論文の内容の要旨
**Abstract of Dissertation**

# Title of Dissertation: Towards improved snow and glacier melt simulations in a distributed hydrological framework

（分布型水循環モデルにおける積雪・氷河融解モデルの改良）

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Seasonal snow cover and glacier are important components of the mountain hydrology as precipitation occurs in solid form in the cold climate and regions of high elevation. Snow, with inherent properties such as high albedo, low roughness and low thermal conductivity, has considerable spatial and temporal variability, which greatly governs the energy and water circulation between the atmosphere and land surface. From a hydrological point of view, the temporal and spatial variability of the snow/ice distribution on a basin-scale plays a key role in determining the timing and magnitude of spring snowmelt runoff. It had been studied that the impacts due to the climatic changes would make the seasonal variation in water resources more apparent in snow dominated river basins, and a considerable amount of mass losses and large reductions in glacier area. Hence, accurate prediction of spatial distribution of snow cover area, and snow and ice melt runoff is imperative to support optimal water resources planning and management practices towards a sustainable society.

To this end, many diverse approaches have been taken in developing hydrological models for better representation of snow processes, ranging from simplified temperature index models to physically based single- or multi-layer energy-balance snowmelt models. Energy balance models can provide realistic simulation of complex snow physics better than the temperature index models and have the ability to integrate the measurable physical quantities. At present, very few hydrological models have included multi layered energy-balance snow schemes for studying the cold region processes, but they can not express the full potential for large-area applications in simulations of open and forest snow processes and glacier melt runoff estimations simultaneously using snow-soil-vegetation-atmosphere-transfer (SSVAT) approach in distributed  framework. In addition, many existing models have used satellite snow-cover information as an input dataset to simulate snowmelt runoff in the mountainous region, limiting their applicability to simulate snowmelt runoff in future. Thus, the hydrological model which can provide the snow cover information as the model output is really a good asset in the field of hydrologic simulation of cryosphere to access the impact of climate change in future.

Furthermore, solid precipitation (snowfall) has the greatest uncertainty among all forcing for the ice/snow melt models due to the effects of multiple factors like wind, topography, wetting and evaporation losses. These biases are evident in basin-scale, where areal distribution of snowfall is a major problem in distributed snowmelt modeling related to gauge density across a watershed and to the techniques used to grid the point data, which results the inconsistency in the basin precipitation and the snowmelt runoff. Thus, reliable estimates of basin-scale snowfall are critical to snowmelt modeling, and are also very important to development of regional and global datasets. Up to now, there are many methods available for systematic bias corrections at point observations, but a general solution has yet to be found for correction of basin-scale snowfall.

To address aforementioned issues, this research is motivated towards an improved snow and glacier melt modeling in a distributed hydrological framework with the development of multilayer energy balance based snow and glacier melt model for accurate simulation of snow/ice cover area, snow/ice melt runoff, glacier mass balances, and to establish a method for basin-scale correction of snowfall amount.

Firstly, a new spatially distributed multi-layer energy balance based (physically based) snow and glacier melt model has been developed by coupling the three-layer snow physics of Simplified Simple Biosphere 3 (SSiB3) model and the Biosphere–Atmosphere Transfer Scheme (BATS) albedo scheme into the Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM). WEB-DHM has single layer snow physics with constant albedo and density, thus it has deficiency in simulating snow processes accurately. Since WEB-DHM inherits the properties of SiB2 model, it can not simulate the water and energy fluxes over the glacier surfaces. A new glacier melt module is developed which accounts the energy balance based glacier (over debris free and debris covered) accumulation and ablation processes in distributed framework. WEB-DHM with improved snow and glacier physics is hereafter termed WEB-DHM-S. WEB-DHM-S can simulate snow processes such as snow depth, snow density, snow water equivalent (SWE), snow albedo, snow surface temperature and snow melt runoff more precisely, in point as well as basin-scale. It can provide the reliable estimate of glacier melt runoff and glacier mass balance in a distributed framework, providing a measure of glacier contribution to the total stream flow. Moreover, the model can simulate 6 different types of snow processes based on the snow/ice grid code [Bare land or forest without snow (9 biomes of SiB2 model), bare land or forest with snow, clean glacier, debris covered glacier, fresh snow over clean glacier and fresh snow over debris].

The WEB-DHM-S model is at first rigorously evaluated with comprehensive point measurements at both open and forest sites. The comparisons of the observed and simulated snow depth, SWE, snow density, surface temperature, snow albedo and snowmelt runoff at the four open sites with different climate characteristics of the Snow Model Intercomparison Project phase 1 (SnowMIP1) reveal that WEB-DHM-S is capable of accurately simulating the internal snow process in seasonal to inter-annual scale. Sensitivity tests (through incremental addition of model processes) are performed to illustrate the necessity of improvements over WEB-DHM and to indicate that both the 3-layer snow scheme and the prognostic albedo scheme are essential. Snow processes evaluation for vegetated surfaces at Fraser site of SnowMIP2 and grassland site at Valdai show that the model is able to capture the seasonal and interannual variability of sub-canopy snow processes well. It can be concluded that the net radiation is the dominant energy source for above-canopy while sensible heat flux is equally important to the net radiation for sub-canopy snow processes.

