Horizontal and vertical variability of observed soil temperatures

Bradley G. Illston and Christopher A. Fiebrich
Oklahoma Mesonet/Oklahoma Climatological Survey, University of Oklahoma, Norman, OK, USA

Correspondence: B. G. Illston, Oklahoma Climatological Survey, University of Oklahoma, 120 David L. Boren Blvd, Suite 2900, Norman, OK 73072-7307, USA, E-mail: illston@ou.edu

The research presented in this paper was funded by the Oklahoma Mesonet and South Central Climate Science Center.

Two datasets of soil temperature observations collected at Norman, Oklahoma, USA, were analysed to study horizontal and vertical variability in their observations. The first dataset comprised 15-min resolution soil temperature observations from 20 September 2011 to 18 November 2013 in seven plots across a 10-m transect. In each plot, sensors were located at depths of 5, 10, and 30 cm. All seven plots observed fairly consistent maximum soil temperature observations during the spring, fall, and winter months. Starting in late May, the observed spread in soil temperatures across the 10-m transect increased significantly until August when the observed spread in temperatures decreased. The range of observed minimum soil temperature was more consistent year-round at the shallower depths, but showed similar patterns to the maximum soil temperature ranges at deeper depths. The second dataset comprised 15-min resolution soil temperature observations from 20 November 2013 to 1 December 2015 in a single plot at the same location as the first dataset. Soil temperature sensors were placed every 2 cm from the surface down to 40 cm deep to study the vertical variability in soil temperature measurements (focusing on a winter and a summer case). Both winter and summer conditions showed that the temperature differences between depths behaved logarithmically with the shallower depths having larger differences than deeper depths.

Geosci. Data J. 4: 40–46 (2017), https://doi.org/10.1002/gdj3.47
Received: 6 April 2017, revised: 23 June 2017, accepted: 11 July 2017
Key words: soil temperature, variability, BetaTHERM, Oklahoma Mesonet

Dataset
Identifier: https://doi.org/10.15763/dbs.mesonet.research.soiltempvar
Creator: Oklahoma Mesonet [Illston, B. G.]
Title: Mesonet soil temperature variability dataset
Publisher: Oklahoma Mesonet
Publication year: 2015
Resource type: Dataset
Version: 1.0

Introduction
Soil temperature measurements are important to many end users ranging from those in the agricultural sector (Stone et al., 1999; Mavi and Tupper, 2004; Patil et al., 2010) to meteorological modellers (Godfrey and Stensrud, 2008) to engineering (Omer, 2008). As a result, more observations of soil temperatures are being collected in networks of varying spatial scales from single watersheds (Cosh et al., 2008; Steiner et al., 2008) to regional (McPherson et al., 2007) to national in scope (Schaefer et al., 2007). With any type of observing methodology, challenges exist in ensuring high-quality data are collected and in understanding the limitations of those observations. In addition, the variability in those observations must be understood to best utilize the collected data. Soil temperature observations are impacted by many factors that can cause variabilities in their measurements (Davidoff and Selim, 1988; Shumway et al., 1989; Mohanty et al., 1995).

Understanding the range of temperatures inherent across an observing station allows one to more accurately quality assure the data. In addition, due to the erosion or deposition of soil, understanding vertical variability in soil temperatures can provide knowledge of the impacts from small depth changes to measured values. Scharringa (1976) showed that horizontal and
vertical gradients can become quite large in the near-surface profile of the soil. Their work showed that vari-
ances can reach 1.2 °C at 5 cm, 0.9 °C at 10 cm, and 0.8 °C at 20 cm over a 20 m × 21 m plot of bare
sandy soil. In addition, variations in soil temperatures
exist due to vegetation (Scharringa, 1976) or
altering of the soil surface from heavy rains or cracks
due to drought (Fiebrich and Crawford, 2001; Fiebrich
et al., 2010).

