves. Thus, it is likely that a similar number of perceived heat events will occur in all regions, with the thresholds varying regionally. Hourly H_i for 178 stations in the coterminous United States was analyzed for the 1951–90 period to determine appropriate threshold criteria. Use of the NWS criteria alone indicated that much of the nation had less than three heat waves per decade, and this value was adopted as the baseline against which to establish suitable thresholds. For all areas, a percentile threshold approach was tested. Using all available data, daytime high and nighttime low thresholds were established separately for each specific percentile. Heat waves were treated as occurring when conditions exceeded both the daytime high and the nighttime low thresholds of the same percentile for two consecutive days. Several thresholds were tested. For much of the South, 1% thresholds produced appropriate values. Consequently, a heat wave was defined as a period of at least 48 h during which neither the overnight low nor the daytime high H_i falls below the NWS heat stress thresholds (80° and 105°F, respectively), except at stations for which more than 1% of both the annual high and low H_i observations exceed these thresholds, in which case the 1% values are used as the heat wave thresholds. As an extension, ''hot spells'' were similarly defined, but for events falling between the 1% values and NWS thresholds, with ''warm spells'' occurring between the 2% and 1% values. Again, stations for which the 1% or 2% H_i values exceed the NWS thresholds were given modified definitions. The preliminary investigation of the timing and location of heat waves resulting from these definitions indicated that they correctly identified major epidemiological events. A tentative climatic comparison also suggests that heat waves are becoming less frequent in the southern and more frequent in the midwestern and eastern parts of the nation.

1. Introduction

Heat waves are regarded by the National Weather Service (NWS) as the major cause of weather-related fatalities in the United States in most years. There have been detailed analyses of individual severe events (e.g., Karl and Knight 1997) and their impacts (e.g., Ellis 1972; Changnon et al. 1996), but relatively little is known about the climatic behavior of heat waves. In particular, it is not possible to answer the question, ''Are heat waves changing in severity and frequency?'' This failure has direct practical implications for the assessment of the potential impacts of climate change (McMichael et al. 1996; Delworth et al. 1999), and a climate description (dataset) is needed to place any particular heat wave in an appropriate historical context. There have been three major factors interacting to impede the development of such a description: the lack of a rigorous definition of a heat wave, the absence of a simple meteorological measure representing the complex interaction between the human body and the thermal environment, and the lack of suitable homogeneous time series for the meteorological variables likely to be involved. The objective of this paper is to rectify this lack, providing a meteorologically based heat wave definition together with preliminary tests of its performance.

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A basic definition of a heat wave implies that it is an extended period of unusually high atmosphere-related heat stress, which causes temporary modifications in lifestyle and which may have adverse health consequences for the affected population. Thus, although a heat wave is a meteorological event, it cannot be assessed without reference to human impacts. A combination of weather elements related to the human sensation of heat must be used. Appropriate thresholds must be established for that combination, considering both daytime high and overnight low values and being related to the climatic variability common to the area. The effect of duration must also be included.

A variety of heat stress indices that relate atmospheric conditions to human heat sensations have been proposed. Driscoll (1985) lists 11 independent ones, and Kalkstein and Valimont (1986) and Hoppe (1999) have produced new ones since then. All investigators emphasize that the whole heat balance of the human body should be considered, which requires meteorological information about temperature, humidity, wind speed, turbulence, and radiation in addition to the nonmeteorological components of fitness and activity level, clothing type, and physiologic adaptation to a particular environment. Meteorologically, the various indices combine the individual components in ways appropriate for a particular application. For any long-term nationwide analysis of heat waves, an index that relies entirely on routine observations is desirable. NWS has selected an index that combines just temperature and humidity to obtain an estimate of how hot it ‘‘feels’’ to the human body. This index was developed by Steadman (1979a,b, 1984), who termed it the apparent temperature T_a. NWS modified this index for operational purposes. Although this modified version is frequently called the apparent temperature, the preferred alternate name of heat index H_i is used throughout the current work to avoid ambiguity. NWS has linked specific H_i ranges to health effects (NWS 1994) and issues excessive heat advisories, watches, and warnings when needed. Thus H_i can serve, for the current purposes, as a suitable meteorological measure of heat stress. Until recently, the lack of a long-term quality controlled humidity dataset has precluded a climatological analysis of H_i. Recent work (Gaffen and Ross, 1999; Robinson 1998, 2000) has provided the needed data. Gaffen and Ross (1999) analyzed the long-term trends in mean T_a but did not consider extreme values or heat waves.

2. Theoretical definitions of heat waves

The NWS has created a de facto basic heat wave definition through the development of criteria for the issuance of heat watches and warnings. These criteria involve nationwide standards but allow deviations for individual stations based on local conditions (NWS 1994). This approach implicitly recognizes the geographically variable nature of heat waves and their impact (Kalkstein and Davis 1989). The approach also suggests that there are two facets to a heat wave, which may be called, somewhat loosely, the ‘‘physiological’’ and the ‘‘sociological’’ aspects. The former centers on the general thermoregulation of the human body, the latter on local adaptations to climate.

The human thermoregulatory mechanism endeavors to maintain a constant core temperature for the body, which commonly requires that the internal heat generated by metabolism be transferred through the skin and, to a much lesser extent, the lungs to the surrounding atmosphere. Should the atmospheric conditions be such that the removal is impeded, the core temperature will begin to rise and health problems, potentially culminating in death, will begin. The threshold combination of conditions required to impede removal varies with each individual, but includes dependence on age, sex, and fitness. Prior conditioning, both through living in a particular climate and through recent exposure to extreme events, also has an influence (Kalkstein 1993). The environmental parameters that influence the human heat balance include ambient temperature and humidity, the radiation regime, and wind speed (Driscoll 1985). Kalkstein et al. (1996) devised a site-specific heat warning system using a comprehensive range of these pertinent variables. However, for operational purposes on a national basis, NWS has adopted the simpler H_i to summarize the heat environment. This index approximates the human heat sensation of the atmospheric environment and allows reasonable estimates of heat stress for use with forecast watches and warnings. Hence, the thresholds adopted by NWS for watches and warnings can be regarded as the physiologic thresholds for heat waves. However, given the relative simplicity of H_i and the range of human variability, it is not possible to use the index or the thresholds to ‘‘predict’’ any specific human health event such as mortality.

Social and cultural practices are also likely to play a significant role in the human perception of and response to heat. In areas where summer conditions frequently exceed the physiologic threshold, cultural practices are likely to have provided opportunities for evasive action. These may involve having a siesta, or adopting housing and urban forms which, for example, maximize air movement throughout the 24 h and provide adequate shade during the daylight. Socially acceptable activity levels may also be modified. Thus, commonly the critical H_i threshold may be higher than that derived from physiologic concerns alone and may represent a sociological phenomenon. The critical value is likely to depend on the distribution of H_i values during a typical summer.

The preceding general discussion indicates that there are two aspects for the establishment of thresholds for heat waves across the nation, as follows.

