Estimation of Average Snow Cover over Northern Pakistan

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Abstract

Pakistan is largely dependent on its frozen hydrological resources, i.e., snow cover and glaciated ice on the mountains of Northern Pakistan, as they maintain the perennial flows in riverine network of country. In winters, western depressions bestow substantial amount of snowfall on ranges of HKH housed by Northern Pakistan and in summers these frozen reserves feed rivers of Pakistan. The runoff is generally stored in reservoirs for hydropower generation and irrigation, therefore, it is imperative to measure snowmelt generated runoff for distribution and allocation of water for different objectives. As, snowmelt runoff is generated through melting of snow and glaciated ice, thus, precise estimation of snow cover of mountain ranges of HKH is highly desirable. To map snow cover over a large area is now viable with advancement of remote sensing using the platforms of satellite. Due to periodic revisits of satellites over the area of interest, it is now convenient to monitor the snow cover at regular intervals. Moderate-Resolution Imaging Spectroradiometer (MODIS) is a reliable sensor, due to its spatial, temporal and radiometric resolution, for mapping snow cover of Northern Pakistan. Images of MODIS, since its inception i.e., 2000 to 2010 are used in this study, as clouds offer obstruction in operation of satellite sensors in visible portion of electromagnetic radiation spectrum and area of interest experiences cloudiness most of the times, thus, endeavor is made to retrieve at least one image per week. Normalized Differential Snow Index (NDSI) is adopted to exploit different wavelengths of electromagnetic radiation to draw snow cover maps. Snow cover area is calculated in square kilometers and curves of snow cover extent are drawn for each year separately and an empirical relationship is made for average snow cover with respect to seasons.

Keywords: Snow Cover, HKH, Northern Pakistan, Snow Melt Runoff, Remote Sensing, MODIS, NDSI, Glaciated Pakistan.

Introduction

Agriculture based economy of the Pakistan is largely dependent on runoff from snow and glaciated reserves of the Northern Pakistan. In winter, western disturbances yields snow over Northern Pakistan that constitutes a substantial snow cover on mountainous ranges of Himalaya- Karakorum-Hindukush (HKH), which generates runoff in rivers of Pakistan on melting in summers. Subsequently, this runoff serves for hydropower generation, irrigation, flood control and distribution among federating constituencies. Further, snow cover of the area is highly vulnerable toward recent episode of global warming, as, Pentad analysis of summer temperatures including data from various sources (1981- 2008) revealed that 30°C isotherm has moved to 725m above the elevation where it existed three decades before. A study conducted in the same area on the basis of meteorological data only showed the position of that isotherm at 350m by the end of 2005 (Rasul et al. 2006). Thus it is also significant to relate snow cover of Northern Pakistan with impact of global warming. The catchment area of HKH in Northern Pakistan is nearly 128730.8 km2. Northern Areas of Pakistan is comprised of districts of Chitral, Dir Swat, Skardu, Gilgit, Kohistan, Mansehra, Batagram, Bunir, Malakand, Abbottabad, Rawalpindi, Azad and Occupied Kashmir. Further rivers like Swat River, Chitral River, Gilgit River, Hunza River, Shigar River, Shyok River, Indus River, Shingo River, Astor River, and Jhelum are fed by the runoff from the glaciers of HKH ranges which serve as the life line for millions of the people in the area (Rasul et al. 2008).

