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Monitoring frozen ground (2004-2005) at Madoi in the source area of the Yellow River, China

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Abstract

Annual variations in ground thermal and hydrological regimes were investigated at Madoi (4273 m ASL), northeastern Tibetan Plateau, by automatic and manual observations of air and ground temperatures, precipitation, snow depth, soil moisture and groundwater level. The first year's data show either the absence of permafrost or the presence of relict permafrost at a depth below 10 m, suggesting significant permafrost degradation during the last few decades. The permafrost degradation is likely to have induced lowering of the groundwater level by a few metres.

Key words: permafrost, seasonal frost, global warming, groundwater, Tibet

1. Introduction

The source area of the Yellow River (Huang He), which involves the northeastern part of the Tibetan Plateau, is widely underlain by perennially or seasonally frozen ground (*e.g.* Zhou *et al.*, 2000). The presence and temporal variation of the frozen ground control the groundwater regime, lake levels and water input to streams, which in turn would significantly influence water circulation and resource in the whole drainage basin. In this context, recent global warming may trigger rapid degradation of permafrost which has been considered to be widespread on the plateau above 4000 m ASL (*e.g.* Wang *et al.*, 2001; Zhang *et al.*, 2004; Böhner and Lehmkuhl, 2005).

Since 2002, we have investigated the distribution and evolution of permafrost in the source area, as a part of a research project on the ground water circulation in the Yellow River basin. The field investigations include geophysical (seismic and geoelectrical) sounding of subsurface water and frozen ground, measurement of near-surface soil moisture and monitoring of ground surface temperature (*e.g.* Ikeda *et al.*, 2004; Matsuoka *et al.*, 2004). In August 2004, a long-term observatory for frozen ground was established at Madoi, southeastern Qinghai Province (Fig. 1). This paper reports the first year's results of monitoring of environmental factors.

2. Site description and instrumentation

The Madoi observatory is located at the Madoi meteorological station (98˚13´E, 34˚55´N, 4272 m ASL), the elevation representing the surrounding plateau area (4200-4300 m ASL). The land surface above the timberline at about 3600 m is dominated by grassland (alpine meadow) that has been subjected to widespread grazing activity and partly occupied by wetlands and lakes. The recent meteorological records in 1997-2002 indicate that the Madoi region experiences a cold-dry climate, with a mean annual air temperature (MAAT) of -2.3˚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). The MAAT represents a marginal value for the presence of permafrost. However, the temperature records show that MAAT rose by 1.9˚C compared with the mean value for 1953-1980 (Zhou *et al.*, 2000), implying significant warming and degradation of permafrost during a few decades. Precipitation concentrates in summer months (May-

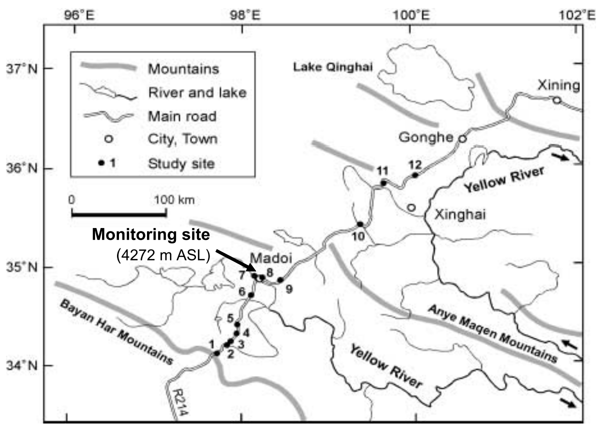

Fig. 1 The source area of Yellow River in SE-Qinghai, showing the location of the monitoring site.

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October), while less than 10 % of the annual amount falls in the rest of a year. The latter leads to very shallow snow and a short snow-cover period. These conditions favour deep seasonal freezing and thawing, providing a deep active layer where permafrost is present or a deep seasonally frozen layer where permafrost is absent.

