Fuzzy Categorization of Weather Conditions for Thermal Mapping

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ABSTRACT

Thermal mapping is a technique that uses a vehicle-mounted infrared radiometer to measure the variation of road surface temperature (RST). Conventionally, the technique is conducted under three qualitatively categorized weather conditions: extreme, intermediate, and damped. These three categories represent basic weather patterns and are widely used in thermal mapping. In real-time operation, however, determination of the weather category is hampered by the lack of systematic classification. Furthermore, certain skills and knowledge of both thermal mapping and meteorology are required. As the thermal mapping technique develops in the direction of providing a platform for automatic and dynamic forecasting of RST over an entire road network, it is necessary to have some kind of hands-off, quantitative, systematic, accurate, and fast categorization of weather conditions for thermal mapping. For this purpose, the relationship between the change of weather conditions and variation of RST was analyzed to define a time domain for application of a reliable categorization algorithm. Fuzzy membership functions were then established, based on cloud amount, cloud type, wind speed, and relative humidity, to compose a fuzzy function of weather categorization for thermal mapping. The results of validation for the fuzzy categorization show that the algorithm can become a useful tool for thermal mapping.

1. Introduction

As a part of an integrated winter road-weather service system, the thermal mapping technique, which uses vehicle-mounted infrared radiometers to detect spatial variation of road surface temperature (RST) in a road network, plays an important role in revealing the real-time spatial distribution of cold and warm road sections in a road network. Combined with a site-specific road ice prediction model, the technique assists meteorologists, as well as highway engineers, in the identification of where and when a stretch of road is likely to fall below the freezing point.

In theory, a thermal mapping survey can be carried out at any time and under any weather condition. In practice, however, the survey usually is done at the time shortly before dawn, when minimum surface temperature often occurs, and under a limited number of representative weather categories or patterns to avoid too many surveys and unnecessarily high costs. Such representative weather conditions and corresponding thermal mapping products (called thermal fingerprints) are categorized as extreme, intermediate, and damped. An extreme thermal fingerprint shows the largest spatial variation of RST; a damped fingerprint represents the smallest variation. An intermediate fingerprint is between the two. An example of an extreme thermal fingerprint in Birmingham, United Kingdom, is shown in Fig. 1. It can be seen from the figure that details of the spatial variation of RST are revealed by the thermal mapping technique. It is obvious that the technique is a helpful tool not only in the study of road weather but also in other micrometeorological studies.

It has been widely recognized that an extreme weather pattern appears on calm, clear, and relatively dry nights usually related to anticyclonic conditions. On the other hand, a damped pattern corresponds to cyclonic conditions with extensive cloud cover and humid air. Any weather conditions between these two extremes (e.g., moderate winds and some clouds) are usually classified into an intermediate category (e.g., Thornes 1991). In defining weather conditions in this way, there inevitably is vagueness concerning descriptive words such as ''moderate'' winds and ''extensive,'' or ''some,'' clouds. Although such vague terms may be understandable to experts, they are not interpretable to amateurs or computers. This vagueness poses a problem to the further development of the technique in the context of an automatic, full-time operational application.

This paper addresses the vagueness or fuzziness problem by using fuzzy set theory to develop a practical algorithm for the categorization of weather conditions for application to thermal mapping. First, it investigates the relationship and response between RST and weather conditions. The investigation provides necessary infor-

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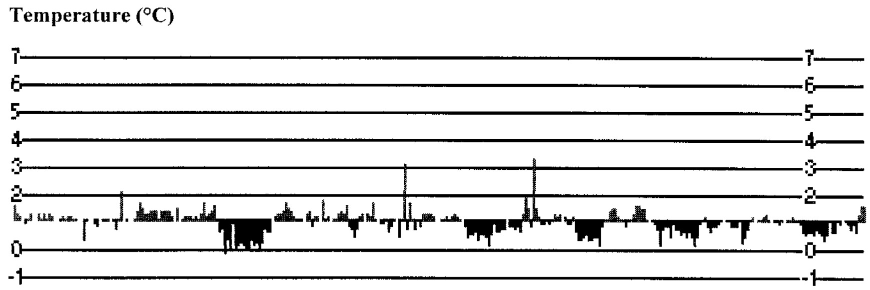

FIG. 1. An example of a thermal mapping fingerprint.

mation about the time domain (or period) during which weather conditions and thermal mapping products are likely to fall into the same category and the proposed fuzzy algorithm becomes effective. Second, a number of important meteorological parameters are chosen, and their membership functions are established. Third, for verification, fuzzy categorization based on these functions is carried out on examples collected in Birmingham. Last, some conclusions are drawn, together with a discussion on the usefulness, limitations, and future development of the proposed fuzzy set algorithm in thermal mapping.

