Postprint: Formation Characteristics and Influencing Factors of Soil Condensation Water in Hoh Xil

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Abstract

The Qinghai-Tibet Plateau is affected by climate change, with the dry-wet transition zone continuously expanding. Condensation water is an important water supply source in arid regions, and studying condensation water is of great significance for the ecology of the Qinghai-Tibet Plateau. To investigate the formation characteristics of condensation water on the Qinghai-Tibet Plateau and the factors influencing its formation, the Hoh Xil Salt Lake area, which has been significantly affected by climate in recent years, was selected as the study area. Micro-lysimeters were used to investigate the evaporation and condensation characteristics of soil moisture in the 0–10 cm layer, and correlation and regression analysis and principal component analysis were employed to explore the factors influencing condensation water formation. The results show: (1) During the period from 14:00 to 14:00 the next day, both air temperature and soil layer temperature exhibited a trend of first decreasing and then increasing. In the 0–10 cm soil layer, significant soil condensation water formation occurred between 00:00 and 10:00, while water evaporation was evident during the remaining time. The ratio of atmospheric water vapor to deep soil water vapor comprising soil condensation water was approximately 1:3. When nighttime near-surface air relative humidity exceeds 64%, near-surface air temperature is below 3.8 °C, and 5 cm soil layer temperature is below 4.1 °C, conditions are favorable for soil condensation water formation, with an average water amount reaching 0.2 mm · d-1. (2) Correlation analysis indicates that total soil condensation water amount shows a significant negative correlation with 5 cm soil layer temperature and the temperature difference between 5–30 cm soil layers, and the linear fitting effect between condensation water amount and related factors is satisfactory; atmospheric water vapor condensation amount shows a significant negative correlation with air temperature and a significant positive correlation with relative humidity. Principal component analysis results show

that micro-meteorological factors in the layer above 0–10 cm have a relatively large influence on condensation water formation.

Full Text

Formation Characteristics and Influencing Factors of Soil Condensation Water in the Hoh Xil Area

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Abstract

Climate change has continuously expanded the transitional zones between dry and wet conditions on the Qinghai-Tibet Plateau, with ecological degradation becoming increasingly severe. Condensation water represents an important water resource in arid regions. To investigate the formation characteristics and influencing factors of condensation water on the Qinghai-Tibet Plateau, this study selected the Salt Lake area in Hoh Xil—a region significantly affected by climate change in recent years—as the research site. Micro-lysimeters were used to monitor evaporation and condensation characteristics of soil moisture in the 0–10 cm layer, while correlation-regression analysis and principal component analysis were employed to explore the factors influencing condensation water formation. The results showed that: (1) From 14:00 to 14:00 the following day, both air temperature and soil temperature exhibited a trend of first decreasing then increasing. Obvious soil condensation water formation occurred in the 0–10 cm layer from 00:00–10:00, while water evaporation dominated during other periods. Soil condensation water was primarily composed of atmospheric water vapor and deep soil water vapor at a ratio of approximately 1:3. When nighttime near-surface relative humidity exceeded 64%, near-surface air temperature was below 3.8 °C, and the 5 cm soil layer temperature was below 4.1 °C, conditions were favorable for condensation water formation, with average water yield reaching 0.2 $\mathrm{mm \cdot d^{-1}}$. (2) Correlation analysis revealed that total soil condensation water was significantly negatively correlated with 5 cm soil temperature and the temperature difference between 5 cm and 30 cm soil layers, with good linear regression fit between condensation water and related factors. Atmospheric water vapor condensation showed significant negative correlation with air temperature and significant positive correlation with relative humidity. Principal component analysis indicated that micro-meteorological factors above the 10 cm soil layer had the greatest influence on condensation water formation. This research provides a scientific basis for the rational estimation of ecological water requirements and vegetation restoration in the Salt Lake district under climate change.

Keywords: soil condensation water; air temperature; soil temperature; air relative humidity; Qinghai-Tibet Plateau

1 Introduction

Water is the most critical ecological limiting factor in arid regions. Condensation water constitutes an important non-precipitation water input to the surface, serving as a water source for plants, insects, and other organisms while reducing groundwater consumption. It represents a vital component of the hydrological cycle. In the Heihe River basin, the average condensation water yield reaches 18.54% of annual precipitation, with similarly high proportions observed in the Taklamakan Desert. Naturally occurring condensation water can be categorized based on formation interface into soil condensation water and plant surface condensation water, among others.