Sediments derived from a 10-m deep borehole (drilled on 11 August 2004) displayed the near-surface stratigraphy. The uppermost 2.4 m consists of sandy silt lacking stones, which probably represents loess. A manual measurement using the thermal properties analyzer KD2 (Decagon) indicates a low thermal conductivity of 0.5–1.0 W m^{-1} K^{-1} for the uppermost 20 cm of soil. Below the topsoil, the material is gravelly to the bottom of the borehole but mostly supported with sandy or silty matrix, which was probably of a fluvial origin. A clayey layer with pebbles is embedded between 5.4 m and 7 m depth. During the drilling, no core was obtained at a frozen state, although the material below the clayey layer was hard and compact.

A Campbell CR10X logger automatically recorded environmental parameters: air temperature at 1.65 m above the ground surface; ground temperature at 0.03, 0.3, 1.3, 2.3, 4.3, 6.3, and 7.8 m depth; snow depth; soil moisture at 0.3, 0.6 and 0.9 m depth; and thermal properties (conductivity, diffusivity and heat capacity) at 0.1 m depth (Fig. 2). Platinum sensors measured the air temperature (with a ventilated radiation shield) and ground temperatures. Rapid backfilling of the borehole by wet, unstable debris inhibited the installation of the platinum sensors below 7.8 m. An ultrasonic transducer detected the level of snow surface, which was translated into the snow depth. TDR (Time Domain Reflectometry) sensors recorded the volumetric water content of soil: the values were calibrated in comparison with direct weighing of soil samples. A solar panel constantly provided the electricity to the data logger. The logging started at 1500 h on 12 August 2004. The first data collection on 13 July 2005 provided hourly data for 11 months.

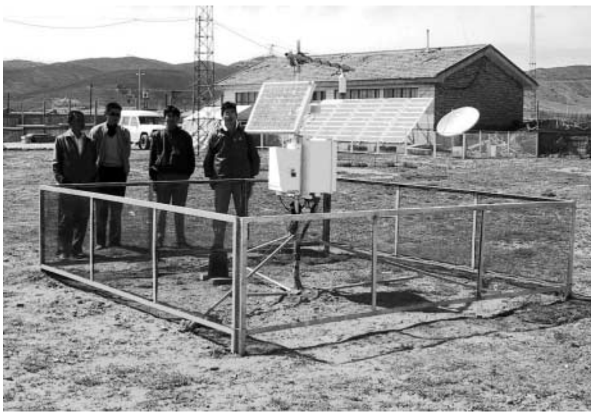

Fig. 2 The Madoi observatory and instruments. The Madoi meteorological station on the back.

In addition to the automated monitoring, data from manual observations were provided by the meteorological station. The parameters involved the daily precipitation and weekly groundwater level.

3. Results and interpretation

3.1. Atmospheric regime

Figure 3 summarizes thermal and hydrological data at the observatory for 11 months. Air temperature records displayed a large annual range which allowed distinction between four seasons: summer frost-free, autumn freeze-thaw, winter frozen and spring freeze-thaw periods. Diurnal ranges were also large, on average 12.4˚C (based on 1-h interval data) for the observation period. The ranges slightly increased in winter, reflecting the frequent sunny days as indicated by the small (<2 mm d^{-1}) and sporadic precipitation. In contrast, precipitation was frequent (>10 days per month with a magnitude of >1 mm d^{-1}) in summer.

The lack of precipitation in winter also resulted in intermittent and very shallow snow cover (Fig. 3). Snow accumulation was mostly ephemeral. Continuous snow cover lasting two days or longer occurred only three times during the year, with the longest period of 20 days in February. During these three periods, however, snow depth never exceeded 10 cm. Extraordinarily deep, but ephemeral snow cover was recorded twice (18 cm at 3 a.m. on 22 May 2005; 40 cm at 6 a.m. on 23 May 2005). Since these events coincided with precipitation and negative air temperature, they are believed to have reflected snow accumulation, but whether or not the records indicate the real snow depth is uncertain. The paucity of snow cover in winter favoured the deep frost penetration (see below).

