POSTER 08

Profiling of Nocturnal Temperature Inversion at an Hourly Interval

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I. Introduction

Because information pertaining to nighttime temperature is necessary for determining the possibility of damage to crops arising from low temperature, studies on simulation of the temperature decrease due to the cold air flow and accumulation in complex terrains have been conducted so that even the resolution of the digital forecast of the Korea Meteorological Administration (KMA) can be compensated. Chung *et al.*(2006) suggested a method for expressing the cold-air drainage from a mountain slope into a mountainous catchment using the accumulation of cold air, and thus effectively expressed the effect of cold air accumulation in such valleys.

However, in the case of flat lowland areas, the temperature distribution based on the existing lapse rate of temperature was all that was available to rely on. To complement efforts to understand lowland temperature, Kim and Yun(2011) applied the cold-air pool effect to a catchment, in which exits were restricted by artificial structures to simulate the lowest temperature of lowlands. However, the closed catchment, considering the relevant geographic features, should be defined first, while areas without such considerations cannot express the temperature distribution of the inversion of temperature. Additionally, the nighttime temperature estimation models of previous studies have been optimized to simulate the distribution of lowest temperature immediately before sunrise and are thus far from capable of estimating the temperature for each time during the night.

Therefore, in this study, (1) on the sidelines of cold air drainage in mountain slope, the inversion of temperature is expressed quantitatively in areas not affected by cold-air drainage or the cold-air pool, while (2) simultaneously preparing plans to estimate the hourly vertical temperature during nighttime.

II. Materials and Methods

2.1. Expression of hourly temperature inversion

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On a clear day with calm winds, an inversion of temperature develops from the surface after sunset and reaches its peak at sunrise, as is shown simply in Fig. 1 In the temperature profile, when defining the deviation (ΔT_{IS}) between the temperature (T_{IC}) of the inversion height (Z_{IC}), which is the highest temperature, and the temperature of the lowest part of the profile, as the inversion strengthens, the inversion strength will increase gradually with time t during the nighttime until the maximum value of $\Delta T_{IS\cdot max}$ is reached. Also, the inversion cap will increase gradually with time t until it reaches the maximum height $Z_{IC\cdot max}$ after sunset.

When considering the surface level of Fig. 1 as the base of a virtual terrain or catchment bottom, the temperature T_i of height Z_i, which is lower than the inversion cap height at predetermined time t, is lower than the inversion cap temperature T_{ICt}, by the amount ΔT_{ISi}. The relationship between ΔT_{ISi}, the inversion strength, and the height of the inversion cap is as shown in Eq. 1.

$$\Delta T_{ISt} : \Delta T_{ISi} = Z_{ICt} : \left(Z_{ICt} - Z_i\right) \tag{1}$$

Eq. 1 can be arranged about ΔT_{ISi} and substituted into $T_i = T_{ICt} - \Delta T_{ISi}$ to derive the Eq. 2 below.

$$T_i = T_{ICt} - \Delta T_{ISt} \frac{Z_{ICt} - Z_i}{Z_{ICt}} \tag{2}$$

Although T_i below the inversion cap Z_{IC} is simulated by Eq. 2, the temperature above it follows the temperature lapse rate. If the way that Z_{IC} and ΔT_{IS} change with time can be expressed quantitatively, the background temperature, ΔT_{IS}, and the temperature lapse rate can be used to calculate T_{IC} at any random time t, and the temperature below Z_{IC} can be calculated in accordance with Eq. 2. Additionally, by applying the temperature lapse rate to the temperature above Z_{IC}, based on T_{IC}, the temperature profile, which is shown at a predetermined timetable, under clear and calm conditions, can be estimated with the simple form.

