Impact of Climate Variability on Snow Cover: A Case Study of Northern Pakistan

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Abstract

Climate Change is one of the major factors affecting snow cover distribution. Precipitation in the form of snow, glacier melting, and rainfall are the major contributors to the ground water. Snow monitoring, mapping, estimation, and analysis of snowmelt runoff is time consuming and an intricate process if performed through traditional means. However, the spatial analysis of snow cover area using satellite data is an attractive and effective method. Additionally, the synoptic coverage of satellite sensors offers temporal change detection benefit as well. This study is conducted to analyze the impact of climate variability on snow cover in Northern areas of Pakistan. Satellite data archived from Moderate Resolution Imaging Spectroradiometer (MODIS) is used in this study. In addition elevation data from Shuttle Radar Topographic Mission (SRTM) is used for the production of Digital Elevation Model (DEM). The temporal snow cover is derived from Normalized Difference Snow Index (NDSI). Temperature data of various years is being used to identify the impact of climate variability on snow cover. Temporal analysis of snow cover using spatial analysis tools revealed variations in snow cover of the study area during different months of 2000 and 2006 data.

Key Words: MODIS, SRTM, DEM, NDSI

Introduction

Snow cover is a crucial hydrological parameter in the global water cycle. By influencing directly the dynamics of the global water cycle, snow cover has control on climate through its effect on energy budget at the surface and lower atmospheric levels (Cohen, 1994). The duration of snow cover for a region, regardless of snow depth, is a sign of climate condition (Leathers and Luf, 1997, Butt and Kelly 2008). The impact of snow cover on climate is intricate due to its reaction with the air temperature (Brown, 2000, Butt 2007) and is a major factor in the study of global climate change (Foster and Chang, 1993, Butt 2006, Almas et al 2004).

In 1960 remote sensing added a new dimension to the snow cover mapping. Early meteorological satellites used visible and near-infrared bands to identify the snow cover and since 1978 passive microwave technology has also provided maps of snow cover (Hall et al 2002). Visible and near-infrared region derived snow maps produced both good spatial and temporal resolution, but requires a clear sky since the radiation in this part of the spectrum cannot penetrate clouds. The passive microwave technique, on the other hand, can penetrate cloud cover and is able to estimate snow cover, snow depth, and snow water equivalent, but has a coarse spatial resolution (Hall et al., 2002). More then 30% of the earth is covered with seasonal snow whereas 10% of the earth is permanently covered with glaciers. These glaciers play a vital role to runoff in rivers since more then 80% fresh water requirement is accomplished with the snowmelt runoff water (Dozier, 1989).

Glaciers are treated as natural lakes. Fresh snow falls on these glaciers in winter season (September – February) and melts in summer season (March – August), thus meets the water requirements of the country. In Pakistan most of the dams depend on snow melt water. In past few years snow depletion is high due to climate variability. Thus in this research our main objective is to study the impact of climate on snow cover. Snowmelt from mountains is the primary source of reservoir capacity management, electric power generation, irrigation practices in Pakistan. It is therefore very important to study snow pack characteristics.

Climate is the average weather usually taken over a 30 year time period for a particular area or region. Elements of climate are precipitation, temperature, pressure, variability of rainfall, efficiency of precipitation, humidity, sunshine, wind velocity etc. According to Intergovernmental Panel on Climate Change (IPCC) the exact boundaries of climate and weather are not defined and it entirely depends upon application. Climate is controlled with latitudes, incoming solar radiation, distribution of land, water masses, altitudes, topography and location of area in relation to ocean currents. It has been observed that the average global temperature increased by 0.5°C from 1900 to 1945 but decreased in the next 25 years. However, the rise in temperature has been observed since then with 1998 being the warmest year of the past one thousand years whilst 20th century being the warmest century during the last one thousand years. The climate of Pakistan is one of the major climates of the world due to the monsoon region and variable latitude, altitude and localized relief. The winds in summer are south-west to north-east and west to north-east in winter.

