A Study of the Severity of Indiana's 1977 and 1978 Winters Using Heating Degree Days Determined from Both Measured and Wind Chill Temperatures

Patricia M. Dare and Phillip J. Smith
Department of Geosciences, Purdue University
West Lafayette, Indiana 47907

Introduction

The past two winters have been distinctive in the severity of the weather experienced over the central United States. Indiana and its adjoining states were particularly hard hit. The objective of this study is to examine the severity of the winters of 1976-77 and 1977-78 in Indiana. The basic tool for this examination is the heating degree day, chosen because of its utility in portraying the cumulative effect of temperature conditions over a period of time.

While temperature itself (or the heating degree day) is a measure of the severity of a winter period, common experience teaches that the effect of temperature is influenced by the ventilating power of the wind. Thus, in order to incorporate this wind influence, a wind chill temperature is also calculated and used to determine a modified heating degree day. By combining the roles of both temperature and wind, a more comprehensive view of the severity of the two winters is achieved.

Included in the study are heating degree day and modified heating degree day conditions at six National Weather Service stations within and bounding Indiana: Indianapolis, Fort Wayne, South Bend, Evansville, Chicago (Midway), and Louisville.

The Winters of 1976-77 and 1977-78

The winter of 1976-77 was marked by severe cold in the central United States. In fact, the nation's greatest temperature anomaly occurred in the lower Great Lakes region, with Illinois, Indiana, and Ohio averaging 8° F or more below normal (11). Further, data published in (6) show that of the six stations used in this study, Evansville, Fort Wayne, Indianapolis, and Louisville listed January 1977 as the coldest January on record. January 1977 was also the coldest month on record at Evansville, Indianapolis, and Louisville. The atmospheric circulation pattern responsible for these conditions formed early in the fall and continued with little change until late February (11). Low pressure centers in the north Pacific Ocean and in eastern Canada were located south of their normal winter positions. Together with a strong ridge on the west coast, they brought extreme cold to the midwest and east coast (8). The strong ridge also resulted in the majority of the Pacific storms moving north into Alaska, leaving most of the United States with below normal precipitation. Indiana's precipitation was two to six inches below normal (12).

The winter of 1977-78 displayed an even greater departure from temperature normals in the Great Plains and Midwest (12). However, even though much of Indiana was about 9° F below normal for the winter, no new temperature records were set. Instead, new snowfall records were established. In January, South Bend, Chicago, and Louisville observed the greatest total monthly snowfall on record, while Evansville, South Bend, and Louisville recorded the greatest snowfall in 24 hours (6). The circulation pattern did not remain as constant as it did the previous winter. A deep trough, which had remained nearly stationary off the east coast in 1966-77, was located in various positions over the eastern United States in 1977-78 (12). Also, the southern portion of the west coast ridge was weaker than in 1976-77, which, when coupled with a strong subtropical jet stream, served to bring storms in from the Pacific ocean. After crossing the Rocky Mountains, these storms accumulated moisture from the Gulf of Mexico and then turned north, giving the eastern half of the country above normal amounts of precipitation (12). Indiana's precipitation was near normal, but a greater than normal amount was in the form of snowfall. The greatest snowfall anomaly in the nation was located around Lake Michigan with Indiana snowfall recorded at three to seven feet above normal (12).

The Heating Degree Day and Wind Chill Temperature

The primary tool used in this study was the heating degree (HDD). Simply stated, it is the departure of the daily average temperature ($\overline{T}$) from a reference temperature (T_R) (7), which in mathematical form becomes

$$\mathrm{HDD} = \left\{ \begin{array}{ll} T_R - \overline{T} \bullet & \overline{T} < T_R \\ 0 & \overline{T} > T_R \end{array} \right\} \quad (1)$$

The name of the variable is derived from its use in estimating winter heating fuel comsumption, which is assumed to be zero when $\overline{T}$ equals or exceeds T_R. The heating degree day variable was used in the present study because it can be conveniently added for successive days to yield a quantity representative of the cumulative temperature conditions for a given winter period. The reference temperature used was 65° F, in accordance with National Weather Service practice (6).