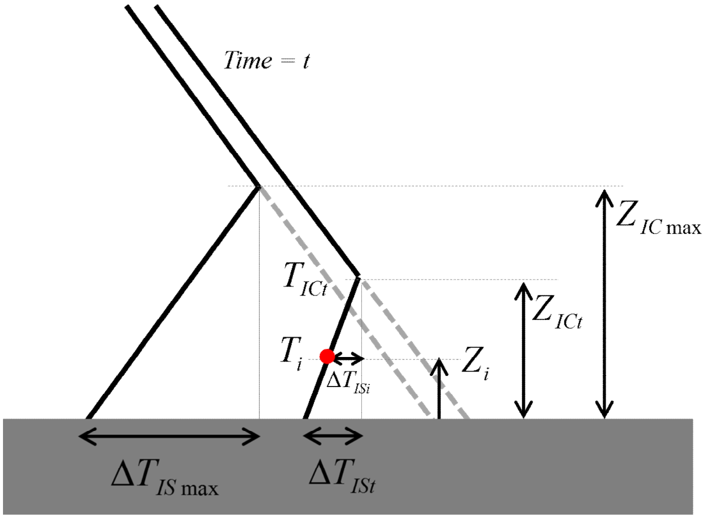

Fig. 1. Diagram of temperature inversion by time.

2.2. Weather data

From May 2007 to March 2008, a meteorological temperature profiler (Model MTP5H, Kipp and Zonen) was installed on the rooftop of the Highland Agriculture Research Institute, located in Daegwallyeong-myeon, Pyeongchang-gun, Gangwon-do, to measure the hourly vertical distribution of air temperature up to the height of 600 m at intervals of 50 m. From data of 172 days including all the hourly measurements of the MTP5H from 1700 to 0700 LST of the next day, except for some missing measurements, the cloud data of every 3 hours, along with hourly wind speed data from the nearby Daegwallyeong weather station, were collected to select days that met the condition of clear sky and calm wind. The criterion for a clear day assumed that the amount of cloud was maintained continuously below 1 from 1800 LST of the day before to 0900 LST of the next day, and the criterion for calm wind assumed that the mean wind speed every 3 hours was below 3 m/s during 1900–2100 LST and below 1 m/s during 2200–0000 LST, 0100–0300 LST, and 0400–0600 LST. The temperature distribution for each elevation of the mountain slope affected by the surface was obtained from temperature/relative humidity data loggers (HOBO U23 Pro v2, Onset Computer Corporation, USA) installed in the Jungdae-ri Valley, located between Gurye-gun, Jeollanam-do and Gwangyang-si, Jeollanam-do, by measuring weather data 1.5 m above the surface from October 3, 2014, to November 23, 2015. The data logger devices were installed at elevations above sea of 401 m, 313 m, 260 m, 159 m, and 103 m, respectively, to avoid the cold-air drainage accumulation in the valley. As the amount of cloud is not measured anywhere near Jungdae-ri Valley, the hourly ‘sky condition’ data from Korea Local Analysis and Prediction System (KLAPS) of the KMA were used to select clear days. The sky condition is expressed as lattice data at a 5 km × 5 km resolution with a 4–value system (clear = 1, partly cloudy = 2, cloudy = 3, and overcast = 4). The days selected had the constant spatial average value of sky condition of 1 during 1700–0900 LST within the ‘Hadong 2 watermark’ of the catchment basin including Jungdae-ri Valley. In addition, by collecting the minutely weather data from the weather station located 1.7 km southeast of the entrance of Jungdae-ri Valley, we calculated the hourly wind speed for every hour before and selected the clear and calm days by applying the same criteria of the wind condition as at the Dargwallyeong weather station. The days selected for Jungdae-ri Valley were divided by halving into two groups, A and B. Group A was utilized for correcting the estimation of temperature inversion, and Group B was used for verification.

