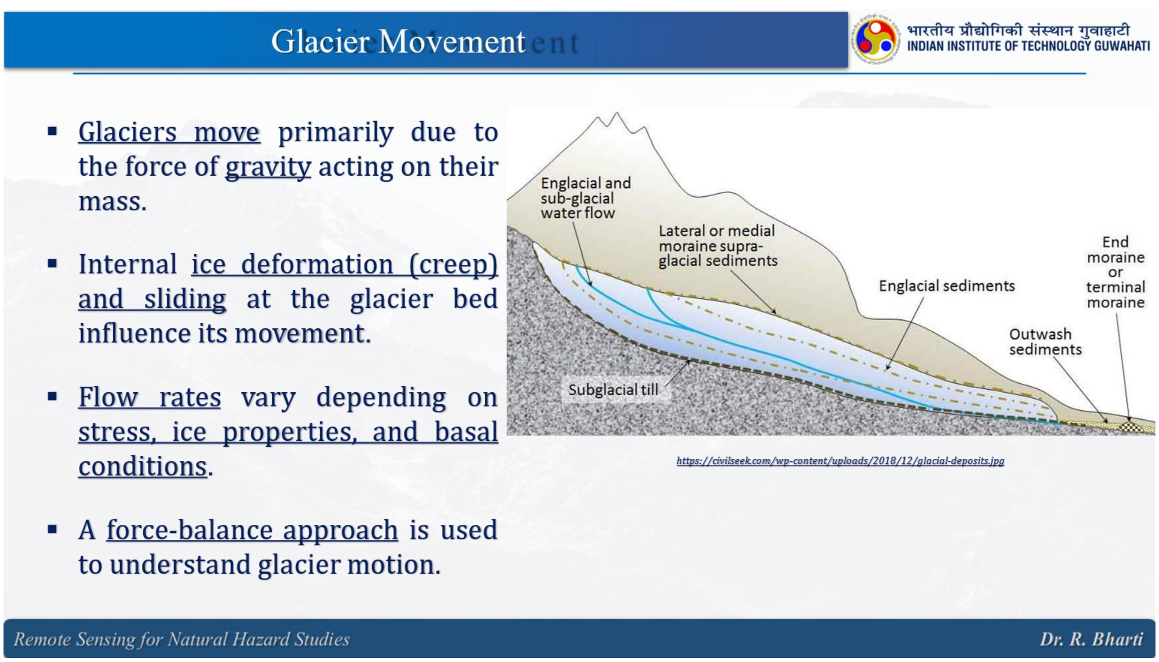
REMOTE SENSING FOR NATURAL HAZARD STUDIES

Course Instructor: Dr. Rishikesh Bharti
Associate Professor
Department of Civil Engineering
Indian Institute of Technology Guwahati
North Guwahati, Guwahati, Assam 781 039, India
e-mail: rbharti@iitg.ac.in
Website: https://fac.iitg.ac.in/rbharti/

Lec 21a: Dynamics of Snow and Glacier Part A

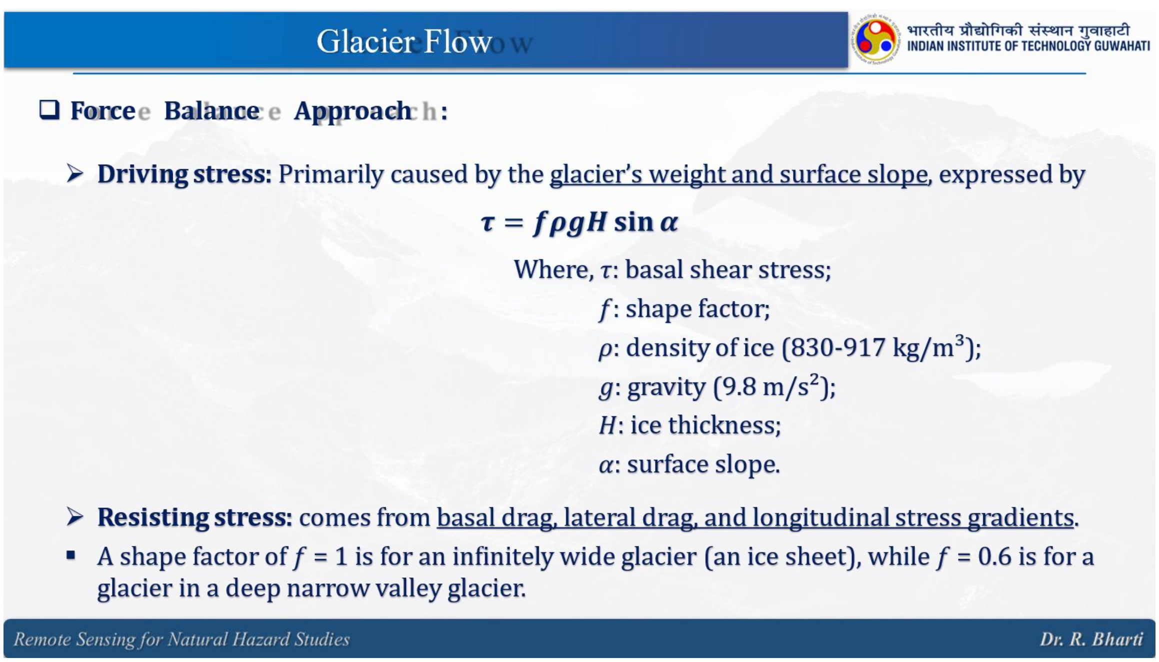
Hello everyone, welcome to Lecture 21. Today we will talk about the dynamics of snow and glaciers. This is part of Module 6. So, let us understand what we mean by glacier dynamics. So, glacier dynamics refers to the processes that govern the movement, deformation, and mass balance of glaciers, which ultimately determine their shape, size, and overall behavior. Here, you can see that because of the glacial dynamics, this particular glacier has taken on this particular shape.

