

季节性冻土区包气带水汽热耦合运移研究进展

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摘要: 季节性冻土区占据中国超过一半的国土面积, 冻融作用会显著改变土壤性质与包气带水、热传输过程, 并且由于温度与气态水对土壤水分运移影响显著, 开展水汽热耦合研究对于探究季节性冻土区土壤水循环过程十分关键。该研究综述了包气带水汽热耦合运移理论的提出与发展历程, 阐明了季节性冻融作用对水汽热耦合运移研究中水力参数及水分相态转化过程的影响, 探讨了水汽热耦合模型适用性, 总结了温度梯度驱动下气态水运移规律及其重要性, 并对该领域尚需加强研究的方向提出建议: 1) 聚焦“土壤-植被-大气”系统水循环过程, 构建适用于季节性冻土区的包气带水汽热-植被耦合模型, 探究土壤水资源生态效应, 为植被恢复与生态系统稳定提供理论指导; 2) 在寒旱区工程建设中考虑气态水的影响, 明确覆盖层下水汽运移机理, 对建设过程中由水汽运移引起的工程病害提出具体防治措施。通过本研究梳理归纳以期深化包气带水汽热耦合运移理论以及解决季节性冻土区相关实际问题提供科学依据与参考。

关键词: 水; 热; 数值分析; 包气带; 水汽运移; 水文循环; 季节性冻土区

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0 引言

包气带作为地球关键带的重要组成部分, 不仅是大气圈、水圈、岩石圈等相互作用的联系纽带, 也为土-气界面间质能交换、土壤水热传输以及植物根系吸水等水分与能量交换活动提供了场所^[1]。土壤和水是包气带中的核心要素, 其中水是进行质、能交换的主要驱动力, 土壤水分变化反映了蒸发、入渗、径流、截留、渗漏等多界面的水文过程及土壤水文性质^[2-4]。传统的包气带水分运移研究主要围绕液态水展开, 而忽略了气态水的影响。近年来随着研究深入, 包气带气态水运移及水-汽相变过程对于土壤水、热传输过程的影响逐渐被证实^[5-6]。尤其是对于干旱半干旱地区, 气态水可为生态脆弱区植被生长及生态系统稳定提供重要水分来源, 其作用不可被忽略^[7-8]。

中国是世界上冻土分布面积第三大国, 其中季节性冻土区占据超过一半的国土面积, 且多数季节性冻土广泛分布于干旱半干旱地区^[9]。在这些地区, 降雨稀少且蒸发强烈, 土壤干燥缺水, 土地荒漠化突出, 冬季土壤年冻结时间长达4~6个月。季节性冻融作用不仅会引起诸如土壤结构、容重等物理性质发生变化, 同时会显著改

变包气带水、热特性及其传输过程, 进而影响到区内农业生产及诸多工程建设活动^[10-12]。相比于非冻结时期, 冻结期内由于土壤孔隙中冰的存在会阻碍液态水运移, 气态水在土壤水分运移中的影响会更加明显, 开展包气带水汽热耦合研究对于厘清季节性冻土区土壤水循环过程尤为关键^[13]。然而, 关于季节性冻土区包气带水汽热耦合运移的研究现状及应加强研究的重点领域鲜有报道。

鉴于此, 本文综述包气带水汽热耦合运移理论的提出与发展过程, 阐述季节性冻融作用对水汽热耦合运移研究的具体影响, 探讨数值模拟技术在包气带水汽热耦合运移研究中的应用, 总结温度梯度驱动下气态水运移规律及其影响, 并从季节性冻土区研究实际需求的视角提出了未来亟待加强研究的重点方向, 以期深化包气带水汽热耦合运移理论以及解决季节性冻土区相关实际问题提供科学依据。

1 包气带水汽热耦合运移理论

1.1 理论提出与发展

基于 Richards 方程, 包气带水分运移研究开始由静态、定性描述为主向动态、定量分析的方向发展。而随着水汽运移概念的提出, Philip 等^[14]首次将非等温条件下水汽运移过程引入包气带水分运移研究中, 提出了包气带水汽热耦合运移理论, 即最初的 PDV 理论。PDV 理论认为当土壤颗粒间存在温度差时土壤水分会在较热一端蒸发、较冷一端凝结, 总体蒸发与凝结速率相等, 即为水汽运移速率, 包气带总水分通量可被看作是由温度梯度与含水量梯度分别驱动下的水、汽通量组成。以 PDV

