Study on Snow Melting Process in Land Surface Model in High Altitudes in Zeravshan River Basin

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Abstract

In Zeravshan River Basin, since water resource is mostly supplied in high altitudes in winter as snowfall, accuracy of snow melting is important in models. However, in previous works with land surface model, there were early trends in river discharge. Therefore, firstly original results were compared with satellite-based snow cover and observed river discharge. Secondly, sensitivity analysis was conducted for altitude dependency of meteorological forcing. Finally, subgrid scale undulation was considered in coarser resolution analysis using elevation band mosaic scheme. As result, altitude dependency of long wave radiation and elevation mosaic scheme produced improvement especially in high altitudes with glaciers.

1. INTRODUCTION

In the Aral Sea Basin, water resource is mostly supplied in winter as snowfall in eastern mountainous region located in Western Tien Shan Mountains and the Pamir Mountains. In western region, where economy is highly depends on irrigated agriculture, climate is extremely arid and high water demand is met by snow melt in summer from upstream (Glantz 1999, Micklin, 2000, Farinotti et al., 2015). The snow melting starts from early spring and gradually increases and maximize in early summer, working as naturally made water reservoir.

However, climate change now becomes obvious in this region. Even though available data is limited, many researches concluded that recent temperature warming in the Central Asia (Unger-Shayesteh et al., 2013). As for glaciers, Narama et al. (2002) showed glacier variations from 1960 to 1995 in the Pamir-Alai and West Tien Shan and North Tien Shan in Central Asia, and shrinking trend was clearly shown since late 1970s. In the Pamir Mountains, long term investigation is limited, in the Tien Shan glaciers, prolonged research showed total volume reduction which is 14.2% from 1943 to 2003 (Aizen et al., 2006) and 27±15% from 1961 to 2012 (Farinotti et al., 2015). In addition to impacts on glaciers, Kitamura et al. (2007) revealed that peak river discharge and plants activity was getting earlier due to temperature rise in the Aral Sea Basin using local hydrological data and satellite analysis. In terms of water resource, when snow melting season would be earlier in future due to higher temperature and radiation, water resource in summer would reduce. To prepare for this problem, impacts should be quantitatively projected as scientific basis.

We have tried to develop physical terrestrial water circulation model in the Aral Sea Basin which mainly consists of a land surface model. The purpose of the model is to clarify water circulation changes by human activity and climate change from past to future. However, in the assessment of results using observed river discharge, while annual water balance could be accurately analyzed, seasonal river discharge had earlier trends showing overestimation of snow melt in land surface model (Touge et al., 2013, Touge et al., 2015, Khujanazarov et al., 2015).

Therefore in this research, originally analysis was firstly compared with satellite based snow cover and observed river discharge. And secondly, altitude dependency of meteorological forcing was made in research by sensitive analysis of long wave radiation and air humidity. Furthermore, subgrid scale undulation was considered and elevation mosaic scheme was introduced especially to consider glaciers.

To make meteorological forcing at high region, altitude dependency has been discussed in many researches. Dynamical downscaling using regional climate models is an effective method. For example, Hara et al. (2008) projected climate change impact on snow depth in Japan using pseudo global warming approach nested by the Weather Research and Forecasting (WRF) and Wakazuki et al. (2015) projected climate change impacts on snow cover in central Japan using CMIP5 results downscaled also by WRF. However, physical model requires detail inputs and computational resource. Since available data is extremely limited in mountainous region especially in developing countries, effectiveness of high load calculation is lower under many uncertainties in inputs. In this research, simple methods to estimate higher altitudes were attempted for land surface analysis.