Glacial area of Pakistan covers approximately 13700 km² which is the 13% of the mountains of the upper Indus Basin. The glaciers in the Himalayas are reducing faster than any other part of the world, if glaciers would reduce with current rate then it would be disappeared by the year 2035 (Rees et al. 2005). Changes in the depth of mountain glaciers and their melting patterns will have massive impact on water resources because the country's 70% of fresh water depends upon these glaciers and snow melting in the high mountains of Himalaya and Hindu Kush. Some of the largest glaciers as given in table 1 of the world outside the Polar Regions also situated in the Northern areas of Pakistan.

Pakistan is situated in the heart of the South Asia and it is located between 24° to 37° North latitude and 61° to 78 °East longitude. The area of Pakistan is 796096 km2. Land borders of Pakistan are 2640 Kilometers with Afghanistan to the northwest, 532 Kilometers with China to the northeast, 2912 Kilometers with India to the east and 909 kilometers with Iran to the southwest. Northern areas of Pakistan have larger spatial distribution, diversified topography comprised of districts of Chitral, Dir, Swat, Sakardu, Gilgit, Kohistan, Mansehra, Batagram, Bunair, Malakand, Abbottabad and Azad Kashmir as shown in figure 1. The study area in this research is located between 33° to 38° Northern Latitude and 71° to 78° Eastern longitudes comprising of sub-mountains to high mountainous areas. High mountains compromises of Himalayan, HinduKush and Karakoram, which includes some famous peaks of the world including Gashbroom II(K-2) and Nanga-Parbat, which are over 7000 meters (23000 ft) high and covered with snow. There are also western mountains separated by the Kabul River from the northern mountains area. Western highlands are dry and lower hills than the northern mountains of Pakistan.

Table 1: Major glaciers of Northern Pakistan

Glacier Name	Length in KM	Surface area (Km^2)
Siachin	75	1167
Biafo	68	620
Baltoro	62	748
Batura	59	287
Hispar	53	615
Kondus	47	307
Rimo	45	504
Panmah	44	474
Braldu	35	200
Bilafound	23	149