So, it is all due to the glacial dynamics. So, here we will talk about movement, deformation, and mass balance. So, here you can see this particular glacier. So, it is moving down the slope. This is the basic characteristic of a particular glacier.

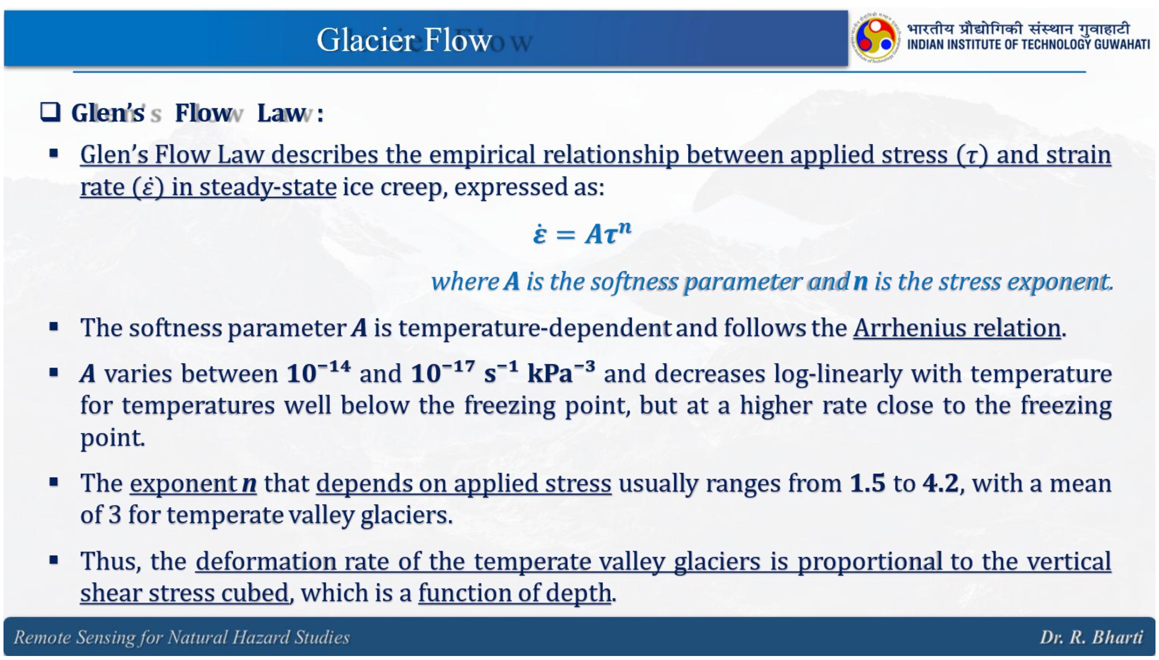


So, the downslope movement of glaciers propelled by gravity causes them to behave like vast rivers of ice. This is how they appear in the satellite image, also when you visit them in the field. Such movement is required to achieve equilibrium with the surplus ice accumulating in the glacier's upper reaches. So, just imagine this is a particular hill or mountain, and this is the snow line above where you have the solid precipitation. So, this is basically the accumulation zone, and because of this accumulation, a glacier will slowly be born, and it will start flowing. So, just imagine if it does not flow, it does not move; then what will happen? This thickness will grow endlessly. So, to bring this entire phenomenon or entire process into equilibrium, this movement is very necessary.

