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Frozen ground monitoring (2004-2006) in the source area of the Yellow River, China

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Abstract

Ground thermal and hydrological regimes at Madoi (4273 m ASL), northeastern Tibetan Plateau, are described on the basis of two years of automatic and manual observations of air and ground temperatures, precipitation, snow depth, soil moisture and groundwater level. The paucity of winter snow cover results in a high correlation between daily air and ground surface temperatures, although the two temperatures show reversed magnitudes of daily ranges between winter and summer. Ground temperature responds to air temperature with a time lag and the annual temperature variations display the phase reversal at 7.8 m depth. Seasonal frost reaches a depth of 2.7 m, below which no subfreezing temperatures occur down to a depth of 7.8 m. Extrapolation of the mean annual ground temperatures suggests that permafrost is unlikely present below an unfrozen talik, while it possibly disappeared within the last few decades. Soil moisture and groundwater level primary vary with the annual frost regime and summer precipitation.

Key words: permafrost, seasonal frost, global warming, ground temperature, Tibet

1. Introduction

A long-term observatory for frozen ground was established at Madoi in the source area of the Yellow River in August 2004. The monitoring aimed at evaluating the influence of ongoing climatic warming on the frozen ground in the source area and further on hydrological and geomorphological processes in the whole drainage basin of the Yellow River. In an earlier report (Matsuoka et al., 2005) we presented first year's data and explored the possibility of recent permafrost degradation. This second report presents observations for two years (2004-2006), highlighting the relationship between air and ground temperatures, as well as the near-surface frost regime and hydrology.

The Madoi observatory (98°13'E, 34°55'N, 4273 m ASL) is located at a representative elevation of the plateau area (4200-4300 m ASL). The meteorological records in 2001-2005 indicate that the Madoi region experiences a cold-dry climate, with a mean annual air temperature (MAAT) of −2.0°C, a large annual thermal amplitude ranging from −14.4°C in January to 9.3°C in July and an annual precipitation of 306 mm (after the Weatheronline homepage: www.t7online.com). Precipitation concentrates in summer months (May-October) and winter snow cover is extremely limited. These conditions favor deep penetration of seasonal freezing and thawing. Sediments derived from a 10-m deep borehole at the observatory shows the uppermost 2.4 m of silty loess and the underlying fluvial gravel embedded in sandy-silty matrix (Matsuoka et al., 2005).

A Campbell CR10X logger recorded environmental parameters at hourly intervals. Platinum probes sensed air temperature at 1.65 m above the ground surface and ground temperature at depths of 0.03, 0.3, 1.3, 2.3, 4.3, 6.3 and 7.8 m. The ground surface temperature was represented by the 3 cm-depth temperature, which was sensed beneath a 3 cm-thick platy stone. An ultrasonic transducer detected the snow depth. TDR (Time Domain Reflectometry) sensors recorded the volumetric water content of soil at 0.3, 0.6 and 0.9 m depth: the readings were corrected with a calibration curve drawn using the sampled soils. Thermal properties (conductivity, diffusivity and heat capacity) were also measured at 0.1 m depth. The logging started at 1500 h on 12 August 2004 and provided continuous data until 1000 h on 3 August 2006. Manual observations at the Madoi observatory provided also data on the daily precipitation and weekly groundwater level.

2. Results and interpretation

2. 1. Snow cover

Figure 1 summarizes two years of thermal and hydrological data at the observatory. Data on the snow depth involved apparent and irregular snow cover during summer, which is unrealistic. This error possibly

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reflected vegetation, animals, human activity, or otherwise mechanical problems. Such a noise was largely removed by saving data only when the ground surface temperature was negative or close to 0°C and at least minimum amount of precipitation was recorded on the station data. This filtering indicated the occurrence of shallow and ephemeral snow cover during the two years. Snow cover lasting for more than two days occurred only five times: late October to early November in 2004, January to February, late March and late October to early November in 2005 and February 2006. Even during these major events the snow depth never exceeded 10 cm. The maximum snow depth was 8 cm in the first winter (2004-2005) and 4 cm in the second winter (2005-2006). Extraordinarily deep snow cover on 22 and 23 May 2005 (up to 40 cm) coincided with nocturnal negative temperatures and a significant precipitation event (8.7 mm for two days), implying the occurrence of snowfall. However, the records may have included some noises, since they indicated that snow accumulated and disappeared within 12 hours.