Research on basic characteristics such as condensation water yield and formation timing typically employs two approaches: energy balance modeling and direct field observation. While the energy balance method provides reasonable fitting for condensation water amounts, it exhibits high dispersion and its simulated results are affected by numerous observational variable errors. In contrast, most field studies utilize custom micro-lysimeters to measure soil condensation water, yielding more accurate measurements with convenient portability and no temporal or spatial constraints.

Numerous studies have demonstrated that soil condensation water formation is primarily influenced by micro-meteorological conditions including surface temperature, air relative humidity, and wind speed, with weather type (e.g., sunny, cloudy) being a key determinant of significant condensation formation. Additionally, seasonal patterns, vegetation cover, micro-topography, soil texture, and groundwater level all exert important effects on condensation water formation, resulting in varying condensation yields across different regions. Global climate warming has significantly impacted many regions, with studies revealing that the Sanjiang Plain has become warmer and drier in recent decades, leading to reduced dew formation. Projections for temperature and relative humidity indicate that dew yield in the Mediterranean region will decline by the end of the 21st century, underscoring the strong influence of climate change on condensation water production.

Previous research on condensation water in arid regions has made substantial progress regarding its causes, formation patterns, and influencing factors. However, with ongoing climate change increasing drought frequency in many regions, particularly ecologically vulnerable areas, current studies lack investigation into condensation water on the Qinghai-Tibet Plateau. The plateau' s ecosystem is fragile and sensitive, with continuous permafrost degradation due to climate warming. Soil water content decreases with increasing degradation, with most regions exhibiting a dry-wet transition state. In 2011, natural breaching of Zonag Lake in the plateau' s hinterland exposed large lakebed areas, causing grassland degradation and desertification. As a sustained and stable water source, condensation water may serve as an active factor in meadow growth and hydrological processes during the plateau' s summer dry period. Therefore, this study investigates soil condensation water formation characteristics in the plateau hinterland to identify key influencing factors and reveal condensation water' s impact on surface soil moisture, aiming to provide scientific basis for water vapor cycle research and ecological water assessment under climate change on the Qinghai-Tibet Plateau.

2 Study Area

The study area is located in the Salt Lake district of the Hoh Xil National Nature Reserve in Qinghai Province, bordered by the Qinghai-Tibet Highway to the east, Tanggula Mountains to the south, Qiangtang Plateau to the west, and Kunlun Mountains to the north, with an average elevation exceeding 4600 m. The climate is cold and arid, with mean annual temperature of -3.6 °C and precipitation of 297.4 mm concentrated mainly in summer, while mean annual evaporation reaches 1316.9 mm. The regional geomorphology is characterized by broad plateau valley basins with gentle terrain. The strata consist primarily of Paleogene and Quaternary systems, with surface soils generally being brown sandy loam 1.5-2.0 m thick underlain by Lower Pleistocene marl. The area features alpine steppe vegetation dominated by *Kobresia* and *Festuca* species. Soil water content decreases with increasing degradation, with most regions showing dry-wet transition conditions.

3 Methods

3.1 Sample Plot Setup

Numerous studies have shown that soil condensation water forms primarily in the 0-10 cm layer. This study selected bare soil near the Suonandajie Protection Station in the Salt Lake area as the research site (Fig. 1), with geographic coordinates of 93°36 E, 35°25 N and elevation of 4464 m. Fieldwork was conducted in July 2021.

3.2 Micro-Lysimeter Design and Installation

Soil condensation water was monitored using micro-lysimeters, which consist of inner and outer cylinders. The inner cylinder holds the soil sample while the outer cylinder prevents disturbance from surrounding soil. The inner and outer cylinders have diameters of 10.0 cm and 11.0 cm, and heights of 8.5 cm and 10.0 cm, respectively. Outer cylinders are open at both ends, while inner cylinders come in two types: (1) fully open type with both ends unsealed but bottom covered with 300-mesh gauze (hereafter "full-pass group"), allowing water vapor passage while preventing soil loss; and (2) bottom-sealed type with upper opening but lower end sealed with plastic film (hereafter "bottom-sealed group"), preventing reception of deep soil pore water vapor. Three replicates of each inner cylinder type were arranged uniformly in a 0.3 m × 0.5 m plot (Fig. 2).