Ice flows from the accumulation zone to the ablation zone, where it melts or curves. So, here let us assume this is the accumulation zone, and slowly it is coming to this particular location, and if this is the accumulation zone and this is the ablation zone, this line is separating these two zones, then here it will start melting, and then it will feed the fluvial system downstream. Without this movement, a glacier would develop an infinitely steep profile, thereby losing its balance. So, this glacier flow is very, very important. So, that is why we will talk about glacial movement. Glaciers react to snowfall changes; gradually, noticeable impacts can take decades to centuries. So, here you can see two photographs, one and two. Here in 1986, the situation was like this. So, here you can see the cyan and blue colors. It is showing the glacier and in 2016, what was the status? It had shrunk. So, the impact of climate change takes time to be represented by our glacier system. So, their movement is influenced by past snow accumulation, as well as the glacier type and size. When the amount of accumulation and glacier movement is unbalanced, glaciers may either shrink or exhibit an irregular flow pattern. Here, you can see that this is one semantic diagram. So, glaciers move primarily due to the force of gravity acting on their mass. Internal ice deformation that we call creep and sliding at the glacier bed influences its movement. Flow rate varies, depending upon the stress, ice properties, and basal condition.

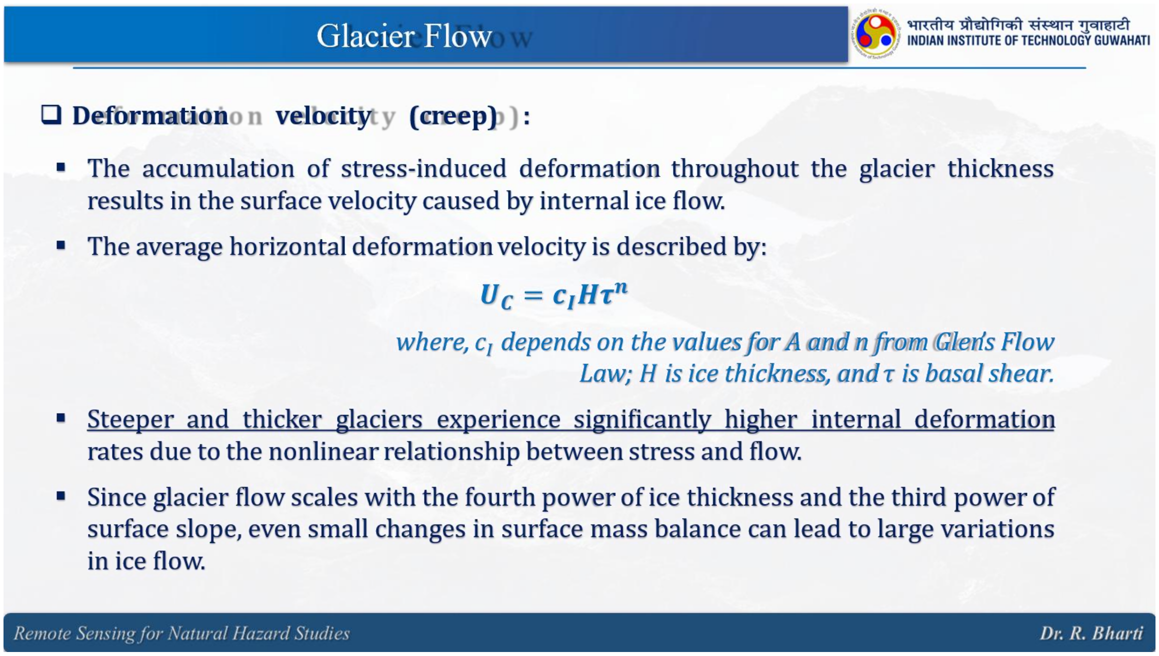


So, here you can see the flow rate will be determined by the stress that is applied to this particular mass. Then ice property rights and the basal condition; this is the basal condition whether it has melted water, what is the proportion that will define the basal condition, and it will indirectly impact the flow rate. A force balance approach is used to understand glacier motion. So, we will examine the force balance approach. In the force balance approach, driving stress is very important, primarily caused by the glaciers weight and surface slope, expressed by this equation. So, here you can see this is a very simple equation. Using this equation, Basal shear stress can be calculated, and we are using the shape factor, density of the ice, gravity, ice thickness, and surface slope. All these parameters are considered here to calculate the basal shear stress and then comes the resisting stress, which comes from basal drag, lateral drag, and longitudinal stress gradient. A safety factor of f is equal to 1 is for the infinitely wide glacier and ice sheet, while f equal to 0.6 is for a glacier in a deep, narrow valley glacier. So, here you can see that the glacier ice basically has a polycrystalline structure and behaves like a nonlinear viscoplastic material. So, it has both viscous and plastic nature under rapid high stress. It fractures, forming crevasses and rifts, while under slow, prolonged stress; it deforms plastically instead of breaking. So, here you can see it is not breaking; it is bending. When stressed, glacier ice initially deforms quickly and then settles into a constant strain rate known as the secondary shear strain rate. The strain rate depends on stress magnitude, ice temperature, stress history, and impurities. So, the impurities also play a significant role here.



