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Variations of Soil Temperatures in Winter and Spring at a High Elevation Area (Boulder, Colorado)

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ABSTRACT

The City of Boulder is located at an average elevation of 1,655 m (5,430 feet), the foothills of the Rocky Mountains in Colorado. Its daily air temperature is much varying and snow is very frequent and heavy even in spring. This paper examines characteristics of shallow (surface and depth = 10 cm) soil temperatures measured from January to May 2015 in the high elevation city Boulder, Colorado. The surface soil temperature quickly responded to the air temperature with the strongest periodicity of 1 day while the subsurface soil temperatures showed a less correlation and delayed response with that. The short-time Fourier of the soil temperatures uncovered their very low frequencies characteristics in heavy snow days while it revealed high frequencies of their variations in warm spring season. The daily minimum air temperature exhibited high cross-correlations with the soil temperatures without lags unlike the maximum air temperature, which is derived from its higher and longer auto-correlation and stronger spectrums of low frequencies than the maximum air temperature. The snow depth showed an inverse relationship with the soil temperature variations due to snow's low thermal conductivity and high albedo. Multiple regression for the soil temperatures using the air temperature and snow depth presented its predicting possibility of them even though the multiple r^2 of the regression is not that much satisfactory ($r^2 = 0.35\text{-}0.64$).

Key words : Soil temperatures, Snow, Spectrum, Rocky mountains, Colorado

1. Introduction

The soil temperatures are affected by a variety of natural and anthropogenic factors including solar radiation, wind, vegetation, rain, snow cover, moisture content, land cover, buildings, etc. (Davidoff and Selim, 1988; Zhang et al., 2008; Kim et al., 2015; Teubner et al., 2015; Yoshioka et al., 2015) and the affecting magnitude of each factor can be varying with location (longitude, latitude, and topographic elevation) and interconnected surrounding environments (Wundram et al., 2010). The varying soil temperatures derived from changing climate, influence nutrient supply, soil respiration, and productivity, hence consequently the biological diversity of the soil environment (Chapin III et al., 2000; Rustad et al., 2000). The changing soil environment eventually affects human life because the thin soil layer of the Earth provides nearly all of biomass production, and in turn impacts the changing climate (Nikolaidis and Ragnarsdottir, 2015).

The alpine or high elevation areas have some different weather characteristics from those of low lands. Drastic change in daily weather is quite common and daily air temperature variation (maximum-minimum) is quite large (on average over 15°C in Boulder). It is severely cold in winter and unbearably hot in summer. When it rains, it is subject to be torrential and snow can occur even in summer. In the meanwhile, the impact of changing climate is more profound in alpine and high elevation areas compared with other areas (Beniston et al., 1997; Beniston, 2006). Thus, it is essential to understand response and changes of soil temperatures responding to outer natural factors like air temperature and snow in such high elevation areas to adapt and mitigate the changing climate.

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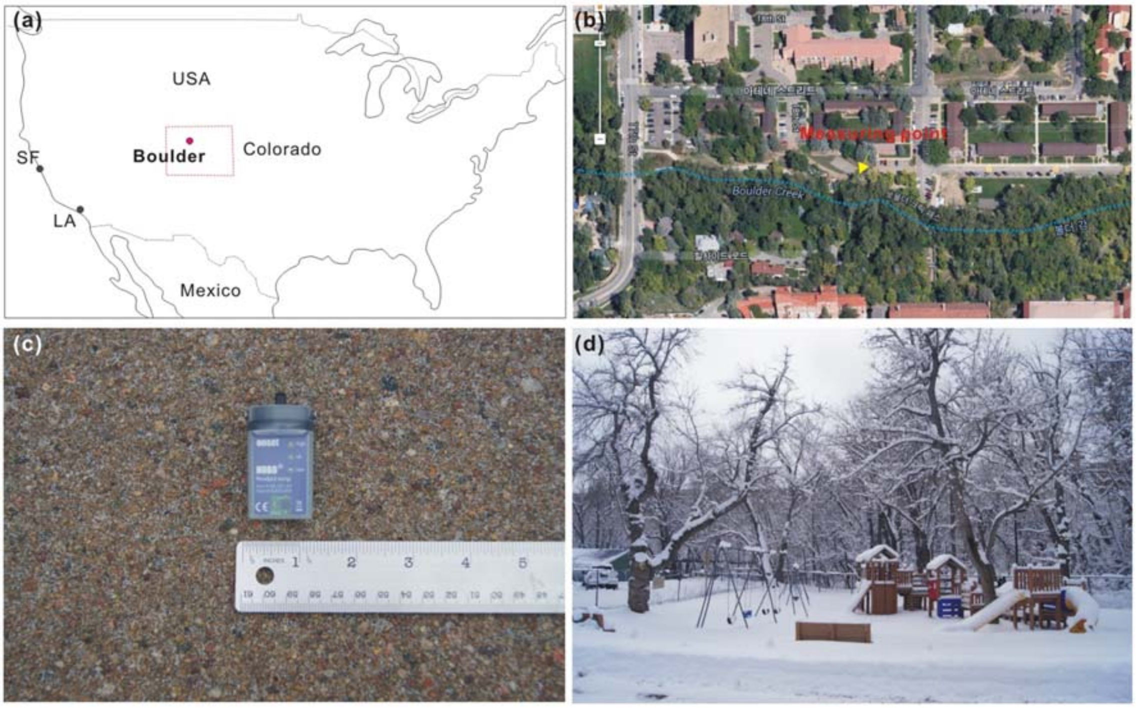