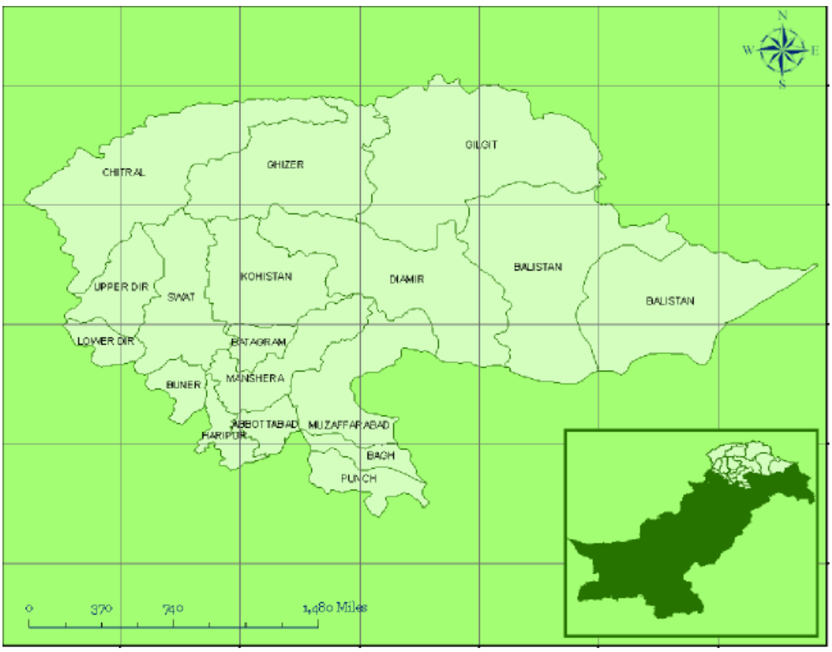

Figure 1: Study Area of Northern Pakistan

Data

Moderate Resolution Imaging Spectroreditometer (MODIS) instrument has been designed in 1995 by NASA and successfully launched onboard the Terra satellite on 18 December 1999. Llater on Aqua Satellite was also launched on 4th May 2002. MODIS collected its first scientific data on 24 February 2000 (Hall et al, 2002, Butt 2001). MODIS is especially designed to cover earth globally both on high and low latitude. MODIS has higher spatial resolution and increase spectral bands which can give better results for snow cover mapping comparing to its counterpart for example, Advanced Very High Resolution Radiometer (AVHRR). The MODIS snow cover algorithm depends on the high reflectance of snow in the visible band (band 4 with wavelength 0.545–0.565 µm) and low reflectance in the near infrared band (band 6 with wavelength 1.628–1.652 µm). Both the band 4 and band 6 are used to calculate the Normalized Difference Snow Index (NDSI) (Hall et al., 1995, Butt 2002). MODIS data of different months for the year 2000 and 2006 is used in this study. Similarly, SRTM data is retrieved from NASA web page whilst temperature data is obtained from Pakistan Meteorological Department (PMD). The elevation data used in this study is the 90 m resolution (3-arc SRTM). SRTM1 files contain 3601 lines and 3601 samples however SRTM3 files contain 1201 lines and 1201 samples. One SRTM Data tile has an approximate coverage of 12205.5168 km² (approx. 111.04 km x 109.92 km). The Digital Elevation Model (DEM) base on SRTM data is shown in figure 2. Average temperature data along with station names for the year 2000 and 2006 is given in Table 2.