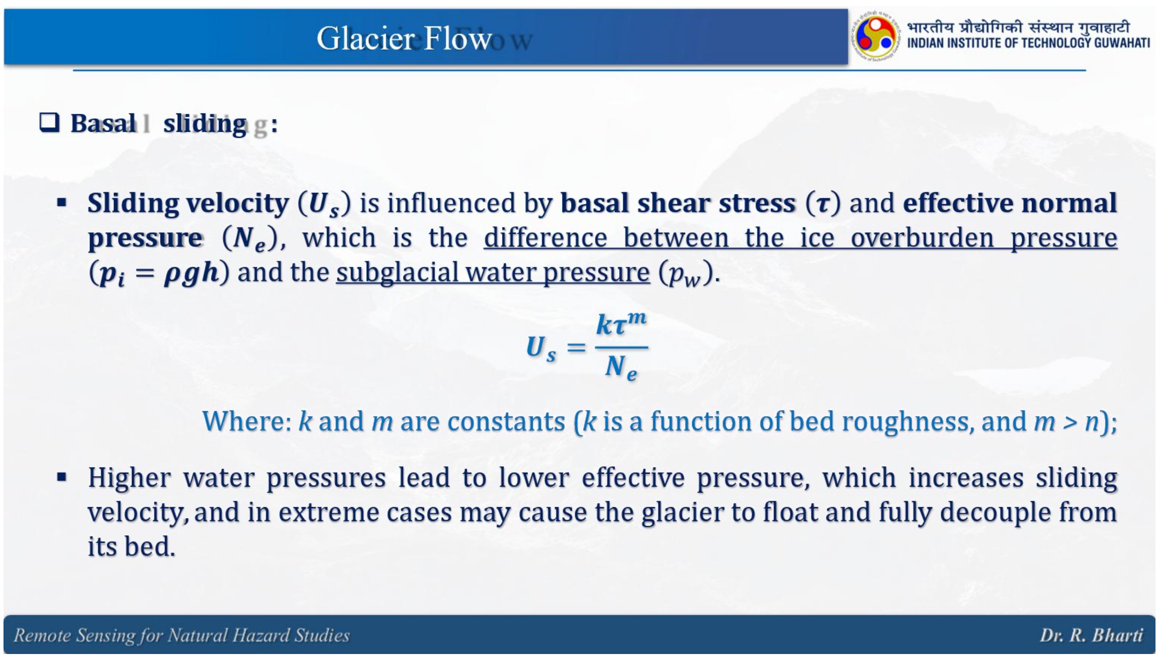
We will try to understand Glenn's flow law. Glenn's flow law describes the empirical relationship between applied stress tau and strain rate in steady-state ice creep, which can be expressed as this equation, where A is the softness parameter and N is the stress exponent. The softness parameter A is temperature dependent and follows the Arrhenius relation. A varies between this value and decreases logarithmically with temperature for temperatures well below the freezing point, but at a higher rate close to the freezing point. The exponent n, which depends on applied stress, usually ranges from 1.5 to 4.2, with a mean of 3 for temperate valley glaciers.

Thus, the deformation rate of the temperate valley glacier is proportional to the vertical shear stress cubed, which is a function of depth. So, depth is very, very important here. Now, let us understand the deformation velocity that we call "creep." The accumulation of stress-induced deformation throughout the glacier thickness results in the surfac e velocity caused by internal ice flow.