The secondary tool used was the wind chill temperature. This is the hypothetical temperature that, when combined with a reference wind speed, produces the same amount of cooling as that produced by the observed temperature and wind speed. This cooling effect of temperature and wind speed was measured by Siple and Passel (9), members of the 1939-41 American Antarctic expedition. While in Antarctica, they performed over eighty experiments in subfreezing temperatures to determine the rate of freezing of a cylinder of water. Cooling rates in kg cal m^{-2} hr^{-1} $°C^{-1}$ were plotted against windspeed (v) in m s^{-1}. The resulting curve, together with an expression of the difference between neutral skin temperature (33° C) and ambient temperature (T) in ° C, was used to derive the empirical formula

$$K_o = (10v^{1/2} + 10.45 - v)\,(33 - T), \quad (2)$$

where K_o is the total dry-shade cooling measured in kg cal m^{-2} hr^{-1}. Applying the verbal definition stated above, an expression for wind chill temperature (T_w) can be derived from eq. (2) as

$$(10v^{1/2} + 10.45 - v)\,(33 - T) = (10v_R^{1/2} + 10.45 - V_R)\,(33 - T_w), \qquad (3)$$

where V_R is the reference wind speed. Solving for T_w yields

$$T_w = \frac{(10v^{1/2} + 10.45 - v)(T - 33)}{(10v_R^{1/2} + 10.45 - v_R)} + 33 \bullet \qquad (4)$$

The reference wind speed is generally considered to be the speed of air movement relative to a person walking on a calm day. This so-called walking wind speed is specified by Falconer (3) and Steadman (10) as 3 mi h^{-1} (approximately 1.3 ms^{-1}). Assuming this speed to be representative at a height of 1.5 m in a neutral stability atmosphere and applying a power law profile for the wind speed with the power set to 1/7 (4), the wind speed at standard anemometer height (10m) would be 3.9 mi h^{-1}. This corresponds to the value of 4 mi h^{-1} used by the National Weather Service (13) in their calculation of T_w.

It should be mentioned that alternate formulas for K_o have been proposed. Court (2) believes different constants in Siple's formula give a better fit to the original data, while Steadman (10) proposes an entirely different formula that includes many additional physiological factors. Since this study is concerned with evaluating the severity of winter periods rather than evaluating their physiological effects, the inclusion of physiological factors other than those common to all of the formulas seemed unnecessary. Further, it is not within the scope of this paper to fully evaluate the various formulas. Since Siple's equation (eq. 4) is the original formulation and appears to be the most widely used (including by the National Weather Service (13)), it was the one chosen for this study.

Data and Computational Procedures

Data used in this study were derived from three NOAA/EDS publications (1, 5, 6). Daily mean temperature and wind speed data for the December through February, 1976-77 and 1977-78 winter periods (hereafter referred to as Winter 1977 and Winter 1978, respectively) were obtained from (6) for each of the six stations included in the study. To provide a basis for comparison against normal conditions, normal daily mean temperature data (1941-1970) were extracted from (1). Finally, normal wind speed data used were monthly mean normals for each station obtained from (5).

These data were used to calculate observed and normal daily and cumulative values of heating degree days (HDD) from eq. (1) and observed and normal daily average wind chill temperatures (T_w) from eq. (4). The latter were then inserted in eq. (1) to produce modified heating degree day (MHDD) values. To insure that the wind chill temperature would never be greater than the ambient temperature, T_w was set equal to T when the mean windspeed was less than 4 mi hr^{-1} (approximately 1.8 m s^{-1}).

Finally, to examine the extent to which the modified heating degree day variable gives a different impression of the severity of the winter than obtained from the regular heating degree day, the following comparative ration was computed:

$$RATIO = (MHDD - HDD)/(MHDD_n - HDD_n), \quad (5)$$

where the subscript n indicates normal values. A ratio value greater (less) than 1 indicates that the inclusion of wind data (through $\overline{T}_w$ and MHDD) suggests a more (less) severe winter than would be concluded without the wind data.

Results

Table 1 presents a summary of cumulative heating degree days, modified heating degree days, their normals, and the comparative ratio for the six stations in this study. In addition a six station average is included as an approximation to the state-wide average. HDD values for winter 1977 are typically 15 to 25% above normal, reflecting the severe cold experienced during this period. MHDD values are similarly well above normal. The comparative ratios, which are in general greater than one, indicate that when the effect of wind is included, the winter appears even more severe than it did on the basis of temperature data alone. In 1978, HDD values are slightly larger than in 1977. However, MHDD values are less than in 1977, reflecting weaker winds during the 1978 period. As a result of these lighter winds, the ratio is consistently less than one, indicating a less severe winter than revealed by temperature data alone. In comparing the two winters, the use of HDD and MHDD values leads to different conclusions regarding which winter was more severe. HDD values favor 1978, while MHDD values favor 1977. In other words, the inclusion of wind data does have some impact on evaluating the relative severity of the two winters.

