Postprint: Advances in Non-Precipitation Water Research

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Abstract

Non-rainfall water is critically important to the water balance and ecology of arid and semi-arid regions. This paper systematically summarizes and reviews the measurement and simulation methods for non-rainfall water, and analyzes the current state of research. Non-rainfall water constitutes a relatively small flux between the land and atmosphere, exhibits strong spatiotemporal variability, and poses difficulties for direct measurement. Considerable dew yields can be obtained using specialized condensers. Dew research has concentrated at the site scale in arid and semi-arid regions, fog water research has focused on coastal and mountainous areas, and water vapor adsorption research has been conducted primarily in drylands. The collection and utilization of non-rainfall water and its impacts on the ecological environment represent active research topics. However, while dew research is relatively abundant, studies on fog water and water vapor adsorption are notably scarce. Furthermore, research on natural surface dew formation, large spatial scales, and long-term investigations remains limited. Significant knowledge gaps exist in understanding the spatiotemporal variation patterns of non-rainfall water.

Full Text

Research Progress in Non-Rainfall Water

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Abstract

Non-rainfall water is critically important for water balance and ecology in arid and semi-arid regions. This paper summarizes measurement and simulation methods for non-rainfall water and analyzes current research status. As a small flux between land and atmosphere with strong spatiotemporal variability, non-rainfall water is difficult to measure directly. Specialized condensers can harvest considerable dew amounts. Dew research focuses on site scales in arid and semi-arid areas, fog water research concentrates on coastal and mountainous regions, and water vapor adsorption studies mainly occur in drylands. The collection and utilization of non-rainfall water and its ecological impacts represent key research topics. However, dew has been studied extensively while fog water and water vapor adsorption research remain notably scarce. Moreover, studies on natural surface condensation, large spatial scales, and long-term observations are limited. Significant knowledge gaps exist in understanding the spatiotemporal variation patterns of non-rainfall water.

Keywords: non-rainfall water; dew; fog; water vapor adsorption

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Non-rainfall water refers to liquid water from the atmosphere that attaches to ground and object surfaces, excluding natural precipitation and artificial irrigation, and exists in forms such as dew, fog, and water vapor adsorption. Dew forms when surface temperatures fall below or equal to the dew point temperature, causing water vapor in humid air to condense. It is important to note that dew does not form in the air before depositing onto surfaces, making "dew formation" more appropriate than "dew deposition." Fog water formation is independent of surface conditions; fog occurs when atmospheric water vapor becomes saturated, creating tiny suspended droplets. Due to droplet settling and surface interception, "fog deposition" describes this process. Water vapor adsorption involves diffusion of water vapor from the atmosphere to soil and its adsorption onto soil particles, requiring soil surface temperature above dew point and atmospheric relative humidity exceeding soil air relative humidity to create a vapor gradient toward the soil.

Micro-meteorological conditions can distinguish fog, dew, and water vapor adsorption. Atmospheric conditions for fog formation are rarely satisfied in continental interiors, so most fog occurs in coastal and mountainous areas where relative humidity is high and vapor easily saturates. Distinguishing dew from water vapor adsorption is difficult. Dew is less constrained by specific climate conditions and can occur widely under most conditions. Compared with dew, water vapor adsorption has lower requirements for surface temperature and atmospheric humidity, making it more likely to occur. Traditionally, land condensation water includes dew, fog, and water vapor adsorption. Some Chinese scholars refer to non-rainfall water as condensation water, but they are not equivalent concepts because their water vapor sources differ. Non-rainfall water vapor originates directly from the atmosphere as a flux between land surface and atmosphere, while land condensation water includes vapor from both atmospheric and deep soil diffusion.

Non-rainfall water is an important water source in arid and semi-arid regions, providing essential moisture for plants, insects, small animals, and biological soil crusts during dry periods. Water scarcity during droughts limits plant growth, threatening seedling survival. Non-rainfall water alleviates plant water deficit, increases plant water content, reduces vegetation water stress, promotes growth, and extends photosynthesis. Some small animals (e.g., mealworms, geckos) collect dew and fog water using their bodies. Non-rainfall water constitutes an important component of terrestrial water balance in arid and semi-arid regions. During dry seasons, non-rainfall water supplements rainfall, and combining both can meet plant evapotranspiration demands. This paper reviews existing research, summarizes observation and quantification methods for non-rainfall water, evaluates characteristics of common methods, reviews research progress, identifies knowledge gaps, and proposes future research directions to provide references for further study.