Fig. 1. (a) Location of the City of Boulder, (b) Soil temperature measuring point near the Boulder Creek, (c) Soil temperature logger, and (d) Scene of a snow day (February 28, 2015) near the measuring point.

The objective of this study is to unravel the temporal and spectral characteristics of soil temperatures measured in a highland city, Boulder, Colorado, USA. For the purpose, the soil temperatures using automatic temperature sensors were monitored and then analyzed using time and frequency domain functions, and multiple regression functions.

2. Methods and Materials

2.1. Study Area

The study area is located in the city of Boulder, Colorado, USA (Fig. 1a) and it is situated at the foothills of the Rocky Mountains. The mean elevation is 1,655 m and the city is home to the University of Colorado (CU), the state's largest university. The city covers 66.5 km^2 and its population is 102,420 as of 2014 (City of Boulder, 2014). The highest air temperature was 36.7°C in 2013 and the lowest was −37.8°C in 1975 (NOAA, 2015). Generally, July is the hottest (monthly mean = 24°C) and February is the coldest (monthly mean = 0°C). The average annual precipitation for 1893-2013 is 4,823 mm, much of it occurs in April and May (NOAA, 2015), and occasionally causes flash floods in the city (Morss et al., 2015). Mean annual snowfall for 1897-2014 is 199.76 cm (snow depth, not water equivalent) and snow occurs in most of months only except July and August (NOAA, 2015). The freezing index of this city is 368 °F·days (NOAA, 2015).

There are two great geologic provinces in the Boulder area; the eastern one is the Great Plains and the western one is the Rock Mountains (BASIN, 2015). The main city area is in the flatland, east of the Rockies. The geology of the city is mainly comprised of sedimentary rocks, from Lyons Sandstone of Permian age in the west to Pierre Shale of Cretaceous age in the east, and on the top of the Shale, there is the gravel cap in the Boulder valley (main city area), from which the name of the city is originated (Fennenman, 1905; Baker, 1974; Bilodeau et al., 1987). Especially, the sandstones of Fountain Formation of Pennsylvanian age (called Flatirons) colored in red mainly due to hematite weathering (Wells, 1967; Baker, 1974; Bilodeau et al., 1987; BASIN, 2015) feature a spectacular landscape and attract many travelers from all over the world.

According to Rigg(1993) the soil properties around the study area in the city are as follows: soil moisture 17.19-

20.38%, pore space 29.99-32.04%, pH 6.13-7.42, organic matter 5.91-8%, bulk density 0.81-1 g/cm^3, NH_4 0.15-0.51 meq/100 g, and SO_4 0.06-0.22 meq/100 g. The soil textures are sand 68.15-83.36%, silt 13.95-20.18%, and clay 2.69-13.45% (Rigg, 1993).

2.2. Data Collection

The soil temperatures were monitored every hour in the campus of CU Boulder (Fig. 1b) from January 12 to May 31, 2015. The three points were selected in the backyard of Faculty Staff Court and they formed a triangle shape with distances of 1 m each other. One waterproof temperature sensor (HOBO temperature loggers, UA-001-64, ONSET, USA) (Fig. 1c) was buried at surface soil (1 cm depth) and two at 10 cm depths (named 10R (right) and 10L (left)). The sensor can measure the temperatures from −20 to 70°C with accuracy of ±0.53°C and resolution of 0.14°C. I also measured air temperature on site using a commercial thermometer and the snow depth using a steel ruler (see Figs. 1b and 1d) for January 12 to March 31, every day around 3 pm. Resolutions of the thermometer and ruler are 1°C and 1 mm, respectively.