TABLE 1 *Summary of heating degree days (HDD) and modified heating degree days (MHDD) for winter 1977 and 1978 presented with normals and comparative ratios.*

Station	Cumulative HDD	Cumulative HDD-normal	Cumulative MHDD	Cumulative MHDD-normal	Ratio
		Winter 1977			
Chicago (Midway)	4141	3447	5906	4995	1.14
Evansville	3437	2739	4271	3845	.75
Fort Wayne	4153	3406	5998	4957	1.19
Indianapolis	3967	3167	5364	4559	1.00
Louisville	3197	2712	4396	3827	1.08
South Bend	3993	3495	5696	5115	1.05
Average	3814	3161	5271	4550	1.05
		Winter 1978			
Chicago (Midway)	4105	3447	5604	4995	.97
Evansville	3575	2739	4540	3845	.87
Fort Wayne	4209	3406	5604	4959	.90
Indianapolis	3860	3167	5113	4559	.90
Louisville	3374	2712	4390	3827	.91
South Bend	4043	3495	5457	5115	.87
Average	3861	3161	5118	4550	.90

Distributions of cumulative HDD, MHDD, and their departures from normal are displayed in (Fig. 1), providing an overall view of the spatial relationships of HDD and MHDD for both winters. With the exception of Fort Wayne, both values exhibit a general north to south decrease. At Fort Wayne, more HDD and MHDD were accumulated and correspondingly larger departures from normal were recorded than at any of the other five stations. This indicates that the general latitude dependence of temperature can be interrupted during periods of extreme cold. The interrupting influence in this case could perhaps be the closer proximity of the two more northerly stations to Lake Michigan and/or to large metropolitan areas.