Subgrid scale effects have been generally considered for land use inhomogeneity in land surface model, however, fewer studied it for topography in mountains. Seth et al. (1994) showed importance of subgrid scale inhomogeneity on vegetation type and geology in Vectorized version of the Biosphere-Atmosphere Transfer Scheme (VBATS), and Giorgi et al. (2003) attempted to find heterogeneous effect on precipitation in regional climate model using Biosphere–Atmosphere Transfer Scheme (BATS) coupled by Regional Climate Model system (RegCM). Since these considerations are for meteorological process, evaporation and Bowen ratio were often discussed, however in terms of water resource, subgrid effect on river discharge and snow melting should be more discussed. Nitta et al. (2012) considered subgrid snow water equivalent distribution in land surface model MATSIRO and found intra- and inter- annual variability of snow cover area in Northern Hemisphere was improved. In this research, river discharge was attempted to be improved in Central Asia where early peaks of hydrograph was remained in original analysis.

2. TARGET BASIN AND MODEL DESCRIPTION

2.1 Target basin

Zeravshan river basin is located in Central Asia and has 1842km^2 drainage area where six million people lives especially in downstream (Fig.1). Its western part is upstream in Pamir Mountains in Tajikistan, where highest elevation in the basin is more than 4000m. There are several glaciers such as Zeravshan glacier which is one of the biggest glacier in Central Asia, however, glaciers has high recession rates over the last decades (Aizen et al., 1997). And the downstream is in Zeravshan valley which is one of the highest populated areas in Uzbekistan and is irrigated agricultural region. Zeravshan River was originally tributary of Amu Darya which is the biggest river flowing to the Aral Sea, but now it has been cut due to over use of irrigation water. Around 97% of water resource is supplied in Tajikistan mainly as snowfall in winter, while 94% is used in Uzbekistan. The snowfall in winter is temporary stored and it melts from spring until summer flowing to river, therefore, peak discharge of

Figure1: Zeravshan River Basin (Dupli Station is indicated by star.)

the river is around in July even though there is no dam which has huge capacity to change seasonal river discharge. Also river discharge is kept in high even after August because of glaciers in mountains.

2.2 Model description

Simple Biosphere including Urban Canopy (SiBUC) was utilized for land surface model (Tanaka, 2004). Land use type is totally 13 kinds including irrigated farm where anthropogenic water management is considered. It has single layer snow model which basic concept is from SiB2 (Sellers et al., 1996).

After vertical water and heat balance analysis, river discharge is calculated by equation 1.

$$Qin = \sum Runoff - \sum \frac{Win}{\gamma} + \sum Wout \qquad (1)$$

where, *Qin* is river discharge, *Runoff* is total outflow from mesh as surface runoff and base flow, *Win* is irrigation water requirement, γ is conveyance efficiency of irrigation canal and *Wout* is irrigation drainage. The analysis was performed in 5km

