REVIEW OF LITERATURE
GLOBAL CLIMATIC CONDITIONS AND ITS INFLUENCE ON WORLD GLACIER REGIMES

The relationship between glacier behavior and climate has long been a central issue of critical debate in glaciology. The selection of thermal regime as the criteria for the categorizations of glaciers throughout the world is the most appropriate one because it takes into account the glacier dynamics and its interaction with various meteorological parameters.

The temperate glaciers are sensitive indicators of global change and have played a significant role in the sea level rise in the last century. The temperate glaciers are significant from the perspective that they play an important role in studying the basic physical processes governing the behaviour of all ice masses (IPCC, 2001).

The Tropics, loosely defined as the region from $30^\circ$N to $30^\circ$S latitude, make up nearly half the surface area of the Earth and serve as shelter for a vast majority of the global population. Detection and characterization of climate change in the Tropics is, therefore, a matter of great concern. Assessing the ability of climate models to reproduce this change is an important part of determining the fidelity with which the models can be expected to forecast the way climate will change in response to future increases in greenhouse gases content.

However, a very significant aspect in the tropics is the glacier-atmosphere interactions. The tropics have a synchronous accumulation and ablation, the ablation being permanent throughout the year (Hastenrath, 1995; Kaser, 2001). On a global scale, air temperature is considered to be the most important factor reflecting glacier retreat, but this has not been demonstrated for tropical glaciers (Houghton et al., 2001). Rather, a complex combination of changes in air temperature, air humidity, precipitation, cloudiness, and incoming shortwave radiation is considered to govern the fluctuations of tropical glaciers (Kaser, 1999). Changes in moisture concentration induce changes in other variables controlling glacier mass balance (Kaser et al., in press), except in mean air temperature.

Few attempts have been made to derive climate scenarios from reconstructed paleo-glaciations in low-latitudes (e.g. Klein et al., 1999; Hostetler and Clarke, 2000), but they do not deal adequately with the particular circumstances of different low-latitude
glacier regimes. A generalized and simplified depiction of three climate regimes at low-latitudes has been recommended by Kaser (2001). The delimitations have been determined as suggested by Kaser (Fig 2.1), on the basis of which they describe the principle differences between the three low-latitude glacier regimes and thus distinguish them from mid-latitude conditions:

   i) the ratio of melting to sublimation and
   ii) the duration of the ablation period.

These two variables are vital components of any model which seeks to depict the characteristic differences of such glacier regimes. The three glacier regimes in the tropics have their specific characteristics and are described as follows:

In the humid inner tropics, stable humidity and temperature conditions lead to a simultaneous accumulation and ablation throughout the year. e.g. Ruwenzori Mountains in East Africa, The Irian Jaya in New Guinea (Kaser and others, 1996b).

In the outer tropics, notable accumulation occurs only during the wet season. During the dry season, there is little or no accumulation and ablation is reduced as well. Because of the dry air, much of the available energy is consumed by sublimation and, therefore, little remains for melting. It is noteworthy that most of the tropical glaciers are found in the outer tropical regime mainly because of the meridional lengthening of the austral summer ITCZ over South America (Fig. 2.2).

Under extreme subtropical conditions, as in southern Bolivia and northern Chile, almost all ablation can be presumed to result from sublimation (Knoche, 1931). The sparse accumulation is from sporadic precipitation which is distributed over the year and is either related to the ITCZ or the westerly frontal zone (e.g. Vuille et al., 2007). The annual temperature variation increases with latitude and consequently the ablation season becomes slightly shorter than in the tropics.
Fig. 2.1: The tropics and their delimitations from a glaciological point of view, and the distribution of the glacier areas by country (after Kaser 1995, and Kaser et al., 1996 a)

Fig. 2.2: A schematic comparison of inner tropical and outer tropical glacier regimes with those of the mid latitudes (after Kaser 1995, and Kaser et al., 1996 a)
GLACIER FLUCTUATION SCENARIO: AN OVERVIEW

The geological history of the earth has witnessed the global climate being extreme cold to intense warm numerous times and this is manifested in the cyclic glacial and inter-glacial periods (Tangri et al., 2004). Geological evidences suggest that the earth has experienced glaciations during Pre-Cambrian, Permo-carboniferous and in the last Pleistocene periods. There have been at least 17 major glacial advances (glaciations) in the last 1.6 million years alone (Goudie, 1983). The most recent, the Last Glacial Maxima, reached its peak some 20,000 to 18,000 years ago and came to an end about 10,000 years ago (Goudie, 1983). Glaciations are followed by ‘interglacial’ periods, during which the glacier ice retreats as a result of global warming. The interglacial typically continues for about 10,000 years before the cooling or the next glaciation begins. This cyclical activity, which recurs at intervals of approximately 100,000 years, is generally accepted to be caused by gradual changes in the earth’s rotation, tilt and orbit around the sun, which affects the amount of solar radiation the earth receives (Milankovitch, 1941; Bradley, 1985).

Glacial advances and retreats are thus natural cyclical phenomena that occur during glacial and inter-glacial periods respectively. The world is now in an inter-glacial warm phase, the previous glacial advance having occurred during the last phase of the last glacial period (15th-19th century), which has come to be called "The Little Ice Age" (LIA). Since then, as a result of the subsequent warming phase, all glaciers have been retreating. The rate of retreat in recent times has, however, been much more rapid than the gradual retreat expected in an inter-glacial warming phase. The glaciologists and climatologists believe that this rapid rate of retreat is due to global warming. This climatic change brought about by human or anthropogenic activities in the post-industrialization period has already resulted in a global increase in the average surface temperature by 0.6° C (IPCC, 2001). A natural consequence of this is increased melt from ice caps and glaciers. A broad overview of the fluctuating scenario of the glaciers worldwide is accounted below.
NORTH AMERICA

The Glacier National Park, USA is witnessing a notable retreat in the last 140 years. The larger glaciers have now reduced to almost a third of their size as compared to that in 1850, and numerous smaller glaciers have disappeared completely. Average glacier area in the accumulation zone for September 1993 was 35% as compared to the required 65% for equilibrium, indicating negative mass balances for most glaciers and continued shrinkage (United States Geological Survey).

Cascade Range

The Cascade Range of western North America accounts for more than 700 glaciers of the U.S. These glaciers have a water storage capacity store almost equivalent to the lakes and reservoirs in the rest of the state. As reported, many North Cascade glaciers were advancing due to cooler/wet weather during the 1944-1976 period. However, by 1987, all North Cascade glaciers were retreating. Between 1984 and 2005, they have lost on an average more than 9.5 m in thickness and 20 to 40% of their volume (Pelto, 2006). The North Cascades climate is known to be sensitive to inter-annual and decadal fluctuations in Pacific Basin climate (Walters and Meier, 1989; Hodge et al., 1998; Pelto and Hedlund, 2001; Bitz and Battisti, 1999). Various long term monitoring studies indicate a strong negative mass balance demonstrating the glaciers response to a regional climate change. There are no distinct regional variations within the range. The glaciers are in disequilibrium with the present climate as indicated by the mean annual balance loss of -0.54 m/a, a cumulative loss of -12.38 m, 20–40% of their entire volume and increasing negative balances despite retreat (Pelto, 2006).

Rocky Mountains

In the Canadian Rockies, the Athabasca Glacier has retreated 1500 m since the late 19th century. It showed a trend of slow retreat in the period 1950-1980, and subsequently became more rapid after 1980. The studies on Peyto Glacier (12 km²), highlights rapid retreat during the first half of the 20th century, stabilization by 1966 and resumption in shrinking in 1976 (Canadian Cryosphere Information Network, 2006).
SOUTH AMERICA:

Andes
The Andes in the South America is showing alarming recession. More than 80% of all glacial ice in the northern Andes is concentrated on the highest peaks in smaller glaciers of one km² in size. Chacaltaya Glacier in Bolivia and Antizana Glacier in Ecuador were examined between 1992 and 1998 showed that between 0.6 and 1.4 m of water was lost per year on each glacier (Francou et al., 2000). Chacaltaya Glacier lost two-thirds of its volume and 40% of its thickness over the same period and it is expected that by 2010 to 2015, the Glacier will no longer exist. Moreover, the glacier is only 10% of its size when first examined in 1940. The evidence also supported findings that since the mid 1980's, the rate of recession for both glaciers has also been increasing (Ramirez et al., in press).