1) Exceedence of fixed absolute values. It may be possible to define an absolute value which, to a first

approximation, represents the lower limit for a physiologic heat wave. Conditions above this value would affect most of the population and require some form of modification of activities to prevent discomfort or health problems. If such a fixed threshold is adopted, it effectively precludes the use of the term ''heat wave,'' defined on any other basis, for events falling below the threshold, however extreme they may be in a particular climatic regime. In practice, it also confines the event, for most of the United States, to summer, however stressful an event at another season may be.

2) Deviation from normal. The sociological components of a heat wave are dependent on the local climate and can be expressed by some measure of departure from the expected or mean conditions. There are several possible approaches, and three methods were considered: exceedence of a fixed percentile of all observed values, exceedence of the daily mean value by a fixed standard deviation, and exceedence of the daily mean by a fixed absolute amount. The first was adopted, because it was directly comparable to the method for a fixed absolute value and required the calculation of a single value for the whole station record, whereas the others required thresholds for each day.

The current discussion emphasizes heat waves, but either method can also be used to identify events with thresholds lower than those of heat waves or for the development of the concepts of intense heat wave. This extension is considered in a later section.

The postulated definitional bases using absolute and percentile thresholds contain no reference to the exact nature of the thresholds, which could involve daytime high, nighttime low, or duration criteria. There is evidence that mortality is more likely during or after the second hot night, when the interior of unairconditioned buildings is likely to reflect the outdoor apparent temperature (Kalkstein and Smoyer 1993). Thus the fundamental criteria for the NWS excessive heat watch and warning system requires daytime H_i greater than or equal to 40.6°C (105°F), with nighttime lows greater than or equal to 26.7°C (80°F), for two consecutive days. It is regarded as immaterial whether the first of the threshold crossings is a day or a night occurrence.

This NWS definition is adopted here as the starting point for the development of definitions. Although the NWS criteria may cover much of the United States, there are no comparable definitions immediately available either for those climates for which the NWS thresholds are frequently exceeded or for the extreme events in cooler climates which, although not life threatening, create socially disruptive hot spells. Nevertheless, it is possible to postulate alternative definitions based on station percentile thresholds. Indeed a series of thresholds, proceeding through warm spells to extreme heat waves and depending on the threshold criteria, are possible and desirable.

Although there is no prior constraint on the number or frequency of any of these events, it is assumed that there will be a tendency for a decreasing number as the severity increases. The number of events meeting the criteria for a heat wave will, for much of the United States, be dictated by the NWS criteria. In warmer regions, it is assumed that the number will be comparable to those in the cooler regions. Thus various possible thresholds and definitions will be postulated and the sensitivity of the frequency of occurrence as a response to the exact definition will be examined. Individual events are considered only where needed to refine or to test the definitions.

3. Data

The temperature and humidity information required for this work was obtained from the Surface Airways dataset archived by the National Climatic Data Center (NCDC) and packaged by EarthInfo, Inc. The air temperature data have been extensively quality controlled and have been used in numerous studies. Quality control procedures developed for the dewpoint temperature data were documented in Robinson (1998, 2000).

For this definitional study, the aim was to use long-term serially complete records for a large number of stations. Data from 178 stations (Fig. 1) for the 1951–90 period were used (Robinson 2000). Data for the initial years of the 1990s were not used because there was a major change in instrumentation at most stations and the record of instrument performance was not long enough to allow confident intercomparisons. Further, this period produces four complete decades for the subsequent analysis. For substantial periods of time, which varied with station, only eight 3-hourly observations per day, rather than the full 24 1-hourly values, were archived. For many stations, these gaps were sufficiently long that interpolation was problematic. Consequently, rather than restrict the period of analysis to those years with the full record, the 3-hourly data were used throughout.

The NWS excessive heat advisory criteria are based on the daily maximum and minimum H_i. However, historical maximum and minimum humidity data are not available. Karl and Knight (1997) assumed that the 24 1-hourly observations effectively capture the daily H_i extremes. Here, a comparison was made between the extremes estimated using 3-hourly and 1-hourly data for a selection of stations and periods for those situations in which the low H_i value exceeded 24°C (75°F). In most cases the differences were below 1°C (commonly 1°F) for the minimum and somewhat above (often 2°F) for the maximum. For a second test, a smooth curve was fitted to the averaged station data, each value being expressed as a departure from the minimum recorded for the day. The results were very similar to those for

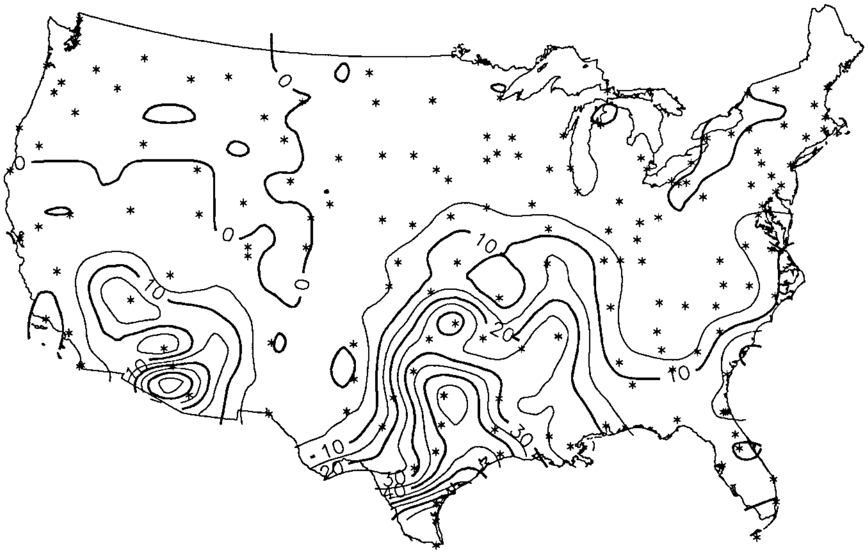

FIG. 1. Number of events per decade when a heat wave is defined as a minimum of 48 h with minimum heat index exceeding 81°F and maximum exceeding 103°F. The contour interval is 5 events (decade)$^{-1}$.

the first test. Last, the impact of the uncertainty on the actual number of heat waves, based on the NWS definition, was examined by comparing results for a set of slightly different thresholds. Using the absolute number of stations recording no heat waves during the 40-yr period as a summary statistic, the response was more sensitive to a change in the high threshold than the low one (Table 1). This result was also apparent when the decadal averages of the number of stations recording less than one event, the average number of events per station, and the maximum number of events at any one station, were assessed (Table 1). Further, the overall spatial pattern did not change appreciably from the general one of maxima in the western Gulf of Mexico, with a marked outlier in the desert southwest, and minima in the North and West (Fig. 1). Thus it appears that the exact values adopted will have little effect on the overall results. Thus, a day with a recorded high of 103°F (39.44°C) was assumed to reach the 105°F threshold, and one with no reading lower than 81°F (27.22°C) was assumed to exceed the 80°F nighttime low threshold.

