

THE REDEVELOPMENT OF A WEATHER-TYPE CLASSIFICATION SCHEME FOR NORTH AMERICA

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ABSTRACT

Synoptic weather-typing, or the classification of weather conditions into categories, is a useful tool for climate impact applications. Numerous procedures have been developed to accomplish this goal. Before the advent of high-speed computers, manual methods were most common; more recently, more automated methods have come into wide use. Both types of classification have shortcomings; manual methods are time consuming and difficult to reproduce, whereas automated methods may not produce easily interpretable results. Several recent methods have incorporated the advantages of both methodologies into a hybrid scheme.

This paper describes the redevelopment of one such hybrid scheme, the Spatial Synoptic Classification (SSC). The SSC, originally developed in the mid-1990s, classifies each day at a location into one of six weather types, or a transition. It has been utilized for several applications, from climate trends to human health. Despite its utility, it has several shortcomings, most notably a lower-than-desired match percentage among adjacent stations and a framework that only allows for classification during winter and summer.

The new SSC (SSC2) has been altered in several important ways. The most notable changes involve the procedure for selecting seed days, days that typify a particular weather type at a particular location. With the new procedures, the SSC can now produce weather-type classifications year-round, instead of only winter and summer. The spatial cohesiveness among stations has also been improved. The SSC has been expanded to include Canada, Alaska, and Hawaii in addition to the lower 48 US states. SSC calendars are now available for 327 stations with a mean length of 44.6 years, and are updated daily on a website.

This paper also presents an important application of the redesigned SSC. It has been used in several heat-stress warning systems worldwide. The synoptic approach is considered to be superior to a traditional apparent temperature approach, as it considers more parameters in its holistic assessment. At each location, one or two of the weather types is associated with mortality levels significantly above the mean. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: synoptic climatology; weather typing; air masses; heat stress

1. INTRODUCTION

Synoptic weather-typing, or the classification of weather conditions or patterns into categories, continues to be popular, and numerous methods have been developed over the past century. The recent increased interest in the procedure is attributed to its utility in solving a wide array of applied climatological problems. Concern over the impacts of weather, especially for the purpose of understanding possible implications of climate change, has driven the search for more, and better, weather-typing schemes.

Yarnal (1993) notes several different subdivisions of synoptic classifications; among these is the distinction of *manual* versus *automated* classification schemes. Manual procedures involve the subjective classification of circulation patterns or weather types from visual analyses of individual synoptic maps. The Muller Classification (Muller, 1977), the Lamb Catalogue (Lamb, 1972), and Grosswetterlagen (Hess and Brezowsky,

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1977) are the best-known examples; they have been applied to problems ranging from insect transport (Muller and Tucker, 1986) to precipitation acidity (Davies *et al.*, 1986). Schemes such as these have several benefits. The investigator is in full control of the process and classification. The classification system can thus be tailored precisely to the researcher's needs. Unfortunately, they are quite time consuming, and can be difficult to export to other locations. Subjectivity can become excessive: different researchers will not necessarily agree on classifications for a given day, rendering these schemes *not replicable* (El-Kadi and Smithson, 1992; Yarnal, 1993).

The computer revolution of recent decades has resulted in the development of many *automated* synoptic classification methods. These include such procedures as correlation-based map patterns (Lund, 1963), and a variety of eigenvector-based techniques (e.g. the temporal synoptic index (Kalkstein and Corrigan, 1986), which incorporates principal components analysis and cluster analysis). With all of these systems, once some initial thresholds are set, a computer then creates classification groups and assigns individual cases entirely based on statistical criteria. These systems have also proved quite useful, from evaluating heat-stress-related mortality (Kalkstein, 1991) to interpolating missing values in a data set (Huth and Nemešová, 1995). Automated methods are much easier to use, and are generally reproducible (Yarnal, 1993). The main drawback to these systems is the lack of comparability between locations. Most of these methods are applied to only one station (or, in some cases (e.g. Vose, 1993), one region) at a time, and comparison of results from station to station is difficult (El-Kadi and Smithson, 1992), as each station may have a different number of classification groups representing different conglomerations.

Having reviewed the benefits and advantages of both manual and automated methods, it seems intuitive that a valuable synoptic methodology could be derived by combining the two methods into a *hybrid* scheme. Attempts at hybrid schemes have been undertaken by relatively few researchers. Schwartz (1991) developed a scheme to classify weather types over the north-central USA. Initial development is subjective: six weather types are identified, and 85-kPa temperatures and dew points for each weather type are taken from days when the weather type is clearly known by virtue of trajectory. Normal curves are then derived for each weather type based on the partial collectives technique (Bryson, 1966), which assumes the overall frequency distribution of a given parameter is comprised of several superimposed normal curves. This automated segment then produces limits of parameter values for each weather type for each station-month.

Frakes and Yarnal (1997) have developed a hybrid procedure that produces map classifications. They initially manually classify 12 years of daily sea-level pressure maps for the eastern USA into ten distinct classifications and an unclassifiable group. A mean pressure field is calculated for each of the classifications. The mean fields then serve as keydays similar to those used in Lund's procedure (Lund, 1963), except that the keydays are effectively manually chosen, not statistically chosen. A correlation-based threshold is then used to assign all days into one of the map types. Results show that on fewer than half of the days do the manual and hybrid procedures match, and although aggregated-group comparisons show consistency, in smaller groups of data the disparity between manual and hybrid becomes readily apparent. Frakes and Yarnal (1997) suggest that much of this is due to the subjectivity of all manual methods, but they believe this method is superior to ordinary manual or automated classifications.

The Spatial Synoptic Classification (SSC) system (Kalkstein *et al.*, 1996) is another hybrid system, developed originally for use in the conterminous USA. The SSC is based on the identification of six different weather types across the North American continent. At a station-by-station level, it assigns each day into one of these weather types, or as a transition between two weather types. It has been used for general climatological purposes as well as numerous applications, including precipitation intensity (Greene, 1996), heat-stress mortality (Kalkstein and Greene, 1997), and the urban heat island (Sheridan *et al.*, 2000). For all its usefulness, however, the original system has important limitations, most notably its availability only during the winter and summer seasons.

This paper documents recent work that has revamped the SSC in several key ways. First, a new procedure entitled sliding seed days permits year-round classification. Second, the spatial continuity of weather types has been improved, as threshold criteria for the particular weather types are now modified automatically. In addition, a considerable expansion in both the number of stations and the spatial extent of these stations has also occurred. This redeveloped SSC system (hereafter referred to as SSC2 to distinguish



Figure 1. Stations for which SSC calendars have been created

it from its predecessor, hereafter SSC1) is presently available for 327 stations in the USA and Canada (Figure 1). Day-by-day calendars of weather types have been available since 1948 for most US stations, and from 1953 to 1993 for most Canadian stations. The average record length of classified days is 44.6 years.

Following this introduction, the paper first describes the six weather types identified in the SSC, and the method of selection of *seed days*, days that typify these weather types at a particular location. The improvements to the system, and a sample of how the system is spatially transferred, are then presented. Following the description of the SSC's redevelopment is an example of the utility of the system: application to heat-stress warning systems. The SSC2 has already been utilized in the development of warning systems for several cities, with additional systems under development.