EUROPE
According to the World Glacier Monitoring Service reports (1995–2000 edition), the variations in the terminal point across the Alps have 103 of 110 glaciers examined in Switzerland, 95 of 99 glaciers in Austria, all 69 glaciers in Italy, and all 6 glaciers in France were in retreat as observed over a period of 1995-2000. Glaciers in France experienced a sharp retreat during 1942–53 followed by advance upto 1980, and then further retreat beginning in 1982.

Other researchers have found that glaciers across the Alps appear to be retreating at a faster rate than a few decades ago. In 2006, the Swiss Glacier survey of 85 glaciers found 84 retreating and 1 advancing. Though the glaciers of the Alps have received more attention from glaciologists than in other areas of Europe and research indicates that throughout most of Europe, glaciers are rapidly retreating (Swiss Glacier Monitoring Services, 2005).

Scandinavia
In the Kebnekaise Mountains of Northern Sweden, 14 glaciers are retreating out of sixteen examined during 1990-2001, one is advancing and one is stable (Andreassen et al., 2005). The 20th century witnessed the advance of Norwegian glaciers. But since 2000, Norwegian glaciers have decreased significantly, the reason supposedly being several consecutive years of little winter precipitation, and record-
warm summers in 2002 and 2003. By 2005, only 1 out of the 25 glaciers was advancing, two were stationary and 22 were retreating, significant among them being Briksdalsbreen, Engabreen, Brenndalsbreen and Rembesdalsskaka.

Iceland

The Breidamerkurjokull, one of the glaciers that is an outlet of the Vatnajokull, the largest ice cap in Europe, has receded by as much as 2 km since 1973. Hundred years ago Breidamerkurjokull, extended up to 250 m of the ocean, Today, Breidamerkurjokull's terminus is three kilometers from the ocean. The glacier retreat has exposed a rapidly expanding lagoon, which is filled with icebergs calved from its front. The lagoon is 350 feet deep and has nearly doubled its size during the past decade. All but one of the Vatnajokull outlet glaciers, roughly 40 named glaciers in all, are receding as of 2000 (Sigurdsson et al., 2007).

Greenland

In Greenland, the period since 2000 has brought retreat to several very large glaciers that had long been stable. The three investigated glaciers; Helheim, Jakobshavns and Kangerdlugssuaq Glaciers, jointly draining more than 16% of the Greenland Ice Sheet have been under rapid retreat in the 21st century. The satellite images and the aerial photographs from 1950s and 1970s show that the front of the glacier has remained in the same place for decades. But, it has shown a retreat of about 7.2 kms during 2002-2005 and accelerated from 20 m/day to 32 m/day (Howat, 2005). Apart from that, Jakobshavns Isbrae in west Greenland, a major outlet glacier of the Greenland Ice Sheet, is generally considered the fastest moving glacier in the world. It had been moving continuously at the speed of over 24 m/day with a stable terminus since at least 1950. In 2002, the 12 km long floating terminus entered a phase of rapid retreat. The ice front started to break up and the floating terminus disintegrated. The glacier accelerated to over 30 m/day (Truffer, 2005).
AFRICA

With almost the entire continent of Africa located in the temperate zone, the few places where glaciers do exist are restricted to two isolated peaks and the Ruwenzori Range. A report from March, 2005 indicated that there is almost no remains of glacial ice on the mountain. Interestingly, it is the first time that much of the surface of the summit has been observable in the last 11,000 years (Guardian, 2005; Peter, 2006).

Observers believe that there will be no more glacial ice on the summit of Kilimanjaro by the years 2015 to 2025. Mount Kenya which lies at 17,057 feet (5,199 m) is the second tallest mountain on the continent and has up to a dozen small glaciers has shown a loss of area at least 45% since the middle part of the 20th century (Thompson et al., 2002).

ASIA

A WWF report concluded that 67% of all Himalayan glaciers are retreating. Out of 612 glaciers in China between 1950 and 1970, 53% were retreating (WWF, 2001). After 1990, 95% of these glaciers were estimated to be retreating, indicating that retreat of these glaciers was becoming more widespread (Guring et al., 2005). Glaciers in the Mount Everest region of the Himalayas are all in a state of retreat. The Khumbu Glacier, which is one of the main routes to the base of Mount Everest, has retreated 5 km (3.1 miles) since 1953. The Rongbuk Glacier, draining the north side of Mount Everest into Tibet, has been retreating 20 m (65 ft) per year. On the other hand, glaciers in the Ak-shirak Range in Kyrgyzstan experienced a slight loss between 1943 and 1977 and an accelerated loss of 20% of their remaining mass between 1977 and 2001 (Khromova et al, 2003). The studies in the Tien Shan mountains asserts that the northern portions of the mountain range have been losing nearly 2 km$^3$ of ice per year between 1955 and 2000. The University of Oxford study also reported that an average of 1.28% of the volume of these glaciers had been lost per year between 1974 and 1990 (Kirby, 2003). Moreover, to the south of the Tien Shan, the Pamirs mountain range located primarily in Tajikistan has many thousands of glaciers, all of which are in a general state of retreat. During the 20th century, the glaciers of Tajikistan lost about 20 km$^3$ of ice. The 70 km long Fedchenko Glacier, which is the largest in Tajikistan and the largest non-polar glacier on Earth, lost about 1 km or 1.4% of its length and 2 km$^3$ (0.5 mile$^3$) of its mass, showing a reduction of
11 km$^3$ of the glaciated area during the 20th century. Similarly, the neighboring Skogatch Glacier lost 8% of its total mass between 1969 and 1986. The country of Tajikistan and neighbouring countries of the Pamir Range are highly dependent upon glacial runoff to ensure river flow during droughts and the dry seasons experienced every year (Novikov, 2002).
STATUS OF GLACIER FLUCTUATION IN THE INDIAN HIMALAYA

Western Himalaya, India

Glaciers in the Himalayas are retreating at an average rate of 15m per year, consistent with the rapid warming recorded at Himalayan climate stations since the 1970s. Winter stream flow for the Baspa glacier basin has increased 75% since 1966 and local winter temperatures have warmed, suggesting increased glacier melting in winter.

Central Himalaya, India

Since the mid 1970s the average air temperature measured at 49 stations has risen by 1°C, with high elevation sites warming the most. This is twice as fast as the 0.6°C average warming for the mid latitudinal Northern Hemisphere (20 to 40°N) over the same time period, and illustrates the high sensitivity of mountain regions to climate change (Shrestha et al., 1999). Glaciers are retreating at a record pace. The Dokriani Bamak retreated 20.1 m in 1998 despite a severe winter. The Gangotri glacier is retreating 29.9 m per year. At this rate the scientists predict the loss of all central and eastern Himalayan glaciers by 2035.

Eastern Himalaya

The Khumbu glacier, popular climbing route to the summit of Mt. Everest, has retreated over 5 kms since 1953. The Himalayan region overall has warmed by about 1°C since the 1970s (Shrestha et al., 1999). As Himalayan glaciers melt, glacial lakes are swelling and in danger of catastrophic flooding. Average glacial retreat in Bhutan is 30-40 m per year. Temperature in the High Himalayas has risen by 1°C since the mid 1970s (ICIMOD, 2002).

In the whole of the Himalayan Range, there are 18,065 glaciers with a total area of 34,659.62 km² and a total ice volume of 3,734,4796 km³ (Qin Dahe, 1999). This includes 6,475 glaciers with a total area of 8,412 km², and a total ice volume of 709 km³ in China. From west to east the Himalayas can be divided into three segments according to its topographic features: the Western Himalayas, the
Central Himalayas and the Eastern Himalayas. The glacier resources for each segment are mentioned in the table 2.1 below.