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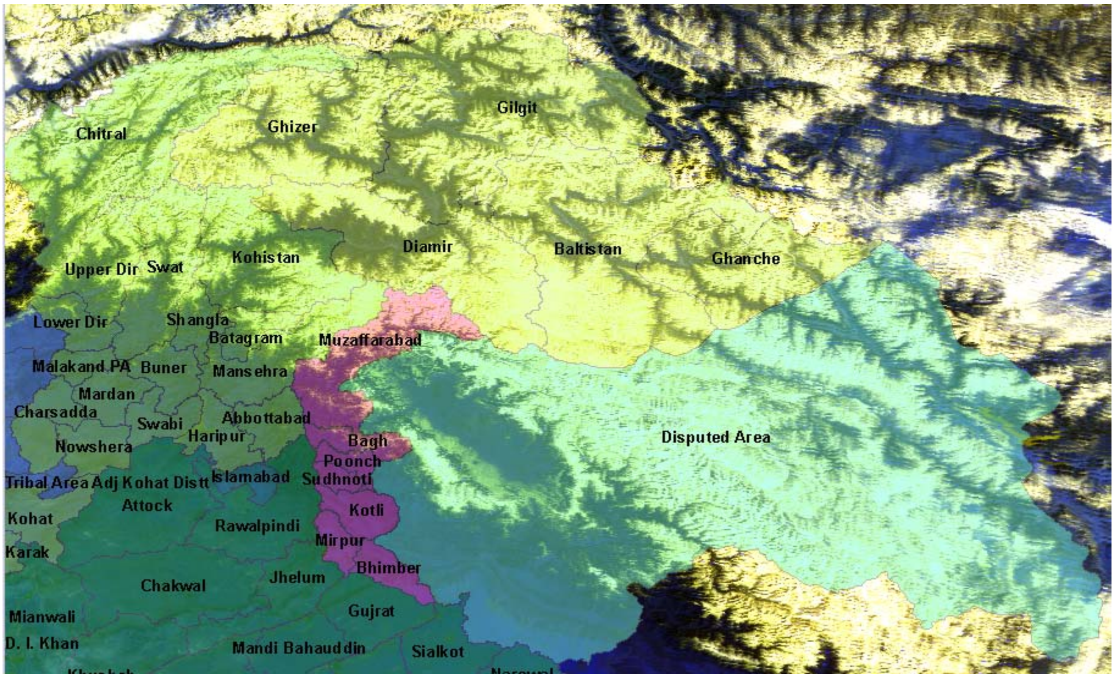

Figure 1: Northern Pakistan

Flows of these rivers are stored in dams at several locales and further water is diverted in channel, through barrages to distribute water among different areas of the country for irrigation.

As, almost all the runoff present in above said rivers is generated through snowmelt, therefore, it is rational to monitor the spatial and temporal variations of snow cover in source region. Lack of data collection points and their reasonable distribution over this complex terrain is a great hurdle for predicting trends accurately (Rasul et al. 2008). Ground monitoring of snow is normally based on point measurement, subject to numerous problems especially inaccessible mountainous terrain. Hence, conventional methods of data collection are time consuming and spatially limited. Thus, remote sensing is the only viable way, particularly at high elevation and in remote areas of the globe where very little in-situ data exists, to estimate the snow cover distribution (Butt et al. 2004). As, areal and spatial distribution of snow and ice cover in alpine regions may vary significantly over time due to seasonal and inter-annual variations in climate. Therefore, there is need for monitoring the HKH ranges in Northern areas of Pakistan, consisting snow covered mountains, with some reliable sensor, and Moderate Resolution Imaging Spectroradiometer (MODIS), aboard Terra Spacecraft of Earth Observing system (EOS) of National Aeronautics and Space Administration, is good choice due to its spectral spatial and radiomimetic characteristics.

Furthermore, snow cover can be derived through MODIS imagery, through exploitation of different bandwidths of electromagnetic radiations. This technique is summed in Normalized Differential Snow Index (NDSI) defined by Hall et al, in 1995. Thus, NDSI was applied on MODIS images since 2000 to 2010, and special consideration was paid to retrieve at least one image of each week on running year. Resultantly, spatial and temporal variability of snow cover in mountain rages of HKH of Northern Pakistan is monitored.