3.2. Ground thermal regime

Ground temperatures also indicated a large seasonal range with a mean annual temperature close to 0˚C at the ground surface (0.03 m in depth), which resulted in deep seasonal frost despite the low thermal conductivity of the topsoil (Fig. 3). The seasonal frost penetration began in early November, decelerated in mid-winter and finally reached a maximum depth of 2.6 m in late April when seasonal thawing had already began from the surface. The thawing front progressed slowly at a semi-constant rate of about 0.9 m per month, which favoured long-lasting seasonal frost until middle July. The ground between 4 m and 8 m in depth was kept at slightly

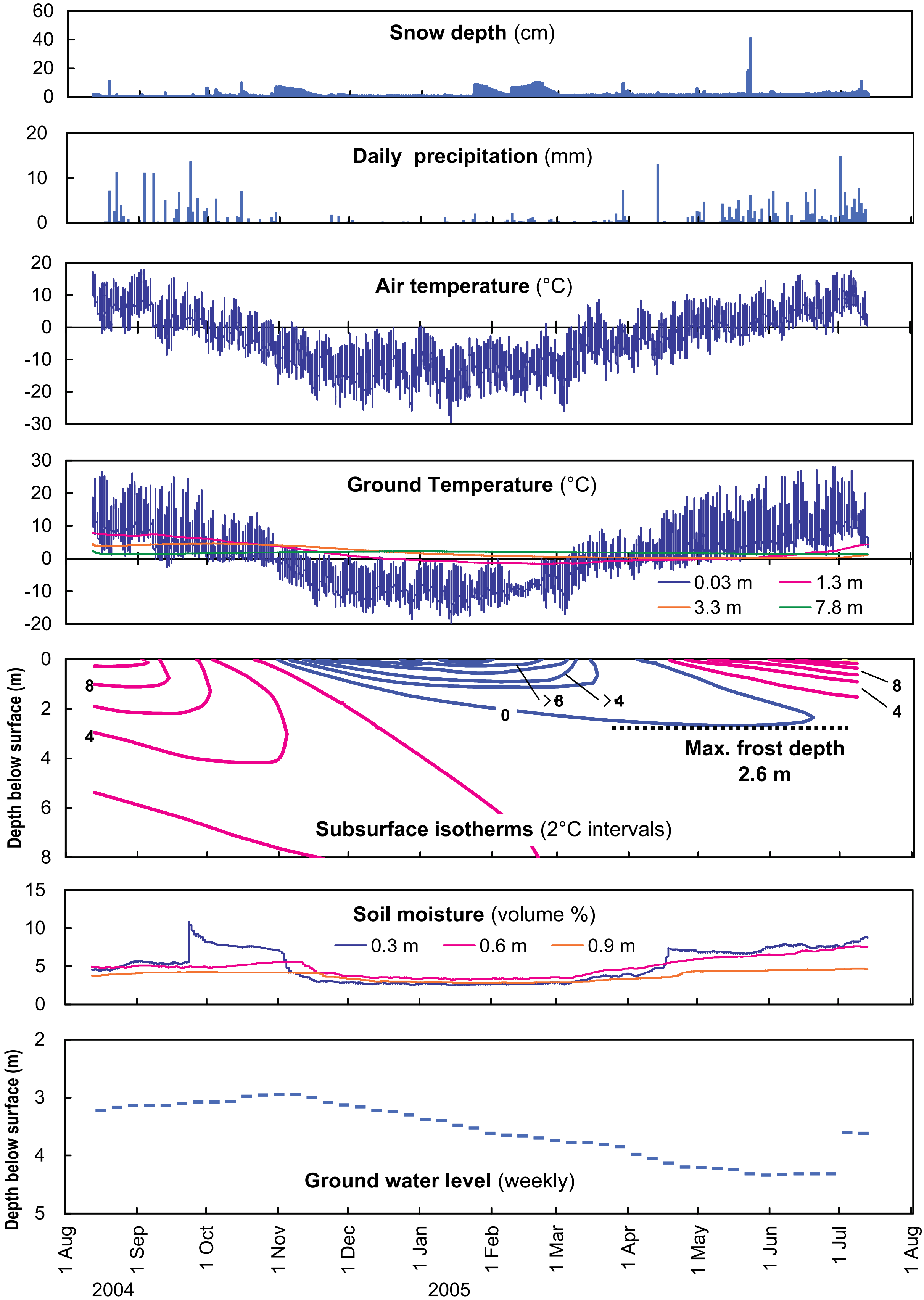

Fig. 3 Annual variations in environmental parameters at the Madoi observatory. Snow depth, air and ground temperature and soil moisture were monitored at 1-h intervals. The isotherms were drawn on the basis of 10-d mean ground temperatures.

positive temperatures (0–4˚C) throughout the year. Extrapolating isotherms suggest that the ground below 10 m was maintained at just above 0˚C and, taking account of recent rapid warming, permafrost might be present below a certain depth.

The ground surface experienced also shallow diurnal frost (temperature cycling across 0˚C), which frequently occurred in two periods from middle September to early November and from middle March to early May (Fig. 3). Since the temperature cycling was often associated with precipitation (*i.e.* moisture source), diurnal frost heaving (including needle ice formation) may have frequently happened within the uppermost few centimetres of the silty soil (cf. Matsuoka, 1996).

3.3. Ground hydrological regime

Soil moisture content at 30 cm depth showed a large seasonal variation but lacked short-term variation responding to the precipitation events (Fig. 3). The latter probably resulted from a small permeability of the silty topsoil. In terms of the moisture content at 30 cm depth, four periods were distinguished: dry late summer, relatively wet autumn, frozen winter and relatively wet spring to early summer. Direct weighing of soils confirmed the difference in the water content between middle August in 2004 (3.7 % vol) and early July in 2005 (8.7 % vol), although whether or not the soil dried again in late summer 2005 is to be confirmed.