The NWS modification of the T_a of Steadman (1984) led to the definition of H_i via a table and set of graphs involving air temperature and relative humidity. An equation (available as a FORTRAN program from NCDC) was also provided:

$$
\begin{aligned}
H_i = {} & 16.923 + 0.185\,212T + 5.379\,41R \\
& - 0.100\,254TR + 9.4169 \times 10^{-3}T^2 \\
& + 7.288\,98 \times 10^{-3}R^2 + 3.453\,72 \times 10^{-4}T^2R \\
& - 8.149\,71 \times 10^{-4}TR^2 + 1.021\,02 \times 10^{-5}T^2R^2 \\
& - 3.8646 \times 10^{-5}T^3 + 2.915\,83 \times 10^{-5}R^3 \\
& + 1.427\,21 \times 10^{6}T^3R + 1.974\,83 \times 10^{-7}TR^3 \\
& - 2.184\,29 \times 10^{-8}T^3R^2 + 8.432\,96 \times 10^{-10}T^2R^3 \\
& - 4.819\,75 \times 10^{-11}T^3R^3 + 0.5,
\end{aligned}
$$

where T is air temperature (°F) and R is relative humidity (%). This equation was used here because it has the advantage of computational convenience. However, it gives singular values that suggest unwarranted precision; the broad tabular values are more appropriately

TABLE 1. Comparison of the number of stations without events and the decadal average number of stations with less than one event, the decadal average number of events for stations having events, and the maximum number of events at any station, as a function of threshold definitions.

	No. of stations recording no events of given length (days)					Decadal values		
Threshold (°F)	2	3	4	5	>5	No. station avg < 1	Average No. events	Max No. events
80/105	81	101	116	132	132	101	5.2	67
80/104	76	99	111	120	127	95	6.1	75
80/103	73	95	109	120	122	88	7.7	93
81/104	86	109	117	131	134	103	5.5	73
81/103	83	105	117	123	129	99	6.9	86

TABLE 2. Summary of heat wave frequency per decade with various percentile threshold constraints.

	5%	4%	3%	2%	1%
Avg No. heat waves based on all stations	5.6	4.9	4.6	3.5	1.8
Avg No. heat waves for stations using NWS thresholds	4.5	4.0	3.2	2.5	1.0
Avg No. heat waves for stations using percentile thresholds	21.8	14.1	13.2	8.5	3.6
Max No. heat waves at any station	32.5	32.0	28.5	19.6	7.5
No. stations above NWS threshold	8	13	17	28	47

suggestive of uncertainty in the methodology of the ultimate derivation. In practice, calculations were performed in Fahrenheit and converted to Celsius for reporting purposes when needed. To obtain a serially complete record, air temperature alone was used when the air temperature was below 75°F, where H_i is undefined.

4. Quantification of the definitions

Events were established using the 24-h H_i extracted from the 3-hourly record. A potential event commenced when either the low or the high exceeded the appropriate threshold. Provided the thresholds continued to be exceeded for the minimum duration, an event was recorded. Thus for a heat wave to be established by the NWS criteria as used here, four consecutive observations, two minima exceeding the 81°F low threshold and two maxima exceeding 103°F, were needed. Thereafter, the heat wave continued as long as the appropriate thresholds continued to be exceeded. Once the threshold crossing failed, the event ended and a new 48-h sequence was required to initiate a new event.

Simple use of the NWS criteria for a heat wave led to zero occurrences at some stations in the North and to well over 60 per decade in the western Gulf of Mexico and the southern deserts (Fig. 1). Sixty-six stations had no heat waves during the period of record. Excluding those stations, the average number of heat waves was less than eight per decade, indicating that the NWS criteria support the subjective notion of a heat wave as a rare event, with occurrence only a few times per decade. However, in the South and Southwest, the events were much more numerous. Here it can be assumed that some sociological adaptation has occurred, that heat waves continue to be a rare event, and that the NWS criteria do not adequately represent the heat wave thresholds. Alternate criteria must be developed. These criteria should produce frequencies that demonstrate a smooth spatial transition between the areas using them and those using the NWS criteria. These thresholds were examined using percentile-based values.

The specification of appropriate thresholds for the southern and southwestern portions of the United States was explored using a range of possible percentile-based values. For each station, the H_i value that was exceeded a specified percentage of the time was determined separately for the overnight low and the daytime high. If both values exceeded the corresponding NWS value, the day/night pair was regarded as a candidate heat wave threshold for that station. The percentiles were based on the full yearly cycle. Although a 10% threshold was tested first, only one station, Phoenix, Arizona, exceeded the NWS values, so there was little change in the results, and this percentile was discarded as a possible heat wave threshold. Thereafter, thresholds at 1% intervals between 5% and 1% were used. The 5% level roughly corresponded to the 20% summer condition level that Kalkstein and Davis (1989) noted marked the onset of health-related effects. At the 5% level, the thresholds for eight stations changed from the NWS values (Table 2). These were all close to the western Gulf of Mexico, with Phoenix as an outlier in the Southwest. At lower percentiles, the influence spread northward, until at the 1% level some stations in the Midwest and the mid-Atlantic regions were incorporated.

In all subsequent analyses, for convenience the heat wave threshold criteria are expressed in terms of the appropriate percentile. This approach indicates that at those stations where the thresholds at that percentile exceed those of the NWS, the percentile thresholds were used. At all other stations, the NWS thresholds were used.

Each percentile was used in turn to determine the decadal average number of heat waves from the 1951–90 data (Table 2). The decrease in the average number for the total network as the percentile decreased was apparent. When only those stations where the NWS threshold still applied were considered, the average declined slowly as the hotter stations were removed. There was a much steeper decline for those stations where the threshold was changed, as the relatively cooler stations were added. The effect was to decrease the overall range for the United States. The spatial distribution was also modified (Fig. 2). Using the 5% threshold, the original major maximum in the Texas area (Fig. 1) was replaced by a much broader maximum covering the western half of the Gulf coast and extending some distance inland. Continued reduction of the percentile threshold continued the trend of reducing the numbers in the South and spreading the region of relatively high values northward. At the 3% level, there was still a general south–north trend, but, at the 2% level and especially at 1%, a midwestern maximum appeared. The results for both the 2% and 1% levels supported the general notion of a heat wave as a rare occurrence and reinforced the subjective perception that they are most frequent in the Midwest but also occur in the South, extending far northward along the Atlantic seaboard. Further, both suggest a