2. METHODOLOGY

2.1. Weather type identification

The first step in the development of the SSC2 involves weather-type (or air-mass) identification. This identification is concerned more with surface meteorological characteristics than with its geographical source region. Because of this focus, some of the *weather types* can be associated with a source region and typical

air mass designation, whereas others cannot. By concerning itself with local meteorological character, the SSC2 will be particularly useful in biometeorological applications, as organisms generally respond to ambient atmospheric conditions, rather than pressure patterns.

After detailed historical climatological analyses, Kalkstein *et al.* (1996) decided that the Bergeron (1930) air mass lexicon (cP, cT, mP, mT) was too limited for application to environmental problems. In its place, six weather types are defined: (1) dry polar (DP); (2) dry moderate (DM); (3) dry tropical (DT); (4) moist polar (MP); (5) moist moderate (MM); (6) moist tropical (MT).

DP air is largely synonymous with the traditional cP (and in extension, cA) air mass. It is characterized by cool or cold dry air, and for much of the continent, northerly winds. Skies typically feature little or no cloud cover. This weather type has its source in northern Canada and Alaska, and is advected into the rest of North America by a cold-core anticyclone that emerges from the source region.

DM air is mild and dry. This weather type has no traditional source region. In much of North America, DM usually appears with zonal flow aloft, which permits air to traverse the Rocky Mountains, to dry and warm adiabatically; in these cases, it is analogous to the Pacific weather type (Pa) identified by Schwartz (1991) and others. In other cases, however, similar conditions can arise from a significantly modified DP weather type or a mixture of DT and MT, or DP and MT, influences.

DT air is associated with the hottest, sunniest, and driest conditions, and is analogous to the traditional cT designation. Most commonly, it is present or advected from its source region, the deserts of the southwestern USA and northwestern Mexico. It can also be produced by violent downsloping winds, where rapid compression heating can produce similar conditions. The Chinook, common in the US and Canadian Rockies, and the Santa Ana winds of California, are two such examples.

MP air is a large subset of the mP air mass. Weather conditions are cool, cloudy, and humid, often with light precipitation. MP can appear via inland advection of air from the North Pacific or North Atlantic. It can also arise when there is frontal overrunning well to the south, or when a cP air mass acquires moisture while traversing a cool water body (the Great Lakes being the primary example).

MM air is also cloudy, but warmer and more humid than MP air. This can form either as a modified mP air mass, or independently, south of MP air nearer a warm front. During summer, it can also occur under mT influence on days with high cloud cover (hence lowering the temperature).

MT air is analogous to mT; it arrives in North America either via the Gulf of Mexico or tropical Atlantic or Pacific Ocean. It is found in the warm sector of a mid-latitude cyclone, and on the western side of a surface anticyclone. This air is warm and very humid, cloudy in winter and partly cloudy in summer. Convective precipitation is quite common in this weather type, especially in summer.

These six weather types, along with a *transitional* (TR) situation, which represents a day in which one weather type yields to another, have not been altered during the SSC redevelopment.

2.2. Seed days

The foundation of the SSC rests upon proper identification of the character of each weather type for a particular location. This is accomplished by the selection of *seed days*. A seed day is an actual day in a station's period of record that contains the typical meteorological characteristics of a particular weather type at that location. In order to identify seed days for each location for each season, first these typical characteristics need to be quantified. Ranges of several different meteorological variables (Table I) are specified, and a computer program extracts from a station's period of record all days during a particular time of year that satisfy these criteria. After the seed day selection is complete, weather maps for the selected days are then analysed to confirm that the days chosen do indeed represent the particular weather type for the given location. If the days are deemed to be non-representative, the seed day criteria would be adjusted and the procedure repeated.

Originally, seed day criteria were specified individually for each location. Naturally, much effort was placed in assuring that neighbouring stations had similar criteria for the same weather type, adjusting for local climatic factors. Different sets of seed criteria were selected for winter (December, January, and February) and summer (June, July, and August). Though the character of a typical DP day does not change significantly between

Table I. Example of seed-day selection criteria, SSC2. DP weather-type criteria for Wilmington, DE, during the winter window (15–28 January) are shown

| Parameter | Minimum | Maximum |
|------------------------------------|---------|---------|
| Maximum temperature (°C) | –3 | 3 |
| Minimum temperature (°C) | –13 | –7 |
| 16 h EST dew point (°C) | none | none |
| Mean daily cloud cover (tenths) | 0 | 7 |
| 16 h EST dew point depression (°C) | 8 | none |
| Diurnal dew point change (°C) | none | 7 |

Maximum and minimum temperatures are from among 04, 10, 16, and 22 h EST observations.

December and February, this is not the case between March and May. Thus, analogous seed day criteria designation during autumn and spring is not possible, and the system is limited to 6 months.

The SSC2 contains an entirely new seed-day selection process. The primary change involves a method entitled ‘sliding seed days’. This method involves the identification of seed days in four 2-week ‘windows’ throughout the year, and the creation of an algorithm to produce a *theoretical* seed day for each weather type for each day of the year. The four 2-week periods shift by location, to correspond with the hottest and coldest 2 weeks and the midway points in between. This method assures the gradual change inherent in the climate system, yet does not involve a burdensome amount of weather-type identification. The ‘window’ length of 2 weeks represents a reasonable maximum period during which seed-day criteria would not change considerably during the transitional seasons.

The procedure starts, as before, with the identification of seed-day criteria (Table I). ‘Extreme’ days (e.g. the coldest DP days, most humid MT days) are avoided, as they are unrepresentative of typical conditions. To discriminate among weather types, the SSC2 requires the following parameters:

- temperature at 04, 10, 16, and 22 h EST,
- dew point depression (temperature minus dew point) at 04, 10, 16, and 22 h EST,
- mean cloud cover (average of 04, 10, 16, and 22 h EST),
- mean sea level pressure (average of 04, 10, 16, and 22 h EST),
- diurnal temperature range (of values at 04, 10, 16, and 22 h EST), and
- diurnal dew point range (of values at 04, 10, 16, and 22 h EST).

Figure 2 presents an example of the sliding seed-day calculation, for 16 h EST temperature for the MP weather type in Wilmington, DE. For each of the 12 parameters listed above, the long-term mean in each of the four windows is calculated (step 1). The mean of the seed days is determined (step 2), and its difference from the long-term mean is calculated (step 3). Then, to obtain the sliding seed days, annual curves are created for each weather type for each meteorological variable. The long-term (period of record) mean of a variable for each day of the year is calculated (step 4). A linear function (step 5) is fitted to the differences calculated in step 3. The annual curve and difference curve are then summed, and a tenth-order polynomial is fitted to these data (step 6). The inclusion of flank half-years (which are later discarded) around the ‘central year’ eliminates the possibility of anomalous values near the end of the polynomial’s range. The polynomials produced curves virtually identical to those produced by a Fourier series, yet are considerably easier to use operationally.