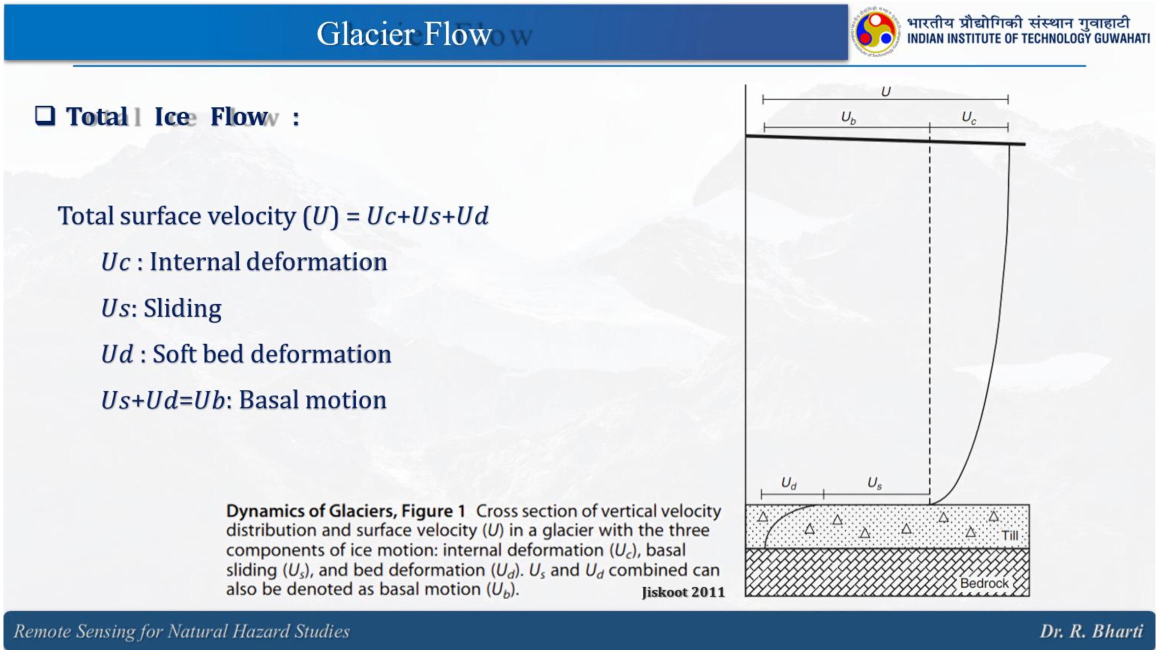
The average horizontal deformation velocity is described by this equation, where we are using A and n from Glen's flow law, H is the ice thickness, and tau is the basal shear. So, we have already calculated that. Steeper and thicker glaciers experience significantly higher internal deformation rates due to the nonlinear relationship between stress and flow. Since glacier flow scales with the fourth power of ice thickness and the third power of the surface slope, even a small change in the surface mass balance can lead to a large variation in ice flow. So, it is having a major impact from the thickness and the surface slope.

Now, let us try to understand basal sliding. So, for the basal sliding here, you can refer to this particular image. So, this is a semantic diagram; here, you can see the internal ice flow has been demarcated, and here is the line along which it is interacting with the surface, So the basal sliding occurs when a glacier is not frozen to its bed, allowing it to move over the underlying substrate. So here you can see this is the ground where this accumulation has happened. Now, here, if you have lubrication, suppose you have melted water, then what will happen? The entire mass will have more flow; they will have high velocity. If they do not have any lubrication here, then the basal sliding will be very, very low. Two key processes that derive basal sliding without cavitation are enhanced creep and regulation. When a glacier flows over bedrock bumps, you can see that these are bumps, So, these will have some obstruction to this particular flow. When the glacier flows over bedrock bumps, the stress concentration on the upstream side of the bump accelerates the deformation or creep of the ice around the obstacles. Due to the pressure variation around the bumps, recirculation happens, and resolution is basically that ice melts on the high-pressure upstream side and refreezes on the low-pressure downstream side. So, here it will be melting, and then here again it may freeze, when subglacial water pressure becomes high, it forms cavities behind bedrock obstacles, reducing contact between the glacier and its bed. So, if you refer to the previous diagram, So, here is what we mean. So, here if you have high water content, then there will be fewer obstacles, and this will reduce the contact between the glacier and its bed. This leads to decreased basal friction and an increase in glacier sliding velocities.



Under certain conditions, the same basal shear stress can produce different sliding speeds, a phenomenon known as multi-valued sliding response. Seasonal melt or surging events can shift the drainage system, causing abrupt and sometimes unpredictable changes in glacier motion. The sliding velocity is influenced by basal shear stress that we have already calculated. Effective normal pressure, which is the difference between the ice overburden pressure and the subglacier water pressure, can be calculated. So, the sliding velocity can be calculated where k and m are constants; k is a function of bed roughness, and m is greater than n. Higher water pressure leads to lower effective pressure, which increases sliding velocity and, in extreme cases, may cause the glacier to float and fully decouple from its bed; because of that, the velocity will increase.

Subglacial till is an unconsolidated sediment mix that you can see here. Ranging from clay to boulders, often found beneath glaciers. So, just imagine you have the glacier body. When water fills the pore space in finer sediments, the till becomes deformable under shear stress. Glaciers underlain by soft saturated till can experience significant bed deformation contributing to basal motion.



The yield strength of till varies depending on its grain size, water content, pressure, and deformation history. Ice flow over a soft bed involves basal sliding and different types of bed deformation. So, here you can see there is no deformation, folding, fold attenuation, and then homogenized diamicton. Deformation may be deep, shallow, or occur along internal sediment boundaries.

This is also possible. The extent of deformation depends on the till thickness, composition, and subglacial water pressure. Due to variability in these factors, soft till is complex and hard to model with a single flow law. So then comes the total ice flow. So, the total surface velocity can be calculated here. You can see the capital U that represents this total surface velocity here.