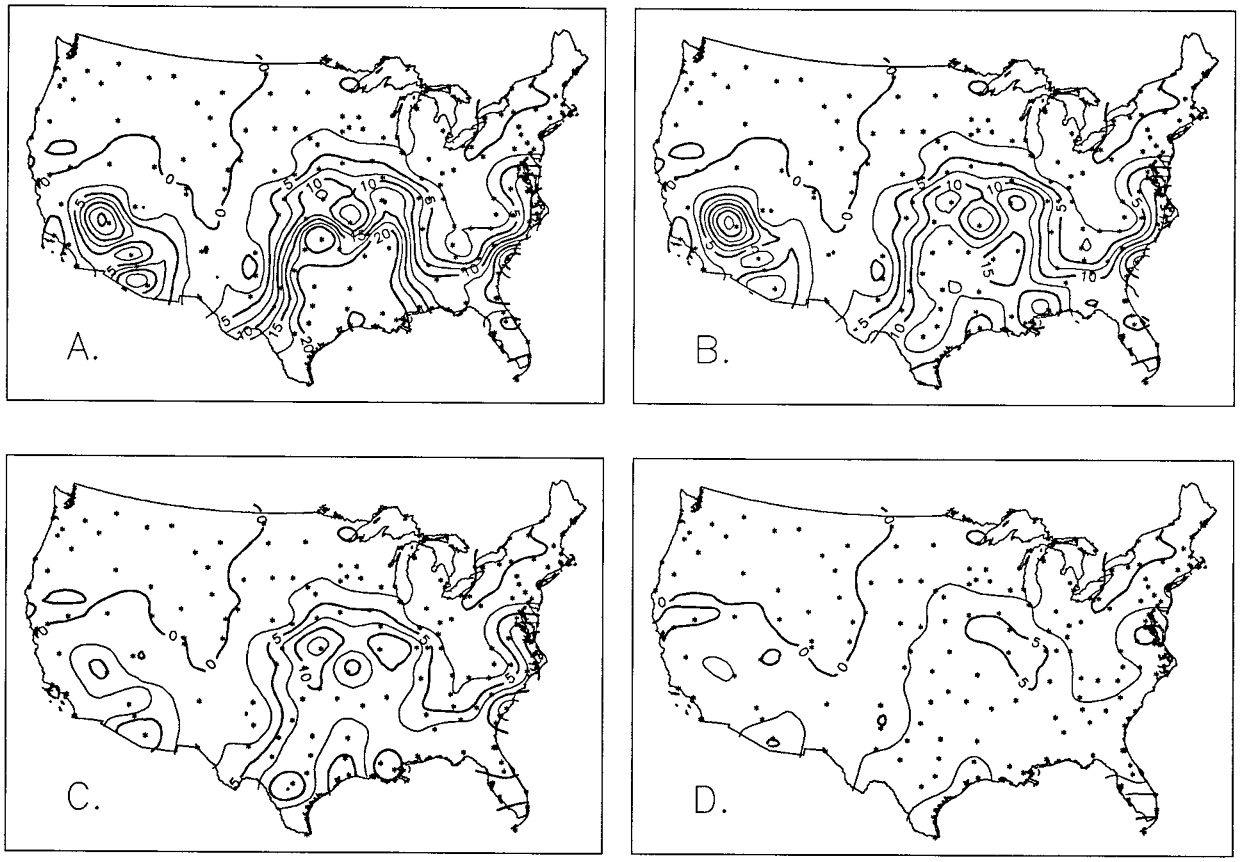

FIG. 2. Distribution of number of heat waves per decade for (a) 5%, (b) 3%, (c) 2%, and (d) 1% threshold criteria. The contour interval is 2.5 events (decade)$^{-1}$.

smooth transition between the areas in which the NWS criteria dominate and those in which the percentiles are most common. Thus, this analysis suggested that either could provide a suitable companion heat wave threshold for the NWS values. The next step in choosing the appropriate threshold and definition, therefore, was to investigate the influence of event duration.

A minimum event duration of 48 h, the NWS criterion, has been assumed so far. The effect of other durations was explored for events defined by both the 2% and 1% thresholds (Table 3). Length was defined as a continuous sequence of threshold exceedences. For each duration, the decadal average number of events was determined using only those stations that had events of that duration, not the entire network. The shortest period investigated, one day, had the most frequent occurrence, and more than 75% of the stations had at least one such event during the 40-yr period. The 2-day events, regarded as the minimum for the establishment of a heat wave, were somewhat less widespread and considerably less frequent. There was a rapid decrease in the number of stations involved and a slow decrease in the frequency as durations increased beyond 2.5 days. This trend was more marked for the 1% than for the 2% threshold,

TABLE 3. Average number of heat waves per decade as a function of length of event, and number of stations with events of specified length at any time during the 1951–90 period.

Length (days)	1*	1.5*	2	2.5	3	3.5	4	4.5	5	5.5	6	>6
					1% threshold							
Avg No. events	4.68	3.36	1.18	1.03	0.52	0.49	0.37	0.34	0.33	0.28	0.27	0.35
No. stations	137	123	111	99	70	56	41	36	19	15	12	17
					2% threshold							
Avg No. events	7.02	5.41	2.01	2.01	0.94	0.86	0.53	0.54	0.39	0.35	0.32	0.51
No. stations	137	123	111	100	73	77	61	57	33	36	22	41

* These lengths do not qualify as heat waves but are included for comparison purposes.

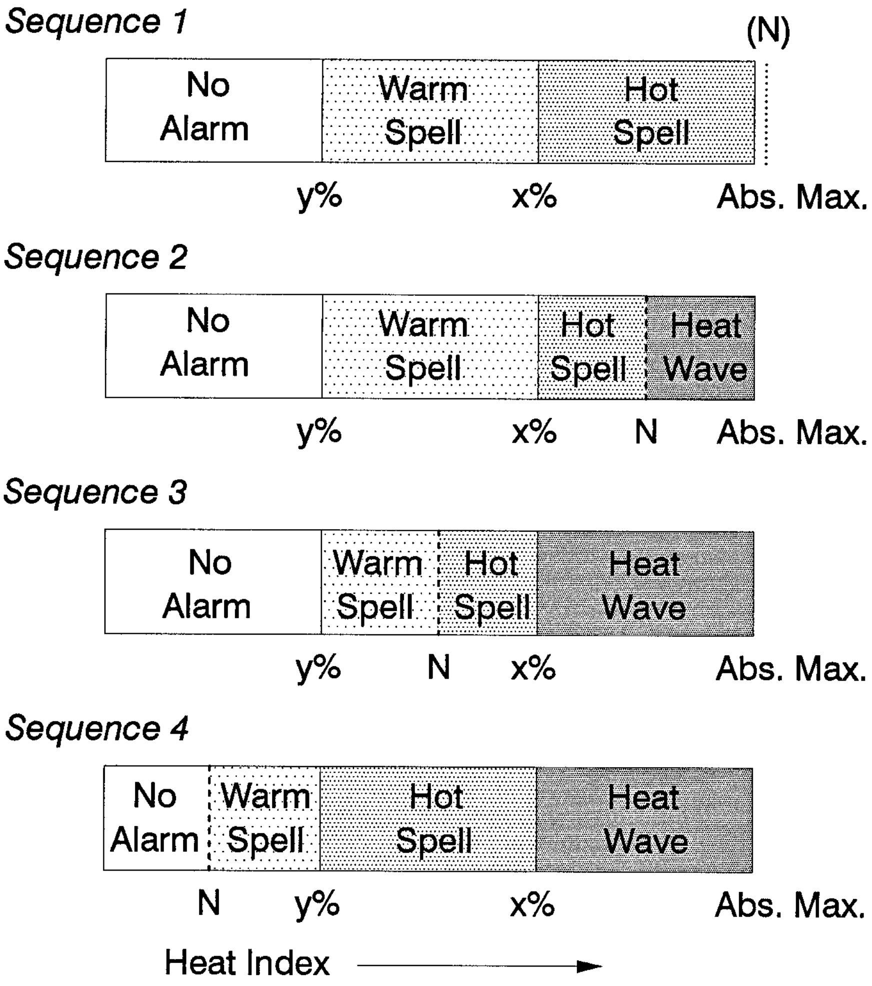

FIG. 3. Schematic diagram showing the possible sequences in the NWS (N), and x and y percentile ($x > y$) threshold relationships.

particularly for the number of stations involved. This result suggests that the 1% threshold gave heat waves that contracted spatially more rapidly as they progressed than did the 2% threshold results. A test of this suggestion is beyond the scope of this paper. The current results did not assist in selecting appropriate percentile thresholds, but they indicated that the 2-day minimum heat wave duration criterion was appropriate. Although the impact of an event is often associated with its length, Table 3 suggests that there is no unambiguous break point for identifying particularly prolonged heat waves. For the present purpose, a value of 4 days was chosen for the onset of an extended heat wave, being 2 days beyond the onset of the heat wave, which itself starts 2 days after the onset of the exceptionally hot conditions.