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理论为基础, 众多学者围绕水汽热耦合运移过程展开研究并不断完善相关理论。例如, Hanks 等^[15]提出若忽略温度影响, 计算蒸发量时会产生约 10% 的误差, 且这一比例在干旱条件下会增大; Milly^[16]提出水分运移的驱动力之一应为基质势而不是 PDV 模型中的含水量, 由此模型可被用于非均质土壤中的研究; Cass^[17]提出了水汽通量的增强因子计算方式; Cahill 等^[18]通过野外试验证明浅层土壤中水汽通量不仅占据总水分通量的 25%, 同时也导致了超过 50% 的热通量。

当冬季土壤冻结后, 包气带孔隙中水、汽、冰三相共存(图 1)。随温度降低/升高, 包气带中未冻水含量减小/增大, 冰-水相变过程对于包气带水、热运移过程影响显著。基于多孔介质水分运移和热平衡理论, Harlan^[19]首次提出了适用于非饱和冻土研究的水热耦合模型, 并利用有限差分法求解模型。随后, Cary 等^[20-22]逐步完善了 Harlan 模型, 如建立了液态水与温度之间的联系等。然而由于水-汽-冰-热耦合复杂性, 在早期非饱和冻土水分运移研究中并未考虑气态水的影响。逐渐地, Nakano 等^[23-25]研究结果均指出深层气态水不断向冻结锋处运移会促进冰的形成, 并且会主导冻层内水分运移过程, 气态水对冻结情况下土壤水、热传输过程的重要性逐渐被认可。

1.2 数学方程

对于一维垂向包气带水分运移过程, 当考虑气态水、冰以及温度共同影响时, 土壤水、热传输控制方程可分别表示为如下形式^[26]:

$$\frac{\partial \theta_l}{\partial t} + \frac{\rho_v}{\rho_l} \frac{\partial \theta_v}{\partial t} + \frac{\rho_i}{\rho_l} \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z} \left[K_{lh} \frac{\partial h}{\partial z} + K_{lh} + K_{lv} \frac{\partial T}{\partial z} + K_{vh} \frac{\partial h}{\partial z} + K_{vT} \frac{\partial T}{\partial z} \right] \quad (1)$$

$$\frac{\partial C_p T}{\partial t} + L_w \rho_l \frac{\partial \theta_v}{\partial t} - L_f \rho_l \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) - C_w \frac{\partial q_l T}{\partial z} - C_v \frac{\partial q_v T}{\partial z} - L_w \frac{\partial q_v}{\partial z} \quad (2)$$

式中 θ_l 、 θ_v 和 θ_i 分别为土壤液态水含水量、气态水含水

量与含冰量, cm^3/cm^3 ; ρ_l 、 ρ_v 和 ρ_i 分别为液态水、气态水与冰密度, g/cm^3 ; t 为时间, d ; z 为垂向坐标轴(向上为正), cm ; h 为基质势, cm ; T 为温度, K ; K_{lh} 和 K_{vh} 分别为等温液态水与气态水水力传导度, cm/d ; K_{lv} 和 K_{vT} 分别为非等温液态水与气态水水力传导度, $\text{cm}^2/(\text{K} \cdot \text{d})$; L_w 和 L_f 分别为蒸发潜热与冻结潜热, J/kg ; λ 为土壤热导率, $\text{W}/(\text{m} \cdot \text{K})$; q_l 和 q_v 分别为土壤液态水和气态水通量, cm/d ; C_p 为土壤的体积热容量, $\text{J}/(\text{m}^3 \cdot \text{K})$; C_w 和 C_v 分别表示土壤中液态水及气态水的体积热容量, $\text{J}/(\text{m}^3 \cdot \text{K})$ 。

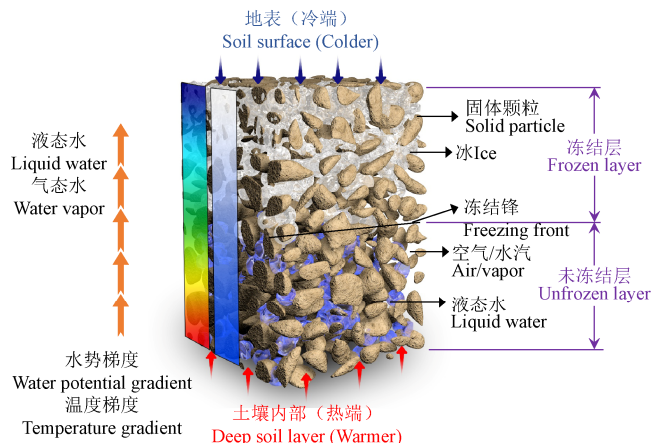


图 1 非饱和冻土中水-汽-冰-热耦合示意图

Fig.1 Diagram of coupled relationship of water, vapor, ice, and heat in unsaturated frozen soil