This process is repeated for every variable for every weather type. The resultant curves can then be evaluated for any particular day of the year, and produce a ‘typical’ set of characteristics for each weather type on that day.

A different procedure selects TR seed days. For each of the biweekly windows, the mean and standard deviation of three variables are calculated:

| STEP 1 16 h Temperature All Days | | STEP 2 16 h Temperature MP seed days only | | STEP 3 16 h Temperature Anomaly (MP - all) | |
|--|--------|---|--------|--|---------|
| Winter | 2.4°C | Winter | 1.5°C | Winter | -0.9°C |
| Spring | 17.0°C | Spring | 9.3°C | Spring | -7.7°C |
| Summer | 29.0°C | Summer | 18.1°C | Summer | -10.9°C |
| Autumn | 16.9°C | Autumn | 9.2°C | Autumn | -7.7°C |

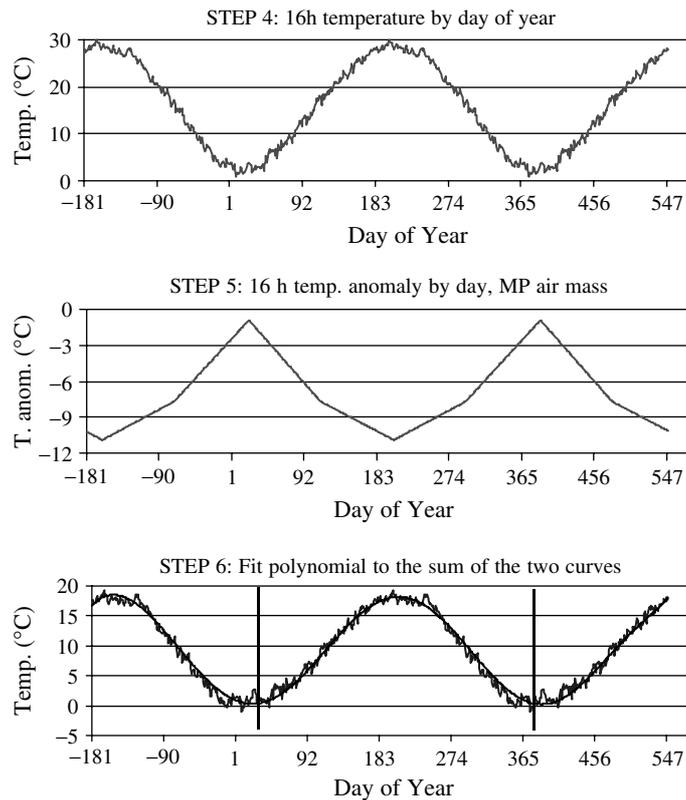


Figure 2. Procedure for the creation of a sliding seed day. Example depicts 16 h EST temperature, MP weather type, Wilmington, DE

- diurnal dew point range (of values at 04, 10, 16, and 22 h EST),
- diurnal sea level pressure range (of values at 04, 10, 16, and 22 h EST), and
- diurnal wind shift (largest difference between any two wind vectors, from among the 04, 10, 16, and 22 h EST observations).

Considerable effort was placed in ensuring that TR frequencies were representative of true transitional situations. As TR frequency with SSC1 was considered adequate, several different parameter thresholds were tested to discern which provided TR frequencies most similar between the SSC1 and SSC2. Following the results of these tests, for a day to become a TR seed day, all three parameters need be at least 1.3 standard deviations above the period mean.

With the SSC1, as mentioned above, seed days were selected individually for each station. Criteria were assured to be similar at neighbouring stations for each weather type; however, no attempt was made to try to obtain the *same* days for seed days. For the SSC2, a seed-day transfer is added to the procedure in order to make a better assessment of local climatological differences. By using the same day when the same weather type was present over two stations, the SSC2 can naturally account for the local meteorological differences between two locations.

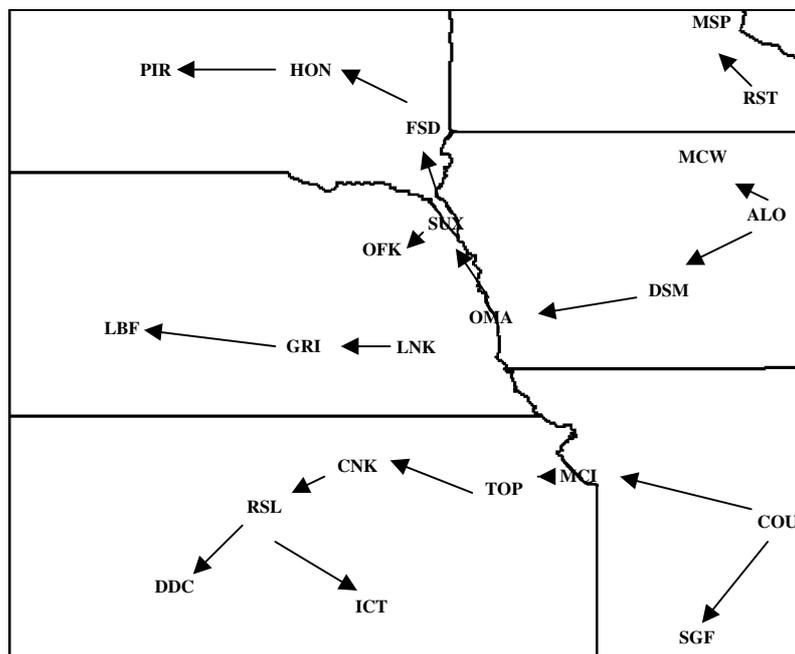


Figure 3. Example of 'roadmap' of station-to-station transfer for SSC2

The first station selected for SSC2 categorization was Wilmington, DE, the station nearest the University of Delaware, where the system was developed. The criteria for Wilmington were derived from the SSC1 and modified to account for the difference in coverage of each period. Once Wilmington's seed days were considered correct, the procedure then skipped from station to station, as in Figure 3. To test the robustness of the system, two other stations were also tested as starting points (Saint Louis, MO, and Columbus, OH). As long as all six air masses are identifiable year-round at a particular station, changing the starting point yielded negligible differences in weather-type classification (less than 3% difference in all but the most infrequently occurring weather types).

2.3. Evaluation

Once seed days are selected, the next step is the daily output of weather type for every station evaluated. The SSC1 utilized discriminant function analysis for delineation purposes (see Kalkstein *et al.* (1996) for a detailed description). Discriminant analysis is designed to measure the separation among multiple groups of objects (here, weather types) with respect to multiple variables simultaneously. The objective is to assign new objects to the predetermined groups using particular classification rules. The rules are the discriminant functions. Unfortunately, discriminant analysis did not lend itself to use with the sliding seed days, where one theoretical seed day was created for each station, not a pool of days.