2.3. Quantification of temperature inversion

With respect to the clear-and-calm day condition in Daegwallyeong, the hourly temperature profile from 1700 to 0700 LST of the next day was composed, and the 50-m-interval temperatures from 100 m to 600 m above surface were used for the quantification of temperature inversion. The reason why the quantification was conducted based on height above 100 m is because that elevation most approximates the height of 103 m, which is the lowest elevation of temperature observation conducted in Jungdae-ri Valley. Among the levels of 100 m through 600 m in Daegwallyeong, the elevation with the highest temperature at the same time during the nighttime was hourly confirmed. When this elevation was higher than 150 m above the surface, the inversion cap was assumed to have developed at that same elevation. Additionally, the deviation between the temperature of the inversion cap at elevation Z_{IC} and the temperature at the elevation of 100 m was assumed as the strength of the temperature inversion and was used to determine hourly the inversion strength (ΔT_{IS}). For the selected clear days, the changes of inversion cap and inversion strength from 1700 LST of the previous day to 0700 LST of the next day were averaged for each timetable. Thereafter, a nonlinear model of a statistics program (SAS Institute, Raleigh, North Carolina, USA) was used to derive a logistic function about time t, as shown in Eq. 3. Herein, the integers from 1 through 15 were assigned to the independent variable t starting from 1700 LST, as 1, and progressing to 0700 LST.

$$y = \frac{M}{1 + \exp\{k(t - t_m)\}} \tag{3}$$

The basic regression formula derived from the Daegwallyeong temperature profile was compared with the Group A clear-and-calm day condition days of Jungdae-ri Valley to adjust the parameter values. Assigning *M* of Eq. 3, regarding the inversion strength, as the maximum inversion strength calculated in Jungdae-ri Valley, *k* was altered by the interval of 0.1. The consequential value of *k* was selected when the root-mean-square error (RMSE) between the results derived from the regression formula and the hourly inversion strength of Jungdae-ri Valley was the least.

2.4. Evaluation of quantification

The elevation above sea level of 103 m, in Group B of the Jungdae-ri Valley data, was used as a virtual terrain, and its observation values were used as the background temperature to estimate the temperatures at the elevations of 159 m, 260 m, 313 m, and 401 m, through Eq. 2 and 3. The air temperature lapse rate was estimated in an hourly manner, using the method of Kim and Yun(2016), from 1700 to 0700 LST on the next day in order to simulate the hourly temperature profile. The estimated hourly temperature for each elevation under the clear-and-calm day condition was compared with the observation values to calculate the mean error (ME) and the RMSE.

III. Results

3.1. Temperature inversion of Daegwallyeong

Within the observation period for Daegwallyeong, the clear-and-calm condition dates that were selected were 6/16, 6/17, 11/7, and 11/12, 2007. From 1700 to 1000 LST of the next day, the elevation of the hourly inversion cap and the inversion strength were calculated, and the average value is shown in the gray area in Fig. 2. The thick line in Fig. 2 refers to the results of the regression formula of hourly inversion cap (left) and inversion strength (right) calculated from the weather data of Daegwallyeong. The parameters of the two logistic functions referring to Eq. 3 are shown in Table 1.

Table 1. Regression coefficients of logistic functions of inversion cap elevation and inversion strength by time *t* derived from the Daegwallyeong temperature profile