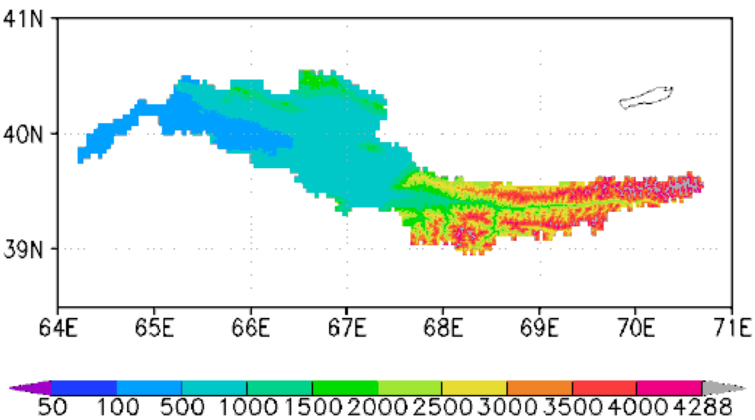


Figure2: Altitude of Zeravshan River Basin

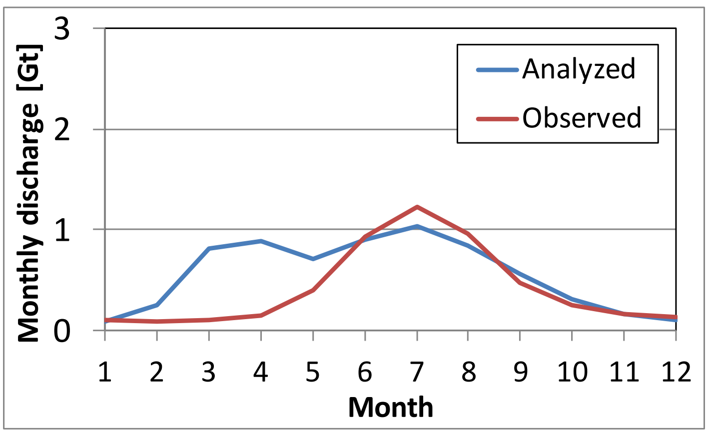


Figure3: Monthly averaged discharge in original analysis at Dupli station

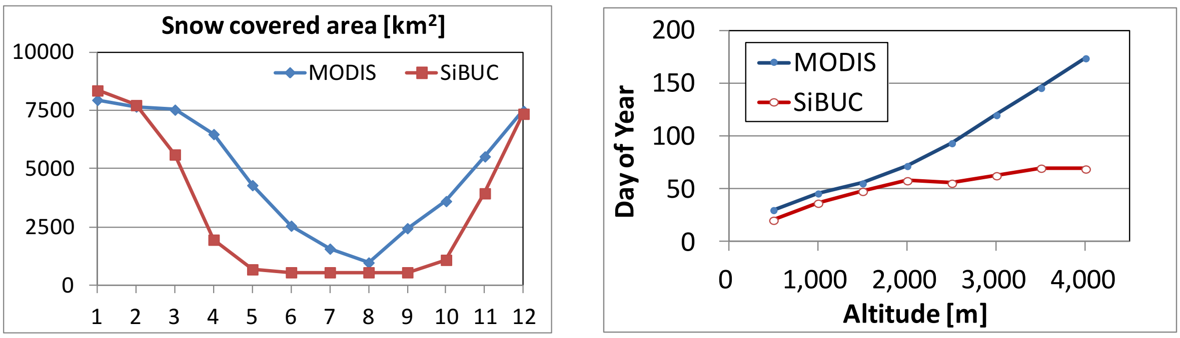
spatial resolution in 10 years from 1991 to 2000.

Reported glaciers area is 610km^2 in basin, lowest elevation of glacier was assumed over where all mesh have glacier. And glaciers were considered in model as huge initial snow depth and physical process was equally conducted between seasonal snow and glacier snow. Since glacier depth was fixed, the lowest glacier level changed depending on spatial resolution of analysis and it was 4288m for 5 km resolution analysis. Fig. 2 shows altitude map of Zeravshan basin with glacier mesh in white color. Input forcing data was from H08 global forcing dataset (Hirabayashi et al., 2008) and JRA25 reanalysis data (Onogi et al., 2007). And land use was from GLCC version2 (http://edc2.usgs.gov/glcc/) global 1km resolution land cover dataset.

2.3 Comparison of original analysis with observation and satellite data

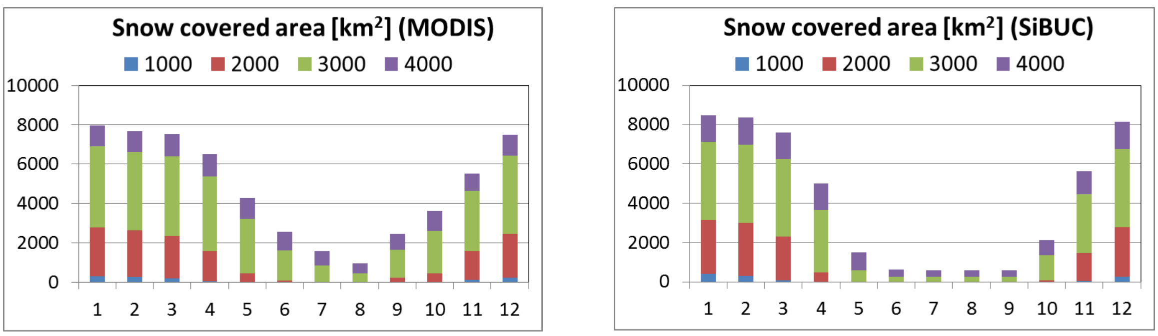
Fig.3 is original analyzed results of average monthly river discharge at Dupli station which is located near border between Tajikistan and Uzbekistan at 1000m elevation point shown in Fig.1. Since this “river discharge” is accumulated *Qin* in all upstream mesh, dam operation and underground water flow were not considered, however, these assumption are small enough comparing with huge gap between the analysis and observation.