1.1 Dew

Dew measurement remains difficult, and no standard method or model exists. Existing methods fall into measurement and estimation categories. Numerous methods and instruments have been developed to measure dew amount, including cloth plate methods, weighing methods, leaf wetness sensors, and lysimeters. The cloth plate method is simple, low-cost, and facilitates comparison of dew amounts at different positions and heights, but results are significantly affected by condenser plate material. Weighing methods are commonly used to measure natural dew formation but require manual collection in early morning, increasing labor costs. Leaf wetness sensors can detect dew presence on leaf surfaces and automatically record data when connected to data loggers. Micro-lysimeters have sufficient sensitivity and precision to quantify dew formation effectively, but surface soil layers more readily absorb water vapor from air, making it difficult to distinguish dew from water vapor adsorption. Additionally, lysimeters are costly. Since dew generally appears at night, most measurement methods require early morning observations, creating difficulties for long-term continuous dew monitoring.

Dew formation accompanies negative latent heat flux to the surface, representing the inverse process of evaporation, so physics-based models can estimate dew amount. Physical models apply to different locations, but construction is complicated by difficulties in simulating heat and radiation exchange. The most widely used physical models are energy balance models and Bowen ratio energy balance equations. Energy balance models applied to artificial condensing surfaces yield good predictive results, though many improvements are needed, such as predicting fog conditions at short microscales, better capturing vertical fog distribution, and addressing underestimation issues. Compared with other methods, the Bowen ratio energy balance model excels in obtaining correct heat and vapor conductance. The Bowen ratio represents the ratio of sensible to latent heat flux, enabling measurement of surface energy fluxes over relatively large areas. Artificial intelligence models can also estimate dew effectively, although they require large sample datasets that pose practical difficulties.

International organizations have promoted dew collection experiments. The International Organization for Dew Utilization (OPUR) recommends dew condensers as the most promising collection method. By comparing different foil materials, placement angles, and positions, harvested dew amounts can be increased. The International Fog and Dew Association (IFDA) has also showcased new materials for dew collection at international conferences. However, dew collectors aim to increase harvestable dew for utilization and cannot reflect actual dew yield.

Empirical, analytical, and artificial intelligence models estimate dew yield. Empirical models build relationships between dew and meteorological variables, typically characterizing connections between dew yield and cloud cover, wind speed, air temperature, dew point temperature, and site elevation. Analytical models establish formulas between fog deposition and parameters, offering simple calculations, but these parameters (e.g., wind speed, relative humidity) are empirical and require experimental or statistical determination. Complex models often couple with three-dimensional meteorological models for fog simulation. The Weather Research and Forecasting (WRF) model is most commonly used for predicting coastal fog and includes modules for microphysics, cumulus parameterization, surface physics, planetary boundary layer physics, atmospheric radiation, and land surface models.

1.2 Fog

Fog water is difficult to measure directly as it is suspended in air. It is typically collected by fog collectors and measured by rain gauges. Different fog collector designs show varying performance; flat-plate collectors demonstrate better collection efficiency than cylindrical collectors. Collector positioning is crucial, generally facing wind direction. Wind speed is the most influential factor on fog collectors, and fog formation probability decreases significantly when wind speed exceeds a certain threshold, though threshold values vary regionally.

Katata summarized fog deposition models for terrestrial ecosystems, categorizing them as resistance models, analytical models, and complex models. Most resistance models are based on the Penman-Monteith equation and its variations, though some physical quantities are difficult to measure and require estimation. The Lovett model established an empirical relationship between fog deposition rate and visibility, providing a method for estimating long-term fog deposition rates. The Körner model calculated fog using only temperature and relative humidity, offering simplicity and good performance but with some overestimation tendency. Complex models often integrate with three-dimensional meteorological models for fog simulation. The SOLVEG model coupled with meteorological models has been used to estimate fog deposition on trees. Numerical Weather Prediction (NWP) models are widely applied in predicting coastal fog.

Satellite remote sensing (e.g., MODIS, CALIPSO, Himawari-8) has improved coastal fog observation accuracy and represents the most effective means for large-scale, long-term sea fog monitoring. Artificial intelligence technology also plays an important role in predicting coastal fog.

