論文の内容の要旨

Integrated Monitoring and Simulation of Snow Amount and Snowmelt Runoff in Mountain Region

(山岳地域の積雪量と融雪流出の統合的なモニタリングとシミュレーション)

デュラン　バレン　シスト　アンドレス

For many communities their economy depends on the available water resources and on the development of related infrastructure such as irrigation of fertile valleys, hydro power plants, transportation, etc. In snow and glacier dominated river basins, the natural reserves of freshwater depend on the seasonal variation of snow and glacier processes (Mool, 2011). Therefore, it is important to accurately simulate the snow and glacier processes to support optimal water resources planning and management (Shrestha, 2012); assess the risk of potential floods and droughts (Mool, 2011); and evaluate the effect of climate change. This may be achieved by monitoring snow cover areas and estimation of snow amount spatial distribution.

However, monitoring of vast snow cover areas like in the Himalayas using field survey is difficult due to harsh weather conditions, locations are hazardous and inaccessible, and in-situ measurements provide limited regional information (Negi, 2011). Nowadays, this problem has been overcome by the application of satellite observations. Presently, with the use of remote sensing instruments, snow cover information and many other parameters can be determined on real-time, year-round over vast, rugged and remote areas (Negi, 2011). On the other hand, global scale observation and measurement by satellite instruments have distinct spectral scales and different viewing conditions. These affect numerous parameters that may not be meaningfully expressed at a course spatial resolution. For example, a large heterogeneous landscape is described in many parameters such as soil type, vegetation, elevation, temperature, snow amount, etc., each with different spatial variations (Frei, 1999)(Fontanilles, 2010). But each of these parameters must be individually expressed at its own meaningful spatial resolution. Therefore, we need an aggregation process for the numerous types of parameters with different spatial variations and spectral resolutions for a heterogeneous landscape when measured by satellite instruments.

Presently, spatial distribution of snow amount derived from satellite observation has only been achieved and validated for relative flat regions using in-situ recorded snow depth data (Tsutsui, 2007) (Lakhankar, 2013). However for mountainous regions, spatial distribution of snow amount has not been addressed yet because remote sensing instruments are very sensitive to the effects of the rough terrain; and because there is no available data, observed or measured, for spatial validation of snow depths in mountainous regions.

Furthermore, some satellite products and previous studies attempt to estimate snow depth, but never before has it been done for mountainous region taking into account the effects of the rough terrain. For example, MODIS Terra Snow Cover Area (SCA) product provides an 8-day maximum snow cover extent global dataset, but snow depth or snow amount information is not available. AMSR-E Snow-Water-Equivalent (SWE) product uses an algorithm that assumes a constant snow grain size to estimate the snow-water-equivalent global dataset, but does not account for the effect of the topographic terrain. In comparison of models capabilities for estimation of snow depth derived from satellite observations, previous studies have only attempted the application in relative flat regions (Kelly, 2003)(Grippa, 2004)(Lakhankar, 2013)(Tsutsui, 2009).

Consequently, this study proposes an aggregation method for the development of a system model for the estimation of snow depth in mountainous terrain derived from satellite observations. In fact, the topography has such an impact on the estimation of snow amount because remote sensing instruments are very sensitive to the effects of the rough terrain. And by making corrections that take into account the slope and aspect of the topographic terrain provide better snow depth estimates in mountain areas. Therefore, the main objective of this research is the estimation of snow amount derived from satellite observations in mountainous region taking into account the effects of the rough terrain on remote sensing instruments.

The Advanced Microwave Scanning Radiometer for EOS (AMSR-E) satellite measures Earth's surface microwave emission in 6 dual-polarized frequency channels. In this study, a new approach was developed to estimate snow amount in mountainous regions using AMSR-E measurements of brightness temperature (Tb). The local slope in mountainous terrain, where the local incidence angle is different than the 55-degree incidence angle of the radiometer scanner in case of flat surface, is taken into account. The terrain DEM is used to calculate the slope and aspect of each terrain grid. Then, with the geolocation of the satellite as it passes over, the local incidence angle is computed from the scalar product between the radiometer scanning vector and the normal vector of the local slope.

In general, remote sensing of snow is achieved by taking the brightness temperature difference between the 18.7 GHz and the 36.5 GHz frequency measured by AMSR-E instruments. The 18.7 GHz frequency measures the brightness temperature microwave emission of the ground surface; while the 36.5 GHz frequency measures the brightness temperature microwave emission of the surface of the snow. In addition, critical influential factors in the measurement of brightness temperature microwave emission are the slope and aspect of the terrain; soil properties such as density, moisture, and frozen conditions; snow properties such as snow grain size, density, moisture, temperature, and snow-age; and the geolocation of the satellite in reference with the target point.