Daily air temperature and snow depth data were collected for the period of January 1 to May 31 from a NOAA observatory (http://www.esrl.noaa.gov/psd/boulder/), 2 km east from the soil temperature measuring points. The NOAA provides daily maximum and minimum air temperatures data (daily mean values are not provided) and maximum snow depth. These data were compared with the manually measured air temperature and snow depth data on site. There is a stream (Boulder Creek), 20 m apart from the measuring points, running west to east (see Fig. 1b). Occasionally the stream water temperatures were also measured for some reference using the thermometer.

2.3. Time and Frequency Domains Analysis

In this study, in order to unravel variation characteristics of air and soil temperatures, some representative time and frequency functions were used, including autocorrelation, spectral density, cross-correlation, and short-time Fourier (Larocque et al., 1998; Lee and Lee, 2000; Kim et al., 2005). Details on these functions can be found in many literatures including Duffy and Gelhar(1986), Box et al.(1994), and Padilla and Pulido-Bosch(1995). In the short-time Fourier analysis, window and its size were Welch and 32 (Hammer, 2012), respectively. The soil temperature is the main focus of this study, so to model the soil temperature, a multiple regression method was applied (Zhang et al., 1997; Adlam et al., 2010) using air temperature and snow depth. All these calculations were done with the help of Hammer (2012). Before the time and spectral analyses, trends were removed from the original time series data using the liner regression (Lim et al., 2011; Hammer, 2012).

3. Results and Discussion

3.1. Weather Conditions

Weather data for January 1 to May 31, 2015 are presented in Fig. 2. During the period, the maximum daily air temperature (from NOAA data) ranged −7.8 to 30°C (mean = 14.1°C) while the minimum air temperature was between −18.3 and 12.2°C (mean = −0.3°C). Around end of February, the coldest air temperature was recorded. The daily variation of air temperature (maximum-minimum) was large, ranging from 2.2 to 30°C (mean = 14.5°C). The manually measured on site air temperature data are generally between the maximum and minimum temperatures (Fig. 2a) and their Pearson correlation coefficient are 0.88 and 0.72, respectively. It is considered the NOAA air temperature data (2 km apart from the site) represent well the air temperature condition on site and thus they were used in the further analysis instead of the shorter manually measured air temperature data.

Fig. 2b shows the daily snowfall and maximum snow depth for the period. The daily snowfall ranged from 0 to 241.3 mm/day with a mean of 13.4 mm/day. For 151 days of monitoring, snow occurred in 27 days (17.9%). Coincident with the coldest weather in late February (see Fig. 2a), a large quantity of snow was also recorded. Among the total of precipitation (2,455.4 mm) during the period, snow accounts for 82.7% (2,029.5 mm). The snow depth in the same period ranged from 0 to 35.56 cm with a mean of 3.89 cm, which is very similar to that manually measured on site ($r = 0.94$ at $p = 0.00$). So it is can be said that the weather conditions at the two sites (the soil temperature monitoring site and the NOAA site, 2 km apart) are very similar.

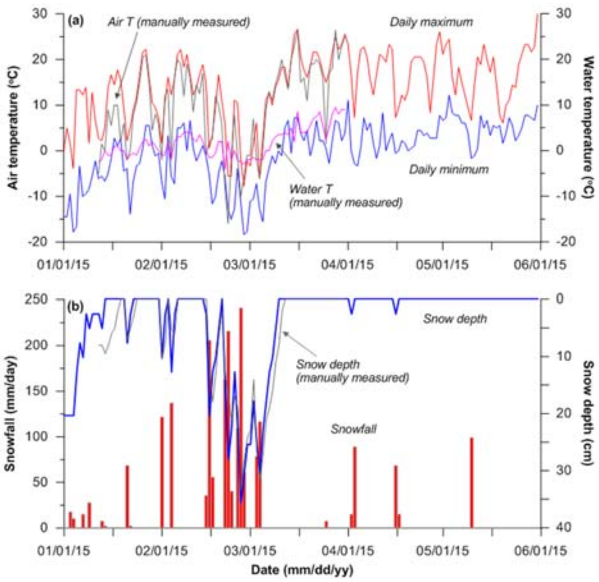

Fig. 2. (a) Daily maximum and minimum of air temperatures (January 1 to May 31, 2015) measured at a NOAA site, 2 km east from the soil temperature measuring point where air temperature and nearby stream water temperatures were also manually measured (January 12 to March 31), and (b) Daily snowfall and snow depth measured at the NOAA site, also showing the snow depth manually measured (using a ruler) at the soil temperature point.