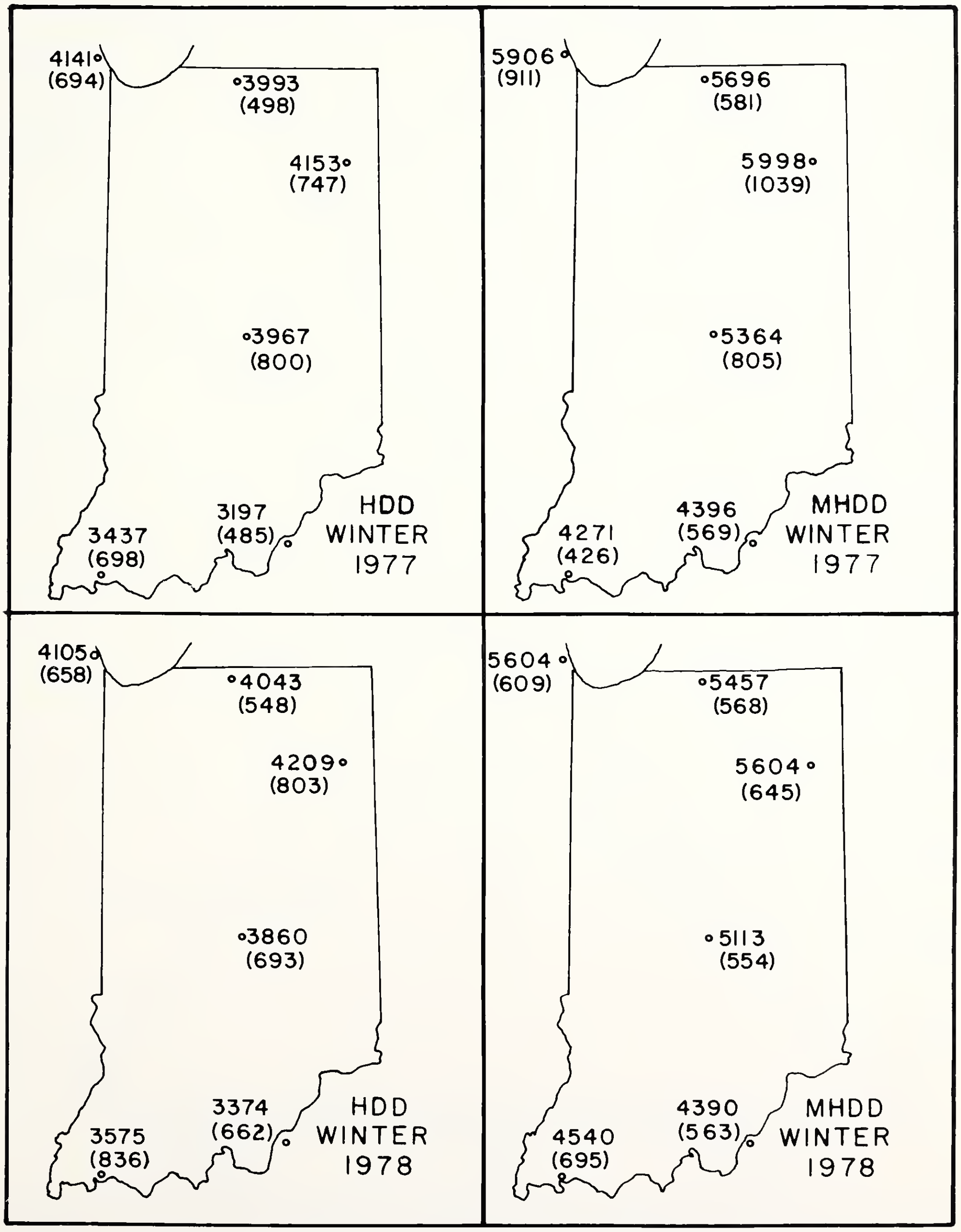

FIGURE 1. *Cumulative heating degree days (HDD), modified heating degree days (MHDD) and departures from normal (in parentheses) for winter 1977 and 1978.*