**Table 2.1: Glacier Resources in the Himalayas**

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of Glaciers</th>
<th>Area/ km²</th>
<th>Ice Volume/ km³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Himalayas</td>
<td>5,648</td>
<td>10,284.75</td>
<td>980.7714</td>
</tr>
<tr>
<td>Central Himalayas</td>
<td>9,449</td>
<td>20,214.54</td>
<td>2,338.7627</td>
</tr>
<tr>
<td>Eastern Himalayas</td>
<td>2,968</td>
<td>4,160.33</td>
<td>414.9455</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18,065</strong></td>
<td><strong>34,659.62</strong></td>
<td><strong>3,734.4796</strong></td>
</tr>
</tbody>
</table>

*(after Dahe Qin et al. 1999)*
REMOTE SENSING BASED STUDIES IN THE FIELD OF GLACIOLOGY: A REVIEW ON THE WORLDWIDE STUDIES CONDUCTED

The remoteness and inaccessible locations of the glaciers and snowfields coupled with adverse environmental conditions makes the glaciological studies and collection of database extremely difficult and hazardous. The availability of satellite Remote Sensing imageries for such areas is of immense value for identifying various features of glaciers and snowfields. The development of Remote Sensing techniques (active and passive systems) has played a major role in obtaining relevant informations.

Remote Sensing data provides synoptic, multi-spectral and repetitive coverage, which is being used for facilitation of natural resources and evaluation of terrain. Satellite imagery permits the observer to perceive the relation of objects and their surroundings. Interpretation of the imagery can be broadly explained as the prediction of what cannot be seen. It is a logical process to detect, identify, measure and evaluate significance of environmental and cultural objects, patterns and spatial relationships (Reeves, 1975). It is an act of examining satellite images of objects for identifying the objects and deducing their significance. The identification is a result of combined deductive and inductive reasoning, based on principles of cause and effect. On the other hand, interpretation may be directed towards understanding of geomorphic or geologic significance or history of broad area.

Satellite Remote Sensing in Glaciology has been inducted to show surveying as early as 1960, when the initial picture taken by first weather satellite TIROS-1 was used to delineate snow cover in Eastern Canada. Since then a number of orbiting and geostationary satellites with improved spectral, spatial and temporal resolutions have been put into orbit and data sensed by them were used for weather monitoring and earth resources studies like ice and snow mapping. In addition, satellites with better radiometric resolutions such as NOAA have been successfully used for ice and snow mapping. Informations generated from these observations have helped in snow studies undertaken all over the world. The potential for operational satellite based mapping has been enhanced by the development of higher temporal frequency satellites and sensors.
The substantial role that satellite observation can play in glaciology has been persuasively demonstrated in the literatures during the past two decades. Airborne and spaceborne Remote Sensing has a long history of being used for delineation of glacial facies and for determination of the physical properties of a snowpack. Early work by Ostrem (1975) demonstrated usefulness of Remote Sensing to glacier mass balance studies through the ability of Landsat Multispectral Sensor (MSS) data to delineate the transient firnline on Norwegian glaciers. The spectral albedo of snow in the visible and near infra-red (VNIR) and the shortwave (SWIR) portions of the electromagnetic spectrum is controlled primarily by grain size (e.g. Wiscombe and Warren, 1981; Dozier et al., 1981) as well as the presence of impurities. Recent works in the VNIR and SWIR portions of the spectra have continued using improved sensors for a variety of snow cover and glacier studies. For example, Dozier (1989) used Landsat Thematic Mapper (TM) for snow cover classification in the Sierra Nevada. Williams et al. (1991) used TM for delineation of glacier facies on the Broarjskull outlet glacier in Iceland. On larger spatial scales images produced by the Advanced High Resolution Radiometer (AVHRR) has been used successfully for snow cover mapping (Rango, 1976). Remote Sensing has also been used to determine the physical properties of snowpacks including ( grain size and liquid water content) using both high resolution SWIR data (Nolin and Dozier, 1993) and radar data (Shi et al., 1993). In the microwave regions of the spectrum, radar backscatter is a function of both the dielectric properties (mainly a function of the liquid water content) and surface roughness. Synthetic aperture radar (SAR) has recently demonstrated the ability to delineate glacier facies in Greenland (Fahnstock et al., 1993). The most exciting new development has been the application of SAR interferometry to glacier motion (Goldstein et al., 1993) providing new information regarding ice flow dynamics (Rignot et al., 1995).
GLOBAL LAND ICE MEASUREMENT FROM SPACE (GLIMS)

A Japanese instrument, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was launched by NASA aboard Terra on Dec. 18, 1999 and is delivering an equivalent flood of multi-spectral stereo images of glaciers. The images recovered are of high quality. Now, ASTER with a pixel resolution of 15 m is also available.

The Global Land Ice Measurement from Space (GLIMS) project is a cooperative effort of over sixty institutions world-wide with the goal of inventorying a majority of the world's estimated 1,60,000 glaciers. Each institution, called a Regional Center (RC) oversees the analysis of satellite imagery for a particular region containing glacier ice. Data received by the GLIMS team at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado are ingested into a spatially-enabled database (PostGIS) and made available via a website featuring an interactive map, and a Web-Mapping Service (WMS) which serves as an Open Geospatial Consortium (OGC)-compliant web interface facilitating GLIMS glacier data available to other data servers (Raup et al., 2007). The data can be accessed by browsing the custom maps and various queries results can be downloaded in GIS compatible formats. Map layers include glacier outlines, footprints of ASTER satellite optical images acquired over glaciers and Regional Center information.

As a part of the operational plan, GLIMS targets consist of all permanent land ice except the 'uniform' interiors of Antarctica and Greenland. A preliminary global set of several hundred observation data acquisition requests (DARs), in the form of polygonal areas, has been submitted to the ASTER mission planning group. These DARs specify nominal seasons for minimal snow cover, nominal gain settings based upon season and latitude, and include several imaging attempts to deal with the likelihood of cloud cover. Coordination of GLIMS is taking place at the U.S. Geological Survey (USGS) in Flagstaff Arizona.
APPLICATIONS OF REMOTE SENSING IN GLACIOLOGY:

Snow and Glacial Mapping

Remote Sensing offers a new and valuable tool for obtaining snow data for predicting snowmelt runoff. Historically, snow data can be obtained manually by means of snow courses, which are extremely labour intensive, expensive and potentially dangerous. Even when available, snow course data represent only point and, at best, can only be used as an index of available snow water content. Recent use of telemetering of snow pillow and storage gauge measurements of precipitation has reduced the need for some fieldwork but has not overcome the point measurement of snow. From a Remote Sensing perspective, ice and snow cover is one of the most readily identifiable measures of water resources from aerial photography and satellite imageries.

Mapping of glaciated area through multi-temporal images has been successfully implemented in accurately determining fresh water reserves, as well as providing an indicator of climate change (Silverio et al., 2005). The first glacier inventory in Peru was prepared based on visual interpretation of aerial photographs. Later on, remote sensing methods have been extensively employed for monitoring of changes in glacier area. Using Normalized Difference Snow Index (NDSI) computations as a parameter on Landsat Thematic Mapper (TM) satellite imagery, an estimate of the glacierised area in Cordillera Blanca (Peru) was carried out for 1987 (643±63 km$^2$) and 1996 (600 ±61 km$^2$) as compared to an estimate of 721 km$^2$ in 1970. The study concludes that the glacier area has retreated in this massif by more than 15% in 25 years (Silverio et al., 2005).
Review of Literature

Retreat and Deglaciation

The retreat of the Mt. Jaya glaciers in Irian Jaya, Indonesia has been studied using IKONOS images (2000-02). The total area of the Mt. Jaya ice masses was 2.326 km² and 2.152 km² in 2000 and 2002 respectively. Ice loss of 0.174 km² or 7.5% has been reported in the period 2000-2002. A comparison of glacier changes with past literature indicates these glaciers have continued their observed retreat that began in the mid-19th century. Between 2000 and 2002 the E. Northwall Firn, the Carstensz, and the W. Northwall Firn lost 4.5%, 6.8%, and 19.4% of their areas as that in 2000. Sometimes between 1994 and 2000, the Meren Glacier has been assumed to disappeared (Kincaid et al., 2004).