2. Thermal mapping and weather conditions

Many factors affect the energy balance of a road surface and thus its surface temperature. These factors can be briefly classified into permanent and nonpermanent ones. Permanent factors include geographical location (e.g., latitude and altitude), topography (hills, valleys, or slopes), road construction (structure and materials of road surface and sublayers), and localized features such as woods, lakes, and urban heat island, which sometimes also are regarded as topographical features. These factors are called permanent because they change little or their influence on surface temperature is more or less at a certain level or ''fixed'' during a winter season. In contrast, there are two nonpermanent factors: traffic and weather. As compared with the factor of weather, traffic has a far less significant influence on RST and changes little during weekdays. Therefore, the only important and changeable factor influencing RST is weather. Table 1 lists these factors and their possible effects on RST.

TABLE 1. Common factors controlling daily variation (mean and amplitude) of RST, and their significance.

Factors	Significance
Latitude	Important in determining average thermal status or temperature in winter.
Longitude	Little effect.
Urban	Minor to moderate.
Topography	Varying locally and depending on scale and pattern of the topographical features and weather conditions; the effect, however, is nearly constant.
Road construction	Minor influence for basic and common roads.
Traffic	Generally small but could be large under heavy traffic and in rush hours.
Weather	Most significant and important, especially under a clear sky and with a calm wind.

It has been shown that under a certain weather condition (i.e., if the nonpermanent weather factor is held fixed), the spatial variation of RST over a road network appears in a consistent pattern (Shao et al. 1996). This consistency enables thermal mapping to be conducted under only a few selected weather conditions. In the United Kingdom, the terms of extreme, intermediate, and damped have been widely used in thermal mapping survey and data analysis (Thornes 1991; Belk 1992; Shao et al. 1996). Although extensive knowledge, experience, and criteria have been used by experts in the practice of thermal mapping, there has been little published information, except Belk's research (1992), about classification of weather conditions, which are described by continuous variables, for thermal mapping. Belk (1992) used the following criteria for defining three kinds of weather conditions:

Extreme:
cloud $\leq$ 1 octa and wind speed ≤ 2 m s^{-1}.

Intermediate:
either cloud = 8 octas and wind speed = 0
or cloud = 0 and wind speed ≥ 3 m s^{-1}.

Damped:
cloud $\geq$ 7 octas and wind speed ≥ 3 m s^{-1}.

All of the above conditions apply from the start to the end of a survey.

There are two problems with the above. First, the criteria do not completely cover all possible combinations of some important weather parameters. For example, cloud type, which is critically important for influencing the variation of RST, is missing. Also, some weather conditions (e.g., when cloud amount is 3 octas and wind speed is 2 m s^{-1}) are not included. The second problem lies with the period (start to end of a survey as suggested by Belk) to which these criteria are applied. Physically, there should be a time lag for RST to follow the change of weather condition because of the thermal inertia of a road's sublayers. For example, if the sky

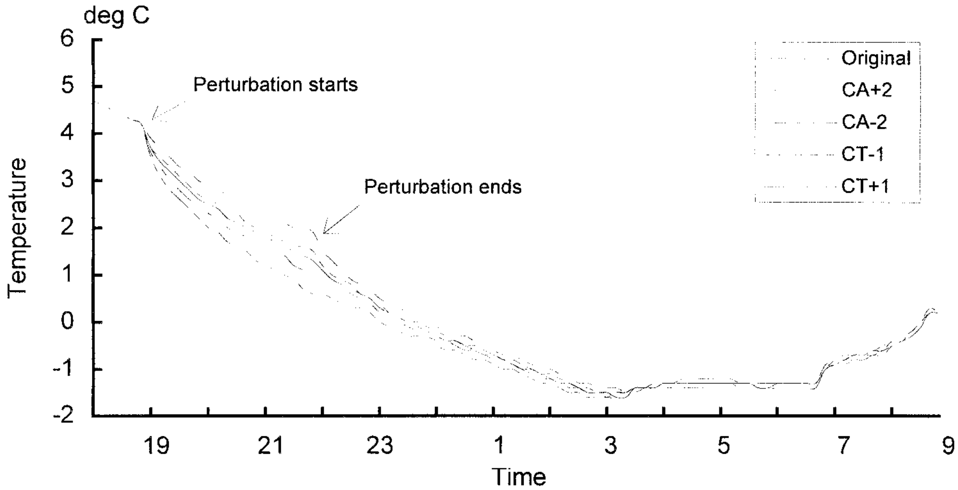

FIG. 2. Variation of RST from perturbation in cloud amount and type (Chapman's Hill, 16–17 Dec 1992).

