

REMOTE SENSING FOR NATURAL HAZARD STUDIES

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Lec 22 a: Geophysical Parameters of Snow-I: Part A

Hello everyone, welcome to Lecture 22. So, today we will talk about the geophysical parameters of snow. So, we have learned about the cryosphere and cryospheric-related hazards. So, geophysical parameters have been proven to be an important source of information that is used in multiple hazard analyses. So, we will try to understand the geophysical parameters, what they are, and what their impact is on the glacial system. So, solid precipitation is the main source of mass for the glacial system.

We all know that the geophysical properties of snow are essential to study the snow glacier system. It can be used as an indicator for any related hazard. So, how are they serving as an indicator that we will understand slowly?

Geophysical Parameters

The definition of snow is usually restricted to the material composed of air and ice that has not changed much since it fell on the ground (Cuffey & Paterson, 2010).

Geophysical parameters of snow encompass a range of intrinsic physical properties that dictate its state and evolution.

Snow cover properties are broadly classified into (1) Optical Properties, (2) Electrical Properties, (3) Mechanical Properties, (4) Thermal Properties.

Optical Properties (Warren, 1982, 2019)

Electrical Properties (Glen & Paren, 1975)

Mechanical Properties (Salm, 1982; Petrovic, 2003)

Thermal Properties (Yen, 1981)

These parameters are not static; rather, they are highly dynamic, undergoing continuous transformation.

Remote Sensing for Natural Hazard Studies Dr. R. Bharti

The important geophysical parameters of snow, like dielectric constant, density, and liquid water content, play a vital role in avalanche studies, hydrological modeling, and flood monitoring. Studying snow geophysical parameters demands continuous monitoring of snowfall and snowpack characteristics. Because unless we have complete

information about the snowfall and the snowpack characteristics in terms of geophysical parameters, we will not be able to characterize a particular system. This requires in situ measurements, which are also necessary to develop a robust model for estimating snow geophysical parameters over time. So, we all know that in situ measurements are the only way we can obtain accurate values. But since we are talking about the glacier and glacial systems, these terrains are very rough. So, it is very difficult to reach and collect information all the time during different seasons.

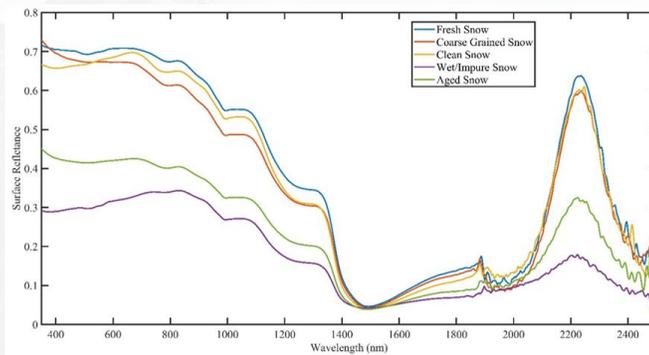
So, that is why, particularly in hilly terrain, the in-situ measurements are challenging and expensive. To retrieve the geophysical parameters of snow, we will need to locate a reliable source of information, and here the role of remote sensing comes into the picture. So, the geophysical parameters of snow are crucial for a wide range of scientific and practical applications impacting various fields, starting from climate science to hazard management, and the importance of the geophysical parameters of snow can be seen in many areas, such as hydrological modeling and water resource management. Climate and energy balance, hazard assessment and prediction, ecosystem and biological processes. So, everywhere the role of geophysical parameters is very, very important.

So, the geophysical parameters of snow, such as albedo, density, wetness, and grain size, are crucial for understanding and modeling the snow-glacier system, climate change, and hydrological processes. The geophysical parameters directly influence the surface energy budget. We will understand this when we talk about the parameters, the hydrological cycle, and the overall health of the mountain ecosystems. So, when we talk about the geophysical parameter and when we define snow, it is usually restricted to the material composed of air and ice. That has not changed much since it fell to the ground.

When we talk about the geophysical parameters of snow, we encompass a range of intrinsic physical properties that dictate its state and evolution. And the snow cover properties or the snowpack properties are broadly classified into optical, electrical, mechanical, and thermal. So, here we have optical properties, electrical properties, mechanical properties, and thermal properties, and the reference is given here. So that if you are interested, you can refer to these papers, and you will get very detailed information about these properties; remember, these parameters are not static. Rather, they are highly dynamic in nature, undergoing continuous transformation.

So, that is why these geophysical parameters need to be monitored throughout time so that we will have a complete understanding of the system.