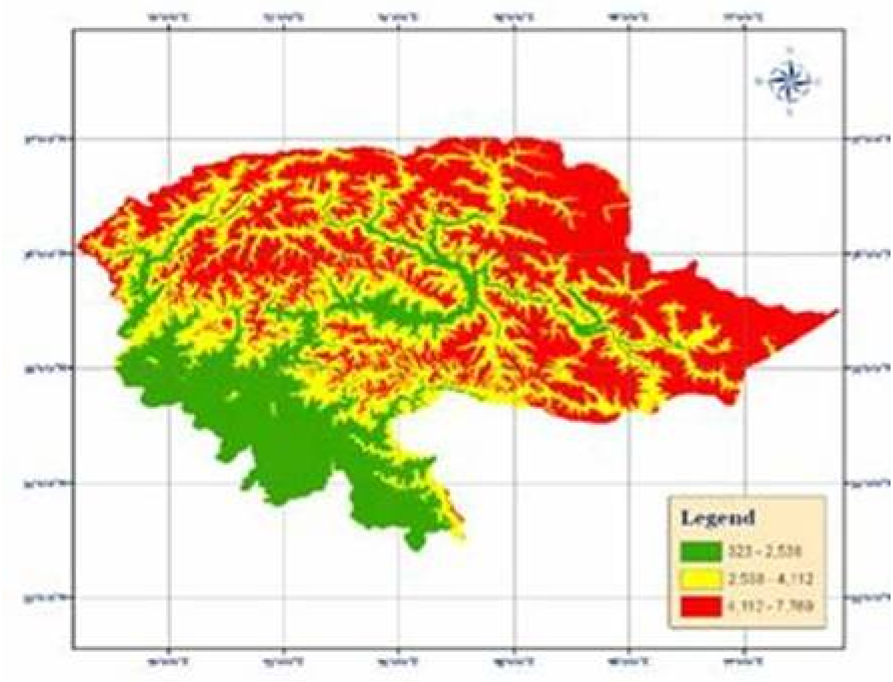

Figure 2: Digital Elevation Model extracted from SRTM data

Table 2: Average temperature records of Northern Pakistan as obtained from PMD

Months	Balakot	Chitral	Dir	Drosh	Kakul	Saidu Sherif	Garidopatta	Muzaffarabad	Skardu	Bunji	Gilgit	Astore	Chillas
Jan-00	14.1	12	12.9	11.3	13.4	14.9	14.4	16.6	1.8	10.9	10.6	3.6	12.7
Feb-00	14.5	10.8	11.5	10.8	12.6	15.6	15.9	18.4	3.4	12.6	13.3	2.9	14.6
Mar-00	20.4	16.8	16.8	17.1	19	21.5	22.6	24.1	11.9	19.1	19.3	9.5	20.5
Apr-00	28.9	26.4	26.5	26.9	27.2	30.8	31.6	32.7	20.1	25.9	26.5	17.5	28
May-00	35.4	34.2	32.9	35.5	33.9	37.1	37.6	38.9	27.5	33.7	34.9	24.9	37.3
Jun-00	34	35	32.7	36.5	32.3	36.8	36.6	37.4	29.3	34.3	35.2	25.3	37.8
Jul-00	30.5	35.7	31.2	36.4	29	34	32.5	33.5	30.3	34.9	34.6	26.4	38.1
Aug-00	30.5	35.7	31.6	36.4	28.9	34.2	33	33.8	29.6	34.8	35.3	26.5	38.2
Sep-00	30	32.4	28.8	33.3	27.8	32.3	31.4	32.6	26.9	31.8	32.9	23.9	35
Oct-00	28.4	28.6	25.9	29.1	27.3	31.1	29.6	31.7	21	26.6	27.8	19.8	29.7
Nov-00	22.1	17.6	19.1	17.7	20.9	22.9	22.7	24.7	13.3	19.4	19.9	12.1	21.5
Dec-00	18.4	13.3	15.5	12.8	17	18.3	19.1	21.7	4.5	13.1	12.9	5.7	14.9
Jan-06	13.2	8.8	9.8	7.6	12	13.9	13.4	13.2	2.1	9.3	8.5	1.7	10.5
Feb-06	20.2	16	17.4	16.7	18.6	21.6	20.3	21.2	9.2	16.5	16.9	8.5	18.1
Mar-06	20.7	18.3	17.7	18.4	18.4	21.7	20.9	22.7	13.9	19.9	20.3	10.7	21.5
Apr-06	27.7	24.5	24.5	24.5	25.1	28.9	26.6	30.4	18.1	24.4	24.9	14.8	27.3
May-06	34.8	34.8	33.4	36	32.7	37.3	36.8	38.4	27.2	32.6	34	24.5	36.3
Jun-06	34.3	34.6	33.4	35.3	31.9	36.5	36.4	36.3	27.8	31.8	32.3	24.4	35.8
Jul-06	33	37.3	32.4	38.5	30	35.6	35.8	35.6	33.1	37	36.8	29.3	40.9
Aug-60	31	34.8	30.9	36.5	27.9	33.4	32.3	33.2	30.6	32.7	32.5	26.1	37
Sep-06	31.1	31.4	30.3	33.2	28.5	33.1	32.9	33.8	26.8	30.9	30.1	23.3	35
Oct-06	28.2	28.6	28	30.1	26.2	30.4	29.6	30.9	21.8	26.3	27.2	18.8	31.6
Nov-06	20.3	18.1	18.2	18.9	18.5	21.2	20.4	22.2	13.8	18.9	19	11.2	22
Dec-06	15.5	9.6	11.2	9.5	13.1	14.5	16.4	16.8	5.6	11.5	11.2	4.1	13.2

Methodology

Snow can be identified using model known as Normalized Difference Snow Index (NDSI) and Normalized difference vegetation index (NDVI) (Klein et al., 1997, Butt and Kelly 1999). NDVI and NDSI are used together to distinguish between snow-free and snow-covered forests. NDSI take advantage of the fact that reflectance of snow is very high in visible part of spectrum and has very low approximately zero near short-wave infrared portion of spectrum (Nolin & Liang, 2000, Butt and Kelly 1998). The use of reflectance improves the identification of snow cover due to the incoming solar radiation and the effect of sun angle. In case of MODIS data NDSI is defined as the difference of reflectance observed in visible band (band 4) and shortwave infrared band (band 6) divided by the sum of the reflections of both the bands as given in equation 1.

$$NDSI = \frac{(Band4 - Band6)}{(Band4 + Band6)} \qquad (1)$$

MODIS pixels with NDSI value greater than or equal to 0.40 are considered as snow. In general, snow is characterized by higher NDSI values than other surface types.