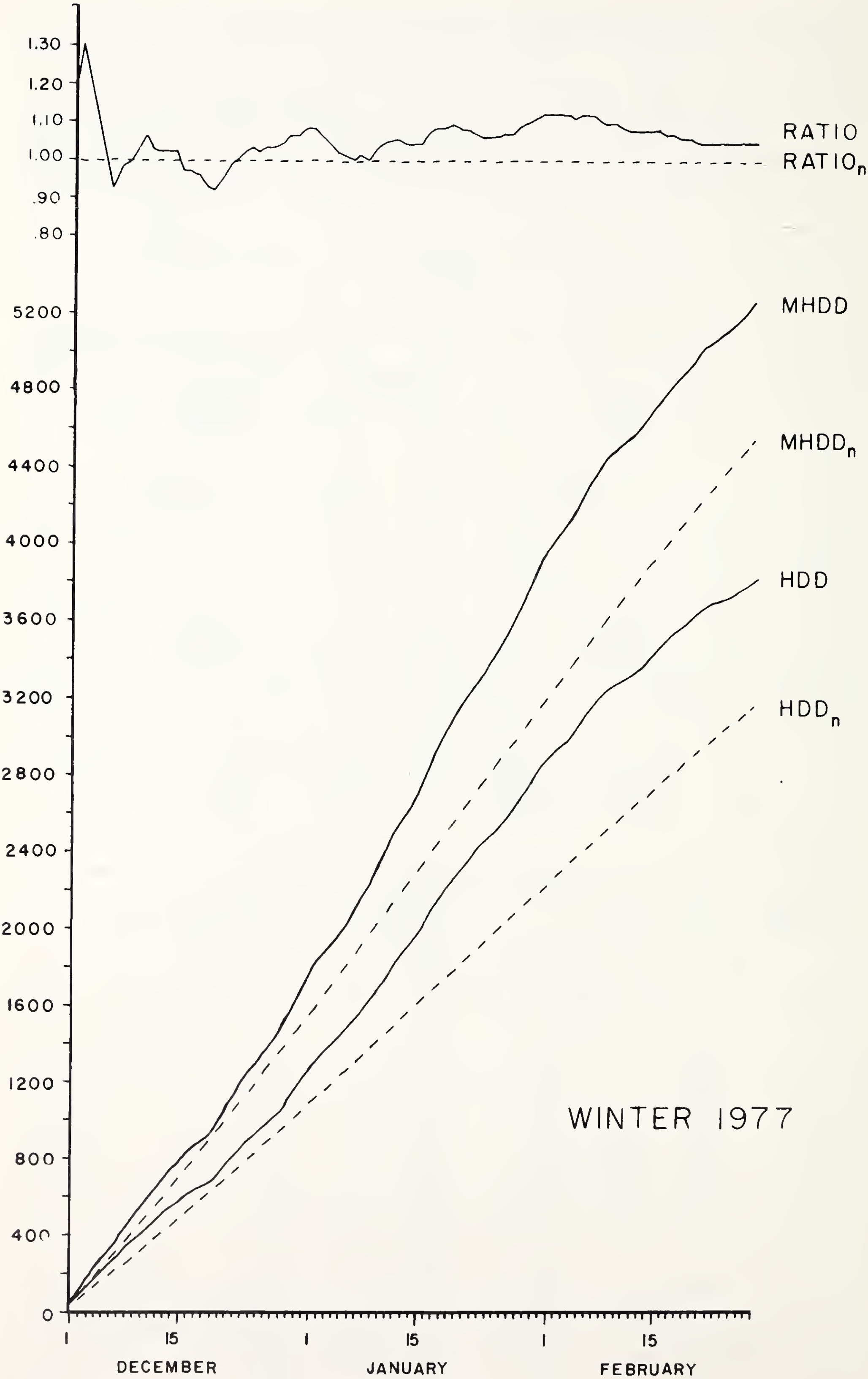

FIGURE 2. *Daily cumulative heating degree days (HDD), modified heating degree days (MHDD), ratios (RATIO) and normals (indicated by subscript n) averaged over all stations for winter 1977.*

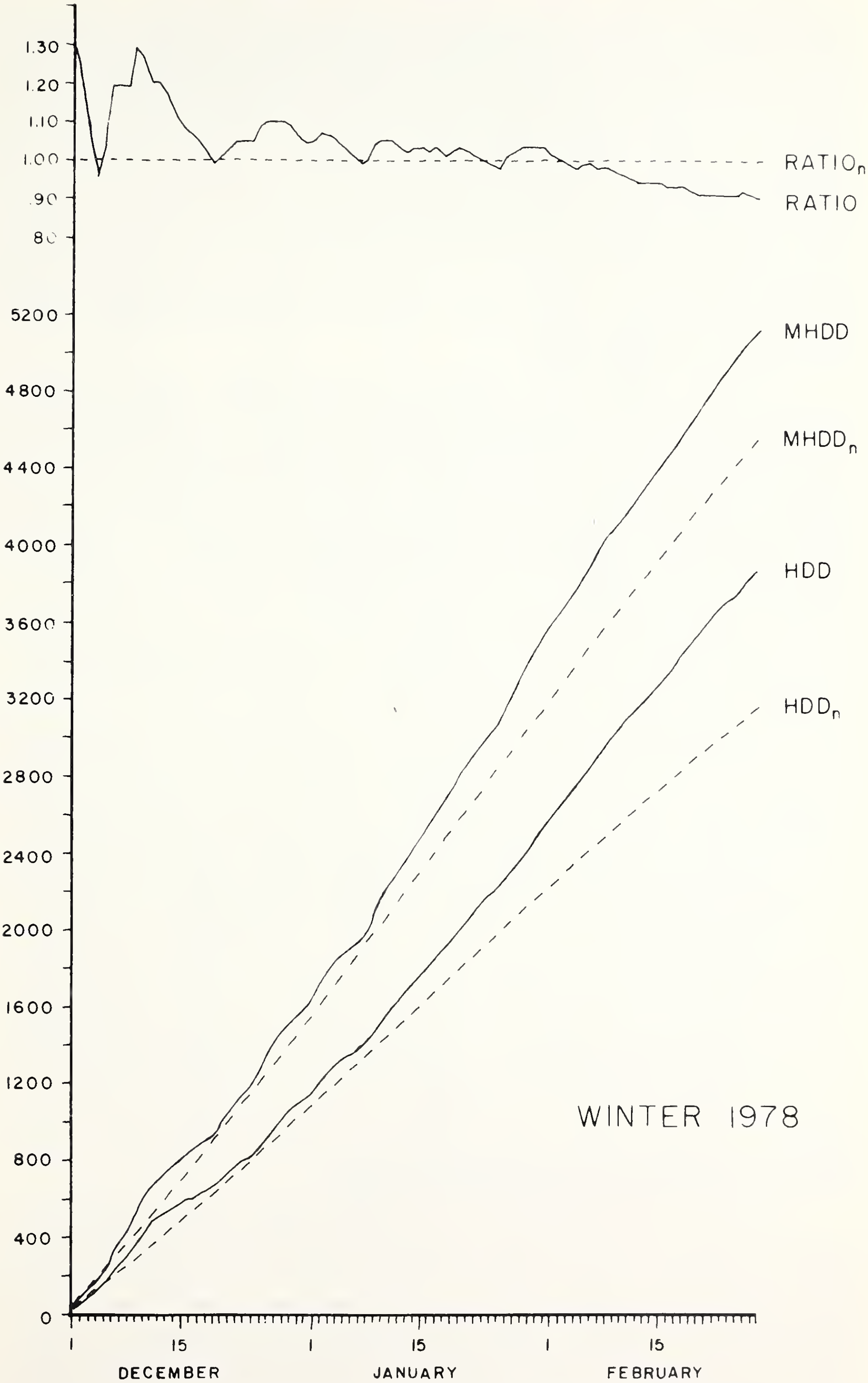

FIGURE 3. *Daily cumulative heating degree days (HDD), modified heating degree days (MHDD), ratios (RATIO) and normals (indicated by subscript n) averaged over all stations for winter 1978.*