So, it is basically the summation of Uc, Us, and Ud. So, the internal deformation, sliding, soft bed deformation, and basal motions are considered here to calculate the total surface velocity. The glacier response time is the delay in length or volume change after a shift in climate. So, you might have heard many times that the climate is changing. So, if the climate parameter is temperature, and if temperature is changing, if it is increasing, what will happen is that melting will be more, but it is not changing so drastically that within 6 months or 3 months you will see major changes, So, the glacier system takes decades to show the effects of climate change.

Sometimes, if there is a major change, you will see some major phenomena, but still, the glacier system takes a decade to express the impact of climate change. It includes reaction times. Delay before response and adjustment time duration to reach a new equilibrium occurs because of what happens when there is a change in the climatic system. When there is a change in climatic conditions, what happens? The glacier system takes time to respond, and at the same time, it also has the mechanism to adjust its system to reach a new equilibrium. Alpine glaciers typically respond over decades to a century, just as ice sheets take centuries. A faster response is linked to a steep slope.

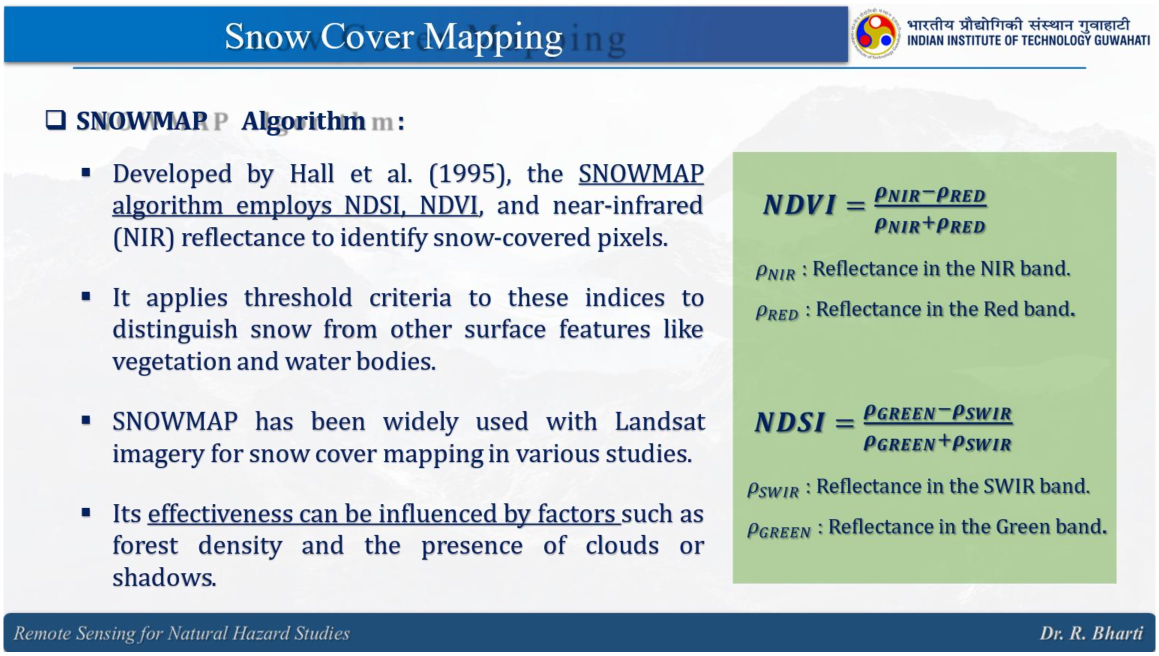
High mass balance gradients and maritime climates. The glacier's size, slope, thermal regime, and hypsometry affect response time. So, here you can see that the glacier response can have many parameters, and depending on the glacier system, the response will be observed. Then comes the snow cover mapping; this is very important. Snow cover is a key driver of climatic, hydrological, and ecological processes.

Now snow cover mapping is essential for understanding hydrological cycles, climate change, and water resource management. Remote sensing has been widely used for snow cover mapping because one major advantage is that it can see a large area from space. So, the remote sensing technique utilizes the unique spectral properties of snow, notably its high reflectance in the visible spectrum and low reflectance in the shortwave infrared, to detect snow cover. Accurate snow mapping supports various applications, including avalanche forecasting, water supply estimation, and climate modeling. So, here you can see some examples; it is from the remote sensing data, how we have identified the flow of the glacier, how it is moving, and what the distribution of the snow cover is in this particular area; this is from this link.

Climate change shortens snow duration and increases the proportion of rainfall over snowfall, affecting water availability for billions and accelerating glacier retreat. The regional factors, like dust deposition, further speed up snowmelt, making snow cover monitoring crucial for assessing climate impact. If you remember, I talked about the contamination of the snow cover in the previous few slides. So, this snow contamination will lead to more melting because those are foreign materials. So, suppose dust is coming and being deposited on this glacier's surface. So, what will happen is its reflectance, the albedo, will be reduced, and then if the albedo is reduced, that means it is absorbing the energy coming from the solar radiation, which will lead to a higher temperature on the surface.