	M	t_m	k
Inversion Cap	363	4.8198	0.6119
Inversion Strength	4.1432	7.2504	1.0136

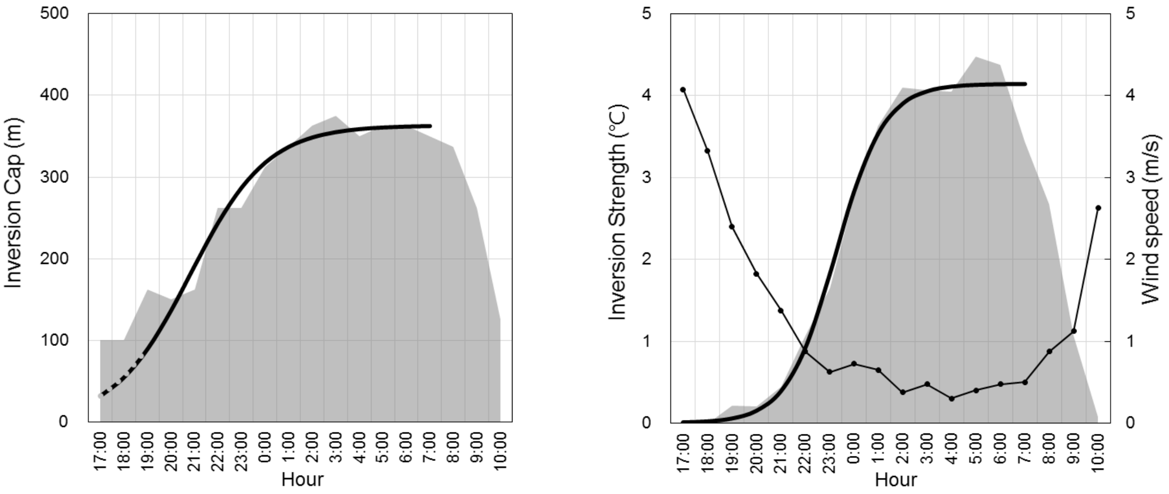

Fig. 2. Changes of hourly inversion cap (left) and inversion strength (right) for clear days with calm wind in Daegwallyeong. The hourly average wind speed at the Daegwallyeong weather station is also shown, along with the right-side graph.

Because the temperature inversion of Fig. 2 considers only the temperature upon reaching 100 m from the surface, inversion cap elevation temperature below 100 m is extended as estimated values (left, dashed line). In Daegwallyeong, the inversion strength from the surface is expected to be calculated as a value larger than that suggested in the right side graph of Fig. 2. In addition, the reason why the inversion strength is weak before 2100 LST is that the temperature inversion, which formed at an elevation of around 100 m or less, was ignored.

3.2. Temperature inversion of Jungdae-ri Valley

For the clear days with calm wind, the inversion cap elevation observed in Jungdae-ri Valley was expressed as the gray area and the line in Fig. 3 (Group A). The elevation of the inversion cap was generally similar to that of the regression formula derived in the above (thick line). However, in some cases, inversion layers occurred as low as the elevation of 159 m around the time of sunset. Also, after sunset, the temperature was highest at the elevation of 401 m (Fig. 3 and 4). This is because the upper area of the Jungdae-ri Valley slope, which is open to the northeast, receives more solar energy early in the morning, so the temperature rises more swiftly.

The hourly inversion strength of Jungdae-ri Valley, shown in Fig. 4, generally shows a weaker and more linear increase than that of the regression formula (thick line). On the other hand, in the early evening, the inversion strength was higher than the regression formula. The temperature inversion regression is based on the temperature profile in the atmosphere from 100 m above the surface, whereas the temperatures for each elevation observed in Jungdae-ri Valley all regard values measured at 1.5 m above the surface. Therefore, the cooling effect of the surface is reflected along with the influence of the temperature inversion in the atmosphere. Moreover, in mountain slopes, as cold air due to the radiation of the ground surface during nighttime flows downhill, the circumstances can be different from those of flat land areas. Although further studies are required, to express quantitatively the fact that the inversion strength is smaller and that the trends by time are different, in comparison with the case of Daegwallyeong, the present study reduced the errors between the regression formula and the observed values by adjusting *M*, the parameter, and *k*, the gradient of the regression formula, to have low values. Herein, the hourly inversion strength of Jungdae-ri Valley, which became the standard, was derived from only the nighttime data of the dates of 10/17–18 and 10/18–19, 2014, among the 3 clear days because the data measured on the dates of 3/7–8, 2015, showed noticeably low inversion strength (Fig. 4, dashed line). Additionally, the inversion cap elevation did not increase from 1900 to 0200 LST on the next day in the case of the date of 3/7/2015 and was constantly maintained as 159 m (Fig. 3, dashed line). Therefore, it can be inferred that there was a factor that deterred the development of the inversion cap. Because the wind data used for selecting the clear-and-calm day condition were derived from the Seomjingang River, which is directly 1.7 km distant from the entrance of Jungdae-ri Valley, there might have been some discrepancies among the wind data of the two locations.