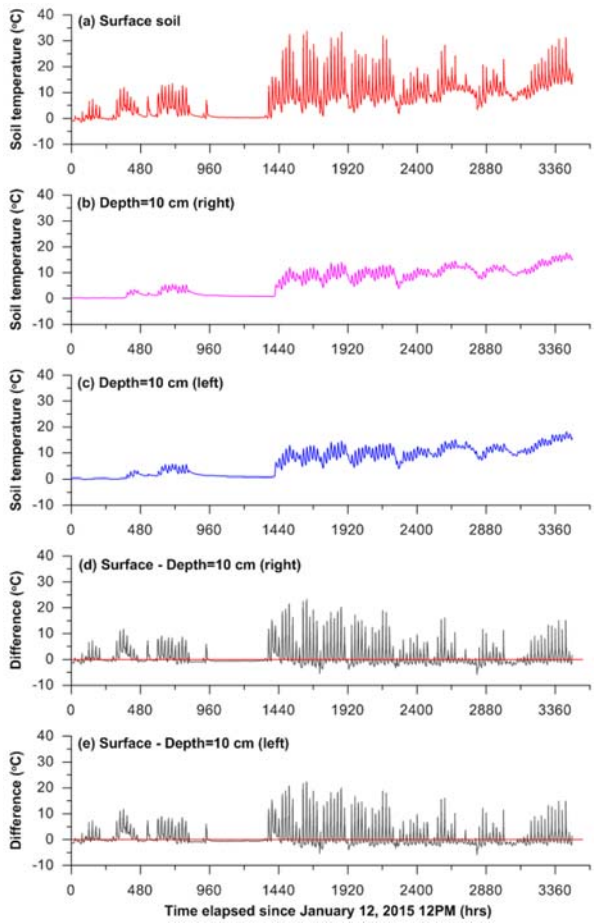

Fig. 3. Soil temperatures (January 12 to May 31, 2015) measured at (a) surface, (b) depth of 10 cm, 1 m right of the surface soil temperature measuring point, (c) depth of 10 cm, 1 m left of the surface soil temperature point, (d) temperature difference between surface and depth 10 cm (right), and (e) that between surface and depth 10 cm (left).

3.2. Time and Spectrum Characteristics of Soil Temperatures

Fig. 3 shows the recorded soil temperatures at surface (a), depth of 10 cm (b and c), and temperature difference between at surface and depth of 10 cm (d and e). The surface soil temperature was between −1.5 and 33.8ºC with a mean of 7.1ºC during the period, with a increasing trend (0.10ºC/day, $r^2 = 0.47$). However, in the late February and early March (heavy snow days), it was nearly constant, not changed. The daily fluctuation of the surface soil temperature was marked and it generally was small in January, was increasing with time. The shallow soil temperatures (depth = 10 cm) showed ranges of 0.1-16.3ºC (mean = 6.3ºC; right) and −0.1-16.9ºC (mean = 6.4ºC; left) and they also showed the increasing trends (0.10ºC/day at $r^2 = 0.80$ and 0.11ºC at $r^2 = 0.79$, respectively).

However, the amplitudes of daily fluctuations were much smaller than that of the surface soil temperature, but also in these cases, the very stable soil temperatures in late February and early March were observed when snow was heavy and its depth was large. Figs. 3d and 3e show the difference between surface and shallow subsurface soil temperatures. The differences were between −5.7 and 23.3ºC (mean = 0.8ºC; Fig. 3d), and between −5.9 and 22.4ºC (mean = 0.7ºC, Fig. 3e). The positive and negative differences were alternating with time but the positive ones are more distinctive and predominant, indicating primarily downward heat flux in the shallow soil during the period. Fig. 4 shows the bivariate plots of the surface and shallow soil temperatures. As expected, the surface and shallow soil temperatures are closely related ($r^2 = 0.72$ and 0.73). Considering the temperature distribution around the 1 : 1 line, it is noted that the surface soil temperature was mostly higher than the shallow subsurface soil temperatures and the temperature turnover was not significant.