Surface, and then subsequently it will be transferred to the glacier system, leading to more melting. Snow cover mapping algorithms have been developed to map snow cover using satellite imagery, each with specific methodologies and input requirements. These algorithms can be broadly categorized into binary classification methods. This indicates the presence or absence of snow, and the fractional method estimates the proportion of snow cover within a pixel. Commonly used methods include NDSI, NDVI, and the reflectance values from various bands.

So, we will have some information related to this in the coming slides; the choice of an algorithm depends on factors such as the desired output type, sensor characteristics, and the specific application or study area. Because you have many sources of satellite data, and depending on your study's purpose, data availability, and the requirements of your study, you will decide which type of sensor, method, or output is desired in your work. SnowMap is one of the algorithms that is very popular.

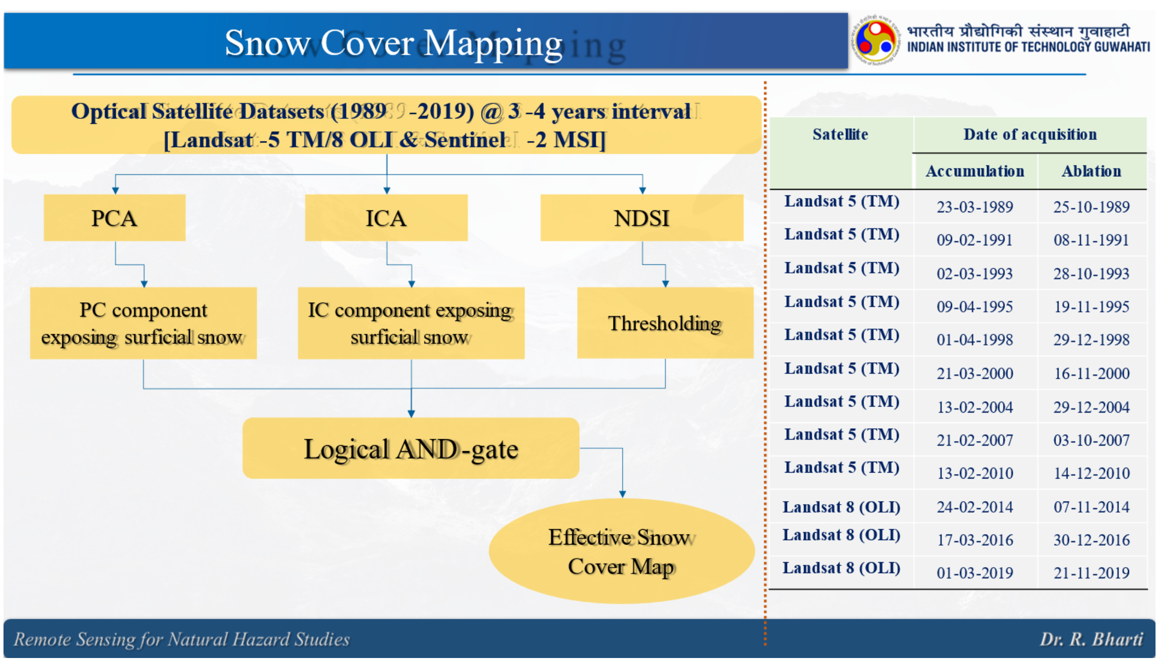


So, it was developed by Hall et al. in 1995. The SnowMap algorithm employs NDSI, NDVI, and near-infrared reflectance to identify snow-covered pixels. So, here you can see the equations for NDVI and NDSI. So, here they are using NIR and the Red Band, and here in NDSI, the SWIR and Green Bands are used. It applies threshold criteria to these indices to distinguish snow from other surface features, such as vegetation and water bodies. That is why we have NDVI and NDSI: one is for vegetation, and one is for water. The snow map has been widely used with Landsat imagery for snow cover mapping in various studies because Landsat is one of the longest series of satellites that we have, and it is in the public domain. So, people are frequently using these Landsat datasets. Its effectiveness can be influenced by various factors. Such as forest density and the presence of clouds or shadows, because we are talking about the optical data, and the optical data sets have their own limitations that we have discussed in the initial lectures of this course. NDSI-based algorithms. So, NDSI uses a fixed threshold, commonly 0.4 or 0.45, to classify pixels as snow-covered or snow-free based solely on NDSI values. So, here you can see this is one of the examples from my work. NDSI applies Otsu's method to determine an optimal image-specific NDSI threshold that accommodates spatial and temporal variability.