Characteristics of MODIS

MODIS features are designed to detect a wide range of the electromagnetic energy, and measure at three different spatial levels, it takes measurements on 24/7 basis; and it has a wide field of view. Due to comprehensive and continual coverage MODIS offers a complete global electromagnetic picture in two days. “MODIS’s frequent coverage complements other imaging systems such as Landsat’s Enhanced Thematic Mapper Plus, which reveals the Earth in finer spatial detail, but can only image a given area once every 16 days— too infrequently to capture many of the rapid biological and meteorological changes that MODIS observes.” (Mark et al. 1998)

These MODIS instruments are designed to take measurements in spectral regions that have been used in previous satellite sensors. MODIS is continually adding to existing knowledge by extending data sets collected by heritage sensors series such as the National Oceanic and Atmospheric Administration’s (NOAA) Advanced Very High Resolution Radiometer (AVHRR), used for meteorology and monitoring sea surface temperature, sea ice, and vegetation; the Coastal Zone Color Scanner (CZCS) and the Sea-viewing Wide Field of View Sensor (SeaWiFS), used to monitor ocean biological activity; Landsat, used to monitor terrestrial conditions; and NOAA’s High Resolution Infrared Radiation Sounder (HIRS), used to observe atmospheric conditions. By extending these data sets, MODIS promotes the continuity of data collection essential for understanding both long- and short-term change in the global environment

MODIS Specifications

Table 1: MODIS Specifications (William L. Barnes, Thomas S. Pagano, and Vincent V. Salomonson, Fellow, 1998)

Orbit	705 km, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (Aqua), sun-synchronous, near-polar, circular
Scan Rate	20.3 rpm, cross track
Swath Dimensions	2330 km (cross track) by 10 km (along track at nadir)
Telescope	17.78 cm diam. off-axis, afocal (collimated), with intermediate field stop
Size	1.0 x 1.6 x 1.0 m
Weight	228.7 kg
Power	162.5 W (single orbit average)
Data Rate	10.6 Mbps (peak daytime); 6.1 Mbps (orbital average)
Quantization	12 bits
Spatial Resolution	250 m (bands 1-2) 500 m (bands 3-7) 1000 m (bands 8-36)

Electromagnetic Properties of Snow

To understand the phenomenon of melting and runoff, thermal properties of snow are vital, and the effect that the presence of a snow pack has on heat transfer between the atmosphere and the surface below the snow. In considering the snow melting between thaw, the usual approach is to relate the melting, measured as the amount (cm) of water, to the accumulated number of degree-days of thaw, through a coefficient ‘α’ that has a typical value of 0.5cm per degree-day.

Fresh dry snow appears white to the receptors of human eye. So it is asserted as highly reflective, with little variation over the range of wavelength (nearly 0.4 to 0.65μm) to which the eye is sensitive. The reason is dielectric properties of ice, and the fact that ice constituting snow is in a very highly divided form with the order of 109 particles per cubic meter. Rees (2001) fully developed this argument and implied that the reflection coefficient of a snow pack should be smaller if the grain size is larger, as the number of air-ice interface will be increased and hence scattering opportunities will be reduced. Besides this, the usually increasing absorption at longer wavelength implies a commensurate reduction in reflectance at these wavelengths.

The density of snow does not affect reflectance directly, though the processes of metamorphism that cause the increase in density over time also leads to an increase in grain size and hence a eventual decrease in reflectance. With the passage of time snow pack ages, compressional as well as diurnal melting takes place and it may also acquire a cover of dust or soot which also decrease the reflectance. While the albedo of a fresh snow cover can surpass 90%, this amount can fall to 40% or even as low as 20% for dirty snow (Hall and Martinec 1985).