Moreover, upon comparing the hourly average

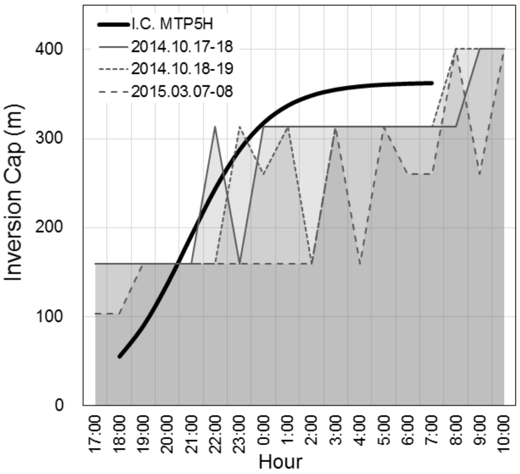

Fig. 3. Hourly inversion cap of Jungdae-ri Valley.

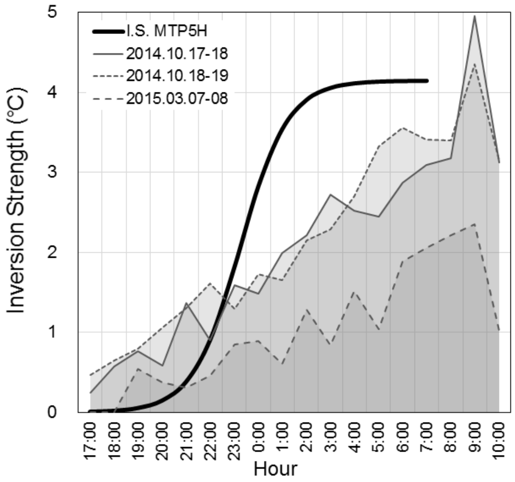

Fig. 4. Hourly inversion strength of Jungdae-ri Valley.

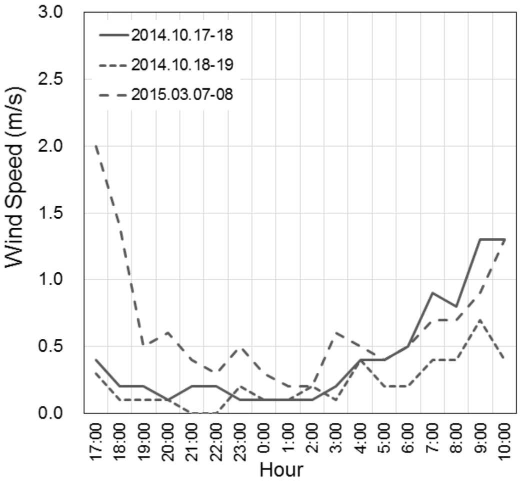

Fig. 5. Hourly average wind speed observed near Jungdae-ri Valley during nighttime.

wind speed before each hour from 1700 to 1000 LST for the selected 3 days (Fig. 5), the wind was weak and mostly below 1 m/s. However, the date of 3/7/2015 showed stronger winds than the other two days from 1700 through 0300 LST. The wind speed was especially strong at around sunset relatively.

The coefficient *M*, which shows the maximum value of $\Delta T_{IS\cdot max}$ in the inversion strength function during the clear-and-calm day condition derived from Daegwallyeong, was replaced with 3.2°C, which is the average value at 0600 LST during the two days when the inversion strength was high in Jungdae-ri Valley.