2. 2. Relationship between air and ground temperatures

The general lack of winter snow cover led to large diurnal fluctuations in the ground surface temperature throughout the year (Fig. 1). In fact, a high correlation (R^2=0.95) was found between the daily mean air temperature (T_a) and the daily mean surface temperature (T_s) in the second year (Fig. 2A). In periglacial environments such a high correlation has been observed only on snow-free ground (cf. Zhang, 2005). The two temperatures were, however, different in two points. First, T_s usually exceeded T_a by 4.4°C on average: the mean annual air temperature (MAAT) was −2.1°C and the mean annual surface temperature (MAST) was 2.4°C in the second year. The temperature difference is significantly larger than that in other cold regions (*e.g.* snow-free ground in Alaska: Zhang, 2005). Second, the magnitude of daily amplitudes showed a seasonal contrast such that

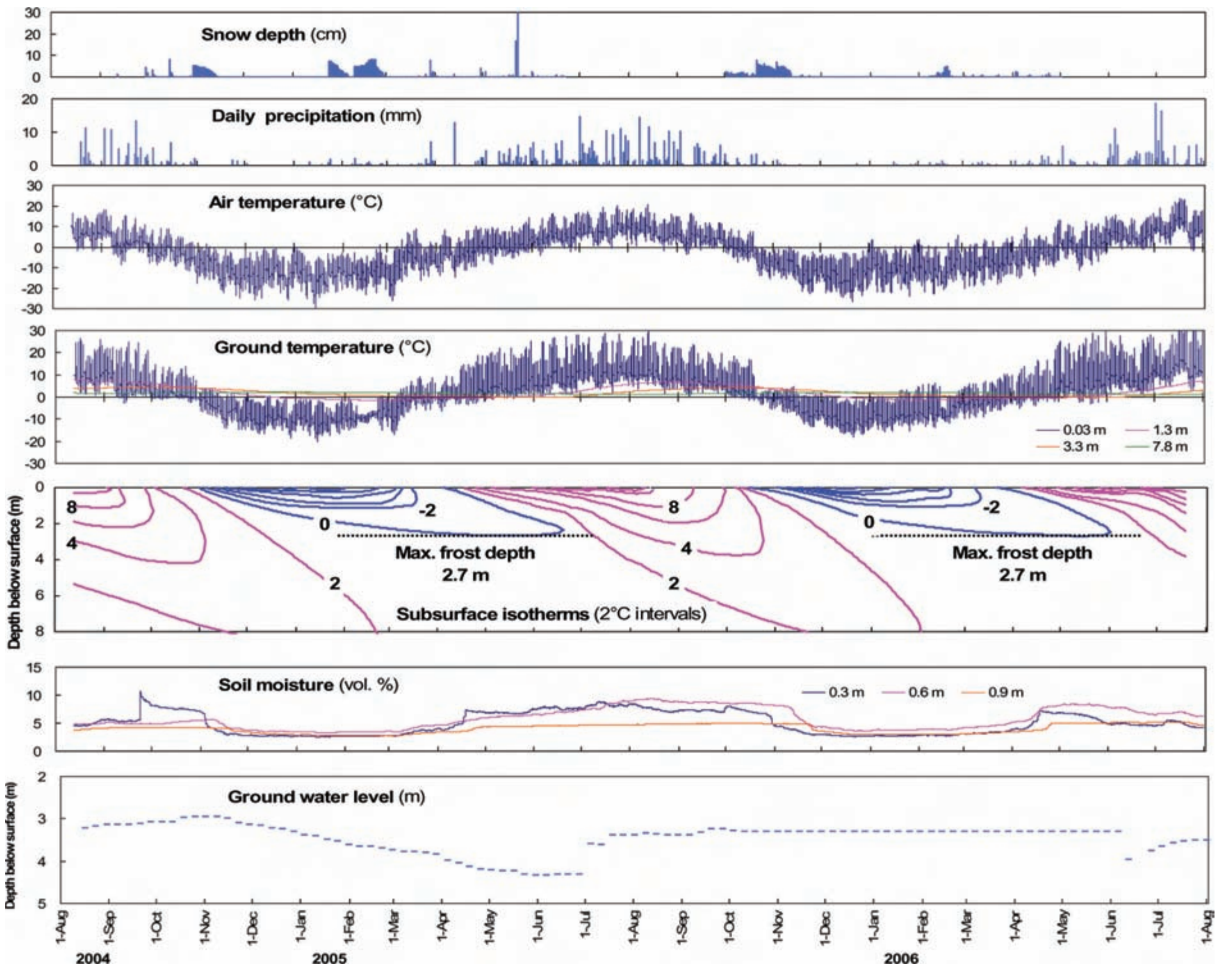

Fig. 1. Time series of environmental parameters at the Madoi observatory. Snow depth, air and ground temperature and soil moisture were monitored at 1-h intervals. The isotherms were drawn on the basis of 10-d mean ground temperatures. The groundwater level derives from weekly manual measurements.