A final analysis designed to specify the appropriate percentile thresholds for heat waves was undertaken by investigating the relationship between thresholds and events less extreme than heat waves. A sequence of decreasing intensity from heat waves through hot spells and warm spells to cool ‘‘no-alarm’’ conditions was postulated. Because the NWS threshold is a fixed absolute value but the percentiles depend on the local climate, nationally four combinations were possible (Fig. 3). Following the NWS heat wave criteria, at least 48 h continuously above the category threshold was required before an event commenced. The warm spells were defined in two ways, first as any event between the two appropriate thresholds, and second in a constrained form in which the daytime high value had to exceed the 80°F NWS threshold, thus retaining some notion of heat stress. An event was identified exclusively by its maximum intensity, so that a heat wave may have had several days qualifying as a hot spell immediately before being upgraded to a heat wave. For convenience, in subsequent sections in which various percentile thresholds are investigated, reference is made to the N-x-y sequence (Fig. 3), irrespective of the actual order of the thresholds at any particular station.

In general, whatever threshold suite was selected, there was a logical sequence whereby the number of

TABLE 4. Network average of event frequencies per decade with various threshold constraints.

Avg No. events per station	N-2-5	N-1-5	N-2-3	N-1-3	N-1-2
Warm spells (unconstrained)	26.3	30.5	13.8	18.2	12.6
Warm spells (constrained)	20.6	25.0	9.5	14.1	9.5
Hot spells	9.5	6.7	8.1	5.3	4.3
Heat waves	3.5	1.8	3.5	1.8	1.8

warm spells exceeded the number of hot spells, which, in turn, exceeded the number of heat waves (Table 4). The unconstrained form of the warm spell definition gave approximately 25% more events than the constrained form. In the subsequent analysis the constrained form was used.

The effect of the choice of threshold suite at individual stations was examined using stations selected to make a transect south along the Mississippi Valley and west into Arizona, with one southeastern station included (Table 5). Most individual stations and threshold sets showed the same trend as the network average (Table 4). However, there were some exceptions for all sets, associated with stations having threshold sequence numbers 3 or 4 (Fig. 3). The most obvious was in the lower Mississippi Valley, where sequence number 4 dominated, such that the relatively large difference between the 1% and 5% thresholds allowed many hot spells, but the closeness of the NWS and 5% thresholds gave few or no warm spells. The influence of the sequence number was evident in the spatial distributions of hot spells (Fig. 4). When the 5% threshold was used, the lower Mississippi Valley dominated. As the *y* threshold of Fig. 4 was decreased, with $x = 1$, a more even distribution was established (Figs. 4a–c). The N-2-3 sequence produced a pattern where the maximum number of hot spells was in the northeast and the west (Fig. 4d). A hot spell, envisioned as a event of slightly lesser rank than a heat wave, has no a priori requirement for a continuous physiological effect, but should be sufficiently unusual to have a distinct sociological impact. Furthermore, that impact should be relatively uniform throughout the region. Thus the N-1-2 sequence is the most appropriate.

The distribution of warm spells using N-1-2 was compared with that using N-1-3 (Fig. 5). Although the two patterns were similar, the former gave higher values in the regions of maxima: the western Gulf of Mexico and the southwestern desert. However, the minima were reversed, with much of the nation having fewer than 10 warm spells per decade for N-1-2 but between 10 and 15 for N-1-3. When compared with N-1-3, N-1-2 gave a smaller number of hot spells more evenly distributed across the United States, while the warm spells were more markedly concentrated in the south. Thus N-1-2 is appropriate in terms of the number, relative frequency, and spatial distribution of heat waves, hot spells, and warm spells.

For conditions with exceptionally high H_i, NWS has

TABLE 5. Number of warm spells (WS), hot spells (HS), and heat waves (HW) per decade, for selected stations with various thresholds, using data for the 1951–90 period.

	N-2-5			N-1-5			N-2-3			N-1-3			N-1-2		
	WS	HS	HW	WS	HS	HW	WS	HS	HW	WS	HS	HW	WS	HS	HW
Norfolk, VA	25.5	2.5	9.8	28.0	5.3	4.5	11.5	3.0	10.0	14.5	5.5	4.5	3.0	5.5	4.5
Minneapolis, MN	24.8	9.8	2.0	30.8	3.8	2.0	5.8	9.8	2.0	11.8	3.8	2.0	6.0	3.8	2.0
St. Louis, MO	22.8	4.8	13.3	22.8	12.3	5.8	3.5	4.8	13.5	3.5	12.5	5.8	4.8	8.0	5.8
Memphis, TN	0.0	29.5	10.0	0.0	35.3	4.3	23.5	6.0	10.0	23.5	11.8	4.3	29.5	5.8	4.3
Baton Rouge, LA	0.0	11.8	13.5	0.0	20.0	5.3	10.3	1.5	13.5	10.3	9.8	5.3	12.0	8.0	5.3
Phoenix, AZ	46.5	13.0	9.0	46.5	18.3	3.8	55.5	4.0	9.0	55.5	9.3	3.8	59.5	5.3	3.8
Waco, TX	39.5	13.8	7.5	39.5	17.3	4.0	47.0	6.3	7.5	47.0	9.8	4.0	53.3	3.5	4.0

