Cold Regions Science and Technology 85 (2013) 217–224

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Influences of winter climatic conditions on the relation between annual mean soil and air temperatures from central to northern Japan

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ARTICLE INFO

Article history:
Received 6 June 2012
Accepted 17 September 2012

Keywords:
Climate zone
Cumulative freezing degree-days
Numerical soil-temperature model
Snow cover
Soil thermal condition
Thermal insulation

ABSTRACT

Annual mean soil temperature (ST_A) is an important factor to evaluate the potential of the productivity of agricultural fields and the amount of ground thermal resources. To assess the influence of the climate on the ST_A, we collected and analyzed a field dataset at five suburban sites from central to northern Japan. Additionally, the effects of winter climate on the relation between ST_A and AT_A were investigated using a numerical soil temperature model. Results show that ST_A was correlated positively with AT_A. The difference between ST_A and AT_A (ST_A/AT_A offset) was approximately 1 °C at the southern sites, where monthly mean air temperatures do not drop below 0 °C. The offset, 2–4 °C in the northern and colder sites, was correlated positively with the cumulative freezing degree-days (CFD). Analyses conducted using a numerical soil-temperature model revealed that the estimated ST_A/AT_A offset under a snow-free condition was 1.2 °C on average in the northern sites, which was similar to the offset in the southern snow-free sites. This similarity suggests that the thermal insulation of snowpack was the dominant factor in raising the offset. Additionally, the numerical simulation showed that the offset reached the ceiling when the winter mean snow cover thickness (SCT_{mean}) exceeded 0.2 m under the air temperature in colder northern sites in Japan. In conclusion, although the ST_A/AT_A offset is known to be influenced by both CFD and SCT_{mean}, the offset increases directly with CFD rather than SCT_{mean} when snow cover is sufficiently thick to insulate the soil from cold air.

1. Introduction

In terrestrial ecosystems, soil thermal conditions control biological and biochemical processes such as plant growth (e.g., Beauchamp and Lathwell, 1967; Stone et al., 1999), nutrient availability for plants (Moore, 1981; Thomsen et al., 2010), greenhouse-gas emissions (e.g. Smith et al., 2003), decomposition of soil organic carbon (Trumbore et al., 1996), and the activities of agricultural vermin (e.g. Jacobs et al., 2011) and weeds (e.g. Hirota et al., 2011). In cold regions, the soil thermal regime also influences hydrological cycles (e.g. Iwata et al., 2008, 2010a), which in turn affects greenhouse gas emissions because of enhanced microbial activities (Yanai et al., 2011). Moreover, the soil thermal regime has attracted attention in terms of the utility of renewable energy for some heat pump systems. Because the performance is influenced by the temperature of the thermal source (Zogou and Stamatelos, 1998), the design must be established based on the soil temperature.

Annual mean soil temperature (ST_A) is an important indicator of the soil thermal regime and agricultural ecosystems in various climate zones. For example, the ST_A at a depth of 0.5 m is used to classify the soil-temperature regime (e.g., frigid, mesic, thermic, and hyperthermic), which is one indicator used to characterize soil productivity (Soil Survey Staff, 1998). Jacobs et al. (2011) demonstrated the importance of ST_A for estimation of nematode activity in agricultural fields. Lawrence et al. (2008) estimated ST_A to predict permafrost degradation under a global warming scenario.

Air temperature marks the upper boundary of soil. Therefore, ST_A is regarded as influenced by the annual mean air temperature (AT_A). It is reported that the ST_A is slightly higher than AT_A by approximately 1 °C in a temperate zone (Jacobs et al., 2011). However, the difference between ST_A and AT_A (hereinafter, the ST_A/AT_A offset) is greater in colder climate zones (Arakawa and Higashi, 1951; Zhang et al., 2005). Grundstein et al. (2005) reported that the ST_A/AT_A offset was

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0165-232X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2012.09.009

induced mainly by the thermal insulation effect of the snowpack, which is in turn determined by the magnitude of thermal resistance. However, their results do not reflect the influences of the different climates because they were based on field measurements obtained from a single study site in North Dakota. In contrast, Zhang et al. (2005) estimated the ST_A/AT_A offset throughout the territory of Canada using a numerical simulation model. They reported that vegetation, snow cover, and air temperature can influence the offset. Smith and Riseborough (2002) assessed the thermal insulation effects of snow and plant cover on the ST_A/AT_A offset to clarify relations between climate and permafrost distribution throughout Canada. These studies, however, targeted high-latitude or permafrost regions; they did not assess mid-latitude regions. Japan is located at the boundary between the warm temperate, fully humid, and hot summer zone (Cfa) and the snow climate, fully humid and warm summer zone (Dfb) in the Köppen–Geiger classification (Kottek et al., 2006) with regional variations of snowfall or seasonal soil frost formation in lowland terrain. To ascertain the nature of relations between ST_A and AT_A, clarifying effects of winter climate on the ST_A/AT_A offset under warmer climate is also necessary. However, quantitative evaluations are not yet completed.