Installation procedure involved vertically pressing inner cylinders into the soil to extract undisturbed soil cores, which were then placed into pre-installed outer cylinders in the plot. The soil surface in inner cylinders was leveled with the surrounding soil surface, with consistent insertion depth maintained between inner and outer cylinders.

3.3 Meteorological and Soil Parameter Monitoring

During the field experiment, a small weather station continuously measured air temperature and relative humidity (Fig. 2) using a louvered temperature-humidity sensor with accuracies of $±$0.2 °C and $±$2%, respectively. Soil temperature and moisture were measured using soil temperature-moisture sensors at depths of 5 cm, 10 cm, 20 cm, 30 cm, and 50 cm below the surface, with measurement accuracies of $±$0.5 °C and $±$3%, respectively. Soil moisture measurements represent volumetric water content. All meteorological and soil parameters were recorded at 2-hour intervals.

Soil condensation water observations began daily at 14:00 using an electronic balance with 0.01 g precision to continuously weigh inner cylinders and monitor condensation and evaporation processes at 2-hour intervals. Before each weighing, moisture on the inner cylinder surface was carefully and quickly wiped with cotton wool. To prevent wind interference, the balance was placed in a wind shield during readings.

3.4 Data Analysis Methods

3.4.1 Water Vapor Flux Calculation Evaporation and condensation amounts were calculated using:

$$h = \frac{40 \times m}{\pi \times d^2}$$

where h is soil water vapor evaporation or condensation amount (mm) in the 0–10 cm layer; m is the mass difference between consecutive weighings (g); ρ

is water density (taken as 1.0 $\mathrm{g \cdot cm^{-3}}$); and d is the micro-lysimeter diameter (cm).

3.4.2 Correlation and Regression Analysis Pearson correlation analysis examined significant relationships between condensation water and micro-meteorological conditions:

$$r = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{[n\sum x_i^2 - (\sum x_i)^2][n\sum y_i^2 - (\sum y_i)^2]}}$$

where r is the correlation coefficient between two variables (x, y), with $r < 0$ indicating negative correlation and $r > 0$ positive correlation; n is sample size; x_i and y_i are meteorological factor values and condensation water amounts at different times, respectively.

Correlation coefficients underwent t-testing:

$$t = r\sqrt{\frac{n-2}{1-r^2}}$$

where t is the statistical value used to determine P values from t-distribution tables. $P < 0.05$ indicates significant correlation and $P < 0.01$ indicates highly significant correlation.

Regression equations between condensation water and influencing factors were established as:

$$\hat{Y} = a + bX$$

where $\hat{Y}$ is the estimated condensation water amount (dependent variable); X is the influencing factor (independent variable); a and b are parameters, with a as the intercept and b as the regression coefficient (slope) calculated from sample observations; $\bar{Y}$ and $\bar{X}$ are mean values of dependent and independent variables, respectively.

3.4.3 Principal Component Analysis Principal Component Analysis (PCA) reduces dimensionality by transforming n correlated original variables into m uncorrelated linear combinations ($m < n$) that retain most information while eliminating overlap. Eigenvalues, variance contribution rates, and loadings determine PCA results. Eigenvalues \$ \$1 indicate important principal components; cumulative variance contribution rates \$ \$70% are acceptable, while \$ \$85% provide good explanatory power. Larger loading values indicate greater influence on factors.

4 Results

4.1 Soil Water Vapor Condensation Process Characteristics

During the experimental period, all days were sunny. Analysis revealed consistent water change trends between full-pass and bottom-sealed groups, showing a pattern of decrease-increase-decrease (Fig. 3). From 14:00–18:00, soil water evaporation rates gradually decreased. Significant condensation occurred from 00:00–10:00, with bottom-sealed group showing notable condensation from 00:00–08:00. The full-pass group exhibited condensation rates exceeding evaporation rates, while bottom-sealed group showed condensation rates lower than evaporation rates during 04:00–06:00, resulting in water loss.