clears just before the start of a thermal mapping survey, RST will not drop significantly, even in an open field, until some hours later. Thermal mapping data collected at that time will not show the sharp contrasts between colder road sections in open fields and warmer sections sheltered by trees, hills, or buildings. In this case, weather conditions may be extreme according to the above criteria, but the thermal fingerprint may be intermediate. Therefore, this lag inevitably will cause inaccuracy and inconsistency of weather and thermal fingerprint classification in some circumstances.

3. Weather effect on RST

It is seen from the above discussion that a complete and quantitative set of criteria for weather conditions (and thus thermal fingerprints) is needed, and that a time domain for application of the criteria should be clearly defined. To decide the time domain, a road ice prediction model called Icebreak (Shao 1990) is used to stimulate the response of RST to the change of weather condition. The simulation aims to find out how fast RST respond to any possible change of weather conditions.

Both research and experience suggest that, in thermal mapping, the most important and variable factors are cloud amount (CA) and cloud type (CT: 0 for no cloud, 1 for low cloud, 2 for intermediate cloud, and 3 for high cloud) (Thornes and Shao 1991). These two factors are largely responsible for the course of RST and air temperature changes at night. Therefore, the model-based numerical test of time domain concentrates on these two factors. First, the model was run based on all actual inputs without changing any of input parameters. This run is called the original run. Then, the test was carried out by varying one of the two factors at a time and keeping other factors constant. It is called a perturbed run. By comparing the original and perturbed runs, the model simulation is able to reveal the possible effects of change of weather condition on RST. Because weather impact on RST is strongest under extreme conditions, an extreme night (16–17 December 1992) at Chapman's Hill (site code WN003) near Birmingham in England is selected for the test.

During the daytime of 16 December 1992, the sky was overcast with low clouds at the Chapman's Hill site. Middle clouds replaced low clouds shortly before sunset at 1545 LT. Around midnight, the sky cleared, and remained clear until shortly after sunrise (0835). Roadside measurements of air temperature, dewpoint, wind speed, and precipitation were collected at a roadside automatic weather station. Cloud data were provided by the nearby Birmingham Weather Centre of the U.K. Meteorological Office. A comparison between the model-based values and surface sensor measurements at the test site on an hourly basis showed that the model's 24-h simulation error has a bias of $-0.02°C$ and an rms error of 0.71°C. A negligible bias and a small rms error mean that the model can be regarded as a reliable tool to represent the change of RST during the night.

Four perturbed runs were designed, with cloud amount and cloud type set at ± 2 octas and ± 1 level, respectively. The perturbation was introduced at 1900 LT (about 3 h after sunset) and maintained for 3 h (because all inputs were in a 3-hourly interval). This means that the perturbation disappeared at 2200. The results of the original and perturbed runs are shown in Fig. 2. It is seen from the figure that the difference of RST between the original and perturbed runs develops rapidly when a perturbation is imposed. The difference becomes obvious at 2100–2200 and then decreases after disappearance of the perturbation. The figure shows that the effect of cloud perturbation on RST becomes negligible after 0300, or 5 h after the perturbation was terminated.