Fig.4 and fig.5 show compared results of snow cover area and snow melt day between MODIS satellite data and analysis. The satellite data is from MOD10A2 and



(a) Seasonal change of snow covered area **(b) Averaged snow melt day**

Figure4: Comparison of snow area between analyzed result and satellite data



(a) MODIS **(b) SiBUC**

Figure5: Monthly snow cover in each elevation band

MYD10A2 products which provide maximum snow cover area in each 8days in 500m spatial resolution. It was made mainly by NDSI (Normalized Difference Snow Index) with modification considering vegetation cover over snow using NDVI. Even though snow depth couldn't be compared in this method, it is conclusive that snow melt in analysis is much earlier than actual and the difference is bigger in higher altitudes. In fig.5, showing monthly snow area in each elevation band, analyzed snow cover melted equally on all elevation bands around April to May, while satellite observation indicated snow gradually melted from lower elevation,

3. ALTITUDE DEPENDENCY OF METEOROLOGICAL FORCING

As one of the reason of earlier trends in snow melting analysis, it is likely that downward heat was over supplied in higher region. Generally, since there are few meteorological stations in higher mountains, forcing data in higher region was interpolated from lowlands. Therefore, altitude dependency is important factor and its sensitivity to river discharge was analyzed in this section.

Seven meteorological components are required for input to SiBUC, which are precipitation, air temperature, specific humidity, air pressure, wind speed, downward longwave radiation (DLWR) and downward short wave radiation (DSWR). Originally, only air temperature and air pressure were regarded as altitude dependent components, but since DLWR is highly depends on air temperature, and condensation was huge in higher mountains, sensitive analysis was conducted for long wave radiation and specific humidity in this section.

DLWR in high region was calculated based on Stefan-Boltzmann equation shown in eq.2.

$$L = \sigma T^4 \tag{2}$$

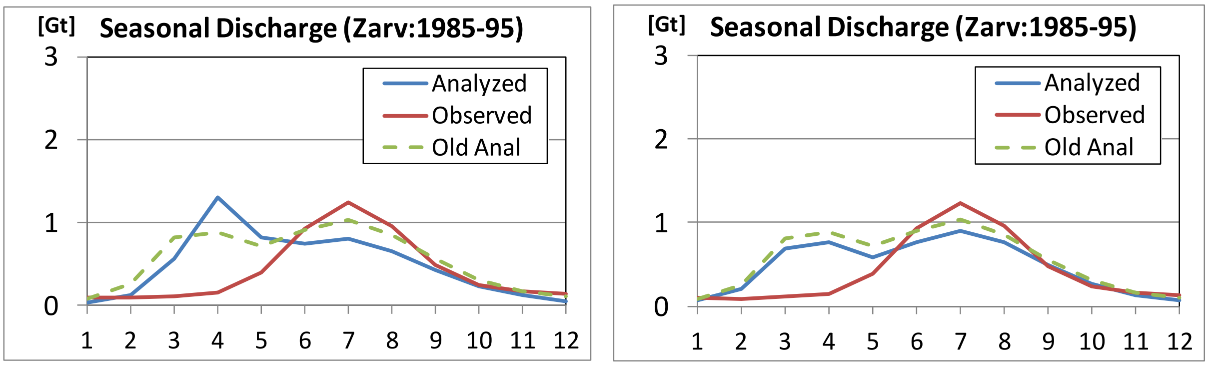
This can be eq.3 after making difference in height.