One-way ANOVA revealed that condensation water variations between groups were non-significant only during 20:00–22:00 and 10:00–12:00 the following day ($P > 0.05$), with significant differences at all other times ($P < 0.05$). Table 1 presents ANOVA results for condensation water amounts (2-hour intervals) across treatments. Fig. 3 shows condensation water variation, where error bars represent standard errors, identical lowercase letters indicate non-significant differences, different letters indicate significant differences, and negative values represent water evaporation. Results demonstrate that after intense midday evaporation, the full-pass group could replenish water from deep soil layers, maintaining higher evaporation rates than the bottom-sealed group.

4.2 Soil Condensation Water Quantity Characteristics

Total soil condensation water (full-pass group) and atmospheric water vapor condensation (bottom-sealed group) showed distinct patterns. Full-pass group condensation exhibited unimodal variation (Fig. 6), peaking at 06:00–08:00 with maximum condensation of 0.200 ± 0.020 mm. Bottom-sealed group atmospheric condensation peaked earlier, during 02:00–04:00 and 06:00–08:00, with peak amounts of 0.012 ± 0.004 mm and 0.008 ± 0.004 mm, respectively (Table 2).

Overall, full-pass group condensation exceeded bottom-sealed group amounts, with atmospheric and deep soil water vapor contributing at approximately 1:3 ratio. When atmospheric condensation was significant, deep soil water vapor dominated soil condensation water formation, accounting for about 75% of total condensation.

4.3 Micro-Meteorological Conditions

4.3.1 Temporal Variation of Environmental Parameters During the observation period, near-surface air temperature showed a decreasing then increasing trend from 14:00–14:00, while relative humidity exhibited the opposite pattern (Fig. 4). From 00:00–10:00, air temperature reached its minimum and relative humidity its maximum, with averages of 3.76 °C and 64.7%, respectively. These conditions were favorable for condensation formation, while other periods showed dominant evaporation.

Soil temperature at different depths varied temporally with distinct patterns (Fig. 5). The 5-50 cm soil layer temperatures showed decreasing then increasing trends, with the 5 cm layer changing most rapidly and deeper layers showing progressively slower rates. The 50 cm layer exhibited minimal temperature change. During 14:00-22:00, soil temperature decreased with depth, peaking at 16:00 in the 5 cm layer. From 00:00-10:00, the 5 cm layer was cooler than underlying layers, reaching minimum temperature during 06:00-08:00. Lower soil layers showed lagged temperature responses, with maximum temperatures decreasing with depth.

Soil water content varied significantly only in the 0-10 cm layer, with minimal variation in deeper layers (Fig. 5). During 00:00-02:00, 10 cm soil water content increased slightly, while 20 cm and 30 cm layers showed continuous increases, likely due to enhanced temperature gradients driving upward water vapor migration. The 0-10 cm layer lost water overall, indicating evaporation exceeded deep soil vapor replenishment. Soil water content remained relatively stable below 30 cm depth. The soil profile showed low-high-low water content distribution from top to bottom.

4.3.2 Correlation Analysis Correlation analysis between condensation water and micro-meteorological factors (Table 3) revealed that full-pass group condensation water (QT) was significantly negatively correlated with 5 cm soil temperature (ST_5) and the temperature difference between 5 cm and 30 cm layers (ST_{5-30}), indicating soil condensation formation is strongly influenced by soil thermal conditions. Bottom-sealed group condensation water (XF) showed significant positive correlation with relative humidity (RH) and significant negative correlation with air temperature (T), demonstrating atmospheric condensation dependence on these factors.

Linear regression between condensation water and significant factors showed good fit ($R^2 > 0.45$), with full-pass group condensation negatively correlated with ST_{5-30}—as the temperature difference decreased, condensation water increased. During condensation periods (00:00-10:00), the 5 cm soil layer was warmer than the 30 cm layer, and condensation decreased with reducing interlayer temperature differences. Bottom-sealed group condensation showed negative and positive correlations with T and RH, respectively, with maximum condensation occurring when air temperature was 0-2 °C and relative humidity was high.