An evaluation of the fusion of DEMs from the ASTER and SRTM has been implemented to derive glacier surface velocities through image matching. The glacier tongues north of the Himalayan main ridge, which enter the Tibet plateau, shows maximum surface velocities in the order of 100–200 m/year (Kaab et al., 2005). In contrast, the ice within the glacier tongues south of the main ridge flows with a few tens of meters per year. These findings have a number of implications, among others for glacier dynamics, glacier response to climate change, glacier lake development, or glacial erosion. The study indicates that remote sensing can provide new insights into the magnitude of selected surface processes and feedback mechanisms that govern mountain geodynamics.

Historical surveys and recent satellite imageries have been used to map and assess glacier recession in the eastern Pamir over the last three decades (Khromova et al., 2003). The topographic maps of 1:100000 scales published in 1943 and 1970; air photos from 1978 and 1990; satellite images (1972, 1978, 1980, and 1990 and ASTER data for 2001) have been used for the above purposes for analysis of the climatic conditions. The study indicates an accelerated trend of change in the area of 5 glaciers and terminus positions of 44 glaciers in the eastern Pamir as a continuation of glacier wastage and retreat. The glacier area has decreased by 7.8% during 1978–1990, and 11.6% in 1990–2001. This corresponds with documented changes in other mountain and subpolar regions in the Northern Hemisphere and specifically in Central Asia. Glacier changes in the eastern Pamir are a response to increasing summer
temperatures. A decrease in glacier area and retreat of glacier fronts, increased debris-covered area and the appearance of new lakes has also been encountered.

Interestingly, widespread wastage of about 278 glaciers with a total area of 2711.57 km$^2$ in the heavily glaciated west Kunlun Shan (WKS) in the northern Tibetan Plateau (TP) has been reported (Donghui et al., 2007). The glacier area decreased by 10 km$^2$ (0.4% of the total area in 1970) between 1970 and 2001. Both the south and north slopes of the WKS presented shrinkage during 1970–2001. On the north slope a slight enlargement of ice extent during 1970–90 was followed by a reduction of 0.2% during 1990–2001 whereas the south slope of the glacier area decreased by 1.2% during 1970–91, with a small increment of 0.6%.

Another study comprising the inventory database of the European Alps and the Southern Alps of New Zealand, reflected that the region comprised of a total of 5154 and 3132 perennial surface ice bodies, covering 2909 km$^2$ and 1139 km$^2$ respectively in the mid-1970s. The ice bodies having an area larger than 0.2 km$^2$ constitute only 35% for the European Alps and 22% for the New Zealand Alps, covering 88% and 86% of the total surface area respectively. A parameterisation scheme was used taking into account four variables (surface area, total length, and maximum and minimum altitude) and comparing the mid-1970s and the ‘1850 extent’. The calculated area change since the ‘1850 extent’ is –49% for the New Zealand Alps and –35% for the European Alps, with a corresponding volume loss of –61% and –48%, respectively (Hoelzle et al., 2007). These volumes correspond to a sea-level rise equivalent to 0.35 mm for the European Alps and about 0.18 mm for the New Zealand Alps. Although of limited significance for sea-level rise, these glaciers represent their vulnerability to climate effects of glaciers in mountain areas with predominantly small glaciers (Barnett et al., 2005). It has been inferred that smaller glaciers would be deglaciated within a few decades, whereas larger glaciers with high elevation ranges will persist somewhat longer before complete deglaciation. Small glaciers, especially in densely populated areas like the European Alps, have a strong impact on natural hazards, energy production, irrigations and/or tourism (Haeberli and Burn, 2002; Kaab et al., 2005 a, b).

A study on the change detection in Cordillera Blanca glaciers (a subset of the study area—the Huandoy–Artesonraju Massif) by comparing data in the GLIMS Glacier

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A study on the change detection in Cordillera Blanca glaciers (a subset of the study area—the Huandoy–Artesonraju Massif) by comparing data in the GLIMS Glacier

\[ E 51.87 S \]
Database to historical data show marked changes in that system over the last 30 years. But there still exists a strong necessity to establish a clear protocol for glacier monitoring from remote-sensing data (Raup et al., 2007).

A preliminary analysis results on the Cordillera Blanca glaciers from the 2003 SPOT images yielded 74 main glaciers with an area of 73 km². The present study has been compared with two previous studies (1962A and 1962G). The number of glaciers has increased due to a few glaciers breaking up into more than one piece as they shrink. Georges (2004) found the area estimate of 1970A (Ames et al., 1989) to be too high, and he corrected the number for his study. For the Huandoy-Artesonraju group only, these preliminary results indicate a reduction in glacier area of 20% in 41 years compared with 1962R, or 11% compared with 1962G (Georges, 2004), showing that glacier termini has risen by approximately 60 m between 1962 and 2003 (Raup et al., 2007). This study, however, has considered the differences in the basic approach in estimating the change detection as compared to the previous studies done. It tries to reflect that the difference in observation might be due to the exclusion of snow fields above the glacier accumulation zones which was otherwise included in the previous studies.

Another observed study on the glacier changes in the Alps through satellite images has revealed that mean glacier area loss per decade from 1985 to 1998/99 has accelerated by a factor of seven compared to the period 1850–1973 (e et al., 2007). As reported in the above study, the glaciers in the Switzerland Alps have lost about 18% of their area in the period 1985 to 1998/99, corresponding to an average relative area loss of 14% per decade. The ice loss in the period 1850 and 1973 was 2.2% and therefore, the comparative study reflects a seven fold loss. Moreover, a higher relative loss of area towards smaller glaciers indicates a very specific behaviour of individual glaciers that are smaller than 1 km². Such small glaciers covered about 18% of the total area in 1973 and account for about 44% of the total area loss since 1973. Another important aspect of this study has revealed that downwasting (i.e. stationary thinning) has become a major source of glacier mass loss. This observation has been confirmed by in-situ mass balance measurements and these changes accelerate further glacier disintegration once they are initiated. As such, it is unlikely that the recent trend of glacier wastage will stop (or reverse) in the near future.
A recent study has been conducted over South-East Alaska (USA) and northern British Columbia (Canada) for DEM generation using the SPOT5-HRS (High Resolution Stereoscopic) images acquired in May, 2004. The DEM is evaluated through comparison with shuttle radar topographic mission (SRTM) DEM and ICESAT data, on and around the glaciers. The results acquired show a horizontal shift of 50 m between the HRS and SRTM DEMs (Berthier et al., 2008). At the same time it is attributed to errors in the SRTM DEM. Over ice-free areas, HRS elevations are 7 m higher than those of SRTM, with a standard deviation of ±25m for the difference between the two DEMs. The 7m difference is partly attributed to the differential penetration of the electromagnetic waves. Another mapping of the topographic changes (in 4 years time interval) induced by a surge of one tributary of Ferris Glacier leads to an outcome reflecting maximum surface lowering of 42 (±10) m and rising of 77 (±10) m. Thinning rates up to 10 (±2.5) m/yr are observed at low altitudes and confirm the ongoing wastage of glaciers in South-East Alaska.

The majority of glaciers in central Chile have receded in recent decades, from more than 50 m to only a few meters per year, mainly in response to an increase in the 0°C isotherm altitude. In the Aconcagua river basin, an earlier inventory using 1955 aerial photographs yielded a total surface area of 151 km² as compared with 121 km² of ice in 2003, implying a reduction in glacier area of 20% (0.63 km² per year) over the 48 years (Bown et al., 2008). A focus on Glaciar Juncal Norte, one of the largest glaciers in the basin, has exhibited a smaller reduction (14%) between 1955 and 2006, and the resulting elevation changes over this smaller period are not significant. The above reduction rates are lower than in other glaciers of central Chile and Argentina. This trend emphasizes water runoff availability in a river where most of the water in the dry summers is generated by glaciers and snowpack, and where most of the superficial water rights are already allocated.