The Oklahoma Mesonet (doi: 10.15763/ dbs.mes-
onet), commissioned in 1994, is an automated net-
work of 121 remote, meteorological stations across
Oklahoma (Brock et al., 1995; McPherson et al.,
2007). Each station measures core parameters that
include: air temperature and relative humidity at
1.5 m; wind speed, gust, and direction at 10 m; wind
speed at 2 m; atmospheric pressure; global down-
wellng solar radiation; rainfall; bare soil temperature
at 10 cm below ground level; and vegetated soil
temperatures at 5 and 10 cm below ground level. In
addition, many stations also measured or currently
measure bare soil temperature at 5 cm; vegetated
soil temperature at 25 or 30 cm; and soil moisture
at 5, 25, and 60 cm. Mesonet data are collected and
transmitted to a central facility every 5 min where
they are quality controlled, distributed, and archived
(Shafer et al., 2000; http://mesonet.org). The Okla-
ahoma Mesonet has measured soil temperature under
bare soil and native vegetation since 1994 at over
100 sites.

1. Materials and methods

To better understand the spatial variability in soil tem-
perature, two separate experiments were conducted
by the Oklahoma Mesonet: a comparison between
seven plots of soil temperature probes across a 10-m
transect (e.g. the width of a Mesonet station) and an
analysis of 21 soil temperature probes placed 2 cm
apart vertically in a single location. Data were col-
clected for over 4 years to provide a sufficient number
of observations for analysis.

The soil temperature sensors utilized in these
studies were BetaTHERM stainless steel encased
10 K thermistor assemblies (Part # 10K3D410 made
by Measurement Specialties in Shrewsbury, MA). The
Oklahoma Mesonet used this style of sensor opera-
tionally between 1996 and 2013 (McPherson et al.,
2007). The BetaTHERM assemblies are a 10K NTC
thermistor housed in a 0.32-cm-diameter, 15-cm-long
stainless steel sheath with the thermistor bead pot-
ted inside the end of the sheath. These sensors
have a calibrated range of −20 °C to 60 °C with an
accuracy of ±0.5 °C. Each sensor went through
quality control in the Oklahoma Mesonet’s calibration
laboratory before deployment (McPherson et al.,
2007). Upon completion of the study, each sensor
was reanalysed in the Mesonet’s calibration labora-
tory to ensure that no bias or drift had occurred
during field use.

1.1. Horizontal variability study

In order to study the horizontal variability in soil tem-
peratures, seven identical installations of soil tempera-
ture sensors were placed across a 10-m transect near
the Norman, Oklahoma Mesonet station (Figure 1).
Each plot utilized a PVC track with holes at the appro-
priate measurement depths to reduce soil upheaval
and ensure that the sensors remained at the required
depths. Each plot had soil temperature sensors
inserted horizontally through the PVC track at depths
of 5, 10, and 30 cm. These depths were selected to
match existing soil temperature measurements depths
of the Oklahoma Mesonet. The sensors’ wires were
looped downwards before emerging from the plot to
eliminate preferential flow of rainfall down the wire
and to the sensor. Each sensor was wired into a data-
logger for data collection every 15 min. Data were col-
clected for over 2 years from 20 September 2011 to 18
November 2013 and were manually quality assured by
an Oklahoma Mesonet research scientist. The vegeta-
tion at the study site was controlled regularly to main-
tain similar conditions to the surrounding native
vegetation. The soil textures at the study location
were silty clay (i.e. 8.3% sand, 49.0% silt, and 42.7%
clay) at 5 cm, silty clay loam (i.e. 17.7% sand, 48.4%
silt, and 33.9% clay) at 25 cm, and silty clay (i.e.
12.5% sand, 41.5% silt, and 46.0% clay) at 60 cm.

1.2. Vertical variability study

Upon conclusion of the horizontal variability study at
the Norman, Oklahoma Mesonet station, the study
area was reconfigured to analyse the vertical variabil-
ity in soil temperature measurements. All 21 sensors
were moved to one plot and placed every 2 cm from
the surface (the first sensor positioned at ground
level) down to 40 cm (Figure 2). Similar to the previ-
ous study, the sensors were mounted through a PVC

Figure 1. Horizontal soil temperature variability study area at Norman, Oklahoma, USA. The seven plots, each instrumented with soil temperatures at 5, 10, and 30 cm, are indicated by orange stakes.
track to ensure that each sensor remained at its desired depth with its wires looped downwards to reduce the impact of preferential flow of rain water. Data were collected every 15 min for over 2 years from 20 November 2013 to 1 December 2015 and were manually quality assured.