$$\frac{\partial L}{\partial T} = 4\sigma T^3 = \frac{4L}{T} \tag{3}$$

Since altitude dependency of air temperature is shown in eq.4,

$$\frac{dT}{dz} = -0.006 \tag{4}$$

Therefore, from eq.3 and eq.4, altitude dependency of DLWR was eq.5.



(a) Long wave radiation **(b) Specific humidity**

Figure6: Monthly averaged discharge at Dupli station (Altitude dependency)

$$\frac{\partial L}{\partial z} = \frac{\partial L}{\partial T}\frac{dT}{dz} = -0.006 \times 4\sigma T^3 \tag{5}$$

where, L is long wave radiation [W/m^2], T is air temperature [K], z is elevation [m] and σ is Stefan Boltzmann constant.

Comparison of long wave radiation between original method and this method is shown in Fig.6 (a). From it, peak discharge is around one month later than original. Moreover, river discharge on August is lower and it seems that melting from glacier reduced.

In this research, relative humidity was kept in higher place instead of specific humidity. Saturated water vapor pressure E_s was required and calculated by Tetens equation shown in eq.6.

$$E_s = 6.11 \times 10^{aT/(b+T)} \tag{6}$$

where, a,b are constant values which are 7.5 and 237.3 on water surface and 9.5 and 265.5 on snow surface, respectively. The surface condition was estimated using higher and lower than 0 degree of air temperature for easier calculation.

Comparison with original analysis was shown in Fig.6 (b). Humidity was drier in higher region in new method. However, there was small difference in seasonal river discharge and it was slightly lower in all month equally than original. The reason would be reduction of condensation and increase of evaporation.

In conclusion, altitude dependency of long wave radiation should be applied since it is physically validated and had huge impact on seasonal discharge. However, the one of humidity had small impact on discharge, but it can reduce over condensation on higher mountain. Since validation with observation is required, it should be compared with sonde observation in future research.

4. SUBGRID SCALE EFFECT

4.1 Subgrid scale effect and spatial resolution

Generally, land surface analysis is conducted on mesh averaged altitude. However, glacier and unmelt snow in summer exist on relatively higher places and valleys, therefore subgrid scale undulation is important to be considered. Since original analysis for whole Aral Sea Basin was conducted in 20km resolution, such smaller scale high place couldn't be considered. Since this subgrid scale heat deficient region is important for water resource in summer even though its area is actually small.

Firstly, four results analyzed in different spatial resolution were compared which were 1km, 5km, 10km and 20km resolution. In fig.7, exceeding area more than each height was drawn every 1m in each spatial resolution. Altitude data was from SRTM (Shuttle Radar Topography Mission) and ASTER-GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer - Global Digital Elevation Map), which are global datasets which spatial resolution are 1km and 30m, respectively. As shown in fig.7, exceedance area in height was almost same with 1km and 30m resolution, but difference between coarser resolutions was getting bigger in higher region including more than 4300m region where is regarded as glacier mesh in this research. Therefore, 1km resolution was high enough in terms of subgrid scale higher region, and coarser resolution more than 5km had possibility to ignore smaller scale high region.