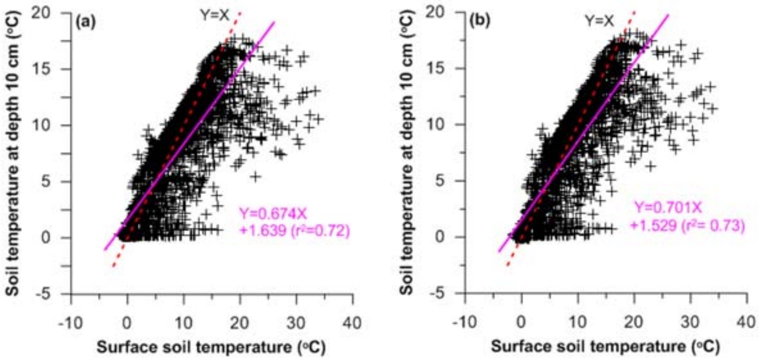

Fig. 4. Bivariate plots of soil temperature at surface and those of depth of 10 cm (a: right (10R), b: left (10L)).

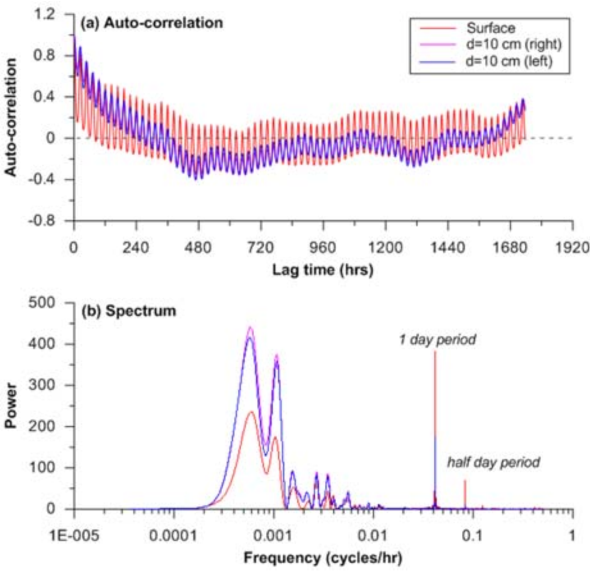

Fig. 5. Auto-correlation and spectrum of hourly soil temperatures.

Fig. 5 shows auto-correlation and spectral density of the soil temperatures. Auto-correlation indicates inter-dependency of successive values (Larocque et al., 1998; Lee and Lee, 2000). The auto-correlation of the surface soil temperature gradually decreases with lag times with periodic fluctuation and reach the null value (0) at a lag time of 82 hours (3.4 days) while the shallow soil temperatures show slower decreasing trends with similar fluctuations and reach the null value at 273 hours (11.4 days) and 250 hours (10.4 days), which indicate the subsurface soil temperatures have a longer memory effect than the surface soil temperature.

The spectrums of the soil temperatures (Fig. 5b) reveal the periodicities of their signals. The highest power (381.2) of the surface temperature at f = 0.0416 means a daily periodicity (cyclic variation) and the second peak (69.3 at f = 0.0834) in high frequencies is indicative of the semidiurnal periodicity. The spectrums of the subsurface temperatures (depth = 10 cm) show somewhat different distributions. The powers of low frequencies (< 0.005) are greatly elevated while those of high frequencies are largely lessened. Even though the daily cyclic behavior is still distinctive (powers 139.3 and 173.7 at f = 0.0416), the semidiurnal variation almost disappeared (powers 8.4 and 10.2 at f = 0.0834). All these spectrums indicate that the surface soil temperatures quickly respond to variations in air temperature or solar radiation while the subsurface soil temperatures slowly respond to that due to heat signal attenuation during transmission through soil.

Fig. 6 shows the short-term Fourier of the soil temperatures during the monitoring period. In the first 800 hours (33.3 days), the spectrum of the surface air temperature shows discernible peaks only in low frequencies, and at around 800-1,500 hours (coincident with heavy rain and thick snow period), the spectrum is greatly strengthened in the lowest frequencies, which is well explained by very stable soil temperature for the time period (see Fig. 3a). After that, some significant spectrums also in high frequencies (> 0.1) can be found and this is closely related with very frequent fluctuations of the surface soil temperatures for the period (after 1,500 hours) due to outer stresses such as changes in air temperature and solar radiation. The above phenomena are also found in the Fourier of the subsurface soil temperatures (Figs. 6b and 6c). However, due to delayed and attenuated heat transmission through soil, spectrums of lower frequencies are highly strengthened but those of high frequencies nearly completely disappeared,