Results and Discussions

For presence of snow with NDSI as given in equation 1, the minimum threshold used is NDSI > 0.40. the maximum snow observed for the year 2000 using NDSI criteria is in the month of February (284373 pixels) and December (290633 pixels) whilst the minimum snow was found in the months of June (48498 pixels), July (32325 pixels), August (43394 pixels) and September (42997 pixels). Similarly, for the year 2006 the maximum snow found is in the month of January (298813 pixels) and December (282307 pixels) whilst the minimum snow was found for the months of August (25920 pixels) and September (43509 pixels). In order to separate snow from water band 2 reflectance values are used. Thus the pixels which have reflectance values greater than 11 % in band 2 are considered as possible snow areas while pixels with less than or equal to 11 % are treated as water. Based on the second criteria the maximum reflectance for the year 2000 is in the months of March (254688 pixels) and April (256775 pixels) while the minimum reflectance is in the month of September (54316 Pixels). Similarly, for the year 2006 the maximum reflectance is in the month of May (282294 Pixels) while minimum reflectance is in the month of November (62664 Pixels). In addition to the above criterion another criteria is used in this study in order to map snow cover area. If the reflectance in band 4 is less than 11 % the pixel is not mapped as snow area. Using this criteria the maximum reflectance is observed in the month of March (260552 Pixels) and April (262551 Pixels) while the minimum reflectance is found in the month of September (59593 pixels) 2000 data. Similarly, for the year 2006 the maximum reflectance is found in the months of February (254880 pixels), March (246681 pixels) and May (242286 pixels) whilst the minimum reflectance is observed in the month of November (69787 pixels). Table 3 shows results for all three criterion used in this study for the 2000 and 2006 MODIS data. The first column shows the months and year for which MODIS data is used, second column indicates the number of pixel having snow after applying the first criteria, third column gives the number of pixel with snow after applying second criteria, fourth column shows the number of pixels snow present after applying third criteria, fifth column gives the number of pixels with snow after using the intersection of three criterion, sixth column indicates the snow area in square kilometer and last column shows the percentage of area representing snow in one MODIS scene. Similarly, the comparison of snow surface area and average physical temperature for different months of year 2000 and 2006 are shown in figures 3 and 4 respectively. It is evident from figure 3 and 4 that the snow area reduced with an increase in temperature. Similarly, figure 5 shows a comparison of elevation with snow covered area. It is evident from figure 5 that the area with high elevation has more snow as compared to low elevations.

Table 3: Comparison of snow covered area for the year 2000 & 2006

Months	Pixel value~0.4	Reflectance in Band2 > 11%	Reflectance in Band4 > 10%	No of snow Pixels	Snow covered area Km^2	Area in percentage
Feb-00	284373	214460	243628	212318	71875.36717	27. 73%
Mar-00	242646	254688	260552	231490	80016.49341	30.91%
Apr-00	249304	256775	262551	239483	78548.00733	30.32%
May-00	183083	183957	196466	174774	58580.71078	22.63%
Jun-00	48498	166182	179559	41809	13753.97243	5.30%
Jul-00	32325	164424	175371	25003	8228.06057	3.17%
Aug-00	43394	110959	84581	32053	10487.69394	4.05%
Sep-00	42997	54316	59593	23033	7715.21422	2.99%
Oct-00	103286	97995	118268	69952	23266.05675	8.96%
Nov-00	58035	70680	94296	35193	11585.31466	4.46%
Dec-00	290633	170089	215447	155413	51109.89034	19.70%
Jan-06	298813	227042	237576	215701	70444.13892	27.19%
Feb-06	273584	241316	254880	228977	75554.5492	29.11%
Mar-06	262221	239056	246681	234418	78265.9964	30.22%
Apr-06	215823	237571	224894	209927	70187.73671	27.11%
May-06	151707	282294	242286	150377	49853.32184	19.22%
Jun-06	85075	211370	125534	80755	26811.22539	10.33%
Jul-06	61107	128018	115408	49416	1638 2.56143	6.32%
Aug-06	25920	169621	110424	21276	7130.44202	2.76%
Sep-06	43509	102076	75153	34589	11714.23965	4.52%
Oct-06	97056	90310	91758	69996	22956.89795	5.07%
Nov-06	118663	62664	69787	60110	19690.28282	7.6%
Dec-06	282307	174247	184599	155698	51172.11677	19.73%