4.3.3 Principal Component Analysis PCA of factors influencing condensation water (Table 4) included variables with correlation coefficients $|r| > 0.45$, excluding strongly autocorrelated factors. The first two principal components accounted for 93.90% of cumulative variance, with eigenvalues >1, indicating they represent most original information.

The first principal component contributed 71.20% variance, heavily loading on micro-meteorological factors above 10 cm depth (relative humidity, air temperature, 5 cm soil temperature). The second component contributed 22.70% variance, loading on deeper soil factors (30 cm soil temperature, 20 cm soil water content, 10 cm soil temperature). The ST_{5-30} temperature difference factor fell between both components as it involves both upper and lower soil layers (Fig. 7).

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5 Discussion

5.1 Formation Characteristics of Soil Condensation Water

This study found that deep soil water vapor contributed approximately 75% to soil condensation water in the Salt Lake area, significantly exceeding atmospheric water vapor contribution. This aligns with results from the Mu Us Sandy Land and Lop Nur region but contrasts with findings from alpine sandy areas, Changji region in Xinjiang, and the North China Plain. Despite being an alpine region, the Salt Lake area' s condensation composition differs from other alpine sandy areas, possibly because the Salt Lake region lies in permafrost zones with higher surface soil moisture (>0.43% in 0-5 cm layer) compared to drier regions like Changji (<0.43% in 0-5 cm layer). Additionally, the Salt Lake area' s high altitude results in lower absolute humidity at the same relative humidity compared to the North China Plain, making atmospheric condensation less favorable.

Condensation water yield reached 0.2 $\mathrm{mm} \cdot \mathrm{d}^{-1}$ during the observation period. Full-pass group condensation showed unimodal variation peaking at 06:00-08:00, while bottom-sealed group peaked earlier at 02:00-04:00 and 06:00-08:00. ANOVA results indicated that after intense evaporation, the full-pass group could replenish water from deep soil layers, maintaining higher evaporation rates than the bottom-sealed group. The duration of soil vapor condensation exceeded that of atmospheric vapor condensation, with bottom-sealed group showing obvious evaporation by 08:00-10:00 while full-pass group continued generating condensation, consistent with findings from the Mu Us Sandy Land.

5.2 Influence of Micro-Meteorological Conditions

Correlation and PCA results demonstrate that micro-meteorological conditions significantly influence condensation water. In July, obvious condensation formed when nighttime relative humidity exceeded 64%, air temperature was below 3.8 °C, and 5 cm soil temperature was below 4.1 °C, indicating that multiple micro-meteorological conditions must be satisfied for condensation formation.

The significant correlation between total condensation water and ST_{5-30} reveals that soil condensation in the Salt Lake area is primarily composed of soil-derived water vapor. PCA showed that micro-meteorological factors above 10 cm depth accounted for 71.20% of variance, indicating that condensation formation is mainly controlled by near-surface conditions including relative humidity, air temperature, and soil temperature. This aligns with previous research showing condensation primarily forms in the 0–10 cm layer. Notably, this study found no significant correlation between condensation water and soil water content in either group, likely because soil temperature changes exhibit lag effects and water vapor transport from deep to surface layers is relatively slow, resulting in weak correlations within the same time period.

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6 Conclusion

This study investigated soil condensation water formation characteristics and influencing factors in the Salt Lake area of Hoh Xil, yielding three main conclusions:

1) Obvious soil condensation formed during 00:00–10:00, composed primarily of atmospheric water vapor and deep soil water vapor at a ratio of approximately 1:3. Formation conditions included nighttime near-surface relative humidity >64%, air temperature <3.8 °C, and 5 cm soil temperature <4.1 °C, with average yield reaching 0.2 $\text{mm} \cdot \text{d}^{-1}$.
2) Total soil condensation water showed significant negative correlation with 5 cm soil temperature and 5–30 cm soil temperature difference, with good linear regression fit. Atmospheric water vapor condensation was significantly negatively correlated with air temperature and significantly positively correlated with relative humidity.
3) PCA indicated that micro-meteorological factors above the 10 cm soil layer were the primary influences on condensation water formation, with deep soil water vapor being the main component of soil condensation water.

These findings provide scientific basis for water vapor cycle research and ecological water assessment under climate change on the Qinghai-Tibet Plateau.

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