Several different new evaluation methods have been considered. Of these, the most feasible involve the summing of squared z -scores, and several possibilities have been tested. The first method is the simplest, an equally weighted sum of squared z -scores. For each of the six weather-type categories, the mean values for each of the variables are evaluated from the polynomials for the particular day of the year. They are then compared with the actual day's data by the following:

$$h_k = \sum_{i=1}^{12} \left(\frac{x_i - \mu_{ki}}{\sigma_i} \right)^2 \quad (1)$$

where i represents one of the 12 variables listed above, x_i represents the value of variable i on the day being evaluated, μ_{ki} the derived mean value of variable i for weather type k from the sliding seed days, and σ_i the standard deviation of variable i for day k (also calculated via a polynomial). The h_k score represents the 'error score', the amount of discrepancy between the typical weather type characteristics and the particular day. Each day receives the designation of the weather type that accrues the lowest h_k score on that day.

All of the other methods tested involve non-rotated principal components analysis (PCA; Yarnal, 1993). For this purpose, PCA would input the 12 variables for the entire period of record, and 'reduce' these variables to eigenvectors and eigenvalues to represent the data. A selected number of eigenvalues are retained, and each day is then assessed by the formula:

$$h_k = \sum_{i=1}^n w_i \left(\frac{x_i - \mu_{ki}}{\sigma_i} \right)^2 \quad (2)$$

where n represents the number of components retained, w_i the weight of eigenvalue i , and x_i , μ_{ki} and σ_i are similar to Equation (1) except they are for the transformed variables. This method has been tested with both three and six eigenvectors retained, and with the weights equal to the eigenvalue and the square root of the eigenvalue.

A typical example of the results from these tests is shown in Table II. Among all methods, similar results are noted, as the tendency for collinearity within the temperature values balances out the importance of temperature as a discriminator, leaving weights close to parity. However, in all cases tested, the weather-type calendar produced by the equally weighted sum of squared z -scores shows the highest match percentage with the calendar produced by the SSC1, and the highest match percentage between adjacent stations' SSC2 calendars. Given that using non-transformed variables yields much more useful and understandable error statistics and troubleshooting criteria, the use of PCA is discounted, and the equal weighting method has been adopted for use in the SSC2.

The decision on whether a day is transitional is done after this original evaluation. The method used is similar to the primary evaluation, except that only three variables are evaluated: range of dew point, sea level pressure, and wind shift. These are the same values used to select transitional seed days, and are the meteorological parameters that generally attain high values during transitional situations. If the transitional error score is lower, the day becomes transitional; if the score is higher, the day retains its original designation.

2.4. Running the SSC

Putting the above methodology into practice involves several steps. The initial step involves running (producing the calendar of weather types day-by-day) the SSC for Wilmington, DE. Once this has been satisfactorily completed, the following process then iterates for each new station (see Figure 3 for example).

Figure 4 highlights the first stage of the procedure. The example provided is for the creation of the Baltimore, MD, calendar, transferred from Wilmington. Although the example only discusses the maximum temperature

Table II. Percentage of matches between the SSC1 and SSC2 for Wilmington, DE. Results are based on the different methodologies used for evaluation in the SSC2

| Method | June | July | August |
|---|------|------|--------|
| Equal weighting | 66 | 68 | 70 |
| PCA, three components, eigenvalue weight | 58 | 53 | 56 |
| PCA, six components, eigenvalue weight | 58 | 53 | 56 |
| PCA, three components, square of eigenvalue | 62 | 60 | 62 |
| PCA, six components, square of eigenvalue | 62 | 60 | 62 |

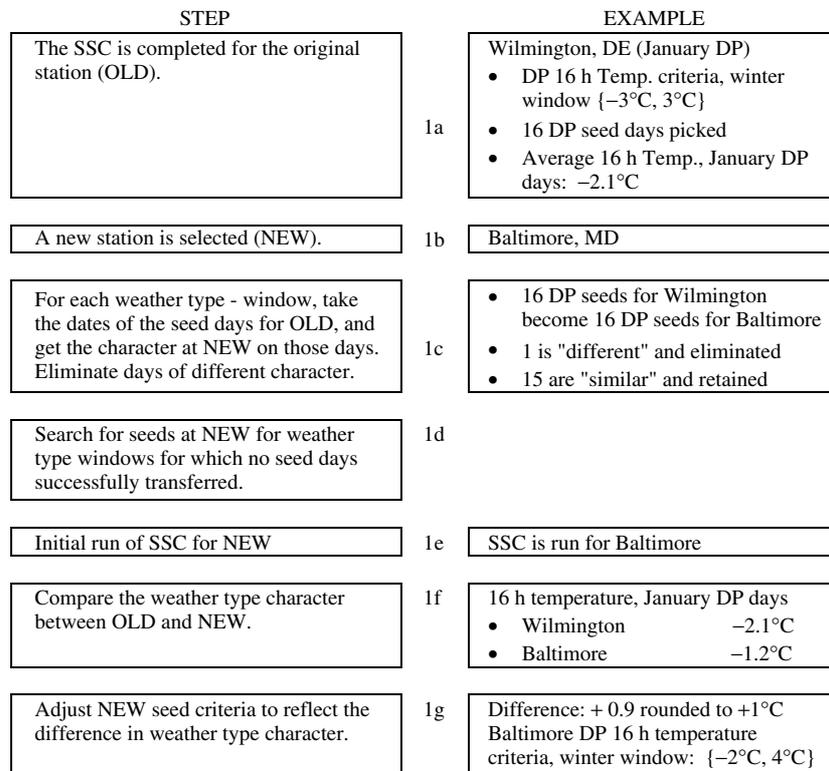


Figure 4. Schematic of the first stage in running the SSC, with an example

in January for DP seed days, it should be remembered that other variables for all four windows for each of the six weather types undergo transfer and modification simultaneously.

Once the original station is completed (step 1a), the next step involves the selection of the adjacent station (step 1b). The station closest to an already-completed station, considering both geographic location and similar climate, is selected; for example, Baltimore is only 90 km away from Wilmington, in a fairly homogeneous climate zone (step 1c). The same days that are seed days at the old station become seed days at the new station. Since there are occasions when the weather types at adjacent stations are dissimilar, a program eliminates days where the temperatures or dew points are more than 4°C and 3°C apart respectively; these values are deemed appropriate limits past which the synoptic situation (and hence weather type) are different. For most transfers, fewer than 20% of days are eliminated.

On occasion, for a particular weather type in a particular window, no seed days successfully transfer (step 1d). This is generally limited to rarely occurring weather types, especially DT, where local moisture and thermal conditions vary widely. To run the SSC properly, all weather types for all windows must have at least one seed day. To get at least one seed day, initially a search is done on the new station's period of record using the old station's criteria. If no seeds are found within the 2-week window, a 6-week window, centred on the 2-week window, is examined. If there are still no seed days, then either the criteria are modified according to climatological differences between the stations, or an *artificial seed day* is created (see below for details).

For the example in Figure 4, there are 16 DP seed days in the Wilmington record for the winter window. Of these 16, one day has markedly different character in Baltimore and is eliminated; the other 15 are retained.

Once all weather-type windows have at least one seed day, the SSC is initially run for the second station (step 1e). For each weather type, the differences between the two stations in all of the parameters listed in Table I are assessed (step 1f). Modifications are then made to the seed-day selection criteria of the new station (step 1g). In this example, Baltimore's mean maximum temperature of January seed days is 0.9°C higher.