1.3 Water Vapor Adsorption

Fewer observation and estimation methods exist for soil water vapor adsorption. Current measurements primarily rely on lysimeter observations, but lysimeters cannot directly determine water vapor adsorption amounts and require water flux partitioning. Estimation methods mainly include water vapor adsorption isotherm methods and soil water retention curve methods. Water vapor adsorption isotherms can effectively estimate vapor adsorption data, but resolution is insufficient and large errors may exist. Fully characterizing the driest portion of soil water retention curves is important for studying water vapor adsorption and can effectively simulate soil water flux oscillations. Some studies also use gradient methods to calculate water vapor adsorption, which causes limited soil disturbance but is highly dependent on diffusion coefficients requiring calibration for high accuracy.

Water vapor adsorption typically occurs in drylands, and although the flux is considered very small, it may be the main form of non-rainfall water input in special environments. Studies using micro-lysimeters on sand dunes in the Namib Desert determined that water vapor adsorption is the dominant non-rainfall water input in sand. In an olive grove in southern Spain, water vapor adsorption measurements showed maximum values farthest from tree trunks. Using three different soil water retention curves to simulate water vapor adsorption data for dune deposits in southern Spain demonstrated that dual-porosity water retention curves best matched measured data with good annual-scale fitting. Currently, soil water vapor adsorption simulation remains a serious challenge requiring more research.

2 Research Progress

Non-rainfall water research concentrates in coastal areas and arid/semi-arid regions. The Negev Desert in Israel has been a key research area since the 1960s. Recent studies on coastal fog have increased significantly. Collection and utilization of non-rainfall water and its ecological impacts remain research hotspots. Since the mid-20th century, dew research has gradually increased, focusing on arid and semi-arid sites and using measurement and simulation methods to study short-term dew amounts. Results show dew is a small flux, but different collection methods yield varying amounts. For example, inverted pyramid condensers have higher collection efficiency than flat condensers. Studies have compared and validated different dew simulation methods, showing surface energy balance models perform better than aerodynamic models. Dew amounts measured by lysimeter and estimated by Bowen ratio energy balance showed good consistency in China' s Badain Jaran Desert, though Bowen ratio values were consistently lower than measured values. Artificial intelligence models can effectively predict dew amounts in dry seasons. Considering dew amount in drought assessment helps evaluate drought more accurately across regions.

Long-term measurements of dew formation are nearly impossible, and assessing long-term trends in dew amount is difficult due to method limitations. Research results demonstrate the importance of long-term observations. In the Taklimakan Desert, multi-year average dew amount in June accounted for a certain percentage of the corresponding period' s average rainfall and annual average rainfall, playing an important role in maintaining regional water balance. Dew amount in China was high in the northeast and northwest in a given year, low in central and southern regions. Vuollekoski used meteorological reanalysis data and energy balance models to map global dew and study collection potential, showing large-scale dew harvesting potential in some water-scarce regions (coastal North Africa and Arabian Peninsula).

Fog water research focuses on coastal areas. To enhance understanding and prediction accuracy of coastal fog, the Coastal Fog Research Program (C-FOG) was launched in 2019, conducting research along coastlines of eastern Canada and northeastern United States, including synoptic conditions, microphysics, dynamics, and modeling. Fog events mostly occur in cyclonic and anticyclonic systems. Evaluating microphysical parameterization observations (e.g., droplet concentration, liquid water content) and developing visibility parameterization contributed to model effectiveness. Chisholm studied marine aerosol particle movement, emphasizing boundary layer roles in coastal fog formation. In model estimation, Dimitrova compared coastal fog observations with WRF model results, finding good performance in calculating fog water amount and meteorological conditions over oceans. China studied coastal fog in the Yellow and Bohai Sea regions in the 1990s. Fog in Shandong Peninsula's Yellow Sea coast often accompanies sea-land breeze circulation; WRF simulations showed nighttime land breeze promotes sea fog formation while daytime sea breeze slows development. Tian Meng observed coastal fog around the Bohai Sea, summarizing synoptic conditions and boundary layer characteristics. Sea fog processes in Fujian coastal areas can be divided into three stages: radiation fog influence, advection fog influence, and sea fog encountering cold air. Sea fog in the Pearl River Estuary benefits from stable boundary layers and suitable weather/hydrological conditions. Considering weather, climate, and boundary layer characteristics is important for understanding coastal fog formation and improving prediction accuracy.