**Inventory Based Studies**

The USGS-led GLIMS project (Global Land Ice Measurements from Space) compiled a global inventory of land ice masses, mainly using data from the radiometers ASTER and ETM+ on board the satellites Terra and Landsat 7, respectively for the first time. A pilot study was carried out to facilitate the compilation of a new Swiss Glacier Inventory for the year 2000 (SGI 2000) from satellite imagery. The study included an
evaluation of different methods for glacier mapping using Landsat TM data. These evaluation criteria were

(1) Manual delineation of the glacier outline,
(2) Segmentation of ratio images from several channel combinations and
(3) Various supervised and unsupervised classification techniques.

The detailed study revealed that a ratio image from TM channels 4 and 5 with the raw digital numbers yield the best glacier mask, with special advantages for glacier areas located in cast shadow (Paul et al., 2003). The TM-derived glacier outlines were compared with manually derived outlines from a SPOT Pan Image and aerial photography. The outlines are within the accuracy of the georectification and the area precision is within 5 percent for debris-free ice. Moreover, methods for an automatic extraction of individual glaciers from the classified satellite map were developed. Besides the specific results for the Swiss glaciers, compilation of the SGI 2000 revealed valuable conclusions for worldwide glacier inventorying. The fusion of satellite data and GIS technology is indeed capable for (repeated) glacier inventorying of large and remote regions by comparably low expenditure (Paul et al., 2002).

Based on the new Swiss glacier inventory (SGI 2000) through satellite imageries, a set of about 300 debris-free glaciers of the Bernese and Valais Alps of area less than 10 km² were computed. These glaciers lost about 21% of area from 1973 to 1998, in comparison to 80% during 1850–1973, both with respect to the 1973 area. In order to track the latest trend in more detail, an intermediate glacier condition has been compiled from satellite imagery of 1985. This analysis gave an increasing speed of area loss (19%) for 1985–1998 (Kaab et al., 2002). It has been observed that the area loss in the period 1973–1985 is markedly smaller than the 1985–1998 loss. Apart from that, the 1973–1985 decadal loss is smaller than the average decadal 1850–1973 area loss, except for the glaciers less than 0.5 km². This exception is justified because of the especially high solid precipitation in the late 1970's. The total sample area of 205 km² in 1973 was reduced by 21% between 1973–1998 (2% for 1973–1985; 19% for 1985–1998). Glaciers less than 1 km² contributed over 55% to the total area loss during 1973–1998 of the sample. This drastic area loss manifests ongoing warming trends even more clearly than reactions of large glaciers but with a higher temporal and spatial variability (Kaab et al., 2002).
Another inventory based work has been carried out in three small icefields comprising of 33 glacier outlets, in addition to 12 small separate glaciers (57 km$^2$) at Isla Riesco, Chilean Patagonia (Casassa et al., 2002). The work has been based on stereoscopic interpretation of aerial photographs of March and December, 1984 and 1:1,00,000 topographic maps. The elevation range of the location glaciers has been observed as 1183 m and 100 m. In this study, Landsat (TM) image has been rectified and analyzed using a supervised classification to estimate snow- and glacier-covered surfaces. Glacier-area data derived from satellite-image analyses have been extrapolated to estimate a glacier area of 215±40 km$^2$ for all of Isla Riesco. Various trimlines and moraines beyond the present position of the glaciers have been interpreted and thereby indicate towards a result of regional warming and precipitation decrease observed during the last century.

In Austria, the first complete glacier inventory (Patzelt, 1980) was compiled from aerial photography taken in 1969 including original aerial photographs, glacier maps (in the scale of 1:10,000), the distribution of glaciated area in different elevation zones and information about former glacier stands. As reported, a total of 918 glaciers existed in Austria in 1969, with a total area of 540±10 km$^2$ (Patzelt, 1980). An attempt to update the existing inventory and to document the occurred changes as a reaction between climate and glacier has been attempted (Lambrecht; 2005, 2007). The present and the earlier work have been re-evaluated by comparison of glacier reactions over a period of 29 years (Lambrecht, 2007). An overall reduction of 17% is observed for almost all Austrian glaciers between 1969 and 1998 and the glacier volume change calculated from the DEMs has been estimated to be about 5 km$^3$ or almost equivalent to 22% in 1969.

A detection of the influences of global warming in high mountain regions has been interpreted by the observation in recent glacier variations in Mongolia using topographical maps, aerial photographs and satellite images (Corona and Landsat). Comprising of an area of about 1400 km, four regions were selected to form the study area: Tavan Bogd region, Turgen massif, Kharkhiraa massif and Tsambagarav massif. The study revealed that the glaciers in these regions lost 10.2%, 19.3%, 28.0% and 28.8% of their area during the period from the 1940s to 2000 or from 1968 to 2000, respectively (Kadota et al., 2007). The glaciers in the Tavan Bogd, Kharkhiraa and
Turgen regions were found to remain almost stationary since 1987/88, while those in Tsambagarav massif showed no significant change in area since 1963. Shrinkage of the glaciers occurred between 1945/68 and 1987/88 in the former regions and between 1948 and 1963 in the latter. Mongolian glaciers seem to behave differently from other glaciers which have been experiencing steady shrinkage recently.
Mass Balance through Remote Sensing

The use of remote sensing methods can be a very efficient tool for inferring the mass balance of a glacier as a proxy estimate. An approach put forward by (Dedieu et al., 2003) takes into account an indirect methodology to determine the distribution of mass balance at high spatial resolution using remote sensing and ground stakes measurements. Three outlet glaciers in the French Alps were chosen to evaluate accuracy of the computed mass balance using a recent time series of images from optical and SAR data. The methodology incorporates the application of snowline determination as a proxy of the equilibrium line altitude (ELA). The key of the transfer is the activity coefficient (db/dz) for the annual mass balance calculation. Comparison between measured and computed mass balance provide a good correspondence ($R^2=0.90$) and allows extending the method on large-scale areas (Dedieu et al., 2003). The limitations are cloudiness for optical data and high slope distortion on SAR images.

A comprehensive review of results obtained from a number of studies of South American glaciers, focusing specifically on the Patagonian Icefields and new results from Glacier Chico, Southern Patagonian Icefield, (SPI), Chile (Bamber & Rivera, 2007) combines a variety of different satellite and in-situ data. Thereby, the mass balance using a geodetic or elevation change approach over about a 25 year period has been estimated.

A detailed study including a combination of aerial photogrammetry with SRTM-derived elevations and in-situ GPS measurements was conducted (Bamber & Rivera, 2007). The results indicated a thinning rate of $-5.4\pm0.55 \text{ ma}^{-1}$ at the glacier front over this time period and $-1.9\pm0.14 \text{ ma}^{-1}$ between 1998 and 2001 for the accumulation area. This latter thinning rate is three times higher than the snow accumulation rate estimated for that part of the glacier (Rivera et al., 2005). The trends reflect the effect of climatic warming reduced precipitation and ice dynamics on the system.
Last Glacial Maxima

The cyclic glacial and inter-glacial periods (Tangri et al., 2004) suggest at least 17 major glacial advances (glaciations) in the last 1.6 million years alone (Goudie, 1983). This cyclical activity, which recurs at intervals of approximately 100,000 years, is generally accepted to be caused by gradual changes in the earth's rotation, tilt and orbit around the sun, which affects the amount of solar radiation the earth receives (Milankovitch, 1941; Bradley, 1985).

The High Plain of Bogota in the Andes of Colombia provides an exceptionally detailed record of glaciation where a two-stage Last Glacial Maximum (LGM) is noted (Mark et al., 2005). The older stage presents an opportunity to reconstruct individual valley glaciers and explore spatial patterns. The reconstruction of 23 palaeo glacier surfaces could be facilitated by well-mapped geomorphic features on topographic base maps. Glacier extent varies across the region, with lower altitudes reached farther to the east. Equilibrium line altitudes (ELAs) have been reconstructed using the area-altitude balance ratio (AABR) method, with BRs in three groups reflecting the W–E gradient in glacier extent and selected by minimizing variation from group means. Average LGM ELA for all palaeo glaciers is 3488 m with a standard deviation of 182 m. The average lowering in ELA from LGM to modern of ca. 1300 m is best explained by a considerable drop in temperature. Significant intra-regional variance in LGM ELA can be ascribed to topography and its influence on precipitation and/or glacier form, with lower headwall elevations being correlated to larger accumulation areas (Mark et al., 2005).