2. Results and discussion

2.1. Horizontal variability study

It became immediately obvious that even though each of the seven test plots were installed with calibrated sensors at identical depths, they rarely recorded identical soil temperatures. The range of temperatures observed across the seven plots varied by depth of the sensor, by time of the year, and by time of day. The predominate impact to the variability in soil temperature measurements came from summer-time heat, but rainfall events also contributed to changes in soil temperature variability during the spring months.

The range of maximum daily soil temperatures at a depth of 5 cm can be seen in Figure 3(a). The range of maximum temperatures across the seven plots was between 1.0 and 2.0 °C for most of the year. However, once daily maximum soil temperatures at 5 cm reached ~30 °C, the range of maximum daily temperatures varied by ~4.5 °C in 2012 and ~6.0 °C in 2013. Thus, it would be impossible to accurately characterize the maximum soil temperature at 5 cm during the summer months with a single sensor. The range of minimum daily temperatures of soil temperatures observed at a depth of 5 cm is shown in Figure 3(b). The minimum temperatures across the seven plots varied between 0.5 and 1.5 °C for most of the year.

The range of observed maximum daily soil temperatures across the seven plots at a depth of 10 cm is shown in Figure 3(c). The range of temperatures had a very similar pattern to the 5 cm data. Maximum daily temperatures at 10 cm varied by 0.5–1.5 °C for most of the year. Again, once daily maximum soil temperatures at 10 cm reached ~30 °C, the range of observed temperatures increases to ~3.0 °C in 2012 and ~4.5 °C in 2013 across the plots. During the spring months, the ranges oscillated up and down due to synoptic scale rainfall and heating/cooling patterns. The range of minimum daily soil temperatures at 10 cm is shown in Figure 3(d). The range of temperatures across the seven plots was ~0.5 °C for most of the year.

The range of maximum daily soil temperatures at 30 cm can be seen in Figure 3(e). The range of temperatures across the seven plots had a very similar pattern to the 5 and 10 cm data with ranges slightly less at ~0.5 °C across the seven plots for most of the year. Once daily maximum soil temperatures at 30 cm reached ~25 °C, the range of temperature values increased to ~2.0 °C in 2012 and ~1.5 °C in 2013. The range of minimum daily soil temperatures at 30 cm is shown in Figure 3(f). Minimum temperatures across the seven plots generally agreed within 0.5 °C for most of the year with an increase in variability during the summer warming periods. Overall, all three soil temperature depths showed similar patterns with smaller variability at deeper depths throughout the year. At 5, 10, and 30 cm, the horizontal range of soil temperatures remained consistent during the spring, fall, and winter months with the range of maximum temperatures at 0.3–2.0 °C, 0.3–1.5 °C, and 0.3–0.5 °C, respectively, and the range of minimum temperatures at 0.3–1.3 °C, 0.3–1.0 °C, and 0.2–0.5 °C. During the late spring, the ranges of soil temperatures peaked in August at values of 4.5–6.5 °C, 3.0–4.5 °C, and 1.5–2.0 °C for maximum temperatures and 1.5–2.5 °C, 1.5–2.0 °C, and 1.5–2.0 °C for minimum temperatures. The ranges then quickly decreased during the cooler seasons. The difference in larger variabilities in maximum soil temperatures between the summers of 2012 and 2013 is likely due to different soil moisture conditions (not shown). The soil remained dry throughout the soil column during summer of 2012, while the soil was more consistently wet at deeper depths during the summer of 2013. This likely led to the reduced variability at 30 cm during the summer of 2012.

2.2. Vertical variability study

To understand the variability in soil temperatures with depth, the diurnal range of temperatures at different depths must be considered as soil temperatures at
2 cm observe larger diurnal ranges than those at 40 cm. In addition, the air temperature, the thermal load, and soil moisture conditions all impact heat transfer rates through the soil profile. Due to different temperature change rates depending upon depth, analysis of the vertical stratification of soil temperatures was performed at the temperatures’ maximum or minimum values. Typically, at sunset during the winter and just after sunrise in the summer, all of the temperatures were nearly identical. In addition, rainfall events and frontal passages caused inconsistencies in the typical vertical stratifications of soil temperatures. As a result, 2 weeks (one summer and one winter) with calm, synoptic conditions were analysed to most

Figure 3. Temperature range (°C, black line) of maximum (a, c, e) and minimum (b, d, f) daily temperatures at 5 cm (a, b), 10 cm (c, d), and 30 cm (e, f) from 20 September 2011 to 18 November 2013 for the seven soil temperature plots. For reference, daily maximum and minimum observed temperatures (°C) from the seven plots are shown by the red lines.
accurately determine how soil temperatures were vertically stratified.