在水分运移方程中, 方程左端包含了液态水、气态水及含冰量的变化, 右端则分别为基质势梯度、重力势梯度及温度梯度驱动的液态水运移, 以及基质势梯度与温度梯度驱动的气态水运移。选取 van Genuchten-Mualem 公式作为非饱和液态水水力传导度计算公式, 式(1)中涉及的传导度及相关参数计算方式如表 1 所示^[26]。在热传导方程中, 方程左端包含了土壤热容量、冰-水相变潜热及水-汽相变潜热变化, 右端分别为热传导、液态水流动引起的热扩散、气态水流动引起的热扩散及气态水相变潜热。

表 1 水力传导度及相应参数计算^[26]

Table 1 Calculation of hydraulic conductivities and related parameters^[26]

水力传导度 Hydraulic conductivity	计算式 Formula	所需参数及其计算方法 Required parameters and calculation method
液态水水力传导度 Hydraulic conductivity for liquid water	$K_{lh} = K_s F_w S_e^l \left[1 - (1 - S_e^{1/m})^m \right]^2$ $K_{lv} = K_{lh} \left(h G_{wT} \frac{1}{\gamma_0} \frac{d\gamma}{dT} \right)$	K_s 为饱和导水率(通过试验获取), $\text{cm} \cdot \text{d}^{-1}$; F_w 为冰对水力传导度的影响($F_w = 10^{-\varphi Q}$, 式中 φ 为由于冰存在引起的阻抗因子, Q 为含冰量所占质量比); S_e 为有效饱和度, $S_e = (\theta_l - \theta_r)/(\theta_s - \theta_r)$, 式中 θ_l 、 θ_r 与 θ_s 分别为土壤液态水含水量、土壤残余含水量、饱和含水量, $\text{cm}^3 \cdot \text{cm}^{-3}$; γ 为土壤水的表面张力, $\gamma = 75.6 - 0.1425T - 2.38 \times 10^{-4}T^2$, 式中 T 为温度, K ; γ_0 为 25℃ 时土壤水表面张力, 取经验值 71.89 $\text{g} \cdot \text{s}^{-2}$; G_{wT} 为温度影响参数, 砂土取经验值 7; h 为基质势, cm ; K_{lh} 为等温液态水水力传导度, $\text{cm} \cdot \text{d}^{-1}$; K_{lv} 为等温气态水水力传导度, $\text{cm} \cdot \text{d}^{-1}$; l 和 m 为经验参数
气态水水力传导度 Hydraulic conductivity for water vapor	$K_{vh} = \frac{D}{\rho_w} \rho_{sv} H_r \frac{Mg}{RT}$ $K_{vT} = \frac{D}{\rho_w} \eta H_r \frac{d\rho_{sv}}{dT}$	D 为土壤中水汽扩散系数($\text{cm}^2 \cdot \text{d}^{-1}$), $D = D_a \theta_a \tau$, 式中 θ_a 为土壤中空气体积分数, D_a 为空气中水汽扩散系数($\text{cm}^2 \cdot \text{d}^{-1}$), τ 为曲折因子; ρ_{sv} 为饱和水汽密度(经验公式计算, 与温度有关), $\text{g} \cdot \text{cm}^{-3}$; H_r 为相对湿度, $H_r = \exp(Mgh/RT)$, 式中 M 为水的摩尔质量(取经验值 0.018 $\text{kg} \cdot \text{mol}^{-1}$), g 为重力加速度(取经验值 9.81 $\text{m} \cdot \text{s}^{-2}$), η 为水汽扩散增强因子 $\eta = 9.5 + 3\theta_l/\theta_s - 8.5 \exp \left\{ - \left[(1 + 2.6/\sqrt{f_c}) \theta_l/\theta_s \right]^4 \right\}$, 式中 f_c 为土壤中黏粒质量分数; R 为气体常数(取经验值 8.315 $\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$); K_{vh} 为非等温液态水水力传导度, $\text{cm}^2 \cdot \text{K}^{-1} \cdot \text{d}^{-1}$; K_{vT} 为非等温气态水水力传导度, $\text{cm}^2 \cdot \text{K}^{-1} \cdot \text{d}^{-1}$