(Fig. 2) and (Fig. 3) display daily cumulative HDD, MHDD, ratios and their normals averaged over all stations for winter 1977 and 1978, respectively. In 1977, both curves diverge from their normals as the winter progresses, with the maximum rate of divergence occurring from mid-January to early February, the period during which cold windy conditions were most prevalent. In December, the ratio values oscillate about 1.0, indicating that the wind had no consistent impact on the severity of the early part of the winter. However, from late December throughout the remaining winter period, the ratio is greater than 1.0, in response to the stronger than normal winds and the more rapid departure of MHDD and HDD from their respective normals. Thus, the cumulative effect of the winds throughout most of winter 1977 was to intensify the severity of the abnormally cold temperatures.

A similar examination of (Fig. 3) reveals that winter 1978 evolved in a somewhat different way than winter 1977. Both MHDD and HDD diverge from their normals at very steady rates from the second week in January through the end of February. However, after early January, the MHDD diverge at a slower rate than do the HDD. This is reflected in the ratio values. In the early part of the winter, oscillations in the ratio are present but rarely dip below 1.0, indicating that in contrast to winter 1977, the net effect of the wind was to increase the severity of the early winter. After the first week in January, the ratio gradually decreases, falling below 1.0 at the beginning of February. Thus, weaker than normal winds after early January reduced the potential severity of winter 1978.

Daily fluctuations of state average HDD, MHDD, and ratios for both winters are presented in (Fig. 4). Of the 90 total days in each winter period, between 70 and 75% experienced above normal HDD and MHDD values (colder than normal). It is interesting that both the maxima and minima on the MHDD curves are often amplified relative to the normal when compared to the same features on the HDD curves. This suggests that stronger (weaker) than normal winds often occurred on cold (warmer) than normal days and is reflected in a similar oscillating pattern in the ratio curves. In addition, the ratio curves show that the wind had its greatest impact in late December and January. The number of days in 1977 and 1978 with ratio values greater than 1.0 were 45 and 35, respectively. Thus, as seen in Table I and (Fig. 2) and (Fig. 3), winter 1977 was affected more significantly by wind than 1978. Comparing the 1977 and 1978 curves confirms that these two very cold winters evolved in quite different ways. Winter 1977 was marked by extreme cold in January followed by a greatly moderated February, while 1978 contained persistently colder than normal weather throughout both January and February.

In order to see the extent to which daily fluctuations vary between individual stations, the ratios for the two extreme stations, Chicago (Midway) and Evansville are shown in (Fig. 5). Chicago, the northernmost city in this study, had the most consistently large ratio for both years, while Evansville, the southernmost city, had the smallest ratio for both years (see Table I). Consistent with the state average, Chicago's 1977 ratio (1.14) was considerably larger than its 1978 ratio (.97). However, Evansville showed an increase from .75 in 1977 to .87 in 1978. The windy city clearly earned its nickname in 1977 with late December and January containing several maxima lasting four to seven days.