As criteria are rounded to the nearest whole degree, Baltimore's maximum temperature criteria are modified up 1 °C, from {−3 °C, 3 °C} to {−2 °C, 4 °C}. It should be noted that seed-day criteria are at no time allowed to overlap, that is, they are not modified so that one day may be selected as a seed day for more than one weather type.

In the second stage (Figure 5), the new, modified criteria are then used to select additional seed days (step 2a) from the new station's entire period of record. These seed days are added to those retained above, with duplicate days eliminated. As there is only addition of seed days and no elimination, all weather-type windows have at least one seed day. The SSC is run for a second time (step 2b), and the difference in weather-type character between the new station's first and second runs is assessed (step 2c). Modifications, usually smaller in magnitude and number, are made again to the seed-day criteria (step 2d).

In this example, Baltimore's new seed-day criteria result in the selection of 18 seed days; of these, 11 are part of the original 15, and seven are new. The seven are added to the original 15 for a total of 22 DP seed days in the winter window. The SSC is run again for Baltimore, with this larger pool of seed days. Once completed, the difference in January DP maximum temperature between the first and second runs is only +0.2 °C, resulting in no change to the winter window criteria for DP maximum temperature.

The third stage of the SSC begins with another round of seed-day selection (step 3a, Figure 6). As few modifications are made after the second stage, in general very few seed days are added here. The new seeds that are selected are merged with those used in the second run. A new program then sorts through all of the seed days, and eliminates those that do not meet the final seed-day criteria (step 3b). Most of the seed days that are eliminated in this segment are those copied from the original station; on average, 20% of seed days are eliminated at this time. Any weather-type windows for which there are fewer than five seed days are reported. In order to increase the robustness of the system, an attempt is made to increase the number of seed days within these groups. A search for new seed days (step 3c) is then broadened temporally: the window is expanded symmetrically from 2 weeks until either five seed days are found, or the window reaches 6 weeks. In the event all seed days for a particular weather-type window are eliminated in step 3b, the seed criteria are either relaxed or an artificial seed day is created.

For the Baltimore example, no new different seed days are found, and three seed days (all dates copied from Wilmington) are not found to meet all of Baltimore's final DP criteria. These three are eliminated, leaving 19 final DP seed days for the winter window.

The SSC is run once again (step 3d), and results are compared with the old station and possibly other neighbouring stations (step 3e). Overall, modification within this scheme produces results markedly similar to the SSC1's prescription of seed-day criteria, testament to the robustness of both methods.

| STEP | EXAMPLE |
|--|--|
| Use modified seed criteria for NEW to pick new seed days from NEW's period of record. Add to seeds retained in 1c, eliminating duplicates. | Baltimore - January DP <ul style="list-style-type: none"> • 18 seed days picked • 7 are different from the above 15 • 7 + 15 = 22 total seed days |
| SSC is run a second time for NEW. | SSC is run again for Baltimore. |
| Compare the weather type character between first and second runs at NEW. | 16 h temperature, January DP days <ul style="list-style-type: none"> • First run −1.2°C • Second run −1.0°C |
| Adjust NEW seed criteria to reflect the difference in weather type character. | Difference: +0.2°C rounded to +0°C Baltimore DP 16 h temperature criteria, winter window unchanged |

Figure 5. Same as Figure 4, except for the second stage

| STEP | | EXAMPLE |
|--|----|---|
| Use remodified seed criteria for NEW to pick more new seed days. Add to seeds from 2a, eliminating duplicates. | 3a | Baltimore - January DP <ul style="list-style-type: none"> • 18 seed days picked • 0 are different from the above 22 • $22 + 0 = 22$ total seed days |
| Use remodified seed criteria for NEW to eliminate seed days that do not meet criteria. | 3b | Baltimore - January DP <ul style="list-style-type: none"> • 3 seed days do not meet criteria • $22 - 3 = 19$ final total seed days |
| Expand search for seed days from two to up to six weeks for weather type - windows with fewer than five seed days. If necessary, create artificial seed day. | 3c | |
| SSC is run a third time for NEW. | 3d | SSC is run again for Baltimore. |
| Subjective analysis performed on final output: modification of criteria if necessary. Rerun SSC if necessary. | 3e | |

Figure 6. Same as Figure 4, except for the third stage

2.5. Artificial seed days

With the SSC1, if a weather type is present at a given location during winter but not summer, or *vice versa*, one could accommodate the situation by not defining seed days for one of the seasons. However, with the SSC2, the continuous function that describes the sliding seed day does not allow for an absence of a weather type at a particular time of year. To remedy this problem, artificial seed days are created for locations where weather types never penetrate during at least part of the year.

The premise of an artificial seed day is geographic in nature. Where there is a limit of penetration of a particular weather type (and hence, a lack of adequate seed days), the assumption is made that if the weather type were to continue to penetrate in that direction, its conditions would be unmodified. Hence, the artificial seed day is defined to be the same as the mean conditions for the closest station for which the weather type is identified. The artificial seed day is then automatically transferred to all new stations; if later a true seed day is discovered, the artificial seed day is deleted. On occasion, days within the actual record are classified into a particular weather type for which only an artificial seed day exists; in all cases, however, mean frequency of occurrence is below 0.2%.

Only one-sixth of the stations have no artificial seed days; most of these stations are located in a belt from Missouri to New York. The tropical weather types, DT and MT, have by far the greatest dependence upon artificial seed days, with averages of 33% and 38% of station-windows respectively. Virtually all Canadian and Alaskan stations have artificial seed days for at least three seasons; much of the interior Rocky Mountain stations have artificial MT seed days for all four seasons, implying the MT weather type never occurs. The other weather types average below 10%; MP and DP in the summertime claim significant numbers of artificial seed days, almost entirely stations in the southern half of the USA.

3. DATA

To obtain all of the parameters needed for the SSC2, the following variables are required: temperature, dew point, u - (east–west) and v - (north–south) components of the wind, cloud cover, and sea-level pressure. Each of these parameters is needed four times daily, at the following standard times:

- for stations in the Newfoundland time zone: 05:30, 11:30, 17:30, and 23:30 h;
- for stations in the Atlantic and Aleutian time zones: 05, 11, 17, and 23 h;
- for stations in the Eastern time zone: 04, 10, 16, and 22 h;
- for stations in the Central time zone: 03, 09, 15, and 21 h;
- for stations in the Mountain time zone: 02, 08, 14, and 20 h;
- for stations in the Pacific time zone: 01, 07, 13, and 19 h;
- for stations in the Alaska/Hawaii time zone: 00, 06, 12, and 18 h.

All of the meteorological data used in this study have been provided by the United States National Climatic Data Center. Most Canadian stations are available for the period of 1953 to 1993 inclusive. Most US stations have data records running between 1948 and 2000; some begin as early as 1940, and many have missing data segments. Stations are included in this system if there are greater than 30 years of available data, or greater than 20 years if they are located in an area of sparse station density.