2 冻融作用对包气带水汽热耦合运移的影响

2.1 水力参数

由表 1 可知, 包气带水汽热耦合运移过程涉及参数较多。与未冻结时期不同, 冻结后由于冰的存在以及冰-水相变过程影响, 土壤水、热性质发生改变, 探究冻融作用影响下的包气带水汽热耦合运移过程时需重点关注以下参数:

1) 土壤冻结曲线

在土壤冻结后, 包气带中未冻水含量变化受土壤温度(负温)影响, 两者之间关系密切。土壤冻结曲线不仅可以刻画土壤水、热之间联系, 同时也是求解水热传输方程中不可或缺的重要参数, 通常情况下可通过经验公式法与土水特征曲线法求取土壤冻结曲线。

在传统研究中, 学者们提出了不同形式经验公式(幂函数^[27]、线性^[28]、指数函数^[29]等)来描述土壤冻结曲线。虽然这些经验公式形式简单, 但由于不同质地土壤性质变化差异较大, 且通过试验方式获取适宜的经验参数较为困难, 总体上该方法在当前研究中应用面临一定困难^[30-31]。

另一方面, 由于土壤冻结过程与土壤逐渐排水干燥过程相似, 在冻结过程中水分不断向冻结锋处运移, 因而可以根据土水特征曲线的概念得到土壤冻结曲线^[32]。利用 Claperon 方程建立负温与基质势之间关系, 随后将其代入 Brooks and Corey 方程^[33]、Gardner 方程^[34]、van Genuchten 方程^[35]等土水特征曲线中, 即可建立负温与未冻水含量之间关系, 如下所示(以 VG 方程为例)^[36]:

$$\theta_i = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \alpha \left(\frac{L_f}{g} \ln \frac{T}{T_f}\right)\right]^m} \quad (3)$$

式中 T_f 为液态水冻结温度(可由基质势计算得到), K ; α 、 n 、 m 为经验参数。相比于传统的经验公式计算法, 通过土水特征曲线法求解结果更加精确且合理, 因而被广泛应用^[37-38]。

2) 非饱和水力传导度

随着温度降低土壤孔隙逐渐被冰占据, 土壤水分在冻土中运移过程受到影响, 非饱和水力传导度显著减小。通常情况下, 土壤冻结时非饱和水力传导度与含冰量密切相关, 其计算方法主要有 3 种, 分别为半理论方法、经验公式法以及基于未冻结时期水力传导度的计算方法。

第一种方法主要基于毛细管理论及吸附理论, 假设冰的形成发生在毛细管中央, 该方法结果与实测值拟合较好, 但由于计算过程较为复杂, 不易应用于数值模型中^[39]。相比较而言, 第二种方法计算过程简单, 但与经验公式法获取土壤冻结曲线类似, 该方法中涉及的参数经验值随土壤性质变化较大且不易获取, 因此在相关研究中同样较少使用^[40]。

由于在前两种方法存在明显的局限性, 因此在当前研究中计算非饱和冻土中水力传导度时通常会采用第三种方法^[41]。该方法认为土壤冻结后非饱和水力传导度减

小的程度与相同基质吸力情况下土壤未冻结时的水力传导度数值有关, 即可以通过土壤未冻结时土水特征曲线与饱和水力传导度计算得到。为了体现冰的出现对水力传导度降低的影响, Taylor 等^[42-43]提出了不同形式阻抗因子的概念, 由于该方法考虑了冻融过程实际影响, 其参数具有一定的物理含义, 并且使用较为便利, 因而被广泛应用。尽管如此, 该方法同样存在不足之处, 如冻结(或融化)过程中基质势不断变化而阻抗因子为定值、不同未冻水含量情况下阻抗因子的确定等问题, 亟待进一步研究^[41,44]。

2.2 水分相态转化

季节性冻融作用引发冰-水相变过程, 对于土壤水分时空分布以及水分运移过程影响明显。根据质量守恒定律, 非饱和冻土中总含水量由固、液、气三相组成, 如式(4)所示。

$$\theta_t = \theta_i + \frac{\rho_v}{\rho_l} \theta_v + \frac{\rho_g}{\rho_l} \theta_g \quad (4)$$