In case of lack of other forms of evidence, past fluctuations of tropical and subtropical glaciers provide important palaeo-climate proxies. Because of the diversity of methods and approaches employed by different research groups, the equilibrium-line altitude (ELA) estimates for tropical and sub-tropical glaciers at the LGM vary widely. Due to these differences in the reported estimates the need for standardised methods is greatly emphasized. The distinctive character of tropical and sub-tropical glaciers, however, means that standard methods for reconstructing former glacier limits, ELAs, and palaeoclimate need to be adapted for local conditions (Benn et al., 2005). A very precise methodology needs to be considered for a careful interpretation of the choice of accumulation area ratios (AARs), balance ratios (BRs) and terminus-
to-head ratios (THARs) etc. because of the fact that such indices are influenced by climatic regime, debris cover and other factors. ELA reconstructions should employ multiple methods, and should be cross-checked and fully reported, to allow assessment of the accuracy of ELA estimates.

The Himalaya has played a key role on global climate in the onset of the Quaternary glaciation. It has been suggested that the extent of glaciation in the northwestern and Trans-Himalaya was sensitive to northward penetration of monsoon-driven moisture (Pant et al., 2006). Thus, the moraine successions in the glaciated valleys along the entire length of the Trans-Himalaya might have responded to changes in moisture and temperature conditions in the past. Therefore, it might be contemplated that a detailed history of the Last Glacial Stage (LGS) would provide a good framework for greater understanding and modelling of climate fluctuation during the Pleistocene. In glacial geomorphology, past temperature and precipitation can be estimated using the equilibrium line altitude (ELA) of glaciers. In the field, ELA is associated with the emergence of lateral moraines.

Another study comprising the inventory database of the European Alps and the Southern Alps of New Zealand estimates the area loss since the ‘1850 extent’ to be 49% for the New Zealand Alps and 35% for the European Alps, with a corresponding volume loss of 61% and 48%, respectively (Hoelzle et al., 2007). The reconstruction of the mean specific mass balances since the ‘1850 extent’ is valuable because it is directly comparable to present day measurements and therefore, to current trends. The precise year of the maximum glacier extension in the Little Ice Age (LIA) period is often difficult to determine (Grove, 1988). In the European Alps, the maximum glacier extension differs considerably from glacier to glacier. Studies at Franz Joseph glacier (Anderson, 2003) have shown that maximum LIA glacier extension was at the end of the 18th century, but that there was only minor glacier retreat to the end of the 19th century. Therefore, here the time of LIA maximum is arbitrarily set at 1850 AD although there are numerous cases where different dates for the maximum extents have been found (Hoelzle et al., 2007).

In another study, optically stimulated luminescence (OSL) dating was applied to glacial sediments and adjacent loess from moraines in the Terskey Ala-Too and the At-Bashy Ranges in the inner Tien Shan, Kyrgyz Republic (Kyrgyzstan). Two large
glacier expansions during the Last Glacial were observed in the two study areas. Teskey Stage I and II moraines were dated to marine isotope stage (MIS) 4–early-MIS 3 and MIS 2, and At-Bashy Stage II in the At-Bashy Range dated to late-MIS 3–MIS 2. The timing of the two expansions during the Last Glacial coincided with global cold periods and with advances of the major Northern Hemisphere ice sheets. However, the fact that the greater expansion occurred in MIS 4–early-MIS 3 in the Teskey Ala-Too Range, suggests that climate during MIS 4–early-MIS 3 was more humid than during MIS 2. It is possible that the strengthened Siberian High during MIS 2 restricted the impact of the westerlies and this reduced precipitation in the study area (Narama et al., 2008).
OTHER APPLICATIONS

DEM in Glaciological Applications

An evaluation of Digital Elevation Model data and its suitability derivations from SRTM and ASTER in the Nevado Coropuna (6426 m) of Southern Peru was attempted. The glacier area was estimated to be 60.8 km$^2$ in 2000, based on analysis of the ASTER L1B scene as compared with the 82.6 km$^2$ in 1962, based on aerial photography (Adina et al., 2007). Of the various interpolation techniques examined, the TOPOGRID algorithm was found to be superior to other techniques, and yielded a DEM with a vertical accuracy of ±14.7 m. The 1955 DEM was compared to the SRTM DEM (2000) and ASTER DEM (2001) on a cell-by-cell basis. Cell-by-cell comparison of SRTM and ASTER-derived elevations with topographic data showed ablation at the toes of the glaciers (−25 m to −75 m surface lowering) and an apparent thickening at the summits. The mean altitude difference on glaciated area (SRTM minus topographic DEM) was −5 m, pointing towards a lowering of the glacier surface during the period 1955–2000. Spurious values on the glacier surface in the ASTER DEM affected the analysis and thus prevented us from quantifying the glacier changes based on the ASTER data.

DEBRIS FLOW

Debris flows from glacier forefields, triggered by heavy rain or glacial outbursts, or damming of streams by ice avalanches are hazardous in glacier valleys. Glacier related debris flows are, in part, a consequence of general glacier retreat and the corresponding exposure of large quantities of unconsolidated, non-vegetated, and sometimes icecored glacial sediments. A significant study documenting the glacier related debris flows at 17 sites in the Italian, French, and Swiss Alps, with a focus on the Italian northwest sector describes the glacier and the instability (Chiarle et al., 2007). Three types of events have been recognized, based on antecedent meteorological conditions. Type 1 (9 documented debris flows) is triggered by intense and prolonged rainfall, causing water saturation of sediments and consequent failure of large sediment volumes (up to 80×10$^5$ m$^3$). Type 2 (2 debris flows) is triggered by short rainstorms which may destabilize the glacier drainage system, with debris flow volumes up to $10^5$ m$^3$. Type 3 (6 debris flows) occurs during dry weather by glacial
lake outbursts or ground/buried ice melting, with debris flow volumes up to $15 \times 10^5$ m$^3$. A data base of historic cases is needed in order to advance process understanding and modelling, and thus improve hazard assessment.

**Glacier Facies Mapping**

Distinct zones and facies are visible in multi temporal Synthetic Aperture Radar (SAR) data, including the dry snow facies, the combined percolation and wet snow facies, transient melt areas and moraines (Partington, 1998). In general SAR senses the dry snow facies as a very dark region, as the grain size of fresh snow is small compared to the wavelength of the SAR system. In the dry snow facies melting will not be a factor in the backscattering coefficient ($\sigma^2$). Any variation in the backscattering coefficient may be expected to derive largely from differences in grain size. It has been observed through simple mechanical derivation that the backscattering coefficient would range from $-20$ dB for a grain mono-distribution with mean radius of 0.25 mm to $-2$ dB for mean grain radius of 1 mm (Partington, 1998). In general, the backscattering coefficient observed for dry snow facies in C band appears to be not more than $-8$ dB.

In percolation facies, the surface snow is occasionally subjected to melt which results in the percolation and refreezing of melt water in the form of pipes and lenses. The presence of ice pipes and lenses whose dimensions are comparable to wavelength of SAR, increase backscattering, more than commonly found in the dry snow facies. In high altitudes, percolation facies show high backscattering in all seasons. In middle zone, it appears dark only in late summer images due to presence of melting ice while in lower zone it appears dark in late and early summer images.

In wet snow facies, the grain sizes are larger since the snow mass reaches melting point as a result of latent heat released by extensive refreezing of melt water. Thus recrystallisation is the norm rather than exception. We can expect the darkest areas in a SAR image of glacier to represent wet snow facies, which are damp.

Superimposed ice zone is a region with high density refrozen melts from the previous years accumulation. In a heavy ablation year, the equilibrium line will be between the superimposed ice and ice facies. The superimposed ice facies is potentially
distinguishable in SAR data as a result of its greater degree of smoothness relative to its ice facies.