The seasonal variation mainly reflected three events: a rapid rise in the volumetric water content from 5.5 % to 10.9 % within 4 h on 23 September (Fig. 4); a fall from 7 % to 4 % in early November; and the reverse in middle April (Fig. 5). The last two corresponded respectively to seasonal frost and thaw penetration. The low moisture values (min. 2.5 %) during the winter months synchronized with the frozen period, thus possibly representing the unfrozen water content of the frozen soil, though calibration is required (*e.g.* Stein and Kane, 1983; Spaans and Baker, 1995; Yoshikawa and Overduin, 2005). The rapid rise on 23 September was problematic. Having followed the second largest precipitation (17 mm in 3 days) during the observation period, this rapid wetting must have responded to infiltration of rain water. However, such a rapid change never accompanied any other precipitation events (Fig. 3). For example, the largest precipitation that happened in early July (23 mm in 3 days, or 50 mm in 10 days) was only accompanied by a gradual rise in water content by less than 1%. Thus, the 23 September event possibly reflected crossing of a wet front at 30 cm depth, but otherwise it may have overestimated the real water content due to the initial instability (*e.g.* lack of close contact between the sensor and soil) or another problem.

The water content changed less dramatically at deeper soils (Fig. 3). The volumetric water content ranged between 3.2 % and 7.6 % at 60 cm depth and between 2.8 % and 4.7 % at 90 cm depth, mainly in response to seasonal freezing and thawing. Slow wetting after seasonal thawing also progressed at both depths. The 23 September event, however, failed to affect the deeper sensors, apart from delayed, slow wetting having progressed at 60 cm depth one month later.