式中 θ_t 为土壤总含水量, cm^3/cm^3 。当土壤温度低于冻结点(由于土壤处于非饱和状态, 冻结点会略低于 0°C), 土壤孔隙中的液态水开始转化为冰, 并随着温度逐渐降低含冰量持续增大且未冻水含量显著减小, 最终在温度足够低时液态水只剩下土壤颗粒附近的吸附水和薄膜水^[45-47]。需要注意的是, 不论温度多低, 这部分水总是以液态形式存在。长期以来, 明确土壤水分的相态转化过程及各组分体积分数是探究季节性冻土区水分运移过程的关键, 其中气态水含量可通过监测水汽压、水汽密度等参数并利用经验公式计算获取, 而液态水含量则可直接通过布设传感器来实时监测。如基于频域分解法原理的传感器, 其工作原理是通过分解土壤中介电常数的实部与虚部来确定土壤体积含水量, 由于土壤中各组分介电常数数值相差较大, 其中液态水介电常数数值约为 78, 远超过土壤基质、冰、空气等其他组分, 因而被证实适用于冻土中液态水含水量监测^[48-49]。根据式(4)及相应的液态水与气态水数据, 并通过烘干法测定土壤总含水量, 可最终确定冻土层内土壤含冰量数值。由于在水势梯度与温度梯度作用下, 土壤深部液态水与气态水不断向冻结锋处运移, 因此相比于冻结之前, 季节性冻土层内总含水量在融化后往往呈现出增大的趋势。

3 数值模拟技术在水汽热耦合运移研究中的应用

由于季节性冻土区野外工作的不确定性, 完全依赖野外试验很难揭示复杂的包气带水汽热耦合运移过程背后机理, 尤其是在当前研究中针对气态水的监测仍难以实现, 因而数值模拟方法逐渐成为了相关研究的主要工具。

3.1 耦合模型构建与适用性分析

基于土壤水分运移及热传导基本理论, 构建适宜的耦合模型是探究包气带水汽热耦合运移过程的基础。在不考虑冻融过程影响时, 许多简单的模型被用于研究包气带水汽热耦合运移过程。随着计算机技术的发展, 逐渐出现了功能较为完整且操作便利的数值模拟软件, 围绕特定时刻包气带水、汽、热通量分布以及特定深度包

气带水、汽、热通量变化规律展开研究, 取得较多成果, 相关模型也都被证实适用于野外实际研究中。

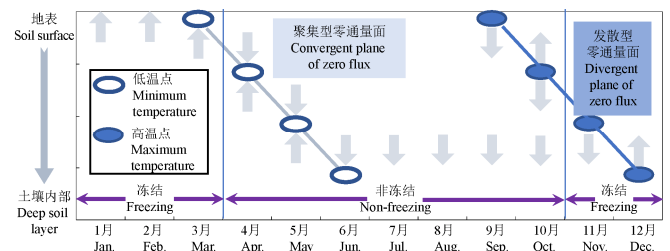
当考虑冻融过程后, 受冰-水相变过程影响, 耦合数值模型的构建面临较大挑战。合理的简化在确保模型精度的前提下有助于模型构建, 在研究中应用较多, 然而过度简化则对模型结果有较大影响。例如, 采用固定冻结温度方法计算含冰量时, 当计算出的土壤温度低于冻结点时, 土壤中液态水全部转化为冰。由土壤冻结曲线可知, 不论土壤温度多低, 孔隙中总有液态水存在, 含水量值与温度有关。因此这种过度简化的方法不仅会给计算结果带来较大误差, 同时也并不符合实际情况^[36]。此外, 当考虑冻融作用后, 模型计算时会出现数值程序不稳定的现象。例如, 在冰-水相变过程中, 由于相变潜热变化导致热容量突变会造成土壤温度计算不收敛^[50]。诸如此类现象的存在, 使得有必要优化程序计算过程以确保耦合模型运行稳定性。当数值程序稳定运行后, 模型计算精度与耗时平衡问题同样值得注意。如何在确保获取较为精确结果的前提下, 通过设置合理的时间与空间步长以控制模型运行时长有重要意义^[51]。