Vertical soil temperature data from a winter week (15 January 2014–21 January 2014) are shown in Figure 4(a). For each day (e.g. Figure 4(c)), the transfer of heat through the soil profile caused all depths to observe relatively homogeneous soil temperatures near sunset (~01 UTC). Daily minimum temperatures typically occurred shortly after sunrise with the coldest temperatures at the surface and warmest temperatures at deeper depths. The change in soil temperature with depth decreased logarithmically with depth as shown from the 19 January data (Figure 4(e); Table 1). A linear regression was performed and a
resulting logarithmic equation was derived (Figure 4(e)) that gave a mean square error of 0.8302; however, this equation is likely only applicable in soil profile characteristics similar to this study site. Similar logarithmic patterns are seen each day with only slight variations.

Vertical soil temperature data from a summer week (20 August 2014–26 August 2014) are shown in Figure 4(b). For 22–23 August 2014 (Figure 4(d)), the shallower depths peaked earliest (e.g. 2045 UTC at 2 cm) while the deeper depths peaked over the next few hours (e.g. 0215 UTC at 20 cm; 0615 UTC at 30 cm; and 0845 UTC at 40 cm). Similar to the winter week, the differences between the maximum temperature of the day for the sensor at the depth above it changed at a logarithmic rate as shown from the 22 August 2014 data (Figure 4(f); Table 1). A linear regression was performed and a resulting logarithmic equation was derived (Figure 4(f)) that gave a mean square error of 0.9780; however, this equation is likely only applicable in soil profile characteristics similar to this study site. Similar logarithmic patterns were observed each day with only slight variations.

Overall, vertical variability in soil temperatures is difficult to quantify due to many external sources that can impact sensors at different times and at different rates. However, both winter and summer conditions showed that the temperature differences between depths changed logarithmically with the shallower depths having larger differences than deeper depths. The winter week had smaller changes than the summer, but this is to be expected given that the diurnal temperature during that period was much smaller allowing for fewer heat loads and releases.

### Table 1. Soil temperature change by depth during 19 January 2014 (“Winter”) and 22 August 2014 (“Summer”).

| Depth       | Winter | Summer |
|-------------|--------|--------|
| 2–4 cm      | 0.98   | –3.05  |
| 4–6 cm      | 0.92   | –1.24  |
| 6–8 cm      | 0.48   | –0.71  |
| 8–10 cm     | 0.30   | –0.46  |
| 10–12 cm    | 0.25   | –0.43  |
| 12–14 cm    | 0.35   | –0.42  |
| 14–16 cm    | 0.12   | –0.29  |
| 16–18 cm    | 0.28   | –0.34  |
| 18–20 cm    | 0.24   | –0.34  |
| 20–22 cm    | 0.21   | –0.15  |
| 22–24 cm    | 0.24   | –0.36  |
| 24–26 cm    | 0.11   | –0.18  |
| 26–28 cm    | 0.24   | –0.09  |
| 28–30 cm    | 0.01   | –0.14  |
| 30–32 cm    | 0.11   | –0.26  |
| 32–34 cm    | 0.19   | –0.07  |
| 34–36 cm    | 0.14   | –0.16  |
| 36–38 cm    | 0.12   | –0.03  |
| 38–40 cm    | 0.18   | –0.09  |

### 3. Conclusions

The goal of these analyses was to better understand the horizontal and vertical variability in soil temperature measurements. Looking horizontally across a 10-m transect, observations of maximum soil temperature typically varied between 0.3 and 2.0 °C from early fall through late spring. Over the summer, the variability in maximum soil temperature increased to over 6.5 °C over seven closely located plots. For minimum soil temperatures, soil temperatures across a 10-m transect typically varied between 0.3 and 1.3 °C from early fall through late spring, but increased to over 2.5 °C in the summer. When looking at a vertical profile of soil temperatures, the temperature differences between depths varied logarithmically with the shallower depths having larger differences (over 0.67 °C/cm in the summer and over 0.33 °C/cm in the winter at 10 cm or shallower) than deeper depths (over 0.11 °C/cm in the summer and over 0.10 °C/cm in the winter at 10 cm or deeper) and colder season temperatures having smaller changes than those during the warm season. With the knowledge gained from this study, those making decisions using soil temperature observations can have a better understanding of its horizontal and vertical variability.