Fig.8 shows analyzed river discharge in each resolution. In this analysis, lowest glacier level changes in each analysis. The results showed significant difference since glacier exists in lower elevation in coarser resolution analysis. Lowest glacier level in each resolution was 3743m for 20km, 3989m for 10km, 4160m for 5km and

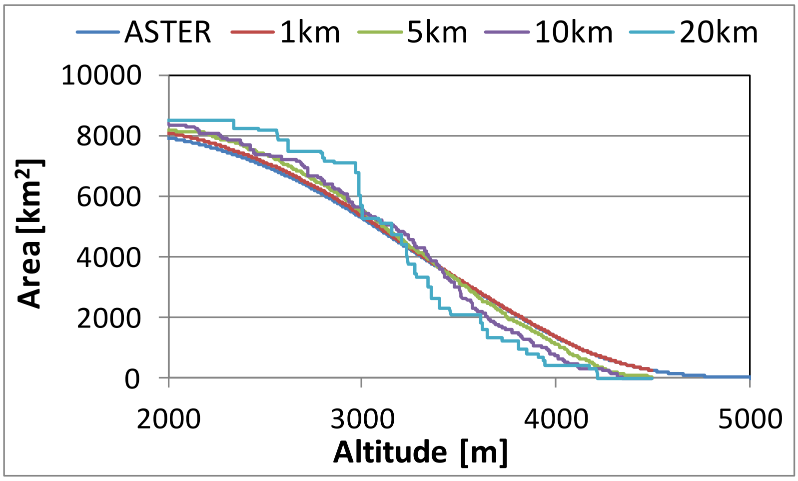


Fig.7 Exceedance area in height

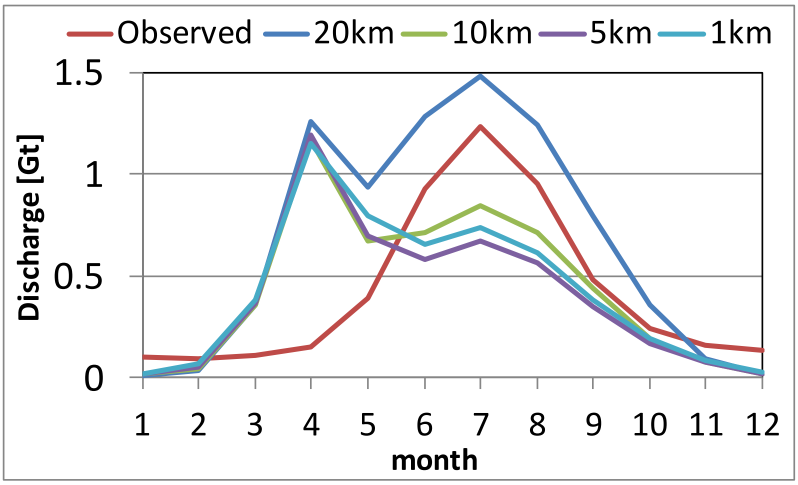


Fig.8 Monthly averaged discharge (spatial resolution)

4288m for 1km resolution. And if lowest glacier level was equally 4288m among all resolutions, there were still huge difference since glacier area is different especially in 20km resolution which highest mesh was lower than 4288m. Therefore, glacier level is important factor and it is difficult to reflect actual value for coarser resolution analysis. On the other hand, difference is smaller for seasonal snow melting in spring. It seems that main reason of early trends for seasonal snow was not only subgrid scale effect. And difference was difficult to be shown since snow disappeared immediately in all elevation bands.

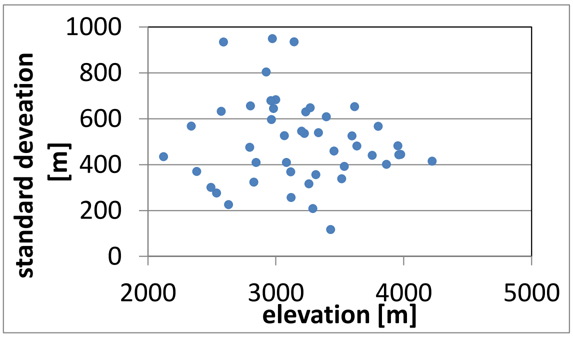
In conclusion, since coarser resolution analysis couldn't consider mixture of elevation bands in mesh, melting process especially on glacier differed significantly. Since seasonal snow melt disappeared immediately in all elevation, difference was difficult to be obvious. Also, even in 1km resolution which is regarded as high resolution analysis in this research, peak river discharge is earlier than actual.