T_s ranged more widely than T_a in summer but the relation reversed in winter (Fig. 3B). The reversal mainly reflected the high daytime (maximum) surface temperatures in summer and low nocturnal (minimum) surface temperatures in winter with reference to air temperatures (Fig. 3A).

The above two features are considered to originate partly from the dry ground surface and the seasonal variation in the length of day- and night-times. The dry ground surface experiences only minimum exchange of the latent heat, so that radiation would play a primary role in determining the surface temperature. The incoming radiation may further be enhanced by the long daytime duration in summer, while the outgoing radiation is promoted by the long night-time in winter. These conditions favor both high daytime surface temperatures in summer and low nocturnal surface temperatures in winter. In contrast, the ephemeral snow cover briefly decreased daily ranges of surface temperature at a few times in the winter, but the effect was minimum. Such an annual variation in daily temperature amplitudes is significantly different from that in humid periglacial regions where snow cover affects the ground temperature (*e.g.* Zhang, 2005).

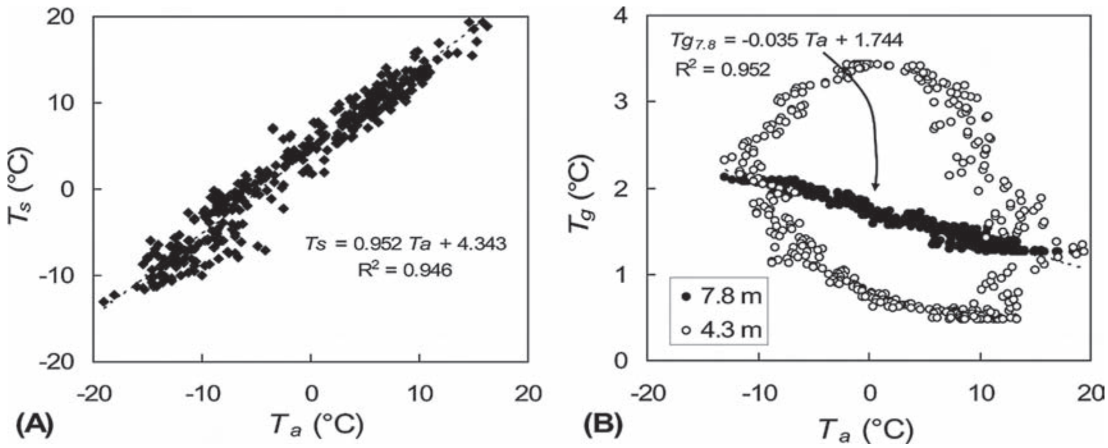

Fig. 2. Relationships between air and ground temperatures for the second year (1 August 2005 – 31 July 2006). A. Mean daily air temperatures (T_a) versus ground surface (at 3 cm depth) temperatures (T_s). B. Mean daily air and ground temperatures (T_g) at 4.3 m and 7.8 m.