Secondly, the model has been applied to the Dudhkoshi region of the eastern Nepal Himalaya to estimate the spatial distribution of snow cover in one snow season during the Coordinated Enhanced Observing Period 3(CEOP-3). The snowfall amount at the CEOP stations is reconstructed based on the available datasets of observed snow depth, albedo, and air temperature. The point evaluations (snow depth, upward shortwave and longwave radiations) at Pyramid (a station of the CEOP Himalayan reference site) confirm the vertical-process representations of WEB-DHM-S in this region. The simulated spatial distribution of snow cover is carefully evaluated with the Moderate Resolution Imaging Spectroradiometer (MODIS) eight-day maximum snow-cover extent (MOD10A2), and the model's capability of well capturing the spatiotemporal variations in snow cover in the study area is demonstrated. Hypsography analyses of the cumulative snow cover area (SCA) versus elevation illustrate that the SCA in the elevation zone from 4500–5500 m is remarkably overestimated (about 6%) during the pre-monsoon season. However, qualitative pixel-to-pixel comparisons for the snow-free and snow-covered grids between the simulation and the MODIS data provide a great immediacy with an accuracy of 90%. The simulated nighttime land surface temperatures (LST) are comparable to the MODIS derived LSTs (MOD11A2) with mean absolute error of 2.42$^{o}$C and mean relative error of 0.77$^{o}$C during the study period. The effects of variance in the air temperature lapse rate, initial snow depth and snow albedo on the snow cover area (SCA) and LST are determined through sensitivity runs.

Furthermore, the contribution of snow and glacier melt runoff to the total discharge was simulated, along with the spatial distribution of snow cover and glacier mass balances at the Hunza river basin of Pakistan in Upper Indus river of Karakoram Himalayan region, where about 34% of the basin area is covered by glaciers. The simulations are performed at hourly time steps at 1 km spatial resolution for 3 years (2002-2004) with the use of Global Land Data Assimilation System (GLDAS) atmospheric forcing (except observed temperature), and APHRODITE precipitation. The qualitative pixel-to-pixel comparisons for the snow-free and snow-covered grids in the region reveal that the simulations agree well with the MODIS snow data with an accuracy of 83% and a positive bias of 2.8 %. The results demonstrate that the model is able to reproduce the river discharge satisfactorily with Nash efficiency of 0.92. But the model highly overestimates discharge in May and June of 2004 due to increased temperature with large uncertainty. Moreover, it is found that the contribution of rainfall to total streamflow is small (about 10-12%) where the contribution of snow and glacier is considerably large (35-40% for snowmelt and 50-53% for glacier melt). The model can simulate the state of snow and glaciers at each model grid prognostically and thus can estimate the net annual mass balance. The net mass balance varies from -3 m to +2 m water equivalent. Compared to the clean glaciers, the melt from debris covered glaciers are simulated less and thus their negative mass balances are milder. Additionally, the hypsography analysis for the equilibrium line altitude (ELA) suggests that the average ELA in this region is about 5800-5900 m, although ELA varies from glacier to glacier and region to region. This study is the first to adopt a distributed hydrological model with a physically based multilayer snow and glacier module to estimate the spatial distribution of snow cover and snow and glacier melt runoff in the Himalayan and Karakoram region.

Thirdly, a method has been established that explicitly corrects the basin-scale snowfall amount by proposing the basin-scale orography-dependent snowfall correction factor (SCF) through pixel-to-pixel analysis of simulated snow cover area (SCA) with the MODIS derived SCA and comparing simulated vs. observed runoff by calculating various statistical parameters at four dam basins of the Upper Tone River of Japan. The model is run at hourly time step at 500 m grid from November 2000 to November 2004. Two types of precipitation (observed rain gauge, called AMeDAS and Radar data adjusted with rain gauge observations, called Radar-AMeDAS) inputs are corrected with this approach since both dataset highly underestimates the snowmelt runoff due to large underestimation of snowfall.

With the use of corrected precipitation datasets, streamflow and SCA are reproduced satisfactorily at Yagisawa dam basin, as compared to the observed discharge and the MODIS-derived SCA respectively. Moreover, point-scale simulation of snow depth at Yagisawa dam site confirms the improvements in snow depth for corrected AMeDAS. The basin average SCFs is 1.87 times for AMeDAS and 3.77 times for Radar-AMeDAS, for which snowmelt runoff are simulated with NSE greater than 0.80 at Yagisawa basin. The overall accuracy of SCA simulation between the MODIS and model simulations is about 91%. In many cases, SCA simulation with corrected snowfall significantly improves SCA at high elevations; however, a remarkable overestimation is simulated in some days, especially at the end of melting season. The SCA overestimation in melt season is believed to come from the known weakness of MODIS in mapping snow over forested areas. Following the similar approach, the AMeDAS and Radar precipitation dataset are corrected at Naramata, Aimata and Sonohara basins with SCF (AMeDAS) at 1.40, 1.46 and 1.46 and with SCF (Radar) at 2.67, 4.3 and 2.33, respectively. Corrected radar data at Aimata basin is not able to improve the discharge due to large missing of snowfall signals. Additionally, the improved discharge at Sonohara basin is still below satisfactory level because of deficiency of representation of large spatial variability in the rainfall. The methods used in this study are simple and robust, and can be applied to any snow-fed river basin to obtain a reliable SCF. Furthermore, long term (1948-2006) simulation of snow depth at Yagisawa dam site is carried out with the use of JP10 reanalysis forcing (high resolution reanalysis dynamic downscaled dataset). Monthly correction factors are obtained from corrected AMeDAS value for the correction of JP10 snowfall. The model is able to capture the seasonal and interannual variability of snow depth well as compared to the observed one. The long-term trend for snow cover days shows that the decadal change is more apparent for snow cover days with snow depth above 50 cm. Moreover, the long-term trend shows the decreasing trend for number of snowfall days.

Nevertheless, following this research, the future work would be to assess the impact of climate change in snow and glacier fed river basins, along with the bias correction of climate change projections for winter precipitation. This would ultimately enhance the understanding of the hydrological variabilities of the cryosphere in response to climate change.