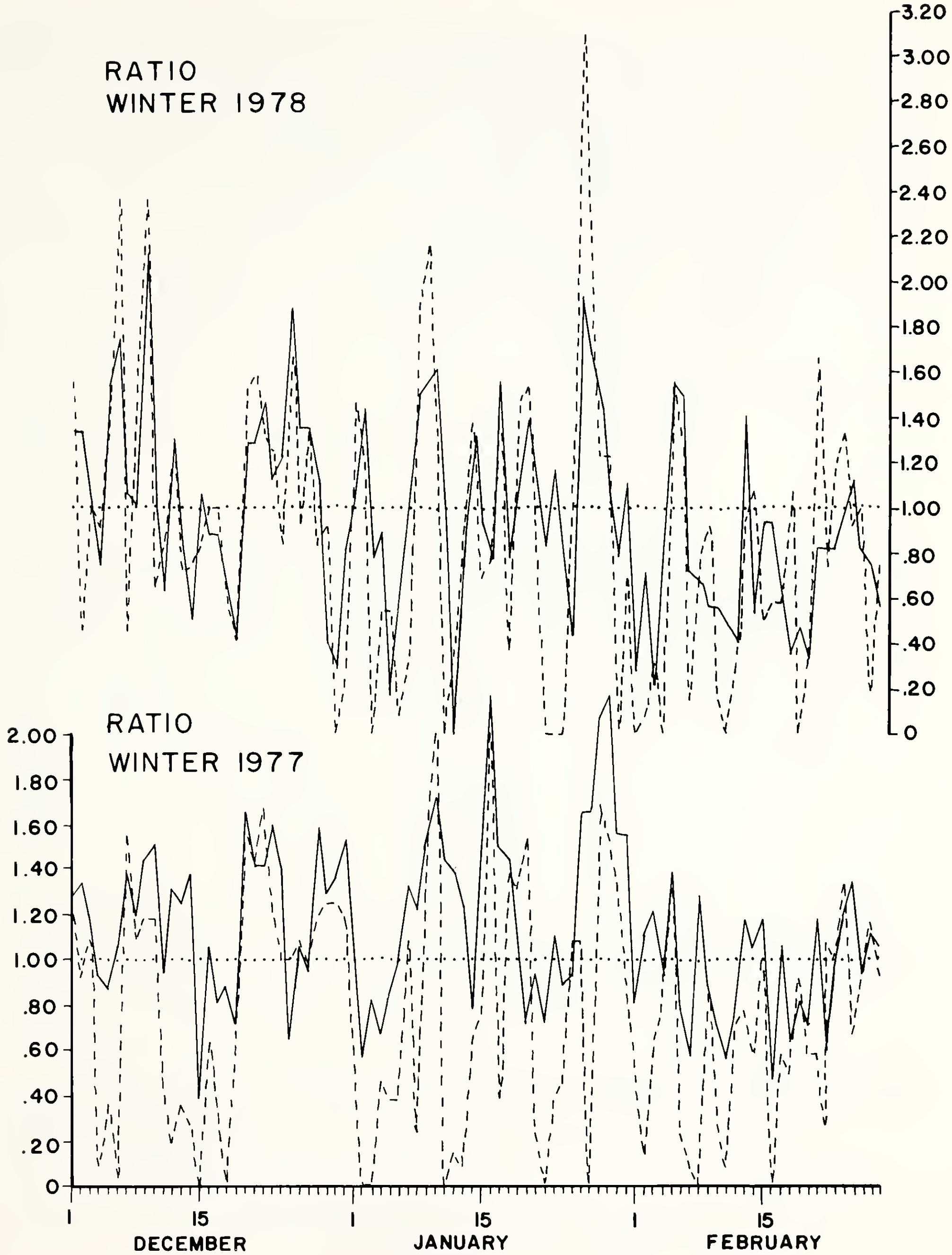

FIGURE 4. *Daily heating degree days (HDD), modified heating degree days (MHDD), ratios (RATIO) and normals (dotted curves) for winter 1977 (solid curve) and winter 1978 (dashed curve).*