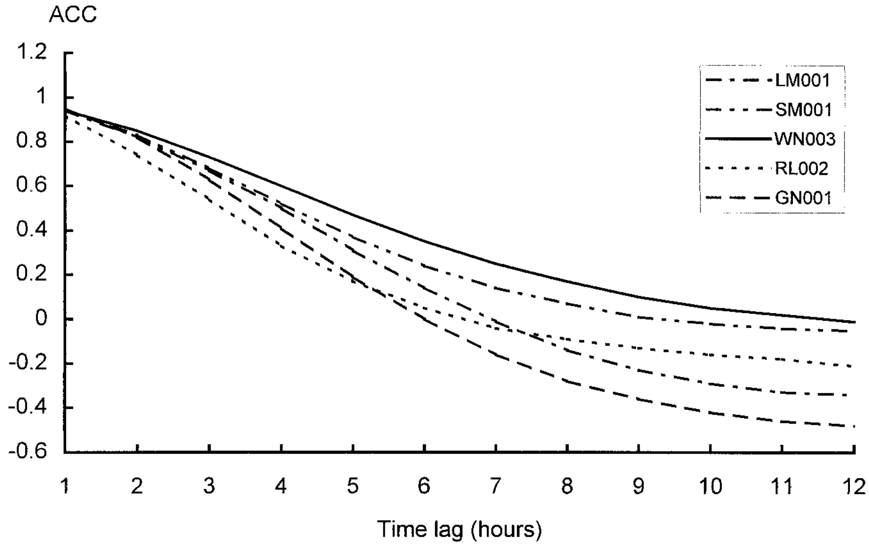

FIG. 3. Autocorrelation coefficients (ACC) of RST.

The magnitude of the perturbation introduced in this example is not great and can be reasonably expected to exist between any two similar nights. The example shown in Fig. 2 indicates that the impact on RST at a night of a change of weather condition that can be expected in winter increases gradually and becomes most significant after 2–3 h. The effect is likely to last about 5 h.

Further evidence supporting the results shown in Fig. 2 is obtained by an autocorrelation analysis of RST series. In the analysis, an autocorrelation coefficient (ACC) is defined by

$$\mathrm{ACC}(\tau) = \frac{1}{n-\tau}\sum_{i=1}^{n-\tau}\left(\frac{T_i - \overline{T}}{s}\right)\left(\frac{T_{i+\tau} - \overline{T}}{s}\right)$$
$$\tau = 1, 2, \ldots, m, \qquad (1)$$

where n is number of temperature records (T); $\overline{T}$ and s are estimates of mean and standard deviation of the temperature, respectively; τ is a time lag in hours; and m is the maximum lag (=24 h). A high value of ACC(τ) means that the temperature at time i has a significant influence on the temperature at $i + \tau$. The analysis was carried out at five automatic roadside weather stations with hourly measurements of RST. The five stations are: Chapman's Hill (WN003, 13–30 December 1988) and Leeming airfield (LM001, 2 March–23 April 1993) in the United Kingdom, San Pietro (SM001, 19 January–16 March 1994) in Italy, Kvassheim (RL002, 10–18 February 1994) in Norway, and Beekbergen (GN001, 13–21 February 1994) in Netherlands. Results of the analysis are displayed in Fig. 3 for $\tau = 1, \ldots, 12$. Generally, ACC falls toward zero fairly rapidly at the first several time lags. If an ACC below 0.4 is regarded as insignificant, it can be generally said to ''cut off'' at $\tau = 5$–6 h in the figure. This result indicates that RST has a good ''memory'' of up to 5 or 6 h, or, in other words, road surface thermal status at time i has a much reduced or insignificant effect after $i + 5$ h. Because RST is largely controlled by weather conditions, this result implies that the influence on RST of a change in dominant weather condition becomes insignificant after 5–6 h.

Both numerical simulation and statistical analysis demonstrate the following.

- The influence of a change in dominant weather condition on RST is most significant after 2–3 h and is negligible after 5–6 h of the beginning of the influence.
- Accurate weather information is essential for delivering reliable thermal mapping results. Therefore, a representative weather category for thermal mapping should consider not only the weather condition when a survey is being undertaken, but also the conditions several hours before the survey.
- Weather conditions under which thermal mapping is being conducted should be consistent and stable for several hours (including the time for the survey), in order for the road surface to reach thermal equilibrium and to allow RST to respond fully and truly to the governing weather conditions.
- Thermal mapping should be carried out once a certain weather condition has persisted for 2–3 h.
- A proper algorithm or method to classify weather conditions and thus thermal fingerprints should have a time domain of 2–3 h plus the duration of the survey.