To infer snow wetness from SAR measurement, an empirical relation between radiation backscattering and snow wetness has to be derived. L band normal polarisation of SAR show that the backscattering coefficient decreases with increase in snow depth and snow wetness for a given snow density and snow roughness. The variation in grain size does not seem to affect this relation. In case of dry snow, there is very little change in backscattering coefficient with change in snow depth. Using this relation, it may be possible to derive snow wetness from backscattering coefficient if we know the snow depth.

However it is not credible to derive a simple empirical relation between snow wetness and radar backscattering, as previous investigations have shown both negative and positive relationships between backscattering coefficient and snow wetness (Shi and Dozier, 1993). This relationship is complicated, as surface roughness affects this relationship.

Measuring Glacial Velocity

Glacier and ground ice plays a crucial role in most high mountain systems. Due to their close proximity to melting conditions under terrestrial conditions, the ice related transports are especially sensitive to climate change. Therefore, monitoring high mountain terrain dynamics serves as an important contribution to climate monitoring and is necessary to understand mass transport system, to detect related environmental variability, and to assess natural hazards.

Due to remoteness of high mountains and due to the spatial extension of most mass relocation processes, Remote Sensing is a prior tool for monitoring high mountain terrain dynamics. Remote Sensing and Digital photogrammetric methods are able to provide data on terrain geometry, terrain cover and 3-dimensional terrain displacements.

Concerning optical satellite data, horizontal displacements on glaciers have been measured mostly from repeated Landsat or SPOT data using different correlation
techniques (e.g. Lucchitta and Ferguson, 1986; Scambos et al., 1992; Frezzotti et al., 1988; Seko et al., 1999; Nakawo et al., 1999; Priymbroek et al., 2000).

There are 2 primary techniques for determining movement in glaciers, using satellites. They are Sequential Satellite Imaging (SSI) and SAR interferometry also called InSAR. A third measurement from Satellite Radar Altimetry does not measure movement per se, but allows determination of flow direction.

Glacier flow monitoring is possible through repeat pass SAR Interferometry. ERS -1/2 images over North East Greenland ice sheet margins have been used to detect rate of flow of glaciers. Goldstein et al. (1993) measured ice stream velocity in Antarctica using ERS 1 SAR images taken six days apart. It was for the first time, ice stream velocity had been measured directly from space without ground control points.

Moraine Dammed Glacial Lake Investigations

The sudden catastrophic discharge of large volumes of water is characteristic of many steep mountain regions, and especially of glacierised mountains. Such discharges are usually the result of the collapse of unstable natural dams that pond ephemeral lake. These lakes are formed when stream channels are blocked by rockfall, landslide, debrisflow, or ice and snow avalanches. Another cause is the outburst of lakes that are dammed by glacier ice or by glacier moraines. These sudden discharges are referred to as jokulhlaup (Icelandic=glacier leap), named from their frequent occurrence and the early investigation of them in Iceland. Geomorphologically, such events cause major downstream changes, in the form of both aggradation and degradation, of an order of magnitude greater than the effects of normal hydrologic peak flows.

In spite of the various documentations on the development of supraglacial lakes, the relationship between glacier dynamics and lake formation is not well understood. The ERS-1 and ERS-2 Synthetic Aperture Radar (SAR) data, SPOT-5 optical imagery and historical aerial photography have been wisely used to illustrate dynamics and structure of glaciers in Tibet (China) and Nepal draining the southern side of the Himalaya (Quincey et al., 2007). The glacier velocity data study reflects virtually stagnant ice (displacements less than 5ma\(^{-1}\)) where lakes are developing on debris-covered tongues. Furthermore, elevation data from Digital Elevation Models (DEM) derived from aerial photography and SPOT-5 HRS data reveal that supraglacial lake
formation is prevalent where glacier surface gradients are less than 2° from the glacier terminus, supporting empirical observations from previous work. The resolution offered by the DEMs and SAR data allows variations in transverse glacier elevations and velocities, thus facilitating the identification of the pattern of lake development on an individual glacier. Integrating the surface gradient and velocity information into a single analysis highlights those glaciers that are particularly vulnerable to lake development over an expected decadal timescale. The wider application of these techniques, based on remote sensing data, is particularly suitable for ‘first-pass’ hazard assessments and for regions where field access is difficult due to severe terrain, political sensitivity or financial constraints. The Kyun Tso is an ancient twin lake system lying to the south of the Indus Suture Zone in NW Himalaya. An extensive mapping of the former limit of these lakes using remote sensing techniques has been approached to understand the palaeo-hydrological conditions (Philip et al., 2005) under which these water bodies developed. It is observed that the dimensions of these lakes invariably fluctuated over time due to ongoing compression in the collisional regime and climatic fluctuations that have been recorded globally. This study also provides an opportunity to evaluate the utility of high spatial resolution Indian Remote Sensing Satellite (IRS) data for geological and geomorphological studies in arid, inaccessible and arduous terrain like the northwestern Trans Himalaya.

The study of supraglacial lakes can be approached through various features and morphometry parameter (Naithani et al., 2001). The accelerated retreat, subsidence and the fast degenerating nature of Gangotri glacier has resulted in emergence of numerous, middle part of ablation zone is full of supraglacial lakes in the middle part of ablation zone.

Glacier outburst floods caused by the moraine-dammed lakes are a common phenomenon in the glaciated terrain of the world. These floods can cause extensive damage to the natural environment and human property; as it can also drain extremely rapidly and relatively small lakes causing dramatic floods (Deslonges et al., 1989). Many events of outbursts floods are reported in North America, Europe and in the Himalaya (Deslonges et al., 1989; Hewitt, 1985). In the Himalaya, outburst flood from glacial lake is reported in Manaslu region, Central Nepal and in Bhutan (Gansser, 1983).
Remote Sensing has also emerged as an important tool in identification of moraine-dammed lakes. It is also necessary to monitor moraine-dammed lakes using multi-temporal and multi spatial data in order to update the information for disaster management and hydroelectric power generation. A systematic inventory of the moraine-dammed lakes is necessary to generate an information system for Himalayan moraine dammed lakes.

GLACIAL REMOTE SENSING BASED STUDIES: A SCENARIO IN INDIAN HIMALAYAS

The Himalaya possesses all the three characteristics of glaciers viz. low, mid and high latitudes glaciers. In the extreme west the climate is purely sub-tropic to mid latitudinal climate and tropical in the east. Therefore, Himalaya provides a unique opportunity to study the mass balance and snout fluctuations of the mountain glacier, which can be modelled for the different kind of climatic regime.

It is worthy to note the investigation carried out (Kulkarni et al., 2007) estimating the 466 glaciers in Chenab, Parbati and Baspa basins from 1962. The investigation has concluded an overall reduction in glacier area from 2077 sq. km in 1962 to 1628 sq. km. However, the number of glaciers has increased due to fragmentation. In addition, the number of glaciers with higher areal extent has reduced and those with lower areal extent have increased. Small glaciars and ice fields have shown extensive deglaciation. The study accounts 127 glaciars and ice fields less than 1 km$^2$ showing retreat of 38% from 1962, possibly due to small response time. The results reflect a combination of glacial fragmentation, higher retreat of small glaciers and climate change as an influencing factor affecting the sustainability of Himalayan glaciers.

The snow-melting zone forms a site of marked physical-hydrological processes, the monitoring of which requires data on the temperature distribution. According to a recent study, temperature distribution has been monitored by repetitive multi-spectral image data sets from IRS-LISS-III for snow mapping in the Gangotri glacier (Gupta et al., 2005). It has been inferred that in the melting seasonal snow zone, the topographically corrected mean near-IR reflectance systematically decreases from
higher to lower elevation levels, and can be broadly related to the environmental
temperature distribution in a restricted range of about 0–5 °C. This method is
presumably potential to provide surrogate data for filling-in gaps in the database as
well as in applications in environmental surveillance, runoff modeling, climatic
modeling and numerous other snowfield studies.