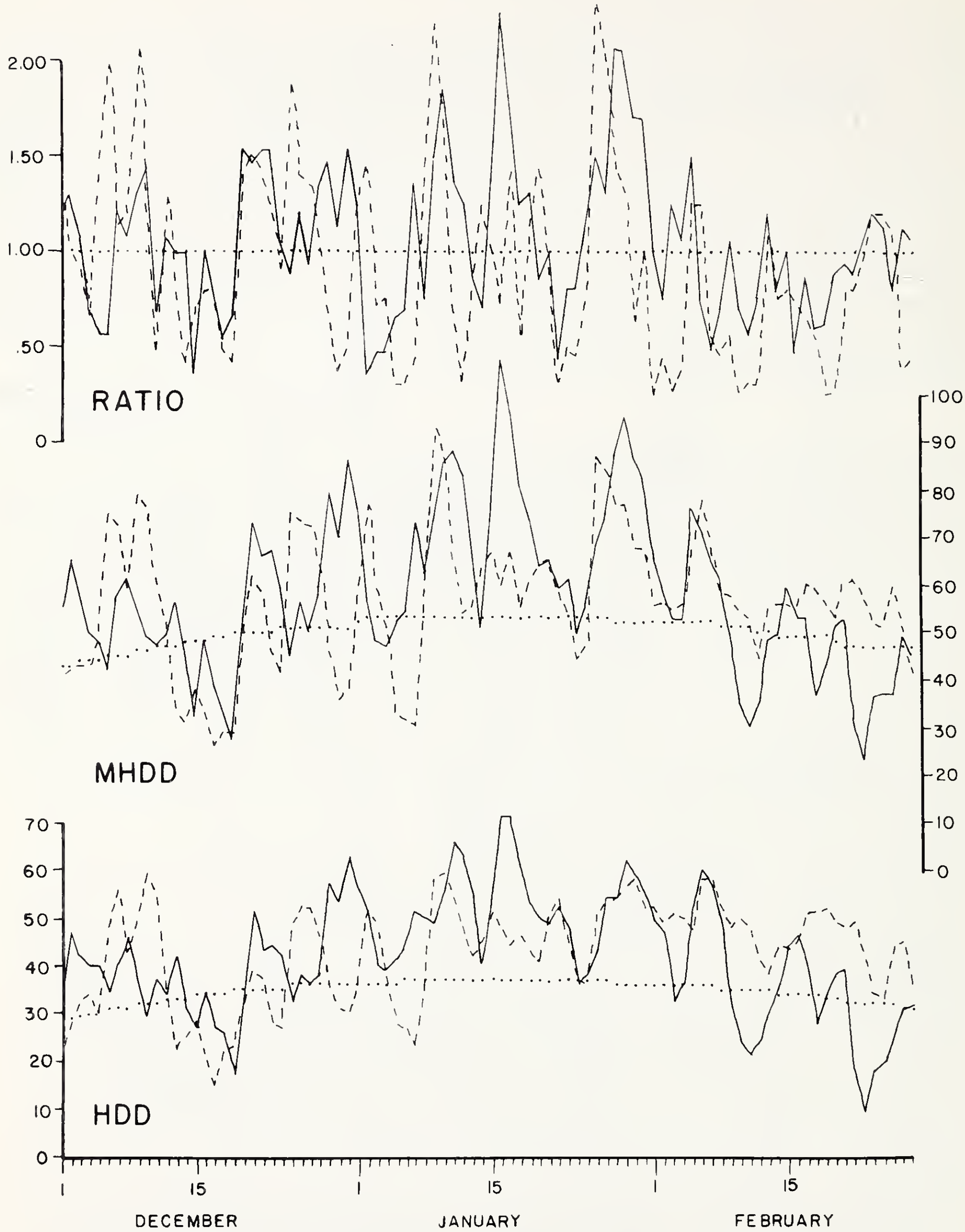

FIGURE 5. *Daily ratios (RATIO) for Chicago (Midway) (solid curve), Evansville (dashed curve), and normal (dotted curve) for winter 1977 and 1978.*

Above normal peaks tended to last three days or less at Evansville. In 1978, a larger number of significant fluctations about the 1.0 line are seen at Chicago with December having more extreme and longer windy periods. In both years, Evansville showed a tendency not only for the winds to be less than normal, but also for their effect to frequently disappear. This happens only when the wind speed is less than the walking wind speed (reference wind speed) previously described. Over the total 180 day period, Chicago only recorded one day when the ratio was 0, while Evansville recorded 21. Even so, in 1978 Evansville had four cases of ratio values that exceeded 2.0 and coincidentally exceeded Chicago's ratio. For these cases, the effect of the wind is over twice its normal effect. For one of these cases, the ratio climbed to 3.08, the only instance encountered in this study in which the ratio exceeded 3.0. This occurred on January 26, the day of the Ohio valley blizzard of 1978.

Conclusions

The relative severity of the winters of 1977 and 1978 differs when the effects of wind and temperature are combined. When temperature alone is considered, as revealed by accumulated heating degree days, 1978 is seen to be just over 1% colder than 1977 for the six stations considered in this study. However, when wind is included, through a modified heating degree day based on the wind chill temperature, 1978 is about 3% "warmer" than 1977. While by any measure the two winters must be regarded as severe, the added influence of above normal wind speeds in 1977 amplified the impact of the cold temperatures, while lighter than normal winds in 1978 lessened the impact of similarly cold temperatures.

In addition, comparison of the two winters reveals the differing characteristics that severe winter periods can possess. In this study, one period was characterized by extreme temperature conditions in January followed by a period of moderating temperatures in February, while the other contained persistent cold throughout both January and February.

Finally, examination of individual stations reveals that most were significantly influenced by the wind in 1977 but experienced lighter than normal winds in 1978. However, in the southwestern part of the state, the lighter wind influence prevailed during both winters.

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