4. Fuzzy categorization

Whereas most traditional tools for classification are crisp (i.e., yes or no type), fuzzy set theory is able to deal with phenomena with vague criteria or ''borders'' (i.e., more or less type) of classes. In thermal mapping, it is neither practical nor reasonable to draw a crisp, deterministic, and precise border between extreme, intermediate, and damped categories. For example, it is not certain if a weather condition with 2 octas of high cloud and wind speed 2 m s^{-1} (a nonextreme category according to Belk) will result in a significant difference in RST, in comparison with that with 1 octa of medium cloud and wind speed 2 m s^{-1} (an extreme condition). Because the borders of classification of weather conditions in thermal mapping are noncrisp, the problem should be dealt with by fuzzy set theory (Zadeh 1965; Zimmermann 1991). Research has shown that fuzzy set theory can be a valuable tool for meteorologists (e.g., Cao and Chen 1983; Boreux 1994; Kuciauskas et al. 1998; Maner and Joyce 1997; McBratney and Moore 1985; Murtha 1995).

In fuzzy set theory, if X is a collection of weather conditions denoted by x, a fuzzy set (A) of certain weather conditions in X is a set of ordered pairs:

$$A = \{[x, \mu_A(x)] \mid x \in X\}, \qquad (2)$$

where $\mu_A(x)$ is called the membership function or grade of membership of x in A, which maps X to the membership space M. Here, fuzzy set A is called normal because the value of its membership function is limited to the values between 0 (lowest grade of membership) and 1 (highest grade of membership). In the fuzzy set theory, the membership function is a crucial component and is usually defined or determined by knowledge and experience.

For thermal mapping, cloud amount (x_1; octas), cloud type (x_2; 0–3), wind speed (x_3; m s^{-1}), and relative humidity (x_4; %) are the four most important weather factors governing the variation of RST. For the convenience of expression of its membership function, cloud type takes the value of 0 for no cloud, 1 for high cloud, 2 for intermediate cloud, and 3 for low cloud in this paper. Research (Thornes and Shao 1991) and operational experience indicate that less cloud amount, higher cloud type, weaker winds, and a drier atmosphere are likely to result in an extreme thermal fingerprints. Therefore, the membership functions of each of the factors are defined as

$$\mu_A(x_1) = \begin{cases} 0 & \text{for } x_1 = 0 \text{ octa} \\ 0.92\exp(x_1/10) - 1 & \text{for } x_1 \geq 1 \text{ octa}; \end{cases} \qquad (3)$$

$$\mu_A(x_2) = \begin{cases} 0 & \text{for } x_2 = 0 \\ \dfrac{x_2}{3} & \text{for } x_2 > 0; \end{cases} \qquad (4)$$

$$\mu_A(x_3) = \begin{cases} 0 & \text{for } x_3 \leq 2 \text{ m s}^{-1} \\ \ln[1 + 0.22(x_3 - 2)] & \text{for } 2 < x_3 < 10 \text{ m s}^{-1} \\ 1 & \text{for } x_3 \geq 10 \text{ m s}^{-1}; \end{cases} \qquad (5)$$

and

$$\mu_A(x_4) = \begin{cases} 0 & \text{for } x_4 \leq 70\% \\ 1 \bigg/ \left[1 + \left(\dfrac{100 - x_4}{5}\right)^3\right] & \text{for } x_4 > 70\%. \end{cases} \qquad (6)$$

The four membership functions are displayed in Figs. 4a–d. The figures show grade of membership of each individual factor. The combined effect of these factors on weather categorization in thermal mapping is expressed in the function

$$\mu_A(x) = [\mu_A(x_1) \cap \mu_A(x_2)] \cup [\mu_A(x_3) \cup \mu_A(x_4)], \qquad (7)$$

where fuzzy intersection operator ($\cap$) and union operator ($\cup$) are defined as ''min'' and ''max'' operations, respectively. Weather categories (A) are determined by specified values of the combined membership function [Eq. (7)] as

$$\mu_A(x) = \begin{cases} 0 & \text{for extreme} \\ 0.5 & \text{for intermediate} \\ 1 & \text{for damped.} \end{cases}$$

Equation (7) and the above criteria mean that

- cloud is largely responsible for creating an extreme condition (hence, the minimum operation between x_1 and x_2), and
- high wind speed or high humidity tends to produce a damped or intermediate condition (hence, the maximum operation between x_3 and x_4).

For a given night y, its categorization is determined by the closeness of the value of $\mu_A(y)$ to either 0 (extreme), 0.5 (intermediate), or 1 (damped). For the reasons discussed in section 3, cloud amount, cloud type, wind speed, and relative humidity should be the average values of 2–3 h before the thermal mapping survey starts.