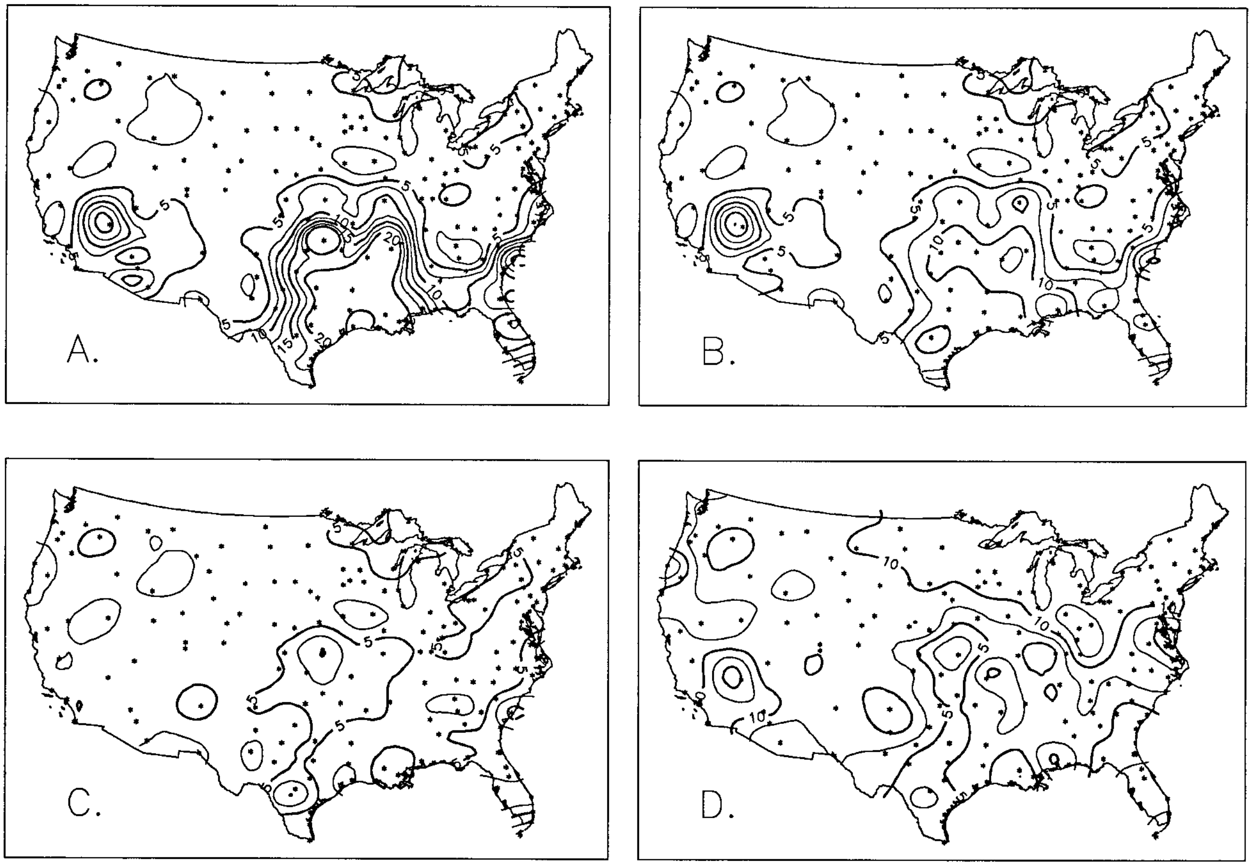

FIG. 4. Distribution of number of hot spells per decade for (a) N-1-5, (b) N-1-3, (c) N-1-2, and (d) N-2-3 threshold criteria. The contour interval is 2.5 events (decade)$^{-1}$.

adopted a criterion that requires issuance of a warning whenever the daytime high is forecast to be at least 10°F above the normal high threshold for a heat wave. This approach could be incorporated directly here, whether the NWS or the percentile value was used as the heat wave threshold. However, the minimum duration of these intense heat waves had to be defined. Durations of 36 and 48 h were examined (Table 6). In theory, the 36-h duration could involve two exceptionally hot days with a warm night between, but in practice almost invariably meant that only a single daytime high 10° above the regular threshold, surrounded by two overnight lows above the regular low threshold, was needed. Thus this result can occur as an isolated, short-lived, but intense event, in keeping with the thrust of the NWS approach. The 48-h criterion required two consecutive days with

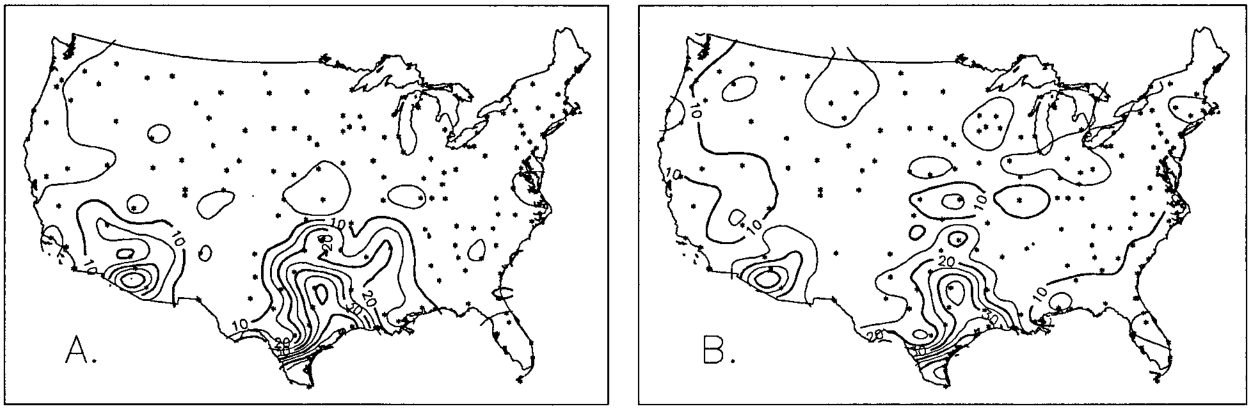

FIG. 5. Spatial distribution of warm spells for (a) N-1-2 and (b) N-1-3 threshold criteria. The contour interval is 5 events (decade)$^{-1}$.

TABLE 6. Influence of the definition of duration on the total number of intense and extreme heat waves per decade and number of stations involved at any time during the 1951–90 period.

	48/96-h thresholds		36/72-h thresholds	
	Total No.	No. stations	Total No.	No. stations
Intense heat wave	5.75	20	20.75	45
Extreme heat wave	0.50	2	1.75	6

extreme highs. This requirement reduced the number of intense events by a factor of 4, making it an extremely rare occurrence. Only 20 stations anywhere in the network at any time during the analysis period experienced an intense heat wave with this definition, with an average of 5 occurrences per decade. The short, sharp, intense event based on the 36-h threshold may be preferable. However, the extended intense event, the truly extreme heat wave, was established as an event in which the intense conditions lasted for at least 72 h, thus involving at least 3 daytime periods with intense heat. These, by design, were rare.

The final set of proposed definitions is given in Table 7 and is shown schematically in Fig. 6. Figure 7 shows the distribution of stations following each of the four sequences. The majority of the stations used in the analysis follow sequence 2, having the NWS thresholds as their heat wave criteria. Most are in the north and west, although some occur in southern Florida. In the interior West are stations following sequence 1, having no heat waves. In the South are a group of stations using the 1% heat wave threshold (Fig. 6). These stations can be divided further into a southern interior region following sequence 3 and a Western Gulf area, encompassing the lower Mississippi Valley and parts of the Southwest, following sequence 4.

5. Tests and applications

A basic heat wave climate of the coterminous United States is given by Figs. 2d, 4c, and 5b and the final column of Table 4. Thus, by the current definitions, there are approximately 1.8 heat waves per decade nationwide. They are most common in the South, especially in the area stretching from Memphis, Tennessee, through St. Louis, Missouri, to Kansas City, Missouri. Other maxima occur along the western Gulf Coast of Texas and in southern Arizona.. Heat waves are rare in the Northwest and in southern Florida. Occasional hot spells occur in most of the United States, with the South again having more than the North. Maxima occur to the west of the area of maximum heat wave frequency in the Mississippi Valley area. Warm spells display a similar spatial pattern to heat waves, but with all areas being influenced and the overall frequency being approximately an order of magnitude higher.