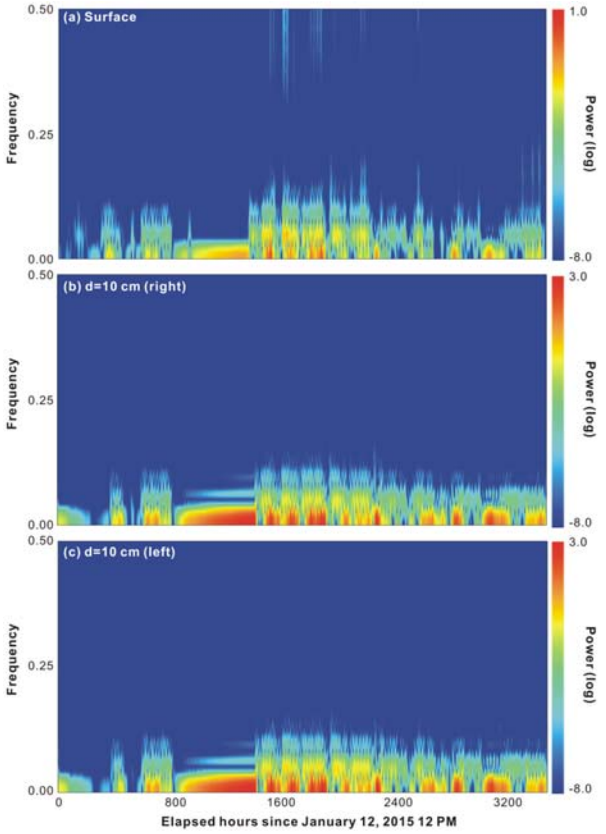

Fig. 6. Shot-time Fourier transforms of soil temperatures. The window function is Welch and its size is 32 (Hammer, 2012).

which is well consistent with the original soil temperatures behaviors (see Fig. 3b and 3c). So the short-term Fourier is very useful to reveal variation characteristics of certain signals with time.

3.3. Correlations with Air Temperatures and Snow Depth

Fig. 7 shows correlations of the soil temperatures with outer air temperatures. The maximum air temperature shows very high correlation (r = 0.80) with the surface soil temperature at null lag time, which means the surface soil temperature responds quickly to the air temperature. The correlation reached the null value at a lag time of 15 days. However, the subsurface soil temperatures show somewhat delayed and lowered peak correlations (r = 0.69 and 0.69 at a lag time of 1 day), which is due to heat flux attenuation during its propagation through soil. The correlations reached the null value at lag times of somewhat delayed 17 days. However, compared with the maximum air temperature, the daily

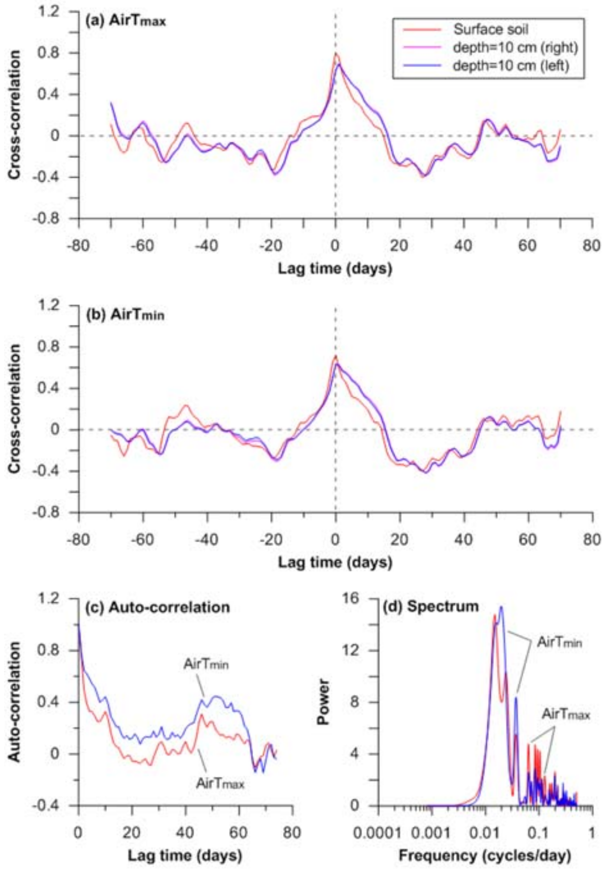

Fig. 7. Correlations of soil temperatures with (a) maximum air temperature and (b) minimum air temperature, and (c) auto-correlations and (d) spectrums of max. and min. air temperatures.