Reflectance of the snow gets little effect with the presence of liquid water in a snow pack. The amount of water rarely exceeds 10% by volume and there is in any case competent dielectric contrast between water and ice to ensure that the multiple-scattering phenomenon continues to take place. The absorption of electromagnetic radiation in water is similar to that in ice for the visible and near-infrared regions. On the second end, the presence of liquid water does have an indirect effect on the optical properties, since it promotes clustering of the ice crystals leading to a larger effective grain size and hence lower reflectance. Model stimulations presented by (Green et al. 2001) take into account both grain size and liquid water contents as influence on the reflectance of snow. The most significant effect of increasing water content appears to be a small shift of the absorption feature at 1030nm to shorter wavelength. Reflection from a snow pack is anisotropic, with enhance specular scattering due to reflection from ice crystals (Middleton and Mungall 1952; Hall et al 1993; Knap and Reijmer 1998; Jin and Simpson 1999). However, most of the studies have neglected this effect (Konig, Winther, and Isaksson 2001). In short, snow's high reflectance in visible EMR and Low reflectance in mid-infrared permits delineation of snow cover from other objects, through satellite sensors.

Normalized Differential Snow Index

MODIS holds special potential to address Normalized Difference Snow Index (NDSI). Normalized Difference Snow Index is prototype of normalized differences indices. It is originated from well known NDVI (Normalized Difference Vegetation Index). This index artfully exploits the interaction of snow with electromagnetic radiations. Snow responses visible portion of electromagnetic spectrum with high reflectivity and in mid-infrared it reciprocates with absorption, furthermore in same region of Electromagnetic Radiations (EMR) clouds are more reflective than snow (Dozier 1989). This analogy helps to discriminate snow from clouds at 1.65μm based fraction of EMR. Using this technique cirrus clouds remain troublesome to differentiate from snow (Hall et al. 1995). Mathematical expression of Normalized Difference Snow Index (NDSI) is as follows:

$$NDSI = \frac{(MODIS\_BAND4 - MODIS\_BAND6)}{(MODIS\_BAND4 + MODIS\_BAND6)} \qquad (1)$$

Resultant pixel values exceeding 0.4 in Equation (1) are considered as snow but it is found that this threshold limit varies with season (Vogel 2002).

An effort was made by Klein, Hall, and Riggs in 1998 and they successfully designed algorithm to map snow by using MODIS instrument. In this endeavor they defined that at pre-launch version of NDSI for MODIS, the pixels with NDSI value greater than or equal to 0.4 were considered as snow. But later on many problems were revealed in detection of snow-cover in forested area, to address this issue amalgamation of NDSI and NDVI was adopted and variable resultant values was accepted for certain cases (Klein et al. 1998). For more authenticity of snow-cover detection two more classification criteria were introduced (Klein et al. 1998). "The first criterion is an absolute reflectance in MODIS band 2 of greater than 11%. This criterion is necessary to separate snow from water, which also may have high NDSI values. The second criterion is a reflectance in MODIS band 4 of greater or equal to 10%. This prevents dark targets from being classified as snow despite high NDSI values."

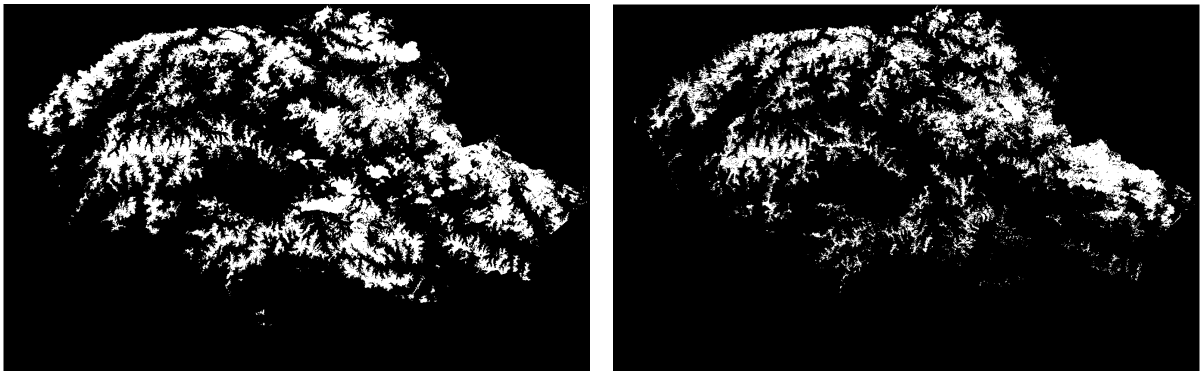

Figure 2: Snow Cover of Northern Pakistan

Results and Conclusions:

Average Snow Cover (ASC) is good tool for snow cover monitoring. It gives a good description of average snow covered area with respect to changes taking place from season to season. In this way average areal snow coverage can be identified at particular time of the year in particular region.

Another benefit of average snow cover is the identification of years with rich or poor snow fall. If the snow cover of some particular year is higher than the normal, it can be corroborated with ASC Curve and vice versa. Further, ASC is a good mean to estimate potential availability of water during the snowmelt season in the corresponding rivers and streams.

Table 2: Statistics of Snow Cover from 2000-2009

Area (Km2)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Max	80864.2	72444.5	84471.9	87636.7	78193.4	97309.18	79085.9	60042.09	73392.3	80788.7
Min	5002.9	3628.5	6430.4	9442.9	11519.6	8078.2	6821.6	5513.5	8231.2	6003.6
Range	75861.3	68816	78041.5	78193.8	66673.8	89230.98	72264.3	54528.59	65161.1	74785.1

Maximum extent of snow cover is estimated as 97309.18 km2 on 26 Feb. 2005 i.e., 75.5% of the total area, whereas, minimum extent is found as 3628.5 km2 on 20Aug. 2001, i.e. 2.81% of the total Northern area, this draws a possible range of 93680.68 km2. On the other hand, mean maximum now cover is 74913.3 km2 i.e., 58.19% of the total area and mean minimum snow cover is 8180.9 km2 (6.3% of total area) with range of 66732.4 km2. Consequently, average range is 30576.78 km2 less than absolute range of last ten years.

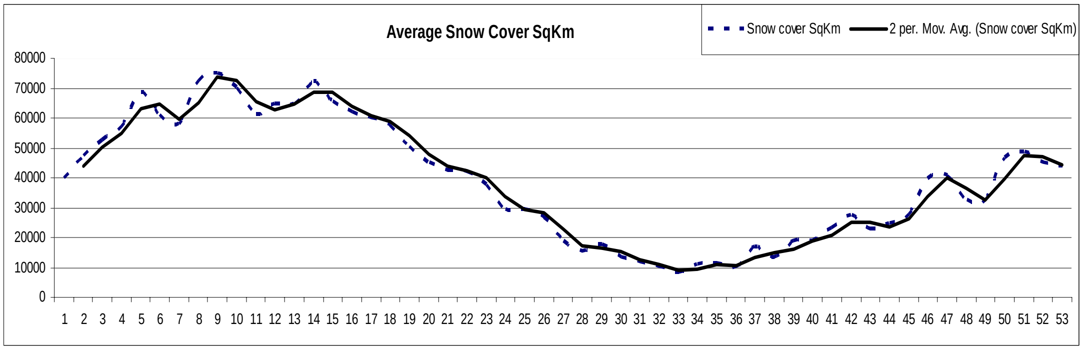

Figure 3: Dotted line represents Average Snow cover (km2), Continuous Black line represents Moving Average of order 2

The snow cover of Northern Pakistan follows an empirical relationship as well. It follows polynomial equation of degree 5. Mathematical equation is as follows:

$$Y = 0.0061x^5 - 0.7334x^4 + 28.44x^3 - 425.09x^2 + 4185.7x + 2399.8 \qquad (2)$$

But to formulate this polynomial relationship, an analogy is adopted. According to this analogy 33rd week of the year holding mean minimum snow cover is taken as first week of snow cover year and 32nd week as the last one. Therefore, it makes a perfect sense by fitting polynomial equation of degree 5. Further, value of Coefficient of Determination (R^2) for average snow and polynomial equation is 0.9579 that is highly correlational and generates confidence for future forecasting (Figure 3). Through this empirical relationship the average snow cover on any given day or week of the year can be estimated.