Only two modifications to the data are made. For US stations, the Automated Surface Observing System (ASOS), installed at all public airports between 1993 and 1995, eliminated the total sky cover observation used as cloud cover. In its place, it reports cloudiness at different levels: the assumption is made that cloud cover is equal to the cloudiest level. No testing has yet been done to ascertain the impacts of changes in wind speed, dew point, and temperature widely reported following the switch to ASOS (e.g. Guttman and Baker, 1996). For Canadian stations, on very cold, dry days the observation of dew point is listed as 'missing'. In many Northwest Territory and Nunavut stations, up to 30% of winter days feature at least one 'missing' observation. To reduce the number of missing days, whenever a station has all available observations except the dew point, and the temperature is below -30°C , the dew point is set to -50°C or the actual air temperature, whichever is lower. The value of -50°C represents the lowest reported dew points in the period of record, and therefore the maximum possible actual value for the missing observation.

4. RESULTS

Mean SSC2 weather-type frequency and character variability among the stations is a useful tool in understanding North American climate. Table III depicts the modification of air masses across the Great Plains of North America; clearly noticeable is the extreme modification of DP in winter, representing the cP air mass advecting southward from the Canadian Arctic. This modification may also be displayed spatially (Figure 7). In addition to the mean weather-type conditions, spatial patterns of mean frequency of occurrence have also been analysed. The Sierra Nevada Mountains are clearly visible as a DP barrier to the Pacific Coast in Figure 8.

Table III. Mean difference in 15 h CST temperature ($^{\circ}\text{C}$) by weather type, between Dallas-Fort Worth, TX, and The Pas, Manitoba

| Air mass | Temperature difference ($^{\circ}\text{C}$) | | | |
|----------|---|-------|------|---------|
| | January | April | July | October |
| DP | 26 | 16 | 8 | 16 |
| DM | 16 | 12 | 9 | 13 |
| DT | N/A | 8 | 7 | 10 |
| MP | 15 | 12 | N/A | 10 |
| MM | 15 | 13 | 7 | 13 |
| MT | N/A | 12 | 8 | 10 |

N/A signifies a weather type is not present at one station.

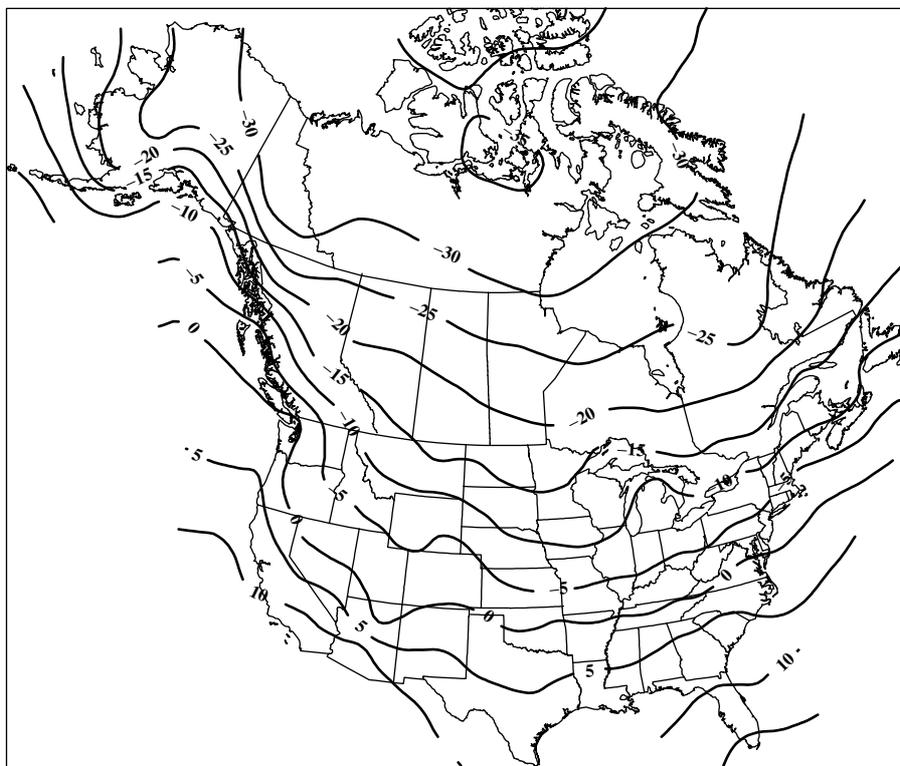


Figure 7. Mean 16 h EST temperature ($^{\circ}\text{C}$), DP air mass, January, for the period 1961–90

One useful measure of the SSC's spatial cohesiveness is the 'match percentage', or the frequency of two adjacent stations receiving the same weather-type classification for the same day. The typical seasonal pattern is depicted in Table IV, which also shows the improvement in match percentage from the SSC1 to SSC2. Owing to the greater differences in weather-type character during the winter, all regions of North America show a better spatial cohesiveness during this season. The mean annual match percentage among adjacent stations is shown in Figure 9; as expected, percentages are generally higher in the more climatologically homogeneous regions, as well as in regions with a greater station density. Among many eastern and central stations, match percentages exceed 70%; in mountainous areas and near the ocean, in some cases no other stations match a particular location on more than half of the days. On mapping a particular day's weather types, similar results are often observed (Figure 10). The transitional situation ('7' in Figure 10) is consistently one of the most cohesively identified weather types.

5. APPLICATIONS

The SSC2 has already been used in several climatological applications. A manuscript focusing upon weather-type variability among teleconnection phases is forthcoming. A more critical use of the SSC2 has been the identification of excessive heat-stress conditions. Synoptic methodologies can identify threshold climatological conditions beyond which organisms will not function efficiently (Kalkstein *et al.*, 1995); the SSC2 in particular (Llanso *et al.*, 2000) has been incorporated into systems developed for: Dayton/Cincinnati, OH; New Orleans, LA; Phoenix, AZ; Rome, Italy; Shanghai, China; and Toronto, Ontario; several more systems are under development.

The synoptic methodology is a more appropriate method of evaluation than the traditional dependence upon 'apparent temperature' (a combination of temperature and humidity) because of its holistic nature. Humans