There are many measures to indicate the degree of fuzziness of a fuzzy set. A simple measure is to regard an index of fuzziness as a normalized distance (Kaufmann 1975). In this paper, the degree of fuzziness of a real set [$A(y)$] belonging to one of the three predefined extreme, intermediate, and damped sets [$A(x')$] is defined by the ''distance'' between them

$$f(A) = \frac{|\mu_A(y) - \mu_A(x')|}{\|\sup(x')\|}, \qquad (8)$$

where $\|\sup(x')\| = 0.25$. The value of the index varies from 0 to 1. The index of fuzziness indicates confidence or certainty of the categorization. The higher its value is (>0.75), the more uncertainty there is in the categorization.

5. Validation

To verify the algorithm expressed in section 4, a number of representative thermal mapping surveys were studied. These sample surveys were based on a research

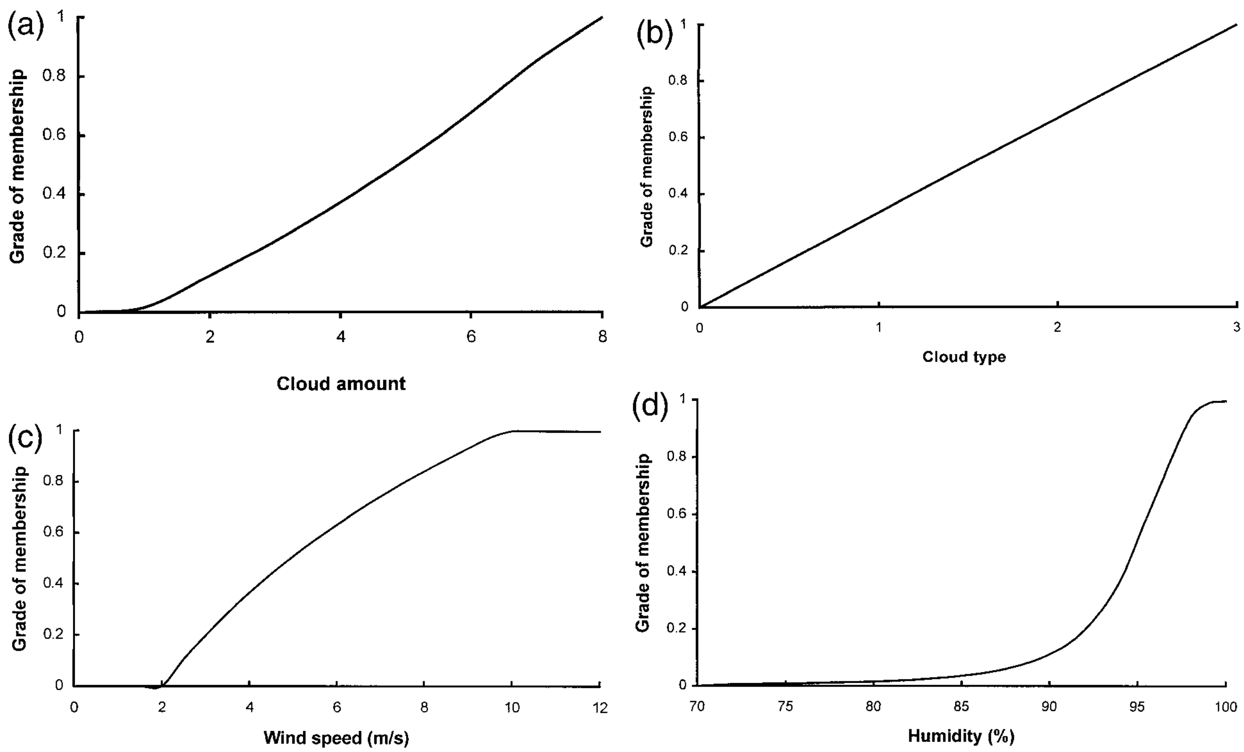

FIG. 4. Display of membership function of (a) cloud amount, (b) cloud type, (c) wind speed, and (d) relative humidity.

route (No. 3) in southeast Birmingham. The route (together with others) has been used and is still used for the purposes of research, testing of new equipment, and training. The route takes about 25 min to complete a single run from start to finish in order to minimize the unpredictable effects of weather condition change on RST during the survey. In the study, hourly cloud data were again provided by the Birmingham Weather Centre of The Met. Office. Hourly wind speed and relative humidity (except the night of 19 April 1995 for which the data were from the Centre) were recorded by sensors at Chapman's Hill, which is about 11 km away from the starting point of the research route.