The time series for heat waves and hot spells for four specially selected stations indicate a clustering in certain periods (Fig. 8). Of these stations two, St. Louis and Topeka, Kansas, represent the national heat wave core; the others are stations using the NWS heat wave criteria. All cover areas where there have been epidemiological investigations of specific heat waves. For the New York stations, Schuman (1972) investigated the 1966 event, noting that it was the first to have a major impact since 1952. The current record shows some scattered hot spells, with a heat wave at one station in 1953, but 1952 had the only heat wave prior to 1966 indicated by both stations. For the same city, Marmor (1975) used 11 hot summer events between 1949 and 1970 to develop temperature and mortality relationships. The current data suggest that 10 of these summers (excluding 1949) have hot spells or heat waves. Ellis and Nelson (1978) studied the mortality associated with the 1976 heat wave identified here, but those of 1972 and 1973 (Ellis et al. 1975), which also had significant mortality, are only designated as hot spells here. Similarly, from the study of St. Louis by Bridger et al. (1976), the events of 1954, 1955, and 1966 are identified as heat waves in the current work, and 1953 is shown as a hot spell. Jones et al. (1982) noted that the 1980 heat wave was the first such event since before 1950 to occur virtually simultaneously at both St. Louis and Kansas City, a contention largely supported by the current data for St. Louis and Topeka.

Overall, therefore, the comparison between the current identification scheme and major epidemiological

TABLE 7. Definitions of heat waves and associated events.

Heat wave. A period of at least 48 h during which neither the overnight low nor the daytime heat index H_i falls below the NWS heat stress thresholds (80°F and 105°F). At stations where more than 1% of both the high and low H_i observations exceed these thresholds, the 1% values are used as the heat wave thresholds.

Intense heat wave. A period of at least 36 h during which the daytime high exceeds the high threshold for a heat wave by more than 10°F, the overnight low exceeding the low threshold for a heat wave.

Hot spell. A period of at least 48 h during which both the overnight low and daytime high H_i have values exceeding those observed 1% of the time at the station, but where conditions fail to meet the criteria for a heat wave. For stations at which the 1% values exceed the NWS heat stress criteria, a hot spell is defined as an event with values falling above the NWS criteria but below the 1% values.

Warm spell. A period of at least 48 h during which the daytime high H_i exceeds 80°F and both the overnight low and daytime high heat index have values exceeding those observed 2% of the time at the station, but where conditions fail to meet the criteria for a hot spell. For stations at which the 2% values exceed the NWS heat stress criteria, the NWS values are the minima for a warm spell, and the 2% values are the minima for a hot spell.

Extended events occur when the required conditions persist for 96 h or more.

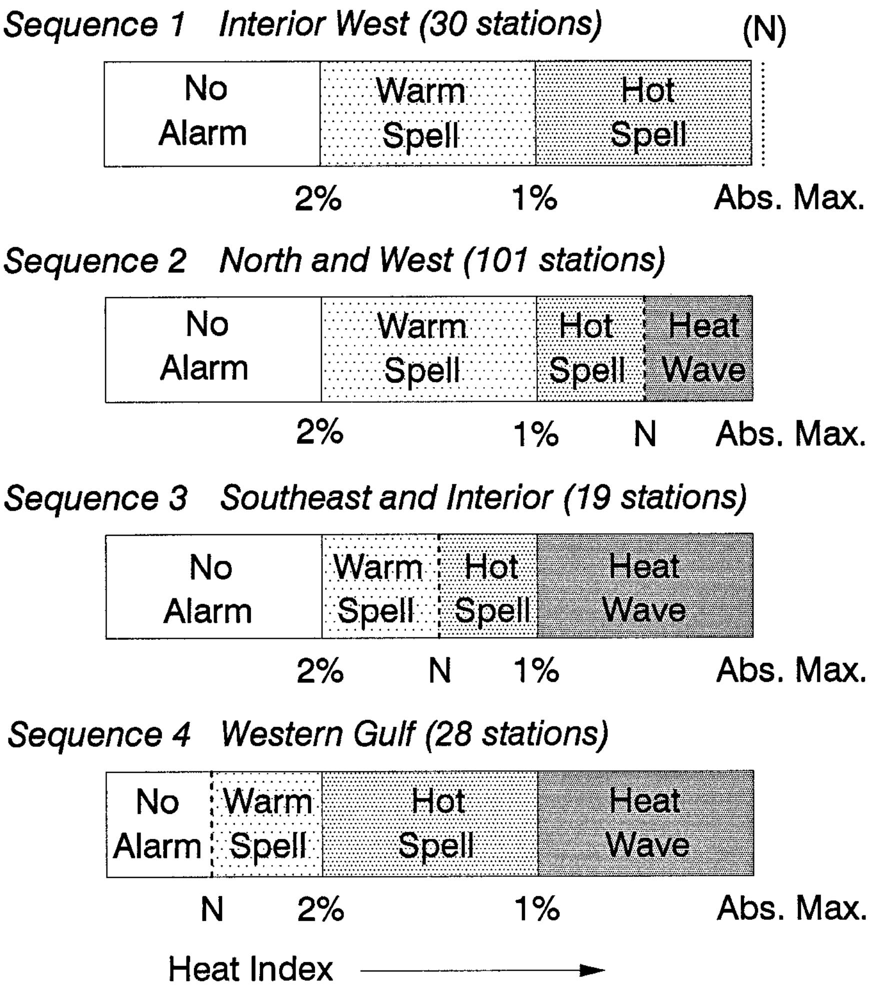

FIG. 6. Schematic diagram showing the set of sequences and thresholds adopted for the heat wave definitions, with indications of the number and location of stations within each sequence.

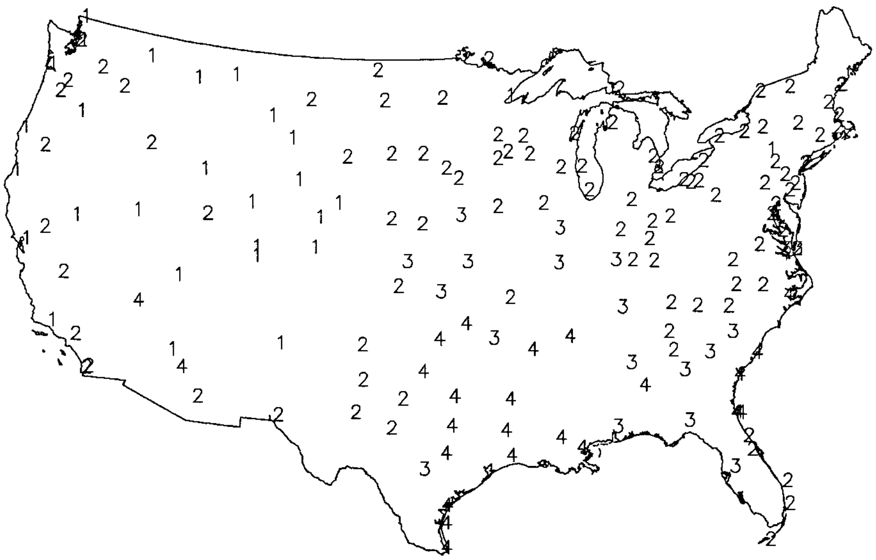

FIG. 7. The locations of stations following each of the sequences indicated in Fig. 6.