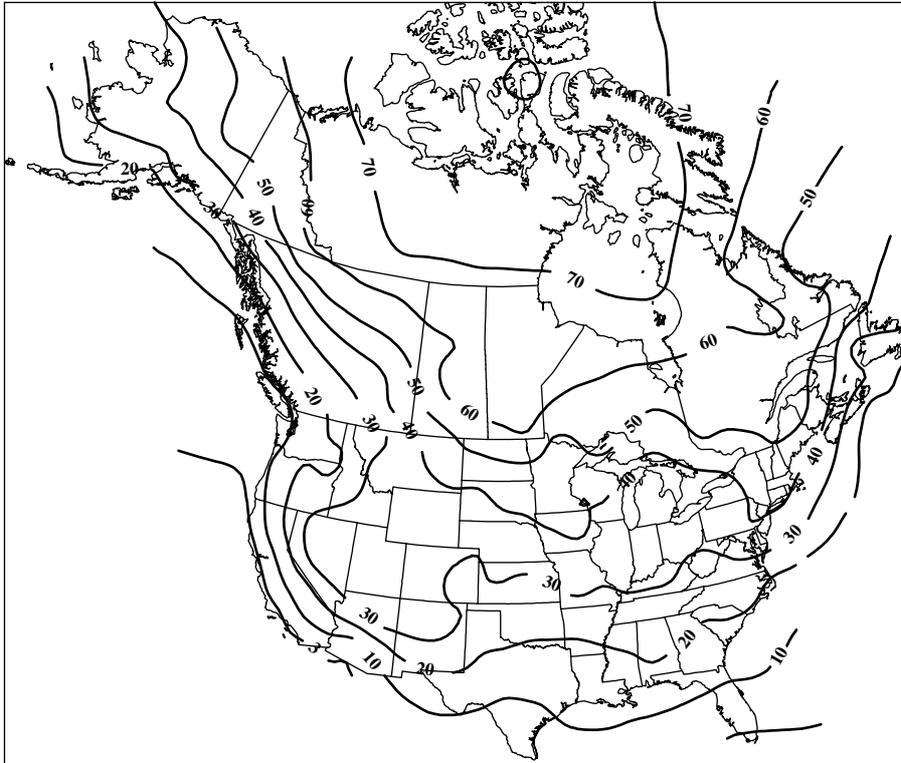


Figure 8. Mean frequency of occurrence (percent), DP air mass, January for the period 1961–90

Table IV. Match frequencies between Baltimore, MD, and Wilmington, DE, for the SSC1 and SSC2

| Month | Match frequency (%) | |
|-----------|---------------------|------|
| | SSC1 | SSC2 |
| January | 72 | 77 |
| February | 75 | 81 |
| March | N/A | 78 |
| April | N/A | 76 |
| May | N/A | 73 |
| June | 62 | 71 |
| July | 63 | 71 |
| August | 65 | 71 |
| September | N/A | 79 |
| October | N/A | 76 |
| November | N/A | 75 |
| December | 72 | 78 |
| Annual | 68 | 76 |

N/A signifies the SSC1 is not available for this month.

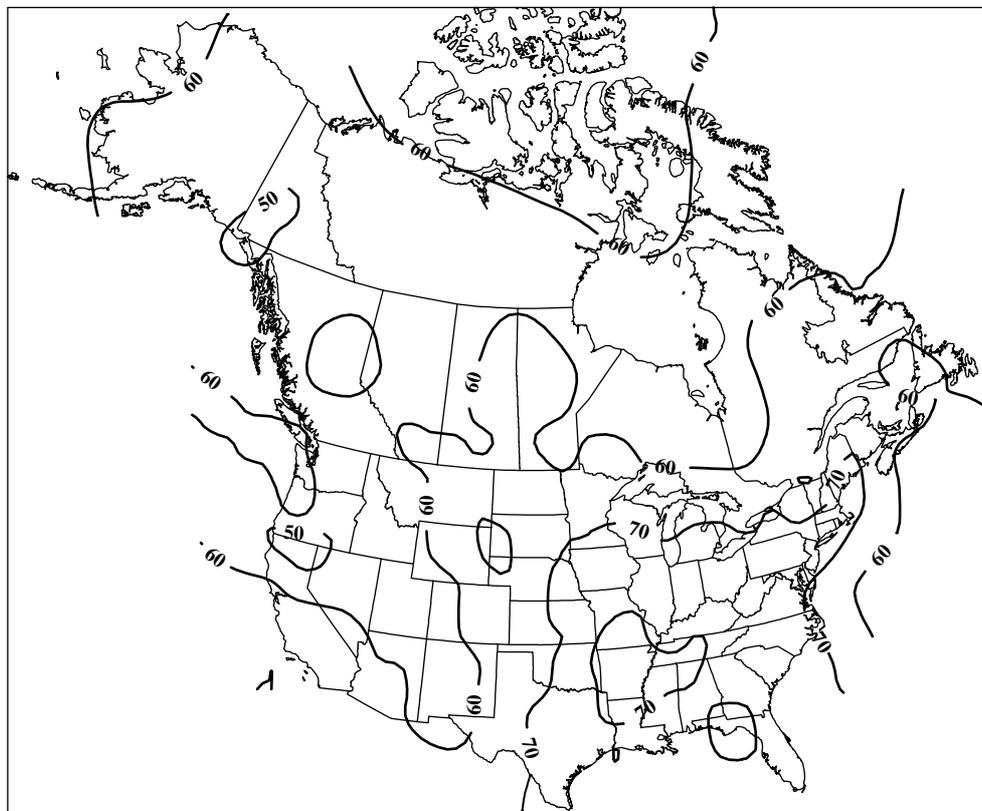


Figure 9. Isopleths of percentage match frequency between each station and its nearest adjacent station

respond to the entire suite of weather conditions acting in concert simultaneously, not to elements individually (Sheridan and Kalkstein, 1998). In addition, the relative aspect of the synoptic approach, where each location has an individualized set of weather types, allows for the determination of local response to stressful weather. Thus, localized thresholds are developed, beyond which human health stresses can be assessed.

For all of the cities for which synoptic-based heat-health systems have been developed, at least one weather type has been associated with increased mortality levels; interestingly, this varies from city to city (Table V). In Rome (Figure 11), two weather types, DT and MT+¹ are clearly associated with excess deaths. In Shanghai, only one weather type, MT+, has this association; however, on average, the MT+ weather type is associated with 42 extra deaths above the long-term mean.

The usefulness of the synoptic approach appears when additional meteorological parameters are correlated with mortality. For most cities for which the hot and dry DT weather type is oppressive, overnight temperature is positively correlated with mortality. This correlation suggests that, with high levels of insolation, the cooling of residences at night is important in determining negative health impacts. In contrast, with MT+ the best-correlated variable is generally afternoon temperature. In this case, whether convective clouds develop, lowering late afternoon temperature, may be the critical factor.

A National Weather Service (NWS) study (Shannon White, personal communication) has evaluated the synoptic methodology with the SSC2 against the traditional excessive heat determinant, the 41 °C (105 °F) apparent temperature threshold used presently by most NWS offices. A critical success index (Donaldson *et al.*, 1975), measuring probability of successfully calling a heat warning on days where excessive deaths occurred, minus the false alarm percentage, shows the SSC-based index outperforming the traditional method, 58% to 24%.