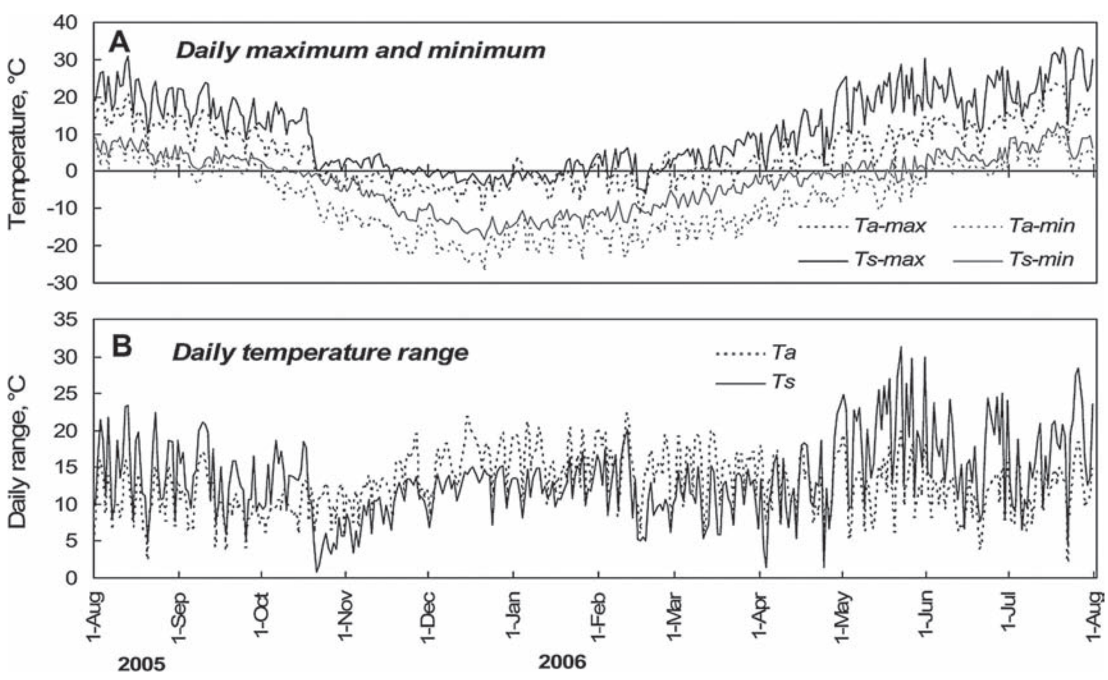

Fig. 3. Annual variations in air and ground surface temperatures in 2005-2006. A. Daily maximum and minimum temperatures. $T_{a\text{-}max}$: maximum air temperature; $T_{a\text{-}min}$: minimum air temperature; $T_{s\text{-}max}$: maximum surface temperature; $T_{s\text{-}min}$: minimum surface temperature. B. Daily ranges for air temperature (T_a) and surface temperature (T_s).

Annual variation in subsurface temperature shows a reduced amplitude and a phase delay with increasing depth (Fig. 1). At Madoi, the annual temperature range (defined by the difference between the maximum and minimum of mean daily temperatures) in 2005–2006 was 32°C at the surface, diminishing to 3°C at 4.3 m depth and to 0.8°C at 7.8 m depth (Fig. 2B). The peak temperatures at the surface were responded three months behind at 4.3 m depth and their timing even completely reversed at 7.8 m depth (Fig. 2B).

2. 3. Ground frost regime

The lack of winter snow cover was also responsible for deep frost penetration. In the first winter (2004-2005) seasonal freezing began in early November and penetrated into the ground at a rate of 0.5–1.0°C per month until January. The frost penetration then decelerated and finally reached a maximum depth of 2.7 m in May (Fig. 1). In the next winter (2005-2006) seasonal freezing began earlier in mid October but slowly penetrated for the first month and then progressed at a similar rate to the previous year. The timing and depth of the maximum frost penetration also reproduced the preceding conditions (Fig. 1).

Thaw penetration began in early April 2005 and in late March 2006 and progressed at a rate of 0.7–1.0°C per month until the ground completely thawed in mid July 2005 and in early July 2006. This indicates that when the maximum frost depth was reached, considerable thawing had already progressed.

Below the maximum frost depth (2.7 m), negative temperatures were never recorded and the mean annual ground temperature (MAGT) was uniformly 1.7–1.8°C over 3.3–7.8 m depth (Fig. 4). Downward extrapolation of this stable MAGT rejects the presence of negative temperature at deeper ground. Thus, even relict permafrost is unlikely present below an unfrozen talik.

Incorporating the rapid warming in the last few decades, however, we estimate that permafrost existed a few decades ago and recently disappeared. Indeed, the long-term weather data at the Madoi station shows a significant rise in MAAT from −4.2°C (mean for 1953–1980) to −2.0°C (mean for 2001–2005). An assumption of the concurrent rise in MAST (about 2°C during the last 30 years) suggests the possible presence of negative MAGT (i.e. permafrost) at shallow depth a few decades ago.

2. 4. Ground hydrological regime

The near-surface soil (at 30–90 cm depth) had low water content (<10 % vol.) throughout the year (Fig. 1). This reflected the small amounts of precipitation, paucity of snow cover and snowmelt water, and the low groundwater level (>3 m). The temporal variation in soil moisture basically followed the frost regime and precipitation. However, the response to precipitation events was generally slow and the short-term (diurnal) precipitation rarely affected soil moisture below 30 cm depth.