The groundwater level also varied seasonally (Fig. 3). It reached highest (2.95 m) in early November when seasonal frost penetration started at the ground surface. The level lowered gradually with frost penetration, lying at 150±20 cm below the freezing front (Fig. 6). Such a concurrent lowering may have reflected a double function of the frozen layer which, on one hand, blocks the infiltration of precipitation and, on the other, uptakes water from the sub-soil. If the latter function was operative, frost heave would have happened near the

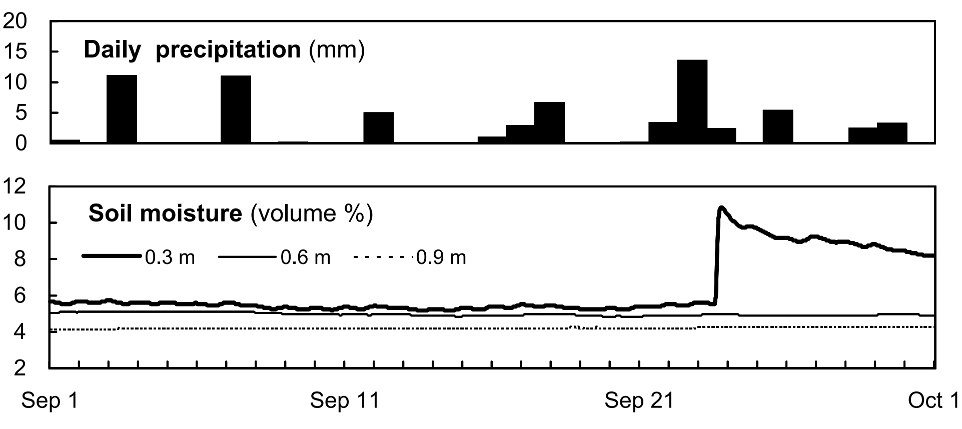

Fig. 4 Precipitation and soil moisture in September 2004.

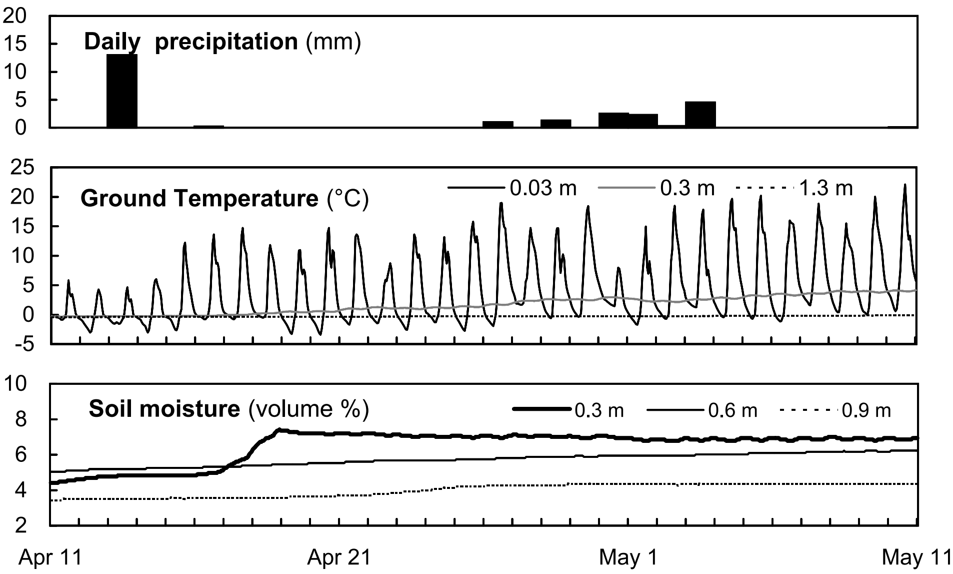

Fig. 5 Precipitation and soil moisture during the thawing period in 2005.