4.2 Elevation mosaic scheme

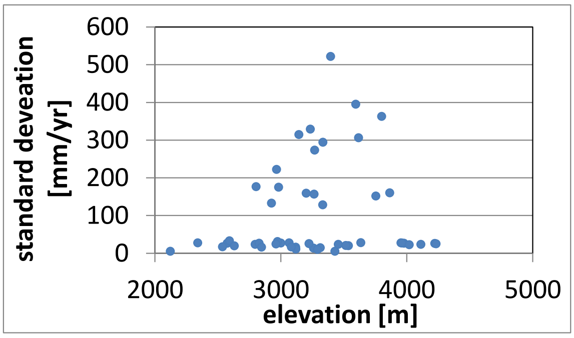
Since subgrid scale undulation had significant effect on seasonal river discharge in previous section, subgrid scale scheme to consider elevation inhomogeneity was developed.

General land surface model has mosaic scheme to consider land use mixture since it is generally key factor on land surface process. In mosaic scheme, firstly vertical water and heat balance was conducted on all land use type in mesh and accumulated with weight of land use fraction. It is calculated in Eq.7.

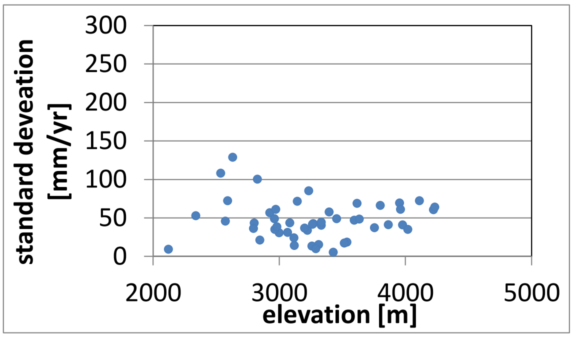
$$F_{total} = \sum_i F_i V_i \qquad \left(\sum_i V_i = 1 \right) \tag{7}$$



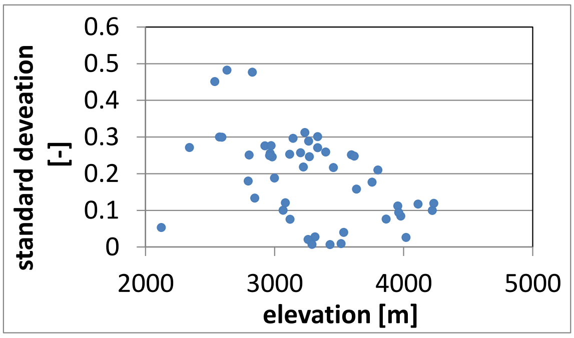
(a) Elevation



(b) Runoff



(c) Evapotranspiration



(d) Bowen ratio

Fig.9 Comparison between mesh averaged elevation and standard deviation of 1km resolution results calculated in 20km mesh

where, *F* is flux, *V* is land use fraction and suffix *i* shows each component which is land use generally. However, land use in higher altitudes tends to be equal and altitude is much dominant factor as shown in Fig.7, elevation mosaic scheme should be applied in higher mountains dividing mesh to several elevation bands and analyzing vertical balance individually. In this research, elevation band mosaic was applied for over 1500m mesh and elevation bands were divided every 500m and added to original land use mosaic. Land use for elevation mosaic region was assumed to be short grass which was actually most common in upstream. However, land use mosaic scheme were applied for water body, urban area and irrigated farm even if its height was more than 1500m since differences from short grass are huge.