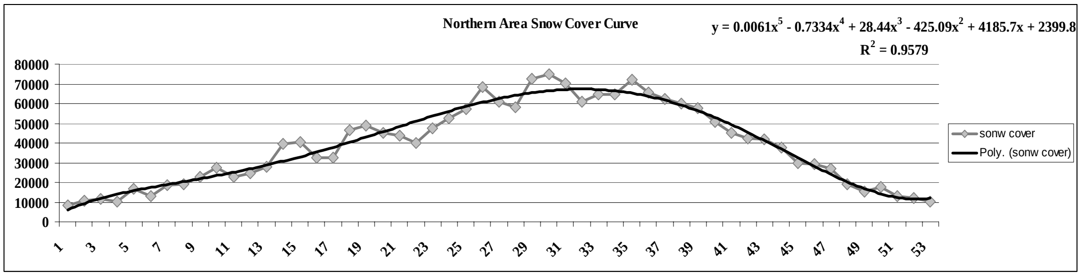

Figure 4: Average Snow Cover from Minima to Minima and its Polynomial Curve of degree 5

Another empirical relationship is established by taking maxima to maxima approach of snow cover curve i.e., at 9th week of the calendar year as first year of snow cover year and 8th week of calendar year is taken as 53rd week of the snow cover year. This equation is also polynomial of degree 5. Mathematical equation is as follows:

$$Y = 0.0053x^5 - 0.8416x^4 + 47.905x^3 - 1080.3x^2 + 6223.6x + 60401 \qquad (3)$$

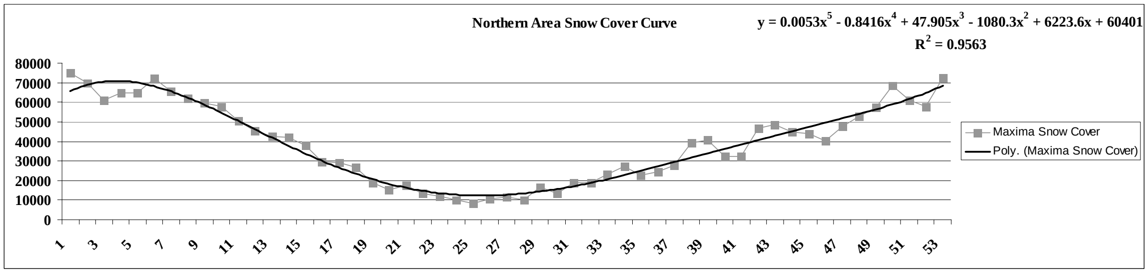

Figure 5: Average Snow Cover from Mixima to Mixima and its Polynomial Curve of degree 5

The value of Coefficient of Determination (R^2) (Figure 4) for average snow and polynomial equation of degree 5 from maxima to maxima analogy is 0.9563 that is again highly optimistic.

Derived average snow cover will be used as criterion to monitor and evaluate present conditions of snow cover and whether it is normal or deviating form the normal. Further, snow cover curve along with its empirical relationships of polynomial of degree 5 will be used to interpolate snow cover data for the runoff modeling and it is also workable to forecast snow cover of summer on basis of maximum snow cover of winter.

Limitations:

Average snow cover experiences kinky behaviour in winter seasons. The reason is unavailability of cloud free imagery on weekly basis. For that reason curve exhibits abrupt rise and fall in months of January, February, March, April, October, November and December. The behaviour of average snow cover curve is reasonably smooth in summer season as monsoon depression does not approach to such lofty mountains to create cloudiness, which later may pose obstruction in satellite imagery. These gaps will be abridged with the passage of time as more workable imagery will be processed and more data will be available to formulate snow cover of the area.

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