A significant change happened when the freezing (or thawing) front reached, basically reflecting the unfrozen water content (*e.g.* Spaans and Baker, 1995; Matsuoka et al., 2005). In particular, soil moisture at 30 cm depth rose sharply during the thawing period. The rapid rise followed a slow increase lasting for a month probably due to increasing unfrozen water content in still-frozen soil. After the meltout of the soil, the moisture variation was slightly different between the summers of 2005 and 2006. In the former, soil moisture was relatively low in the early summer and rose toward the late summer, reflecting a number of precipitation events during the early summer. In the latter, moisture was highest just after the meltout and

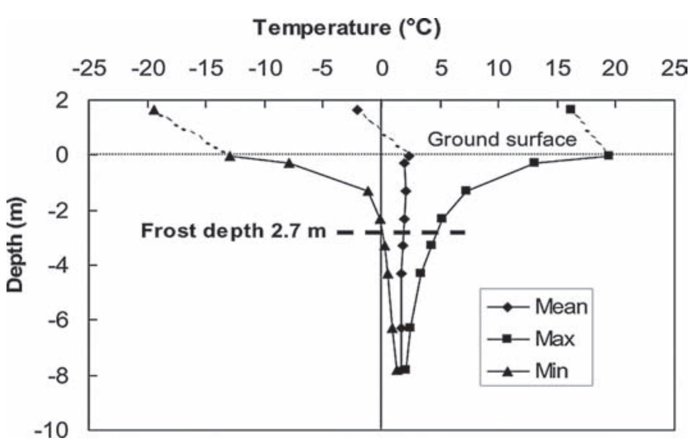

Fig. 4. Ground temperature profile in 2005-2006, indicating mean annual temperatures, maximum and minimum of mean daily temperatures and seasonal frost depth. Air temperature at 1.65 m is also shown.

gradually lowered until early July, probably reflecting the very small precipitation in May (13 mm in total). A sudden rise recorded at 30 cm depth on 23 September 2004 (Fig. 1) followed precipitation (17 mm in 3 days), but this event may have included an error due to the initial instability of the sensor or another electrical problem (Matsuoka et al., 2005).

The groundwater level also varied seasonally (Fig. 1). Having reached a peak (2.95 m) in early November 2004 when seasonal frost started, the water level lowered gradually with frost penetration, lying at about 150 cm below the freezing front (Matsuoka et al., 2005). Complete thawing of the seasonal frost raised the water level by 0.7 m within a week in early July 2005, due probably to downward percolation of both meltwater from the frozen layer and rain-induced water stored above the frozen layer. This temporal variation did not recur in the second winter. Although the water level gradually rose until early October when the seasonal frost penetration started, it was kept constant at 3.3 m depth until the complete thawing of the seasonal frost (Fig. 1). The reason for this constant value is unclear, but a possibility is that a blocking ice film formed at 3.3 m depth in early October and stayed there until thawing. Thus, in the second winter the measurement failed to represent the actual water level that must have underlain far below the assumed ice film. The apparent lowering of the water level in early July 2006 is attributable to the collapse of the ice film, and in reality the actual, sub-seasonal frost water level is considered to have risen as in the previous summer.

3. Summary and perspectives

The two years of observations at the Madoi observatory demonstrate the absence of permafrost. Geophysical soundings (one-dimensional geoelectrical and seismic surveys) support this interpretation, since they failed to identify a frozen layer (high resistivity/velocity layer) within the uppermost 50 m of sediment at the observatory (Ikeda et al., 2004, submitted). The observatory is located at a representative elevation of the widespread alluvial plain (4200–4300 m ASL) on the plateau. The geophysical soundings at a number of sites near the observatory suggested the presence of permafrost only at a few sites (Ikeda et al., 2004, submitted). Boreholes also indicated sporadic occurrence of permafrost (Zhang et al., 2004). These observations indicate that a large part of the alluvial plain is devoid of permafrost but that relict permafrost is locally preserved where topography permits the accumulation of cold air. Incorporating the recent continuous warming, ca. 2°C during the last 30 years, we estimate that permafrost has been disappearing rapidly from the study area, where permafrost may have been ubiquitous a few decades ago (Wang, 1987). The observed ground water level (3–4 m in depth) at the Madoi observatory may represent a lowered level in response to the recent permafrost melting, since the water level is considered to have overlain the permafrost table at 2-3 m or shallower when permafrost was present (cf. Peng et al., 2003). Recent retardation of a number of lakes in the Madoi region would reflect regional lowering of the groundwater level due to permafrost degradation.

This report described an overview and preliminary interpretations of data from the Madoi observatory. More detailed results will be presented elsewhere on the basis of thermal analysis using thermo-physical soil properties, mapping of contemporary permafrost distribution using geophysical data and modeling of long-term permafrost degradation.

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