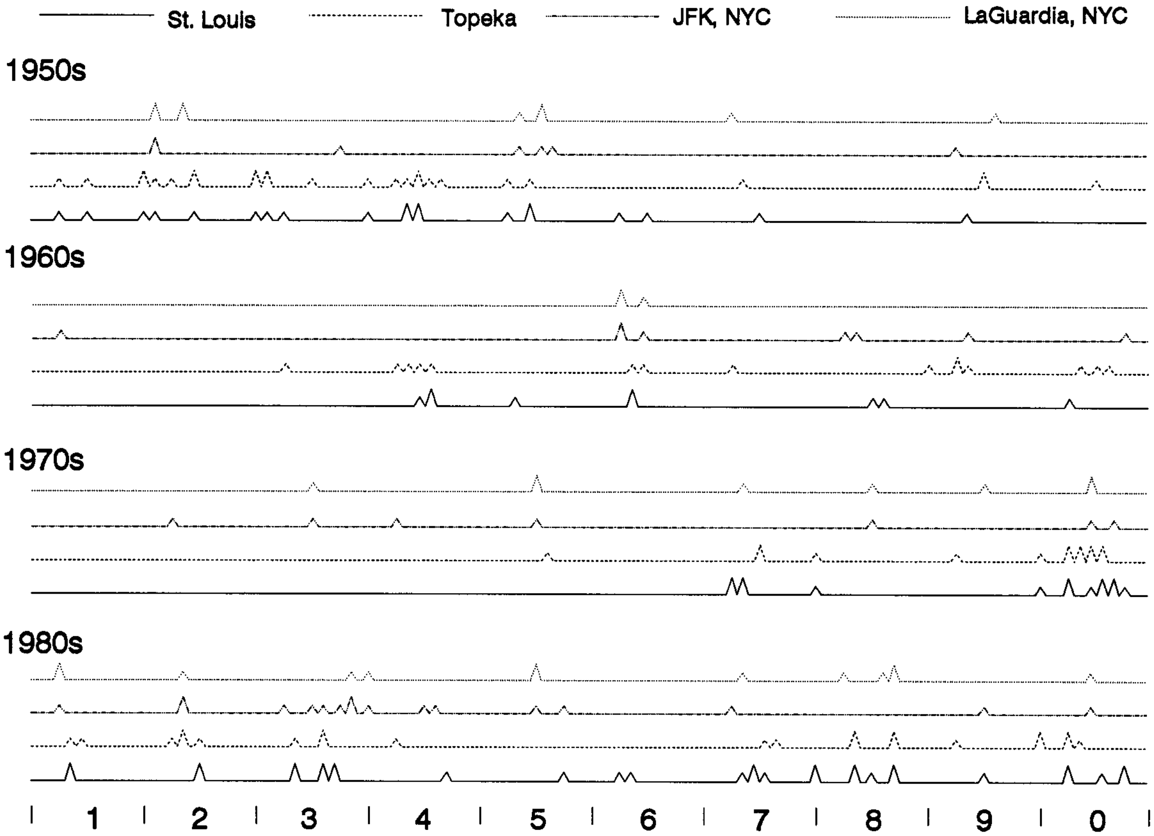

FIG. 8. Time series of heat waves (major peaks) and hot spells (minor peaks) for four stations (St. Louis, MO; Topeka, KS; and John F. Kennedy Airport and LaGuardia Airport, New York City, NY, for the period of 1951–90.

FIG. 9. Change in the number of heat waves (all types) between the 1950s and the 1980s. Arrows indicate the direction of change, with the triangle showing stations without heat waves in either decade. The crossed or overlapping arrows indicate the results for closely spaced stations.

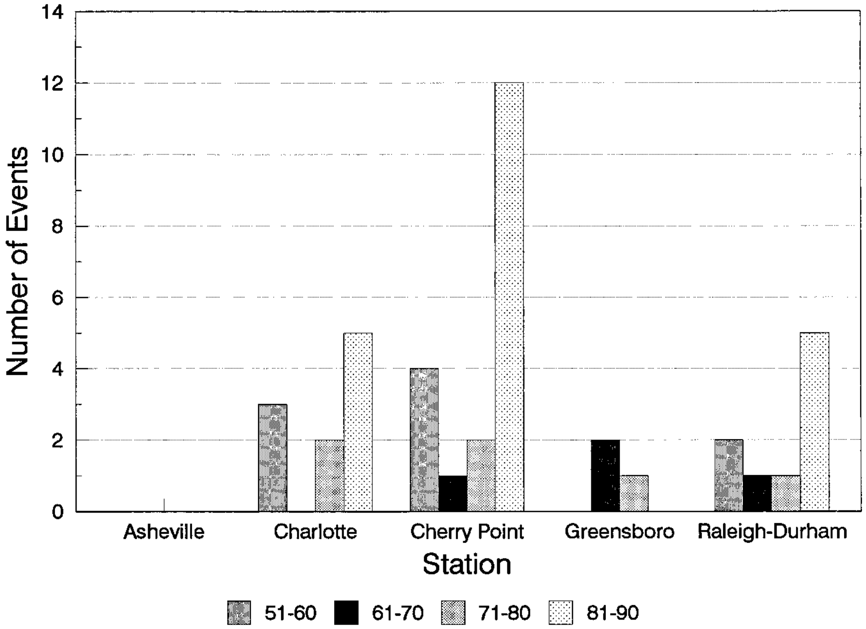

FIG. 10. Number of occurrences of heat waves (all types) per decade at four stations in North Carolina.

analyses suggests a reasonable correspondence. Because the current scheme is not designed for epidemiological purposes, and the studies cited do not purport to provide a complete time series of events, further comparative analysis in this form is unwarranted. Rather, the correspondence indicates that the current scheme is capable of identifying events of major health concern.A preliminary investigation of trends in heat wave frequencies, using the difference in the decadal total number of heat waves between the 1950s and the 1980s, suggests distinct regional patterns (Fig. 9). The Great Lakes, the desert Southwest, and the Atlantic and eastern Gulf Coast regions all indicated an increasing frequency. The interior South and the western Gulf of Mexico displayed a decrease. Some areas of the upper Midwest and the Southeast showed no change. In general, therefore, those areas with current high frequency of heat wave occurrence showed a decrease, and those with low frequency showed an increase. The Arizona region was something of an exception. The Southeast showed variable trends. A more detailed analysis using four North Carolina stations (Fig. 10) indicates that the trends are not monotonic and that the adoption of single regional values without regard for the time period involved may be misleading.

Taken together, these preliminary analyses provide a baseline climate description of heat waves for the United States. The results indicate that the approach and the thresholds provide a realistic basis for the investigation of events that have an influence on lifestyle, human comfort, and human health, particularly in the light of potential temperature increases associated with the current overall warming trend. Each analysis raises major questions concerning the meteorological causes of the individual events and the climatological basis for the trends, and thus for the future frequency and intensity of heat waves.

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