诸如 SHAW、CoupModel、Hydrus-1D、STEMMUS、COMSOL 等功能强大的数值软件出现, 为研究冻融作用影响下包气带水热传输过程提供了便利^[52]。由于起初研究目的不同, 不同软件建模时采用的控制方程与物理机制存在差异。例如在传统水汽热耦合运移理论中, 假定土壤中空气压强与大气压强保持平衡, 因而忽略了空气流动影响, 只考虑了水汽扩散过程, 导致了部分水汽通量计算误差。为了消除这一误差, STEMMUS 中将空气压强作为状态变量, 引入了空气流动方程, 考虑了水汽对流、弥散过程影响^[13]。相比较而言, Hydrus-1D 软件在包气带水、汽、热运移研究中应用最为广泛^[53-55]。以该软件为例, 具体介绍此类软件在水汽热耦合运移研究中的应用。基于 Saito 等^[56]的研究成果, 水汽热耦合模块被嵌入了标准版的 Hydrus-1D 4.0 版本中, 并由此被广泛应用于土壤未冻结条件下农业灌溉、水资源合理利用等方面的研究中。以该模块为基础, 结合 Hansson 等^[26]提出的 Hydrus-1D 冻融模块, Zheng 等^[57]开发了适用于冻融过程的包气带水汽热耦合运移程序, 并利用榆林、锡林郭勒、玛曲等不同冻土区实测数据验证模型精度, 证实所建立的模型适用性。在修改后的程序中, 基于有效能量方法修改了相变过程中由于表观热容增大引发的数值计算问题, 并优化了含冰量计算程序, 相比于 Hansson 版本, 模型运行稳定性显著提高, 且并未遇见数值计算问题。

3.2 气态水运移规律及其重要性

利用上述模型, 学者们围绕包气带水汽热耦合运移过程展开大量研究, 其中关于液态水运移机制及其影响研究取得较多成果, 在此不过多介绍, 重点探讨气态水运移规律。通常在季节性冻土区, 4—10 月以及 11 月—次年 3 月间土壤分别处于未冻结与冻结状态。如图 2 所示, 受包气带温度季节性变化影响, 水汽运移呈现显著的季节性变化规律。在未冻结时期, 表层土壤温度较高,

温度梯度方向向下, 驱动气态水向土壤内部运移。土壤内部存在有聚集型零通量面, 随着土壤温度不断升高, 其位置也不断向下移动。通常在夏季 7 月、8 月时温度梯度最大, 此时向下的水汽通量值最大。而从 9 月开始, 随着气温下降, 土壤温度降低, 包气带向外放热, 浅层开始出现发散型零温度梯度面并不断向土壤内部移动, 驱动深层气态水不断向表层运移。整体来看, 在非冻结期内气态水主要向包气带内部运移, 而在土壤冻结后则主要向地表处运移。此外, 气态水同样存在显著的日变化规律, 主要表现为白天浅层土壤温度较高时向深部运移, 而在夜间主要由深部向地表处运移。



注: 箭头表示包气带内不同时期气态水运移方向。

Note: The migration direction of vapor water in the vadose zone at different periods are indicated by arrows.

图 2 温度梯度驱动下气态水季节性运移规律示意图

Fig.2 Diagram of seasonal transfer characteristics of soil vapor water driven by temperature gradient

相比于液态水通量, 在包气带绝大多数层位中气态水通量数值相对较小, 尤其是在 40 cm 以下范围内, 气态水通量普遍小 1~2 个数量级。但在浅层土壤中, 气态水对水分运移的影响是不可被忽略的, 造成这种现象一方面是由于浅层土壤含水量较低, 土壤通气孔隙较多, 导致水力传导度较大; 另一方面, 浅层土壤温度受气温变化影响明显, 温度梯度较大, 即水汽运移驱动力较大。对于水资源较为短缺的干旱半干旱地区, 土壤含水量较低、液态水通量小, 浅层土壤中水汽通量在总水分通量中占比往往在 10%~30%之间, 并且水-汽相变过程对于热通量变化同样影响显著^[58-61]。而对于降雨极为稀少的干旱地区, Du 等^[62]研究表明浅层气态水通量在总水分通量占据主导地位。虽然在深层土壤中水汽通量数值较小, 但气态水却在始终不间断运移, 累积的水分对于干旱的包气带而言同样至关重要^[63]。由于干旱半干旱地区降雨主要集中在夏季, 在其他时期降雨较少, 包气带含水量偏低, 而土壤孔隙中相对湿度总是处于近饱和状态, 只要温度变化就会引发水汽凝结现象, 在温度梯度作用下水汽源源不断从包气带内部向浅层迁移并凝结, 可以补充浅层土壤中由于蒸发作用所消耗的水分。此外, 在冬季土壤冻结后, 冰的出现会阻碍液态水运移, 造成液态水通量数值减小 1~5 个数量级, 此时气态水将会主导冻土层内水分运移。并且在温度梯度驱动下, 深层土壤中气态水源不断向冻结锋处运移, 引起冻层内总含水量增大^[64]。可以看出, 不论是在非冻结期还是冻结期, 温度梯度驱动下的气态水通量均为总水分通量的重要组成部分, 其对季节性冻土区包气带水分与能量平衡影响不可被忽略。