The benchmark glacier Chhota Shigri was studied to assess the mass balance related
glaciological parameters using ASTER data and its subsequent comparison with the
published results of in-situ measurements carried out using stakes and snow pack
observations (Mishra et al, 2007). The glacier was classified into zones of snow, firn
and ice using three atmospherically corrected surface reflectance products of ASTER
of end of ablation season period (2002, 2003 and 2004). The topographic correction
was done through an ASTER DEM and the glacier delineation found effectively
through ASTER thermal band. The next approach was assessment of snowline and
AAR followed by a comparative study between in-situ net balance measurements of
years 2002-2003 and 2003-2004. A good fit between the mass balance measurements
and accessed snow line and AAR was found (Mishra et al., 2007).

The poorly sampled Himalayan glaciers has witnessed a consistent gap in the
sampling of mass balance dataset and an attempt has been made to utilize remote
sensing data in monitoring glacier elevation changes and mass balances in the
Spiti/Lahaul region (Berthier et. al., 2007). A comparison of a 2004 digital elevation
model (DEM) to the 2000 SRTM (Shuttle Radar Topographic Mission) elucidates an
overall specific mass balance of −0.7 to −0.85 m/a (water equivalent) between 1999
and 2004. This rate of ice loss is twice higher than the long-term (1977 -1999) mass
balance record for Himalaya reflecting an increase in the pace of glacier wastage. The
glaciers were classified into 3 classes and the dependence of ice loss to size was
further confirmed by subsequent values showing ice loss, the loss being higher for
glaciers larger than 30 km² (Berthier et al., 2007). The benchmark Chhota Shigri
glacier shows a good agreement between the satellite observations and the mass
This significant study and methodology clearly demonstrate the utility of future
studies to determine the possibility of similar ice losses in other parts of the
Himalaya and, in turn, allow evaluation of the contribution of this mountain range to
ongoing sea level rise.
The estimation of seasonal snow cover as a parameter is vital in assessing the availability of water in the Himalayan Rivers, forecasting and assessing avalanches and numerous other applications. A study aimed at evaluating the significance of Normalized Difference Snow Index (NDSI) technique has been conducted to monitor snow cover using an AWiFS sensor onboard RESOURCESAT-1 (Kulkarni et al., 2006). Satellite data and field investigations were carried out to assess the correct NDSI value representing snow. This technique is particularly useful for the Himalayan region as it can also be applied under mountain shadow conditions. An algorithm has been developed to provide changes in the areal extent of snow at intervals of 5 and 10 days.

Application of remote sensing data has been made to differentiate between dry and wet snows in a glacierized basin. The study on Gangotri glacier, using IRS-LISS-III multi spectral data (March–November, 2000) and the digital elevation model involves conversion of satellite sensor data into reflectance values, computation of NDSI, determination of the boundary between dry/wet snows from spectral response data, and threshold slicing of the image data. (Gupta et al., 2005). The dry snow area has been compared with non-melting area obtained from the temperature lapse rate method, and the two are found to be in close mutual correspondence (<15%). Four water-bearing zones in the glacierised basin have been observed i.e. dry snow zone, wet snow zone, exposed glacial ice and moraine covered glacial ice. Each one possesses unique hydrological characteristics and can be distinguished and mapped from satellite sensor data. The input of data on the position and extent of specifically wet snow and exposed glacial ice can be directly derived from remote sensing, thereby, improving hydrological simulation of such basins.

Interestingly, an unusual retreat of the Parbati glacier in the Parbati river basin, Kullu district, Himachal Pradesh is reported (Kulkarni et al., 2005). An interpretation of the satellite data of 1990, 1998, 2000 and 2001 reveals a retreat of 578 m between 1990 and 2001, almost 52 m per year, which was confirmed by field observations of glacier terminus in October, 2003 and also by comparing the position of glacier snout by comparing its relative position with other features in field as well as in satellite images. It has been inferred that this glacier has been retreating at a higher rate as compared to other glaciers in the Himalayas. This might be because of the fact that about 90% of the glacier is located in the altitude range lower than 5200 m, almost
equal to the average altitude of the snow line at the end of the ablation season. The specific mass balance computed using AAR method for the year 2001 is -86 cm. The amount of retreat along with maximum length was predicted as 1461 m between 2001 and 2022, more than the present rate of retreat.

A case study of moraine dammed lakes in the Sutlej and Chenab basins brings into picture the mapping of 22 lakes in the Sutlej and 31 lakes in the Chenab basin. In the Chenab basin two lakes are of very large size, the areal extent being 105 ha (toposheet 52H11) and 55 ha (52H02) respectively (Randhawa et al., 2005). The latter lake, located near the Gepang glacier was monitored by satellite data and it was found that the areal extent increased to almost double of its size (27 ha to 55 ha) during the period 1976-2001 suggesting the constant increase in the lake size, thus contemplating outburst flood. By considering the average depth, the volume of the lake water and the instantaneous discharge of 350 m$^3$/sec was estimated. This large discharge for a small stream like gepang gut can be extremely dangerous for many civilian and defence establishment.

Another important study accounting the mass balance for 19 glaciers in Himachal Pradesh using a regression relationship between AAR and specific mass balance elucidates a correlation with $r^2$ as 0.8 (Kulkarni et al., 2004). The relationship was developed using field data from 1982 to 1988 for Shaune Garang glacier and 1976 to 1984 for Gor Garang glacier. Moreover, AAR for 2000 and 2001 was estimated for 19 glaciers in the Baspa basin by systematic weekly analysis (May-September) of WiFS images. Mass balance during 2001 and 2002 for 19 glaciers suggest overall specific mass balance value of -90 and -78 cm, respectively and reveals a loss of 0.2347 km$^3$ of glacial ice in the last two years. Further, four glaciers located in lower-altitude zones have no accumulation area. These glaciers are expected to face terminal retreat due to lack of formation of new ice, thereby posing serious problem of availability of water to many villages located in the Baspa basin.

A significant study was made to estimate the mass balance by using the accumulation area ratio (AAR) and Equilibrium Line Altitude (ELA) and regression analysis suggest 0.44 for the AAR representing zero mass balance in the western Himalaya (Kulkarni, 1992). This method was applied to individual glaciers such as Gara and Gor Garang in Himachal Pradesh, India. The correlation coefficient(r) using 6 and 7
Yrs of data respectively were 0.88 and 0.96 for Gara and Gor Garang glaciers, respectively. The correlation, however, was 0.74 when the data from six western Himalaya glaciers was correlated. A higher correlation was observed between ELA and Mass Balance. The field data from Gara and Gor Garang glaciers shows a high correlation coefficient i.e (-0.92) and (-0.94), respectively (Kulkarni, 1992). The ELA values obtained from the Landsat satellite images combined with topographic maps suggest positive mass balance for the year 1986-87 and negative for 1987-88.

**MASS BALANCE STUDIES OF GLACIERS THROUGH FIELD METHODS**

To understand a glacier fully, the mass balance study of that glacier is a must. Mass balance studies needs a proper networking throughout the world, although the network is incomplete and methods used are of different types in different countries.

The World Global Monitoring Services (WGMS) in Zurich, Switzerland is at present the central point, from where the glacier of the world is monitored and all informations on glaciers are collected and distributed. Preliminary mass balance values for the year 2006 are now available from more than 80 glaciers worldwide. The continuous mass balance statistics below are calculated based on the 30 glaciers in 9 mountain ranges with long-term data series back to 1980.

**LIMITATIONS OF THE TECHNIQUES USED IN GLACIOLOGICAL STUDIES:**

The above discussed various studies reflect that an overall integration of the field based techniques and satellite based remote sensing techniques can give a holistic picture about the diverse characterization of the glacier dynamics and its relation to environmental factors. However, all these techniques cannot be claimed to be free from certain limitations. Field based checks are definitely more appropriate and authentic in the study of various aspects in glaciological investigations. But, considering the enormous number of glaciers in the Himalayas, the remote sensing techniques serve as a useful platform because of the great time range and large spatial
extent. Since very little work has been carried out in the Indian Himalayas and there is an acute shortage of manpower, therefore satellite imageries provide a great help in facilitating large scale studies. The utilization of satellite based data can be more useful in providing a complete and representative picture of any vast region. Considering the various difficulties in logistics in carrying out the field studies, the remote sensing methods although with some limitations