minimum air temperature shows different behaviors, showing lowered peak correlations (r = 0.72, 0.64, and 0.64, respectively) without lag times. These differences are derived from differences in time and spectral characteristics of the two air temperatures (Figs. 7c and 7d). The minimum air temperature has a longer memory effect like the soil temperatures and it has higher powers of low frequencies (longer periodicity) while the maximum air temperature has a shorter memory and higher powers of high frequencies (Fig. 7d).

The correlation of the daily soil temperature variations (maximum-minimum) with the snow depth was also examined. Fig. 8a shows relationships among the snow depth (SD) and daily variations in air temperature (ATV), and soil temperatures (STV). The daily air temperature variation was between 2.2 and 23.9ºC (mean = 14.2ºC) but it was not much varying with time (coefficient of variation (CV) =

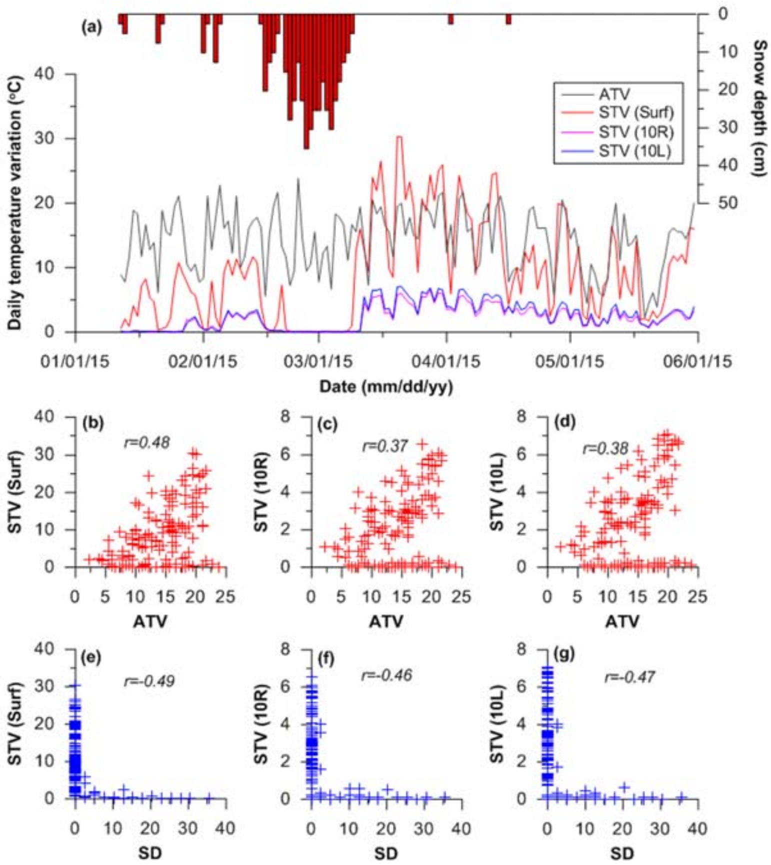

Fig. 8. Daily soil temperatures variations (maximum-minimum; STV) with those of air temperatures (ATV) and snow depth (SD), and their correlations. Surf: surface soil, 10R: depth = 10 cm (right), 10L: depth = 10 cm (left).

0.33). The daily variation in the surface soil temperature was between 0 and 30.3°C (mean = 9.2°C) and it is generally increasing towards the warming months (CV = 0.85) except for the heavy snow days (late February to early March).

The subsurface temperature variations were very similar to those of the surface soil temperature except the amplitudes of the variations were much smaller. Also in these cases, the practically no variations of the subsurface soil temperatures are found in the snow days. As one of main influencing factor on the soil temperatures, the air temperature variation is substantially positively linked with the soil temperatures variation (r = 0.48, 0.37, and 0.38, respectively; Figs. 8b-8d). The snow depth, however, is inversely related with the soil temperature variations (r = –0.49, –0.46, and –0.47, respectively; Figs. 8e-8f). Therefore, it is considered the snow depth strongly affects the soil temperature variations due to its insulation effect by low thermal conductivity and high albedo (Zhang, 2005; Zhang et al., 2008).