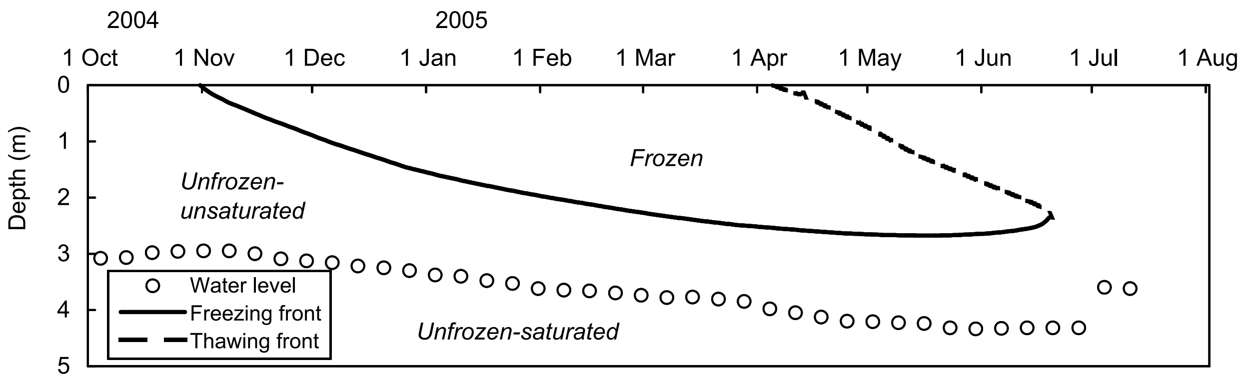

Fig. 6 Seasonal variations in frozen ground and groundwater level in 2004-2005.

base of the frozen layer, although the gravelly sediment and a large loading pressure were generally unfavourable for frost heaving.

At the beginning of July the water level recovered by 0.7 m within a week, following complete thawing of the seasonal frost. The rise of water level seems to have lagged behind the complete thawing by about one week, although the weekly observations failed to record the precise date. Both of the supra-frost meltwater that had been stagnant above the frozen layer and the newly melted water would have percolated downward and finally raised the water level.

4. Summary and implications

The first year's data from the Madoi observatory indicate either the absence of permafrost or the presence of degrading (relict) permafrost at a depth below 10 m. One-dimensional geoelectrical survey supports the former interpretation, since it failed to identify a high resistivity layer indicative of frozen soil but only detected the groundwater level (to be reported elsewhere). Since the observatory is located on a flat terrain and at a representative elevation of the northeastern Tibetan Plateau, a large part of the plateau may be devoid of permafrost or accompanied only by relict permafrost. Taking the recent continuous warming (ca. 2˚C during the last 30 years) into account, permafrost is likely to be degrading rapidly from the plateau, where permafrost may have been ubiquitous a few decades ago (Wang, 1987). Seismic soundings in the Madoi region also support this conclusion (Matsuoka *et al.*, 2004). The deepening permafrost table, or even disappearing permafrost, would also have lowered the (supra-permafrost) groundwater level over the wide area of the plateau.

In contrast to the lack of (shallow) permafrost, the ground experienced deep and long-lasting seasonal frost reaching a depth of 2.6 m. Such an annual freeze-thaw cycle significantly controls the groundwater regime. At the Madoi observatory, the groundwater level varied seasonally between 3 m and 4.3 m. When stable permafrost was present, it was most likely accompanied by an active layer 2–3 m in depth, and the (supra-permafrost) groundwater level would have lain in the similar depth range. Thus, lowering of the groundwater level by about 1–2 m may have happened during the last few decades at the observatory. Peng *et al.* (2003) also reported lowering of the groundwater level by 0.52–1.18 m during nine years (1992–2001) at 17 wells in the Madoi region. Towards more extensive and precise evaluation of changing permafrost and water resources in the Yellow River basin, we plan in the final step of the 5-yr project further to investigate the presence and depth of permafrost and the groundwater level at many locations, as well as to model ground thermal and hydrological regimes.

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