Mountain fog water research is mostly based on cloud water interception in montane cloud forests. Trees act as fog collectors, and intercepted fog water in Dhofar mountains can increase throughfall by 15%-150%. Canopy fog interception differs at different altitudes. Fog collection potential varies significantly at different mountain positions. A 3-year study in Bolivia assessed spatial variability of fog collection potential. Atashi used energy balance models to simulate dew amount spatiotemporal variation in Iran, finding high dew yield and frequent formation in northern mountains, with dew as an alternative water source in water-scarce central and southern regions. This research aids scientific dew harvesting in water-scarce Iran.

Large-scale dew research is very limited, and obtaining continuous spatiotemporal dew distribution at large scales is difficult. Dew amount spatiotemporal distribution helps identify areas with high dew collection potential, promotes efficient dew resource utilization, advances terrestrial water cycle research, and deepens understanding of climate change impacts. Tomaszkiewicz measured dew yield at 15 stations around the Mediterranean during dry seasons and created dew yield maps using geostatistical interpolation, identifying high-yield areas and laying foundations for reducing groundwater dependence.

Stable isotope tracer techniques provide unique tools for evaluating ecohydrological processes of non-rainfall water and are widely applied in fog water research. Dew or fog water is more enriched in heavy isotopes than precipitation, making stable isotopes effective for studying ecohydrological effects. Fog water isotope research aims to explore recharge to surface runoff and groundwater, while dew isotope research focuses on evaporation during dew formation, both addressing how vegetation utilizes non-rainfall water. Fog water isotopes in dry-season Chishui forest were enriched compared to precipitation, recharging local groundwater and surface runoff. Fog water in Czech Republic was enriched compared to precipitation and throughfall, with high ion concentrations contributing significantly to atmospheric deposition. Excess deuterium can extract evaporation information, revealing different evaporation processes (equilibrium and kinetic fractionation) during dew formation, with equilibrium fractionation playing a more important role than kinetic fractionation in controlling dew isotope composition. Measuring plant leaf water isotopes can determine water sources; xylem water isotopes showed tropical forest plants in Xishuangbanna use fog water as important supplement during dry seasons, with lianas utilizing more fog water than trees. Leaf surface moisture of Populus simonii in northeastern China mainly originates from dew.

Research on interactions between non-rainfall water and biological soil crusts has increased significantly. Non-rainfall water is crucial in arid/semi-arid regions, and biological crusts cover large areas of these regions, making their relationship important for water and carbon biogeochemical cycles. Biological crusts are combinations of soil organisms (mosses, lichens, algae) with surface soil and serve as model ecosystems for studying arid regions due to their environmental sensitivity. Biological crusts potentially enhance non-rainfall water amounts by improving soil texture and regulating soil water balance, strengthening non-rainfall water cycling. Non-rainfall water activates biological crust physiological activity, extends metabolism, reduces drought stress, but can cause negative carbon balance and low carbon fixation rates. Whether non-rainfall water is an important water source for biological crusts depends on whether it reaches activity thresholds. While most scholars consider non-rainfall water important for all biological crusts, research shows moss or lichen crusts utilize non-rainfall water more effectively than cyanobacteria crusts, which may even experience carbon loss. This may occur because lysimeters overestimate non-rainfall water amounts, while actual amounts are far below cyanobacteria thresholds. The interaction mechanisms and impacts between non-rainfall water and biological crusts in arid/semi-arid regions require further study.

3 Research Outlook

Non-rainfall water research has achieved many results but remains in its early stages with many unresolved issues. Current studies cannot provide overall understanding of spatiotemporal variation patterns. Future research should: (1) enrich studies on natural surface non-rainfall water across different regions, developing new technologies and methods for collection, observation, and modeling to enable more accurate estimation at broader spatial and temporal scales; (2) explore large-scale and long-term observation and simulation to reveal spatiotemporal distribution patterns, promoting rational assessment and utilization; (3) under Earth system theory guidance, deepen investigation of non-rainfall water’ s significance for water cycling, ecohydrology, and climate to improve land surface and Earth system models and understanding of climate change responses and feedbacks.

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