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論文内容の要旨

As an important component of the global cryosphere, permafrost plays an important role in global climate stability and environmental sustainability of inland areas. Permafrost is also an important component of the global carbon pool, which can help reduce greenhouse gas emissions and thus serve to curb climate change. In recent years, scientific research has revealed that the continued degradation of permafrost not only affects the global climate, but may also trigger catastrophic consequences, the most alarming of which is the re-emergence of ancient viruses. Due to the continued degradation of permafrost, these ancient viruses that have disappeared may be released, posing a serious threat to human health. Therefore, we should enhance the protection of permafrost to prevent the re-emergence of ancient viruses.

Remote sensing technology is becoming increasingly indispensable in observing large areas of permafrost to assess the effects of global climate change and to protect important social frameworks. Using satellite and aerial photography, this technology can provide important information about permafrost and its impact on the environment and human activities. However, the usual remote sensing permafrost models have some problems that need to be improved in terms of analysis scale, applicability range and parameter accuracy.

Especially, the Top Temperature Of Permafrost (TTOP) permafrost model and Land Surface Temperature (LST)-zero-curtain permafrost model, which have been applied more in recent years, have some problems that must be improved in these aspects. For example, the TTOP model should improve the overall resolution of the data, improve the accuracy of the soil thermal conductivity, and reduce the error caused by the temperature observation range, etc. And the LST-zero-curtain model needs to remove the influence of vegetation and snow layer, and set the lower limit of temperature for curve change.

To address these issues and the relevance of both models, in this study we propose a new permafrost analysis model for more accurate permafrost assessment than the traditional TTOP and LST-zero-curtain models. The new model's active permafrost layer

is temperature controlled by the LST and the TTOP. By using these two parameters, the model provides an accurate and reliable picture of temperature changes in the permafrost zone.

Because the water content of the soil must be taken into account when determining the TTOP level for curve changes. Here, the soil thermal conductivity at the net water content state is introduced to correct the soil thermal conductivity at the saturated water content state in the original TTOP equation. After that, the corrected TTOP value is used as the lower limit temperature of the new model, and the LST replaces the 2-10m air temperature value as the upper limit temperature of the new model, and then the lower and upper limit temperatures are used together to determine the temporal and spatial extent of the occurrence of the zero-curtain effect in the subsurface. Then the change of zero-curtain effect and the duration are used to analyze the existence of permafrost and the change law of stability. This new approach to permafrost analysis is referred to as the TTOP LST-zero-curtain (TLZ) permafrost model in this study.

In order to better apply, analyze, and validate the TLZ model, the most representative region in permafrost research, the central-eastern part of the Qinghai-Tibetan Plateau was selected as the study area for the TLZ model. There are not only a lot of long-period satellite observations from National Aeronautics and Space Administration (NASA) but also a variety of meteorological data from the China-Meteorological-Data_service-Centre (CMDC) in the study area, which provides a rich data guarantee for the smooth implementation of this study. After extensive data processing and analysis required for the TLZ model, the permafrost changes, classification and stability in the study area for the period 2012-2021 were evaluated and mapped according to the principles of the TLZ model. The results of the analysis showed that the permafrost in the study area showed an overall significant degradation trend in terms of stability and continuity during the period 2012-2021, but the permafrost that continued to degrade around 2018-2019 showed a certain degree of recovery, which we believe may be more related to the increase in vegetation and rainfall in these two years.

Later, to validate the results of the TLZ model, the Mean Anuual Ground Temperature (MAGT) model was constructed using twice-daily ground temperature data from 27 CMDC sites near the center of the study area, where daily average ground temperature data at 300, 60, 50, and 30 cm depths at each site were used to calculate daily average ground temperatures at each of the 27 sites for the period 2012-2021. Afterwards, the MAGT model results were compared with the TLZ model ground temperature estimates for validation.

Here, the comparison of ground temperature at 300 cm depth was done to verify the accuracy of TTOP values after adding the net moisture content soil thermal conductivity factor, while the comparison of ground temperature at 60, 50, and 30 cm was done to verify the accuracy of determining the zero-curtain effect in this study. The validation results showed an average SE of 0.25 ° C, an average MAE of 0.27 ° C, and an average RMSE of 0.19 ° C at different depths. Finally, the superiority of the TLZ model was demonstrated by comparing the results with those of the TTOP and LST-zero-curtain models in the traditional study.

The TLZ model not only identifies areas where large- and medium-scale permafrost exists, but also allows for detailed small-scale stability analysis, periodic change patterns, permafrost type conversion, and degradation predictions. These features of the TLZ model offer significant advantages over traditional permafrost analysis methods. The TLZ model provides insight into permafrost conditions in a region and is expected to be a useful tool for assessing the impact of climate change on permafrost in other parts of the world. Such a detailed analytical model will help to better inform permafrost management decisions in these regions. It also provides a new direction for the development of multi-scale analytical models for permafrost with a high degree of accuracy. Further research work will be conducted on LST and 0cm ground temperature conversion, and removal of tall vegetation to better refine the TLZ model.

論文審査の結果の要旨

永久凍土のモニタリングは、地球温暖化の影響評価や社会インフラの維持管理等の観点で重要である。そして、広域に分布する永久凍土を効率的にモニタリングするツールとして衛星リモートセンシングが注目されている。こうした背景の下、本学位論文では、中国・青海チベット高原を対象に、衛星光学リモートセンシングによる永久凍土モニタリングのための新しいモデルとして、TTOP-LST ゼロカーテン(TLZ)モデルを提案している。このモデルは、地表面温度(land surface temperature; LST)と地下の永久凍土層の上面温度(temperature at the top of the permafrost; TTOP)を組み合わせたもので、LST は衛星観測から導出し、TTOP は従来モデルに降水-蒸発散係数を組み込んだ新規モデルを用いて算出する。そして LST 及び TTOP に基づいて活動層内の各深度の地中温度を推定し、これを時系列で解析することによってゼロカーテン効果の有無や持続期間を調べ、永久凍土の状態を評価するものである。このモデルを用いて行った 2012～2021 年の 10 年間における青海チベット高原の永久凍土の解析では、永久凍土を時間的安定性の観点で 7 つのクラスに分類し、これを踏まえて地球温暖化の影響と考えられる永久凍土の劣化状況を考察している。また、現地の地中温度データを用いた年平均地温モデルとの比較に基づいて地中温度の精度評価を行っており、提案モデルの妥当性を示している。本モデルは青海チベット高原向けに開発したものであるが、同地域と類似した環境と必要なデータがあれば、他の地域への適用も可能である。以上により、本モデルはリモートセンシングによる永久凍土のモニタリングに有用であり、今後の幅広い活用が期待されるものといえる。今回の成果は博士後期課程進学後に得たもので、その主要部分は英文の査読付き学術論文１篇(インパクトファクター付き)に掲載されている。また、この分野で著名な米国の学者に掲載論文を送付してコメントをもらい、本学位論文の執筆に生かしている。

令和 5 年 5 月 8 日に本学位論文の公聴会、審査会、最終試験をこの順でハイブリッド方式により実施し、研究科外審査委員はこれらにオンラインで参加した。審査会では学位論文審査結果に基づいて論文審査を合格と判定した。最終試験では質疑応答に的確に答弁し、研究遂行能力と十分な専門知識を有すると判断された。

以上を総合して、本学位論文は茨城大学大学院理工学研究科における博士学位論文の評価基準を満たしており、合格と判定する。