4 现有研究不足及进一步研究建议

尽管相关研究已经取得了一定的成果,为深化包气带水循环理论提供了重要参考,但是在现有研究中仍存在一定局限性。受季节性冻土区野外试验与监测条件限制,部分研究现象以及耦合模型建立是基于室内试验数据开展。相较于复杂的野外实际情况,如土-气界面复杂性、土壤非均质性等,室内试验存在一定局限性,并不能很好反映野外实际情况。并且由于耦合模型建立过程中涉及参数较多,参数精度对于模型验证及模拟结果可靠性影响较大,对于诸如水汽增强因子与冰的阻抗因子等参数而言,其数值随土壤质地等条件改变而明显变化,因而应尽可能通过采用试验手段而非经验公式来获取此类参数,并结合反算等方法进一步优化参数,以获取更为精确且可靠的研究结果^[65]。同时,现有的研究大多偏重于理论探索,在实际应用层面取得的成果较少。基于现有包气带水汽热耦合运移研究理论成果,结合季节性冻土区实际情况,应围绕生态水文、水灾害等实际问题展开进一步研究:

1) 由于季节性冻土区多属于干旱半干旱区域,区内降雨稀少,植被较为稀疏、生长缓慢,土地荒漠化突出,这些地区因此成为生态建设的重点区和“硬骨头”。虽然实施了一系列生态保护措施,沙地植被发生明显变化,但由于部分地区种植密度过大,植物耗水过多,不仅导致了地下水位下降,并且由于沙地土壤水分被大量消耗,引发了人工造林植被的衰退和死亡现象^[66-67]。受降水较少及部分地区地下水位较深影响,土壤水资源成为诸如沙柳、樟子松等固沙造林植被生长的重要支撑,生态效应显著,而其中气态水通量的影响不可忽视,水汽凝结与聚集有助于植被克服土壤干旱胁迫,对于维系荒漠植被生态系统有重要意义^[54,68-69]。然而在现有研究中,关于气态水对植被根系吸水的影响尚未形成统一的认识。更重要的是,受冻融期根系吸水影响因素复杂及其与土壤水、汽运移之间的互馈作用不明等制约,对于季节性冻土区土壤水资源生态效应研究仍处于探索阶段。通过建立合理的植被根系生长与吸水模型,将其耦合进包气带水汽热传输方程中,聚焦“土壤-植被-大气”系统水循环过程,最终建立适用于季节性冻土区、可获得稳定及精确数值解的包气带水-汽-冰-热-植被耦合模型,阐明包气带水汽热-根系吸水耦合动力学机制,可为生态系统脆弱区的植被恢复与生态系统稳定提供科学依据。

2) 在温度梯度驱动下,冻融期内气态水向土壤表层聚集、迁移的过程,对于许多工程建设活动影响较为明显。如李强等^[70]发现在西北干旱半干旱地区,高速公路与铁路路基存在有大范围冻胀以及稀泥状土现象,这主要是受不透水覆盖层影响。在覆盖层下气态水运移受阻,以冰的形式储存于表层土体,并且由于冻层内水汽密度减小也加剧了深层水汽向上迁移过程。传统研究主要侧重于冻胀过程中液态水迁移,在工程建设中也会考虑防水作用,但却很少考虑气态水迁移影响,进而容易引起工程病害^[71]。针对该问题,贺佐跃等^[72]通过室内试验发

现当考虑气态水迁移成冰作用时,产生的冻胀量与实测值拟合较好,较好地解释了冻胀现象发生的原因。通过进一步开展现场监测与相关室内试验,结合数值模拟等手段明确不同覆盖层下水汽运移机理,为此类问题提出具体防治措施,对于寒旱区工程建设而言十分必要。