3.4. Estimation of Soil Temperatures using Multiple Regressions

The possibility to modeling the soil temperatures using multiple regression of the air temperature (maximum and minimum applied separately) and the snow depth, most influencing factors that are available, was examined. Fig. 9 shows the multiple regression results for the surface and subsurface soil temperatures. It is seen that the surface soil temperature is comparatively well represented by both the parameters even though they cannot explain well that for the heavy snow days (Fig. 9a). Interestingly, in the case of using the minimum air temperature, the surface soil temperature is better explained (r^2 = 0.64) than the maximum air temperature (r^2 = 0.56). In both cases of the subsurface soil temperatures (Figs. 9b and 9c), the soil temperatures in the cold days (around before March) were poorly represented by the multiple regression while those in warmer days (after March) are relatively better explained by them. Consider-

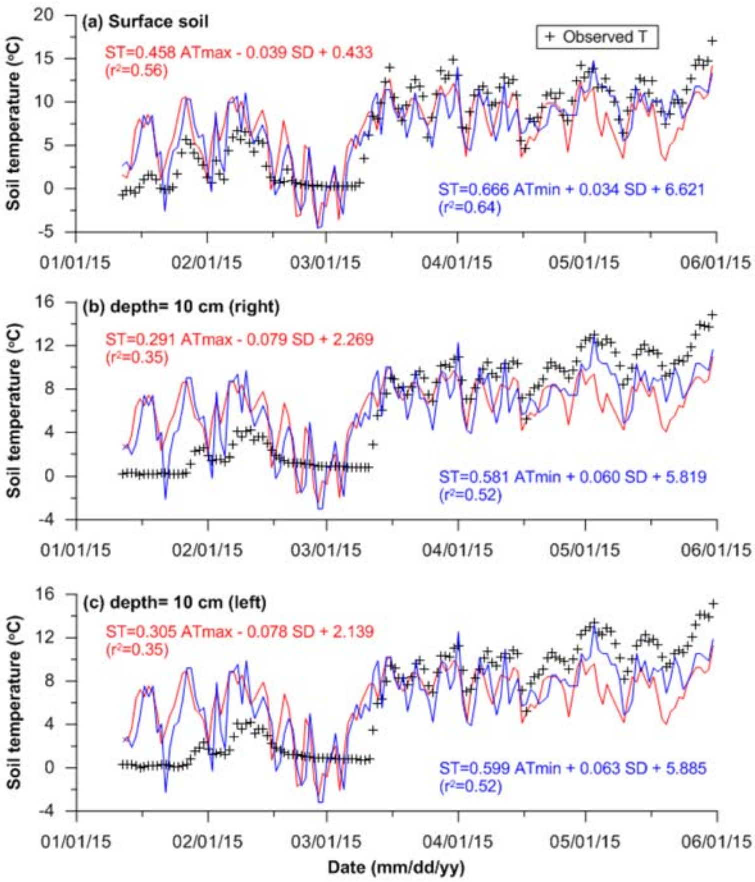

Fig. 9. Estimated soil temperatures using multiple linear regression based on air temperature (ATmax and ATmin) and snow depth (SD).

ing the low multiple r^2 (0.35 and 0.52) of those regression, however, there is a room for large improvement regarding the multiple regression by incorporating other important parameters even though the minimum air temperature shows still a better performance. It is noted that there are many influencing factors on soil temperatures (Zhang, 2005; Kim et al., 2015). Therefore, the somewhat unsuccessful analyses in this study using two parameters in estimating the soil temperatures are not discouraging. If more data such as solar radiation and moisture content are available, the prediction can be more accurate and reliable.

4. Conclusion

The temporal and frequency characteristics of the soil temperatures measured from a high elevation city Boulder, Colorado were examined. The weather condition in the city is much different from low lands in that there is frequent snow and a large daily change in air temperatures. Main findings from this study are as follows: 1) The surface and shallow subsurface soil temperatures well respond to changes in the air temperature but the daily variation amplitude is larger in warmer days, 2) The short-time Fourier is useful to uncover the spectrum characteristics of the soil temperatures with elapsing time, 3) The soil temperatures variations are inversely related with the snow cover depth due to its insulation effect by low thermal conductivity and high albedo, and 4) the shallow soil temperatures are not well explained by the multiple regression using air temperature and snow depth, so further incorporation of other important parameters is needed for a better prediction. Finally additional monitoring at various points considering land use in the city is essentially required for more reliable analysis.

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