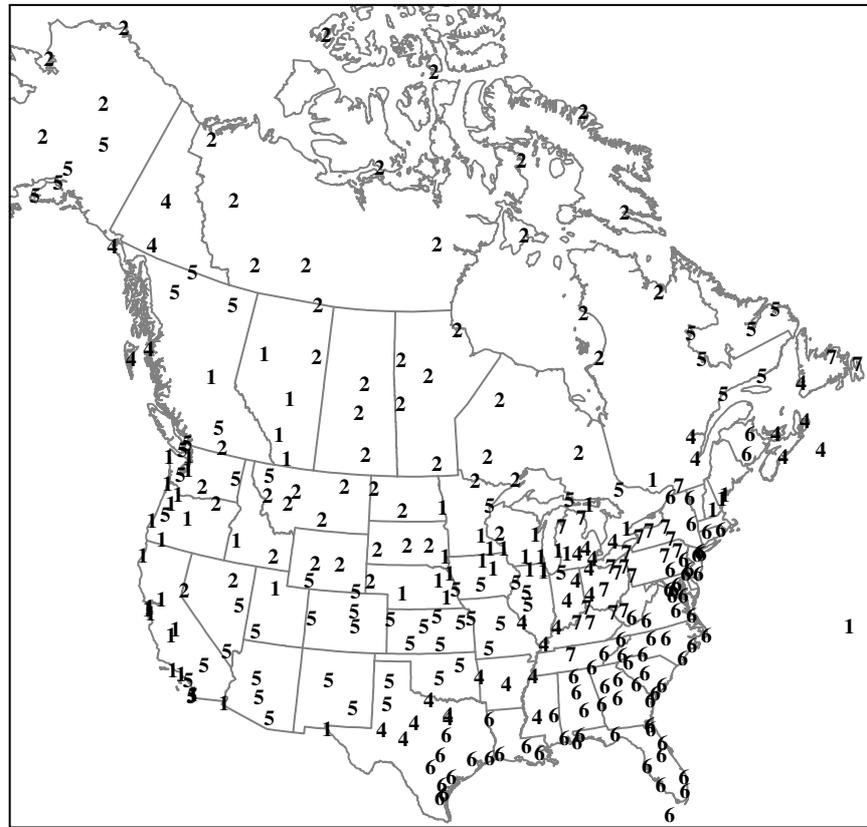


Figure 10. Weather types on 18 January 1990. 1: DM; 2: DP; 4: MM; 5: MP; 6: MT; 7: TR

6. CONCLUSIONS

The SSC2 is clearly a versatile and powerful tool for environmental analysis. Over five million station-days across North America have been classified and are available for any applied climatological use. These calendars are available on the Internet at <http://dept.kent.edu/geography/sheridan/ssc.html>. A real-time preliminary evaluation of yesterday's weather types for the USA can be found at <http://sheridan.geog.kent.edu/sscnw.html>.

This hybrid SSC combines the automated methodology of seed-day transfer and evaluation with the manual original identification of weather types and their typical meteorological conditions. The principal benefit of the SSC2, in relation to the SSC1, is the availability of a year-round calendar that more appropriately deals with the change of season. The restriction of the SSC1 to 6 months of the year prohibits its use for many applications, and reduces the usefulness of the SSC1 in describing a region's climatology.

As mentioned above, with the SSC2 the match percentage among neighbouring stations has increased (Table IV). An increased match percentage inherently implies better spatial cohesion, and therefore a more reliable classification system, since an underlying assumption is that the weather types are usually synoptic-scale features, even if the classification scheme limits itself to local meteorological conditions. Despite the simpler evaluation techniques, the match percentage between Baltimore, MD and Wilmington, DE increases from 68 to 76% with the SSC2, a one-quarter reduction in mismatches. This magnitude of improvement is fairly consistent throughout the year. Although a 5 to 10% increase is typical for the system across the continent, it must be noted that in this example, on 24% of the days, the two stations still do not agree. Some of this can be ascribed to a true difference in weather-type presence; there *are* days on which the two cities do not have the same weather type. Also, transitional situations

Table V. Oppressive weather types by location. Weather-type frequency is mean for period 15 May–30 September; excess mortality is mean total deaths per day greater than normal; meteorological conditions are mean weather-type conditions during July

| Weather Type | Frequency (%) | Excess mortality | Temperature (°C) | | Dew point PM (°C) | Cloud cover PM (tenths) |
|-------------------------------|---------------|------------------|------------------|----|-------------------|-------------------------|
| | | | AM | PM | | |
| Dayton/Cincinnati, USA | | | | | | |
| DT | 1.9 | +4.4 | 19 | 33 | 14 | 2 |
| MT+ | 6.5 | +1.8 | 22 | 32 | 22 | 5 |
| New Orleans, USA | | | | | | |
| MT+ | 2.4 | +3.6 | 27 | 35 | 25 | 3 |
| Phoenix, USA | | | | | | |
| DT+ | 1.3 | +2.7 | 29 | 45 | 6 | 0 |
| Rome, Italy | | | | | | |
| DT | 6.8 | +6.2 | 21 | 33 | 15 | 1 |
| MT+ | 3.9 | +5.0 | 22 | 31 | 20 | 4 |
| Shanghai, China | | | | | | |
| MT | 11.0 | +42.4 | 29 | 34 | 26 | 6 |
| Toronto, Canada | | | | | | |
| DT | 3.4 | +4.2 | 20 | 33 | 16 | 3 |
| MT+ | 3.9 | +4.0 | 22 | 30 | 21 | 5 |

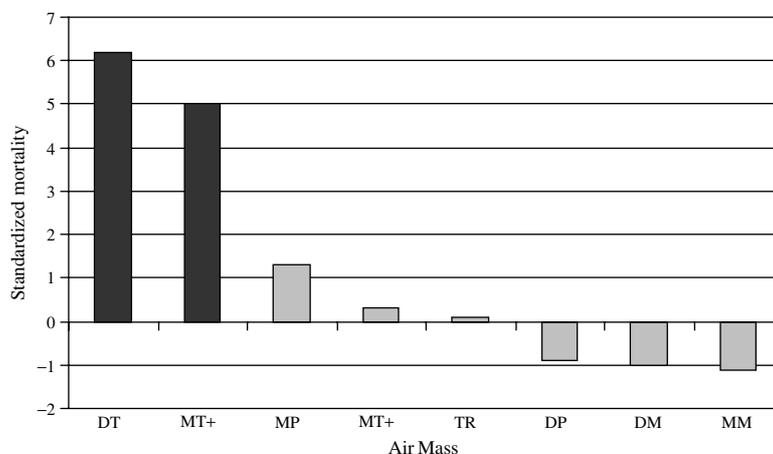


Figure 11. Mean standardized mortality by weather type, for Rome, Italy. Period includes summers (15 May–30 September) from 1987–98

may be so timed as to include one station but not the other. Although difficult to quantify, it is likely that these situations account for, at most, half of the mismatches. This problem is inherent to any classification system, and reducing the mismatch percentage further is one of the principal future goals for the SSC2.

Other future work includes an expansion of the system spatially wherever data availability is sufficient. The system has already been applied to locations in China, Portugal, Italy, and Germany, with no changes to the weather-type definitions yet necessary. At locations where one weather type dominates, more definite subdivision procedures (similar to those that defined MT+ above) will be evaluated. It is also acknowledged that many mismatches are 'borderline' days, where error points for two or more weather types are close in value. Future SSC calendars shall incorporate this, by noting which days are borderline, and which are more 'pure'.

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NOTE

1. Several of the cities for which synoptic-based heat-stress warning systems have been developed have one weather type present on a majority of all summer days (e.g. Shanghai, MT, 67%). In order to clarify the classification, these common air masses have been subdivided, with the hottest and most humid subset receiving the suffix '+'. Conclusive methods for this subdivision are still being developed; presently the '+' designation is given to those days for which the afternoon and morning apparent temperatures both exceed the value calculated from the sliding seed days.

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