### Acknowledgements

Continued funding for maintenance of the Oklahoma Mesonet is provided by the taxpayers of the State of Oklahoma. Financial support for this research was also provided by the South Central Climate Science Center.

### References

Brock FY, Crawford KC, Elliott RL, Cuperus GW, Stadler SJ, Johnson HL, Eilts MD. 1995. The Oklahoma Mesonet: a technical overview. *Journal of atmospheric and oceanic technology* 12: 5–19.

Cosh MH, Jackson TJ, Moran S, Bindlish R. 2008. Temporal persistence and stability of surface soil moisture in a semi-arid watershed. *Remote Sensing of Environment* 112: 304–313.

Davidoff B, Selim HM. 1988. Correlation between spatially variable soil moisture content and soil temperature. *Soil Science* 145: 1010.

Fiebrich CA, Crawford KC. 2001. The impact of unique meteorological phenomena detected by the Oklahoma Mesonet and ARS Micronet on automated quality control. *Bulletin of the American Meteorological Society* 82: 2173–2187.

Fiebrich CA, Morgan CR, McCombs AG, Hall PK, McPherson RA. 2010. Quality assurance procedures for mesoscale meteorological data. *Journal of atmospheric and oceanic technology* 27: 1565–1582.

Godfrey CM, Stensrud DJ. 2008. Soil temperature and moisture errors in operational eta model analysis. *Journal of Hydrometeorology* 9: 367–387.

Ilston BG. 2015. Mesonet soil temperature variability dataset. Oklahoma Mesonet. https://doi.org/10.15763/dbs.mesonet.research.soiltempvar
Mavi HS, Tupper GJ. 2004. *Agrometeorology: Principles and Applications of Climate Studies in Agriculture*. The Haworth Press: USA; 43–47.

McPherson RA, Fiebrich CA, Crawford KC, Elliott RL, Kilby JR, Grimsley DL, Martinez JE, Basara JB, Illston BG, Morris DA, Kloesel KA, Stadler SJ, Melvin AD, Sutherland AJ, Shrivastava H. 2007. Statewide monitoring of the mesoscale environment: a technical update on the Oklahoma Mesonet. *Journal of atmospheric and oceanic technology* 24: 301–321.

Mohanty BP, Klittich WM, Horton R, van Genuchten MT. 1995. Spatio-temporal variability of soil temperature within three land areas exposed to different tillage systems. *Soil Science Society of America Journal* 59: 752–759.

Omer AM. 2008. Ground source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews* 12: 344–371.

Patil RH, Leaegdsmond M, Olesen JE, Porter JR. 2010. Growth and yield response of winter wheat to soil warming and rainfall patterns. *Journal of Agricultural Science* 148: 553–566, https://doi.org/10.1017/s0021859610000419.

Schaefer GL, Cosh MH, Jackson TJ. 2007. The USDA natural resources conservation service soil climate analysis network (SCAN). *Journal of atmospheric and oceanic technology* 24: 2073–2077.

Scharringa M. 1976. On the representativeness of soil temperature measurements. *Agricultural Meteorology* 16: 263–276.

Shafer MA, Fiebrich CA, Arndt DS, Fredrickson SE, Hughes TW. 2000. Quality assurance procedures in the Oklahoma Mesonet. *Journal of atmospheric and oceanic technology* 17: 474–494.

Shumway RH, Biggar JW, Morkoc F, Bazza M, Nielsen DR. 1989. Time and frequency-domain analysis of field observations. *Soil Science* 147: 286–298.

Steiner JL, Starks PJ, Daniel JA, Garbrecht JD, Moriasi D, McIntyre S, Chen JS. 2008. Environmental effects of agricultural conservation: a framework for research in two watersheds in Oklahoma’s Upper Washita River Basin. *Journal of Soil and Water Conservation* 63: 443–452.

Stone PJ, Sorensen IB, Jamieson PD. 1999. Effect of soil temperature on phenology, canopy development, biomass and yield of maize in a cool-temperate climate. *Field Crops Research* 63: 169–178.