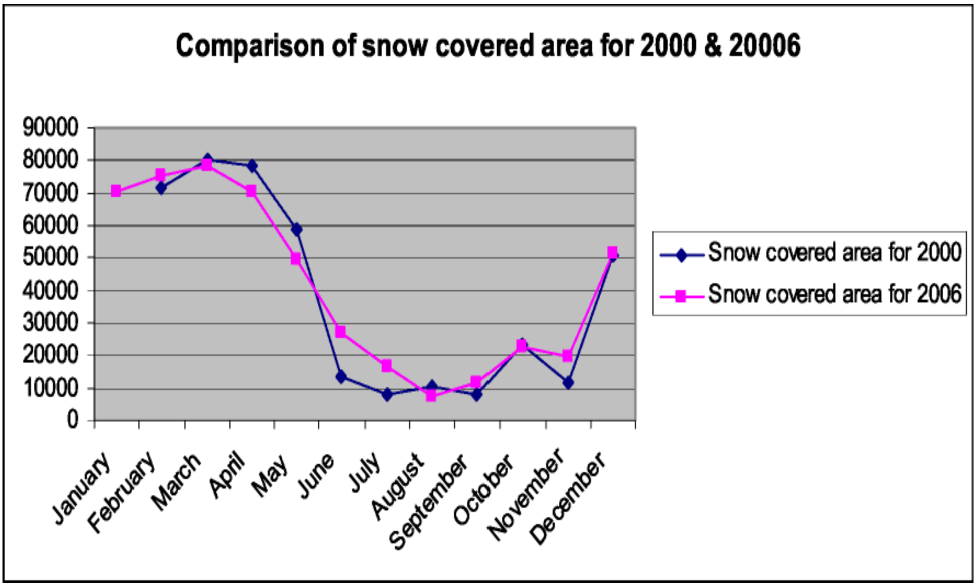

Figure 3: Snow surface area for the year 2000 and 2006

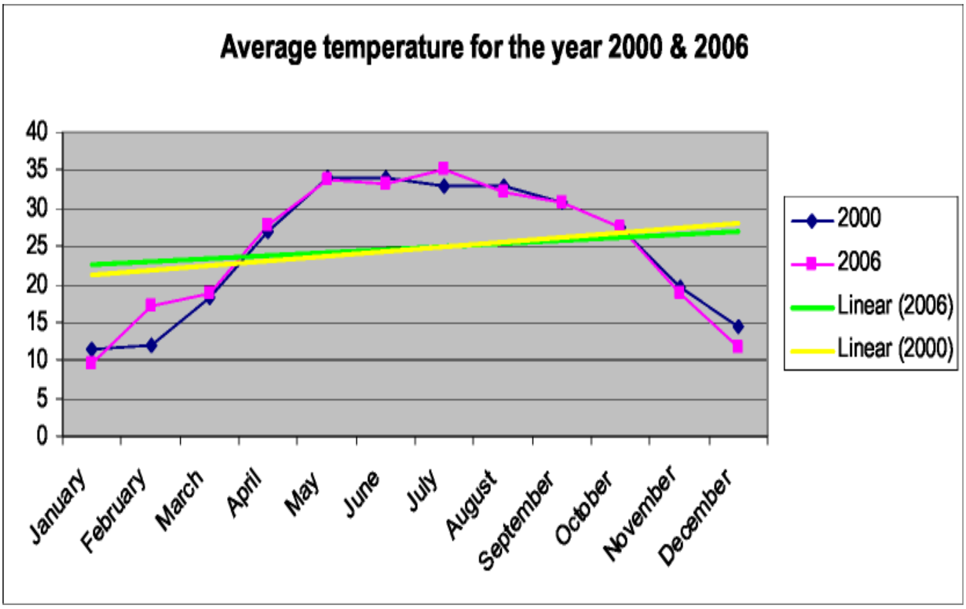

Figure 4: Comparison of average temperature for the year 2000 & 2006

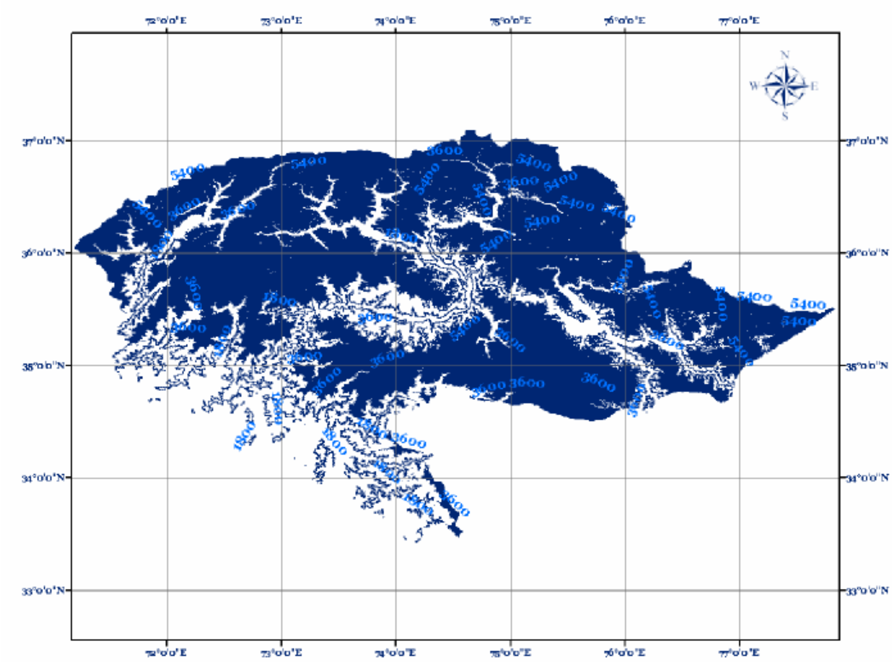

Figure 5: Comparison of elevation with snow covered area

Conclusions

Twenty three temporal MODIS satellite images have been selected for both the years to identify the climate variability in snow covered areas. NDSI is used to estimate the snow covered area in the Northern Pakistan. All the three criteria have different results for snow pixels. It is evident from this work that in summer 2006 temperature has increased from that of summer 2000 whilst during winter of 2006 the temperature has reduced from that of winter 2000. This pattern concluded that the temperature has been increasing from summer 2000 to summer 2006 while decreasing from winter 2000 to 2006. This trend is also evident from figure 3 and 4 which shows that the daily temperature is an important parameter in the snow cover area. However there are many other factors that effect snow pack distribution. If we compare the snow covered area for the year 2000 and 2006 then we observe that Results show no massive change in snow covered area in these six years. It is also evident from this study that from 2000 to 2006 temperature is increasing rapidly in summer and reducing in winter, as an indication of extreme weather conditions both in summer and winter. Rising temperature causes snow to melt in the early spring and changes the runoff timings/volume. Changes in snow melt pattern also affect the freshwater, natural system, hydropower generation and agriculture. Increasing temperature in winter season causes more rain instead of snow. By comparing the contours of elevation data with snow covered area as shown in figure 5, we observe that area with high elevation has more snow pack as compared to low elevations again the reason is associated with increase in temperature.

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