Fig. 6 shows the results derived by changing the gradient *k* from 0.1 to 1.0 using an interval of 0.1 and calculating the RMSE between the hourly inversion strength of the function and the actual inversion strength during the two days. The *k* value with the lowest RMSE was 0.3. Therefore, the regression coefficients of the consequential inversion strength estimation are M = 3.2, t_m= 7.25 (no change), and k = 0.3. The function of the inversion cap elevation was assumed as exactly what was derived from the case of Daegwallyeong.

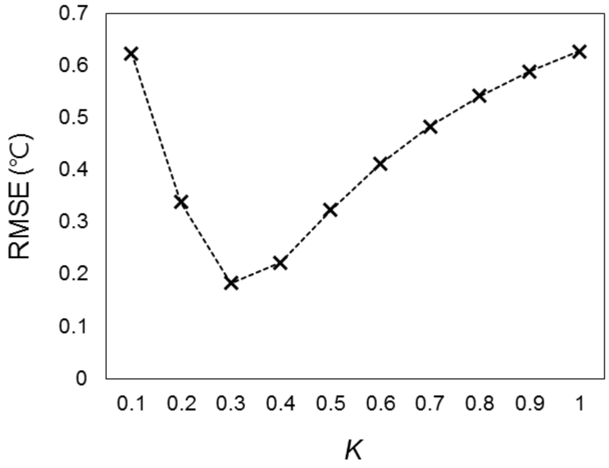

Fig. 6. RMSEs between the hourly inversion strength of the function by changing the gradient *k* and the actual inversion strength during the clear-and-calm days.

3.3. Performance of hourly temperature inversion estimation

Group B of Jungdae-ri were the nighttime data of the dates of 10/6–7, 10/18–19, and 11/3–4, 2015. After estimating the hourly temperatures of four points in Jungdae-ri Valley from 1700 to 0700 LST on the next day, the temperatures were compared with the actual measurement values, as shown in Table 2. The overall ME was –0.33°C and the RMSE was 0.76°C. For each point, the trend of RMSE of the temperature was different by each elevation. The elevation of 401 m, which was assumed to be outside of the inversion cap, showed that ME was 0.18°C and the RMSE was close to the average; however, the elevation of 159 m showed significant underestimation (ME of –0.85°C).

The quantification of temperature inversion applied to the temperature estimation assumed the maximum temperature inversion. Therefore, in actual situations, factors that can offset the temperature inversion, such as wind, should be considered. In particular, because the temperature inversion model simplified in this study cannot represent a temperature profile with a gentle curve, the RMSEs of the temperature below can increase as the inversion cap rises. In addition, as the breaking of the temperature inversion during the period of sunrise is not expressed, follow-up studies with the goal of complementing the quantification are required.

Table 2. Hourly RMSEs of Jungdae-ri Valley on clear and calm days using the temperature inversion quantification

	Elevation (m)				**AVG**
	159	**260**	**313**	**401**	
ME	-0.85	-0.19	-0.47	0.18	-0.33
RMSE	0.93	0.60	0.81	0.70	0.76

Acknowledgements

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References

Chung, U., H. H. Seo, K. H. Hwang, B. S. Hwang, J. Choi, J. T. Lee, and J. I. Yun, 2006: Minimum temperature mapping over complex terrain by estimating cold air accumulation potential. *Agricultural and Forest Meteorology* **137**, 15-24.

Kim S. O., and J. I. Yun, 2016: Feasibility of the lapse rate prediction at an hourly time interval. *Korean Journal of Agricultural and Forest Meteorology* **18**(1), 55-63. (in Korean with English abstract) doi: 10.5532/KJAFM.2016.18.1.55

Kim, S. O., and J. I. Yun, 2011: A quantification method for the cold pool effect on nocturnal temperature in a closed catchment. *Korean Journal of Agricultural and Forest Meteorology* **13**(4), 176-184. doi: 10.5532/KJAFM.2011.13.4.176 (in Korean with English abstract)