The date and observations of the variables required in the algorithm are shown in Table 2. In the table, the values of meteorological variables were averaged over a 5-h period prior to the end of each survey. These averages represent the prevailing weather conditions before and during the surveys. The results of each survey have been categorized into damped, intermediate, or extreme according to weather conditions by Vaisala's staff using their own criteria similar to Belk's and their personal experience after in-office data analysis. Standard deviation (SD) of RST is also shown in the table. The reason for using SD as an index of degree of RST development (or degree of spatial variation) can be found in Shao et al. (1996). In general, a higher value of SD is related to extreme thermal fingerprints and a lower SD to damped fingerprints.

The category of thermal fingerprints derived by the fuzzy algorithm and its fuzziness [$f(A)$] are given in Table 2, together with the category by the staff without taking account of SD. The three categories are labeled as E for extreme, I for intermediate, and D for damped. It is seen from the table that the fuzzy method based on basic meteorological parameters produces the same

TABLE 2. Examples of thermal mapping survey and their categorization (Cat.) by thermal mapping experts and the fuzzy method (research route 3, Birmingham, United Kingdom). Here WS is wind speed and RH is relative humidity.

Date	CA (octa)	CT (1–3)	WS (m s^{-1})	RH (%)	Experts		Fuzzy method	
					Cat.	SD	Cat. (μ_A)	$f(A)$
17 Dec 1992	1	3	0.0	85	E	2.1	E (0.02)	0.1
3 Jan 1995	1	1	1.2	81	E	2.0	E (0.02)	0.1
24 Jan 1995	6	1	11.0	83	D	0.7	D (1.0)	0.0
27 Jan 1995	0	0	3.0	83	E	1.4	E (0.2)	0.8
19 Apr 1995	0	0	1.4	95	I	1.4	I (0.5)	0.0

categories as the conventional method that requires intensive before- and after-survey analysis, calculation, and personal experience. It is noticed in the table, however, that the fuzziness of the survey on 27 January 1995 is so large (0.8) that some doubts can be cast regarding the categorization of this case. More detailed investigation (for instance, analysis of SD and road surface state) through the night reveals that the fingerprint should be recategorized more appropriately as a subcategory between extreme and intermediate.

The results show that the fuzzy method is not only able to categorize weather conditions and thermal fingerprints correctly, but is also able to provide more information on the certainty of the categories by using a fuzziness index. The results also show that the current three (extreme, intermediate, and damped) weather/fingerprint categories in thermal mapping are not enough to represent all possible situations.

6. Discussion and summary

It has been shown that

- a proper time domain, during which weather conditions should remain relatively stable, is important for correct classification of weather conditions for thermal mapping; and
- the fuzzy categorization algorithm is able effectively to emulate experts in the task of classifying weather conditions that affect RST evolution.

It should be pointed out, however, that when weather conditions are subject to a rapid or significant change, it is difficult and impractical to identify accurately a dominant and representative weather category by the algorithm (or any other algorithm). Apart from this limitation, it can be seen that more-detailed categories (e.g., subclasses of each of the extreme, intermediate, and damped categories) can be readily made by assigning different grade values of combined membership functions, using Eq. (7), to the subclasses. For example, a value of 0.25 of Eq. (7) can be regarded as a border weather type between extreme and intermediate, and 0.75 as another border between intermediate and damped. These two borders can be used to derive two subcategories: extreme–intermediate and intermediate–damped. Adding the two extra categories will make the overall categorization more accurate and realistic.

In summary, it is demonstrated in this paper that a reasonable change of weather condition (e.g., cloud amount increases or decreases by 2 octas) in thermal mapping triggers a significant road surface temperature response. The impact (called ''lagging effect'') of weather condition on the temperature becomes significant after 2–3 h and remains effective for about 5 h. This lag means that a representative thermal mapping survey should take account of weather conditions 2–3 h before the survey. Because of the lagging effect, a correct weather categorization of thermal mapping becomes possible when and only when weather conditions are relatively stable for a period of 2–3 h preceding the survey and during the survey.

This paper also shows that correct categorization of weather conditions can be achieved by using fuzzy set theory. The algorithm represented in this paper is quantitative, more practical, and more applicable than existing qualitative measures. It will help the current site-specific road weather warning system to provide automatic, full-time, and accurate weather warnings in two dimensions across a road network in near future.

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