論文の内容の要旨

Thesis Summary

論文題目(Title of Dissertation)

Modeling and Assimilating Frozen Soil Hydrology (凍土水文過程のモデル化と同化)

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Frozen soil is widely distributed in high latitude Arctic and Antarctic region, and mountainous region in low latitude, which takes up 35% total land area of earth. It plays an important role in the cryosphere hydrology, climate change, ecosystem and social economy, which are closely tied to human life. It is crucially important to understand frozen soil processes and its impacts, to simulate the frozen soil processes, and to project the future variation of frozen soil. Although previous studies have achieved advance progresses in frozen soil modeling, the frozen soil processes are still defectively represented in most of land surface models and hydrological models. Therefore, it is necessary to introduce frozen soil processes into hydrological and land surface modeling, to make use of satellite data for enhancing large-scale observation of frozen soil, and to reproduce hydrological and thermal processes of frozen soil.

An enthalpy-based frozen soil model was developed for the simulation of water and energy transfer in cold regions. To simulate the soil freezing/thawing processes stably and efficiently, a three-step algorithm was applied to solve the non-linear governing equations: 1) a thermal diffusion equation was implemented to simulate the heat conduction between soil layers; 2) a freezing/thawing scheme used a critical temperature criterion to judge the phase status, and introduced enthalpy and total water mass into the derived Clapeyron equation to represent ice formation/melt and corresponding latent heat release/absorption; and 3) a water flow scheme was employed to describe the liquid movement within frozen soil. In addition, a parameterization set of hydraulic and thermal properties was updated by considering the frozen soil effect. The performance of the frozen soil model was validated at point scale in a typical mountainous permafrost basin of China. An ice profile initialization method is proposed for permafrost modeling. Results show that the model can achieve a convergent solution at a time step of hourly and a surface layer thickness of centimeters that are typically used in current land surface models. The three-step frozen soil algorithm we developed can solve highly non-linear energy and mass equations of frozen soil stably and reduce the computation time for greater efficiency. The simulated profiles of soil temperature, liquid water content, ice content and thawing front depth are in good agreement with the observations and the characteristics of permafrost. The model is capable of continuously reproducing the diurnal and seasonal freeze-thaw cycle, simulating heat - water transfer within frozen soil and predicting streamflow in permafrost basin, which can be widely applied in simulating hydrological processes of cold regions.

Passive microwave remote sensing has outstanding advantages for monitoring the ground freezing and thawing processes, because of ability of soil penetration and strong sensitivity to soil water. We clarified the mechanism of radiative transfer processes in frozen soil that emission from deep soil has to be considered, because frozen soil is more transparent than normal soil. Volume scattering by soil and ice particles plays a dominating role in the radiation transfer processes within soil medium, rather than absorption. Surface scattering of frozen soil is so weak that the transmissivity of air-soil boundary is quite higher, due to the less surface discontinuity of dielectric constant between air and soil. The frozen soil phenomenon, negative gradient spectral, is also explained by the stronger scattering at high frequency.

We tried to clarify the mechanism of frozen soil radiation transfer processes by developing a frozen soil radiative transfer model. The radiative transfer processes of frozen soil are described as 2 separate processes in the model: 1). soil emission transfers within frozen soil: In cold season, water absorption is so weak that the penetration depth becomes deep. Emission from deep soil and the volume scattering effect of soil particles is considered as dominant process in this RTM. 2). Soil radiation passes through soil-air boundary: surface scattering of frozen soil is so weak, due to the less discontinuity of dielectric constant on the boundary that the transmissivity of air-soil interface is high. While the dielectric constant discontinuities become significant when frozen soil thaws, which in turn causes strong surface scattering in air-soil boundary. A multiple parallel-layer frozen soil radiative transfer model is developed by coupling a modified 4 stream fast model, dense media radiative transfer model QCA-CP and Advanced Integral Equation Model (AIEM) in consideration of both surface scattering and volume scattering.

The model is validated by comparing with the AMSR-E Tb observation in a seasonal frozen soil station, in Tibet, China. Results show that this RTM can predict Tb of frozen soil from 6 GHz to 36 GHz with good accuracy and the phenomenon of negative spectral gradient are also successfully reproduced, which has not been achieved in previous studies. According to the validation result, the radiative transfer mechanism we proposed does correspond to the reality and can explain the phenomenon of microwave radiation transfer in frozen. Therefore, it is demonstrated that the frozen soil RTM offers a realistic and quantitative understanding for frozen soil radiative transfer mechanism and has a good capability of simulating the radiative transfer processes in frozen soil at frequencies from 6GHz to 36 GHz.

Obtaining realistic initial soil profiles is a major challenge for permafrost modeling in the region without soil observation. Although we have not enough ground stations, satellite based passive microwave sensors can frequently and continuously monitor large scale area. Frozen soil is dry enough for microwave radiation to penetrate and makes deep soil information detectable. Microwave signal of different frequencies can reflect the fluctuation of soil moisture and temperature along with freeze and thaw cycles. By utilizing both physical reality of modeling and penetration capacity of passive microwave remote sensing, we developed a method for estimating the optimum initial soil profile: assimilating passive microwave satellite data AMSR-E Tb into frozen soil state of frozen soil model and identify a suitable soil profile among hypothetical ones. This method is applied in 2003-2004 freeze-thaw seasons in a seasonal frozen soil station. Results show that optimum initial soil profiles with lowest RMSE value are in close proximity to the observed soil moisture profile among 10 hypothetical profiles. It is proved that the method can effectively obtain suitable initial soil profile which may broad the application of the frozen soil model and improve forecast of frozen soil modeling.

In conclusion, this research bridged the gap between frozen soil physical modeling and frozen soil radiative transfer investigation. It provides a deeper and quantitative understanding on the physics of freeze-thaw process, heat and water transfer inside of soil and hydrological processes of frozen soil region. And the mechanism of radiative transfer processes are clarified for the first time by a numerical simulation considering both surface scattering and volume scattering. These contributions can empower the frozen soil modeling application in permafrost prediction and hydrology research under climate change in cold regions at the basin or regional scale.