The partitioning of radiative energy incident to the soil surface is well known to be influenced by surface conditions such as vegetation, moisture, and snow and ice cover. To elucidate the relations between ST_A and AT_A under humid climate conditions in the mid-latitude zone, and to ascertain the thermal insulation effect of snow cover, a long-term (6–25 years) observation near arable lands was conducted at fields having bare or clipped sod soil conditions, located from central to northern Japan. The relation between ST_A and AT_A was examined at each site. Then the effect of climatic conditions on ST_A was examined using a numerical soil-temperature model. This study was undertaken to quantify the relations between the ST_A/AT_A offset and climate factors in agricultural lands and to elucidate the mechanisms of snow-cover influence on the offset in mid-latitude Japan.

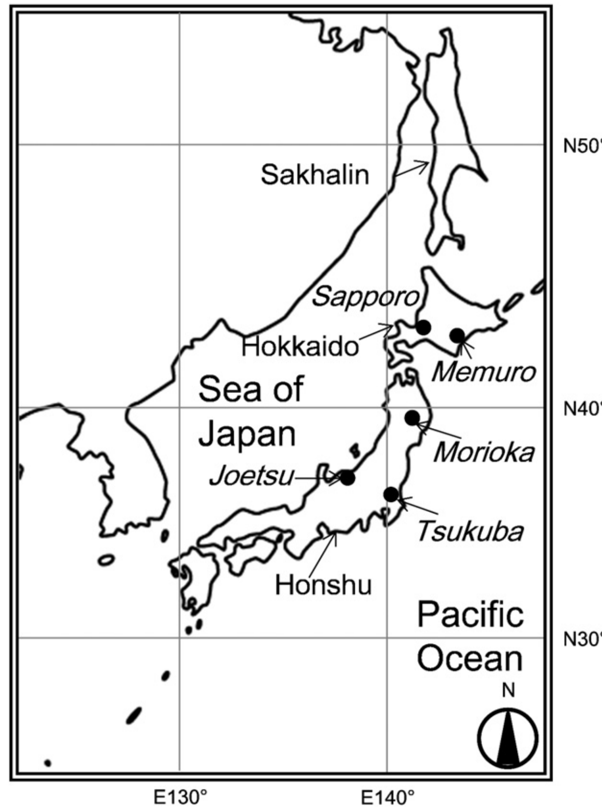

Fig. 1. Map of study sites from central to northern Japan.

2. Site descriptions and methods

2.1. Climate at each site

Soil and air temperature data were obtained at five sites located in flat terrain (13–155 m a.s.l.) from central to northern Japan (Fig. 1) with different climates (Table 1).

(1) The Tsukuba site is located at the Institute for Rural Engineering in the inland area from the Pacific Ocean on Honshu (the largest island of the Japanese archipelago). Its climate is characterized by hot summers and mild winters, with little snow cover or soil freezing. Its Köppen–Geiger climate type is Cfa.
(2) The Joetsu site is located at the Hokuriku Research Center in the National Agriculture and Food Research Organization (NARO) Agricultural Research Center in a lowland area near the Sea of Japan on Honshu. Its climate is characterized by hot summers and mild winters. Although the Köppen–Geiger climate type is Cfa, winter precipitation by winter monsoons often causes heavy snow, with large interannual variation. Because of mild winters, the soil does not freeze.
(3) The Morioka site is located at the NARO Tohoku Agricultural Research Center in the Kitakami Basin of northeastern Honshu. Its climate is characterized by moderately cool summers and moderately cold winters. The Köppen–Geiger climate type is Cfa. However, this site is located near the northern boundary with Cfb (warm temperate climate, fully humid, warm summer zone) or Dfb. The ground surface is usually covered with snow during January–February. Soil freezes to a few centimeters below the surface during winter.
(4) The Sapporo site is located at the NARO Hokkaido Agricultural Research Center (Sameshima et al., 2008), inland from the Sea of Japan on Hokkaido, the northernmost large island of the Japanese archipelago. Its climate is characterized by cool summers and moderately cold winters. Snow falls frequently because of winter monsoons, but soil does not usually freeze more than 0.1 m during winter because of thermal insulation by the thick snow cover (Iwata et al., 2011). The Köppen–Geiger climate type is Dfb.
(5) The Memuro site is located at the Memuro Upland Farming Research Station of the NARO Hokkaido Agricultural Research Center inland from the Pacific Ocean in the Tokachi region of Hokkaido Island. In winter, sunny days continue and low air temperatures result from strong radiative cooling. However, heavy snows occur several times when low pressure systems pass through this region. Soil freezing often reaches to depths greater than 0.1 m during winter (Hirota et al., 2006). The Köppen–Geiger climate type is Dfb.

All study sites were located on the premises of the agricultural experimental station. Ferguson and Woodbury (2004) reported that the ground temperature is considerably higher in urban centers than in the suburban areas because of the heat flow to the ground from closely spaced buildings. Such temperature rises are negligible in areas at more than a few hundred meters distance from any heated structure. Our study sites are surrounded by fields of the agricultural experimental stations, and are separated by 0.2–2.2 km from the boundary with low-density residential areas (Table 2). Therefore, effects of the heated buildings are regarded as slight.

2.2. Measurements

Air temperatures were measured using a ventilation pipe positioned at 1.5–2.1 m height from the ground surface (Table 2), fairly conforming