5 结 论

综合分析国内外研究,本文回顾了包气带水汽热耦合运移理论的发展历程与研究现状。对于季节性冻土区,土壤冻结后孔隙中水、汽、冰三相共存,冻融作用不仅会引起土壤水、热性质发生改变,而且对于土壤水分相态转化与剖面土壤水分分布影响明显。由于季节性冻土区野外工作复杂性,数值模拟技术逐渐成为研究水汽热耦合运移过程的主要手段。通过构建适宜的耦合模型模拟分析,液态水与气态水运移模式及其驱动力机制逐渐被揭示,并通过定量描述阐明了气态水对于包气带水分运移过程的影响。研究结果表明开展包气带水汽热耦合运移研究不仅符合季节性冻土区实际情况,而且有助于探究土壤水循环过程背后机理。

然而,现有研究大多偏重于理论探索,在实际应用层面取得的成果较少。结合季节性冻土区情况,应围绕生态水文、水灾害等实际问题展开进一步研究:1) 聚焦“土壤-植被-大气”系统水循环过程,建立适用于季节性冻土区的包气带水汽热-植被耦合模型,探究土壤水资源生态效应,为植被恢复与生态系统稳定提供科学依据;2) 在寒旱区工程建设中考虑气态水的影响,明确覆盖层下水汽运移机理,对建设过程中由水汽运移引起的工程病害提出具体防治措施。

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Review of coupled water, vapor, and heat transport of the vadose zone in the seasonal frozen soil region

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Abstract: Seasonally frozen soil regions refer to those areas where soil is frozen for 15 days or more per year. More than half of land surface is occupied with the seasonal snow cover in China. The freeze-thaw process can significantly change the soil properties, as well as the water and heat transferring in the vadose zone. Among them, temperature and water vapor have posed a significant impact on the soil moisture, due to the soil subjected to the dry condition in most of the seasonally frozen regions (belonging to the arid and semi-arid areas). It is gradually recognized as the significant effect of vapor flow on the soil water movement for both freezing and non-freezing periods over the past several decades. It is a high demand to couple the water, vapor, and heat transport suitable for the actual conditions of seasonally frozen soil regions, in order to reveal the influencing mechanism of soil hydrological cycle. The coupled theory of water, vapor, and heat transport was firstly proposed by Philip and de Vries. The total soil water flux was then divided into four components, including the liquid water flux and water vapor flux driven by water potential and temperature gradients, respectively. Since then, extensive researches were also carried out to continuously improve on the coupled transport. Once the soil was frozen, the liquid water, vapor, and ice were coexisted in the unsaturated zone. Two aspects were also observed in the influence of phase changes between liquid water and ice on the coupled water, vapor, and heat transport. Several hydraulic parameters were calculated to determine the hydrological cycle, such as the soil freezing curve, and hydraulic conductivity for the liquid water. The spatial and temporal distributions of soil moisture in the vadose zone were dominated by the seasonally freeze-thaw process as well. The contents of unfrozen water and ice also changed significantly with the variations of soil temperature. Numerical simulation was gradually utilized in this research field with the ever-increasing computational capacity and simulation accuracy. Great challenges were still remained on the coupled numerical model, due to the influence from the ice-water phase change. An appropriate coupling model was crucial to the numerical simulation via the reasonable simplification. The underlying mechanism of coupled water and vapor flow was gradually revealed from the simulation using different models. Specifically, the vapor flux was one of the most important components in the soil water movement, usually accounting for 10%-30% of the total water flux. Furthermore, the vapor flux was depended mainly on the relatively low soil moisture and large temperature gradient in the shallow layer. The vapor flow was much more significant during the freezing period, due mainly to the impeded flow of liquid water in the presence of ice. Consequently, some research directions that needed to be strengthened in this field were proposed to deepen the theoretical fundamentals and the practical tasks in the seasonal frozen soil areas. Firstly, the condensation and accumulation of water vapor can greatly contribute to the vegetation under soil drought and freezing stress. It is of great significance to maintain the desert vegetation ecosystem, where the soil water is critical to the vegetation growth in the fragile ecological areas. The vegetation module can be combined with the coupled model water, vapor, and heat transferring. Further studies can be implemented to explore the specific impact of liquid water and vapor on the surface vegetation in seasonal frozen region. Secondly, the coupled transport of liquid water and vapor can also impact many engineering construction activities as well, such as the frost heave in the railway embankments that caused by the continuous liquid water and vapor transport from the deep soil layer. Finally, in-situ monitoring and simulation can be strengthened to reveal the detailed process of liquid and vapor transport below the surface impermeable layer. The finding can also provide the scientific basis for the disaster prevention and control during freeze-thaw process.

Keywords: water; heat; numerical analysis; vadose zone; vapor transport; hydrological cycle; seasonal frozen soil region