At the same time, brightness temperatures values can be calculated as well. The Radiative Transfer Model (RTM) computes the brightness temperature for both frequencies and creates a reference Lookup Table (LUT) accordingly. For an arbitrary range of snow depth from 1 cm to 200 cm and snow temperature from 223 K to 273 K, the input parameters to calculate the brightness temperature for the 18.7 GHz and 36.5 GHz frequencies are: soil density (constant value of 0.4 g/cm^3), snow grain size (from 0.6 mm to 1.4 mm), and the local incidence angle (from 25° to 85°). This means, one brightness temperature value is computed for each frequency at each combination of snow depth, snow temperature, snow grain size, and soil density for every incidence angle value.

Although, AMSR-E data resolution is about 25-km, at this resolution the topographic terrain cannot be meaningfully expressed. Therefore, a terrain DEM resolution of 200-meter is used. The strategy is first to estimate the brightness temperature for the 18.7 GHz and 36.5 GHz frequencies for each topographic grid at the 200-meter scale taking into account the local slope and local incidence angle. Furthermore, to overcome the difference of spatial resolution between AMSR-E data and the terrain grid, the brightness temperature is then averaged for the larger satellite footprint grid based on the occurrence of the same local incidence angle. A uniform snow depth and snow temperature is assumed within each satellite footprint.

Likewise, the brightness temperature computation process is carried out for each topographic grid at the 200-meter scale with its own local incidence angle and range of parameters. Then, the same strategy is used to compute an Average Lookup Table (ALT) for each model grid. That is, an average lookup table for each satellite footprint is computed as a weighted average from the local brightness temperature values in the terrain grid based on the occurrence of same local incidence angle.

In short, the snow model uses a Snow Retrieval Algorithm to derive the snow depth and snow temperature spatial distribution over the target region. This snow retrieval algorithm compares AMSR-E satellite observations of brightness temperature at the 18.7 GHz and 36.5 GHz frequencies to the calculated values of brightness temperature in the average lookup tables generated by the RTM model. Next, the snow retrieval algorithm selects the corresponding snow depth and snow temperature in the lookup table and outputs these values. This snow model has been previously validated in relative flat and homogeneous region using in-situ recorded snow depth data (Tsutsui, 2007, Tsutsui, 2009).

For this study, the first approach for validation was a Point-Scale evaluation. Using recorded data from the meteorological station *Pyramid Everest* in Nepal, comparison of recorded and modeled snow depths was performed. However, the evaluation proved the point-scale validation to not be meaningful for the model's spatial output. Therefore, a 2-Dimensional spatial comparison for validation is needed.

Consequently, due to the lack of in-situ snow observation the following research strategy was proposed. For the estimation of snow depth amount, the results are validated with the outputs of snow depth from a physically-based hydrological model. In other words, because there is no available data for spatial validation, the model Water and Energy Budget based Distributed Hydrological Model with improved Snow physics (WEB-DHM-S) (Shrestha, 2011, Shrestha, 2010, Wang, 2009), which can simulate the snow processes more accurately through the physically based multi-layer energy balance modeling approach at the basin scale, is used to evaluate the RTM model performance. Independently, the WEB-DHM-S outputs of stream discharge and snow cover area are beforehand validated. Validation of this hydrological model is achieved by comparing the output of stream discharge and seasonal snow cover area to observed stream discharge from gauge stations and observed snow cover area data by MODIS, respectively.

To summarize, a new approach for estimating snow amount is applied in mountainous regions taking into account the local terrain slope and local incidence angle of the radiometer scanner. Furthermore, the estimated snow depth spatial distribution by the RTM was evaluated by comparing with the WEB-DHM-S snow depth outputs. The RTM successfully estimates the seasonal snow depth trends and accurately resembles the observed snow cover area.

In conclusion, by identifying the RTM capabilities and contributions, these outputs may also be used with other models to improve the seasonal projections of snow and climate systems. Analogously, these estimates can also be used for assimilation into General Circulation Models. Additionally, it is important to accurately estimate the snow amount in snow-melt dependent basins such as the Himalayan river basins, because their flow regime do not depend only on the amount of precipitation. Finally, the integration of monitoring and simulation of snow amount can also provide means for further analysis of climate change impact on snowpacks and stream-flow regimes; and can provide reliable information for the communities to assess the risk of floods, droughts, and available water resources.