Fig.9 is results to clarify subgrid inhomogeneity of land surface results. Mesh averaged elevations in 20km resolution were compared with standard deviation of model results calculated in 1km resolution inside the mesh. Fig,9 (a) firstly showed elevation inhomogeneity in 20km mesh and its variation was biggest around 2500-3000m in the basin, but correlation with height was still small. Evapotranspiration had also small trend which variation was bigger in lower altitudes where land use variation is bigger. And runoff variation was biggest when it was higher than 3000m, where glacier and unglacier mesh are existing together. On the other hand, clear decreasing trend of Bowen ratio was found in height. Since

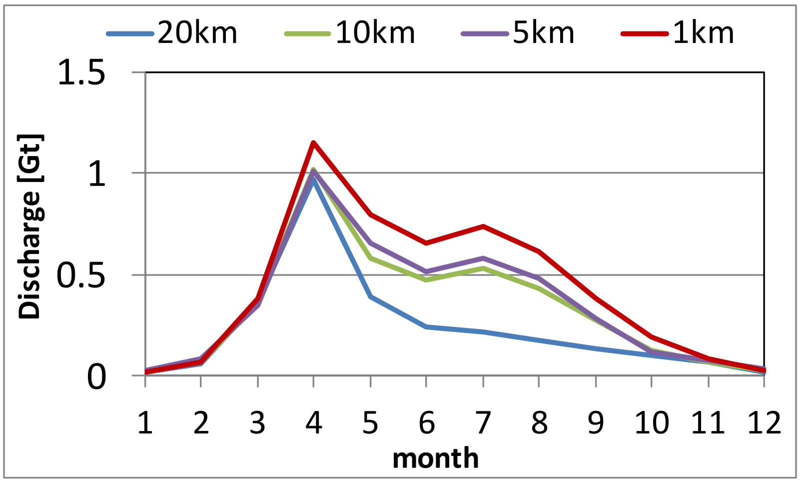


Fig.10 Monthly averaged discharge (elevation mosaic)

potential evaporation was much higher than actual due to arid climate, evaporation was seems to be decided basically by precipitation and there was few trends in height as shown in fig.9 (c). Therefore, when downward total heat supply decreased in high altitudes, only sensible heat reduced resulting in reduction of Bowen ratio.

Inhomogeneity of land surface analyzed results differed depending on components, and in terms of water resource runoff, existence of subgrid scale glaciers was important to be considered. Fig.10 finally showed hydrograph of Zeravshan River with elevation mosaic scheme. Remarkable improvement was shown comparing with fig.8 that could consider subgrid scale snow process even in 10km resolution analysis especially seasonal snow melt. However, underestimating trend remained in glacier melting in summer especially in 20km resolution. The reason seems to be representability of forcing data.

5. CONCLUSION

In this research, land surface analysis in mountain region was studied in Zeravshan River Basin. Firstly, original analysis was validated with observed river discharge and satellite measurement. As the result, peak river discharge was several months earlier and snow cover melted immediately in spring while it lingered at high altitudes until summer. Therefore, altitude dependency of meteorological forcing and subgrid scale undulation were examined.

As for altitude dependency, sensitive analysis was conducted about downward long wave radiation (DLWR) and specific humidity. Altitude dependency of DLWR was formulated from Stefan-Boltzmann equation and it had a high sensitivity to river discharge, resulting in one month later shift of peak river discharge. And about humidity, relative humidity was assumed to be equal in height. It had actually few effects to seasonal discharge, but it reduced extraordinary condensation.

Subgrid scale undulation was conducted in study firstly by comparing analysis in several spatial resolutions and secondly by applying elevation band mosaic scheme. As the results, there were significant differences between results in each spatial resolution especially at high altitudes with glaciers. It was also found in comparison between elevation and inhomogeneity of analyzed results, inhomogeneity of runoff in mesh was highly depended on subgrid scale glaciers. Therefore, elevation mosaic scheme was attempted and difference between spatial resolutions was considerably reduced.

Even though several attempts were conducted in this research, seasonal river discharge still had earlier trend. In future analysis to improve accuracy, slope orientation to modify downward short wave radiation and multi-layer snow model would be considered.

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