These methods are straightforward and computationally efficient but may struggle in areas with mixed land cover or varying illumination conditions. So, that is the limitation of the NDSI based algorithms. Their accuracy can be improved by integrating additional indices. So, you can use different types of indices, and you can have better output. So, alternative snow mapping methods are like the blue snow threshold method.

Then we have Dozier's method, Klein's algorithm, and these different types of algorithms; it is not limited to what I am showing here. There are many other methods available. So, these algorithms aim to address specific challenges in snow mapping, such as vegetation interference and varying snow condition. So, depending on your study area, you have to choose a method wisely. Salomonson and Appel have developed a method to estimate fractional snow cover (FSC) using a linear relationship with the NDSI value.

So, this approach provides continuous measures of snow cover within a pixel, offering more detailed information than binary classification because in binary classification, what happens is you have either snow yes or snow no. So, it will be a yes or a no. So, this kind of classification is known as binary, whereas these fractional snow cover methods emphasize within a pixel whether 50 percent is snow and 50 percent is non-snow. So, that can be done using the fractional snow cover estimation method. So, here in this method, they employ a sigmoid function to model FSC based on NDSI, enhancing performance in a heterogeneous landscape.



Fractional methods are particularly useful in areas with patchy snow cover or mixed land surfaces. So, here we are not talking about the glacier; it is the snow cover. So, snow cover cannot be continuous in all areas. So, there will be some areas where you have patchy snow covers. So, if you want to identify or map those locations, fractional snow cover methods are more useful. So, here you can see this is one of my works where we have used the satellite data set at intervals of 3 to 4 years, and we started from Landsat 5, then Landsat 8, Sentinel 2; all these are listed here. Then we used PCA, ICA, and NDSI, and we brought them together, using the logical AND gate to identify the effective snow cover areas, So, here you can see it. Based on that method, we have derived the snow cover map for the accumulation period. I hope this spatial distribution of snow cover mapping is clear now. Now we will talk about the snowline delineation. It is very, very important. The snow line is the distinct boundary that separates snow-covered terrain from snow-free areas on a mountain or landscape. So here, if you see this particular line, it is dividing the area into two portions: one has snow, and the other is non-snow.

It represents the lower elevation limits of permanent and seasonal snow accumulation. Snow lines can vary spatially and temporally due to factors such as solar radiation, slope, aspect, and regional climate. So, maybe this was the condition in 1980. In 1999, it went up. Here is the situation in, let us say, 1980; in 1999, it may come here.

So, this snowline is always changing. Every year, there is a new snow line, and it depends on the solar radiation, slope, aspect, and regional climate. The snow line is typically expressed as an elevation contour and is observable in satellite imagery and aerial photographs. The importance of snow line extraction, so let us understand the importance of snow line extraction. Snowline elevation serves as a sensitive indicator of climate variability and glacier mass balance. So, here you can see this will be the accumulation zone, and every year if it is changing, which separates this from the non-snow area, that means it is changing with time.

Monitoring snow line change helps to estimate the seasonal snowmelt, which is vital for water resource management in mountainous regions. Accurate snow line extraction supports hydrological modeling, flood forecasting, and glacial dynamics analysis. It also aids in validating remote sensing snow products and assessing the performance of snow cover algorithms. Now, there are some pre-processing steps for snow line delineation. It is very critical; though it is a very generic one, I hope it will help you.

So, missing data due to clouds, shadows, or sensor gaps is addressed using a neighborhood-based pixel interpolation technique. Binary snow cover maps are cleaned using morphological operations such as closing and opening. Isolated small snow or snow-free patches are removed using area-based filtering to improve spatial consistency. These preprocessing steps enhance the quality of the snow cover map, which is critical for accurate snow line detection. So, here the canny edge is one of the very popular methods to extract the snow line.

Threshold parameters for edge detection are empirically tuned to match varying snow conditions and image characteristics. Here you can see that this is the median snow line altitude. The method detects continuous well-defined contours that represent the snow line across the terrain. So, this is the one. Elevation information from digital elevation model (DEM) can be linked to extracted snow line contours to quantify snow line elevation.

Ultimately, the snow line will represent the altitude from where you are experiencing snowfall in a particular year. So, it may change with time, and then with post-processing and validation. So, detected snow lines near regions with high uncertainty, for example, unfilled NAN areas, are filtered out to improve reliability. Spatial smoothing and line simplification techniques may be applied to refine snow line geometry because if these are broken, you need to have a consistent line or a continuous line that demarcates the boundary. Validation is performed by comparing the extracted snow line with a reference dataset or manual interpretation, or you can also validate it in the field.

Performance assessment considers factors such as terrain complexity, land cover type, and input data resolution. So, that is used for validation. With this, I will end part 1 of this lecture. We will continue this discussion in the next part. Thank you.

Thank you very much.