Spectral signature of Snow is characterized by high reflectance in the visible spectrum and lower reflectance in the shortwave infrared (SWIR) region (Hall et al., 1995).



Snow shows high reflectance in the VNIR range (400–1000 nm), which decreases with aging, impurities, or the presence of liquid water due to changes in its microstructure and increased absorption.

In the SWIR range (1500–2500 nm), snow shows low reflectance due to strong absorption by ice and liquid water, aiding in remote sensing-based snow type classification.

Different snow condition reflectance values were measured in Arunachal Pradesh, India.

When we talk about optical properties, let us try to understand the spectral signature of snow. So, here you can see the different snow spectra that are captured in Arunachal Pradesh. So, here we have fresh snow, coarse-grained snow, clean snow, wet or impure snow, and then aged snow. So, we have collected the information, and then you can see how they are behaving in different electromagnetic wavelength ranges.

So, the spectral signature of snow is characterized by high reflectance in the visible spectrum and lower reflectance in the shortwave infrared region. The snow shows high reflectance in the VNIR range, which is 400 to 1000 nanometers. This decreases with age, impurities, or the presence of liquid water due to changes in its microstructure and increased absorption in the SWIR range. So, here, snow shows low reflectance due to strong absorption by ice and liquid water, aiding in remote sensing-based snow type classification. So, because of these absorption features and their change in intensity, we can easily identify what type of snow we have or what type of grain sizes we have.

So, that can be identified using these optical properties when we discuss the electrical properties. So, these are primarily governed by their liquid water content. Temperature, density, and impurities are typically described in terms of dielectric constant, which is nothing but the permittivity and the electrical conductivity. So, we will have a detailed discussion on this. So, this is just the basic information. So, the snow permittivity is one of the important electrical properties of snow that varies with electromagnetic frequencies. And remember, here I have given some very important references. So, if you are interested, you can refer to these papers; they are very nice papers and have detailed information about these properties. Snow dielectric properties, including dielectric constant and dielectric loss, are influenced by density, moisture, and microstructure. So,

the electrical conductivity of snow increases with liquid water content, temperature, and impurities like salts or soot.

This enhances the mobility of ions within the snow matrix. So, now you understand why these electrical properties are important because they are the indirect measures of the status of your glacier system. When we talk about the mechanical properties, the mechanical characteristics of snow are primarily investigated for their role in avalanche initiation and mitigation. Additionally, they are crucial for addressing practical challenges such as vehicular mobility, snow clearance, and infrastructure development in snow-covered environments. And the main requirement for this mechanical property is the constitutive equation, which relates the stress tensor to the motion, and the second one is the fracture criteria, which limit the range of validity of the consecutive equation.

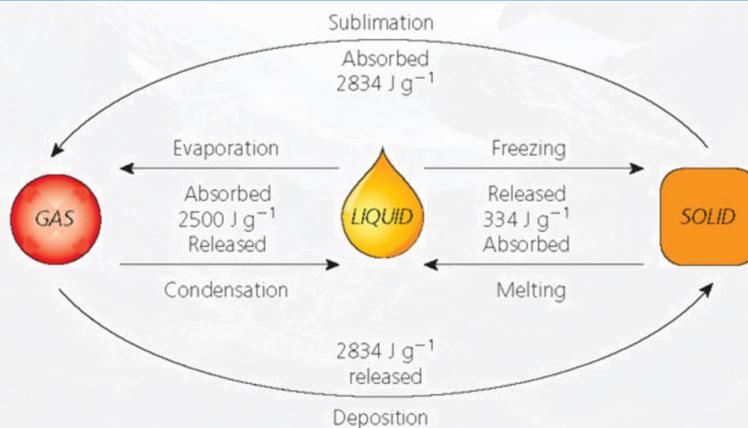
So, the tensile strength of ice varies from 0.7 to 3.1 megapascals, and the compressive strength varies from 5 to 25 megapascals over the temperature range from minus 10 to minus 20 degrees Celsius. The tensile strength of ice decreases with increasing ice grain size; the ice compressive strength increases with decreasing temperature and increasing strain rate, but ice tensile strength is relatively insensitive to these variables. Snow is an open cellular form of ice; both the strength and fracture toughness of snow are substantially lower than those of ice.

So, these mechanical properties are very important, especially when we are talking about snow avalanches or maybe ice calving. So, this can give you more information about the target snowpack.

Thermal Properties



Snow exhibits fascinating thermal properties that play a crucial role in its behavior and its impact on the environment. These properties are largely influenced by snow's highly porous structure, which traps air.



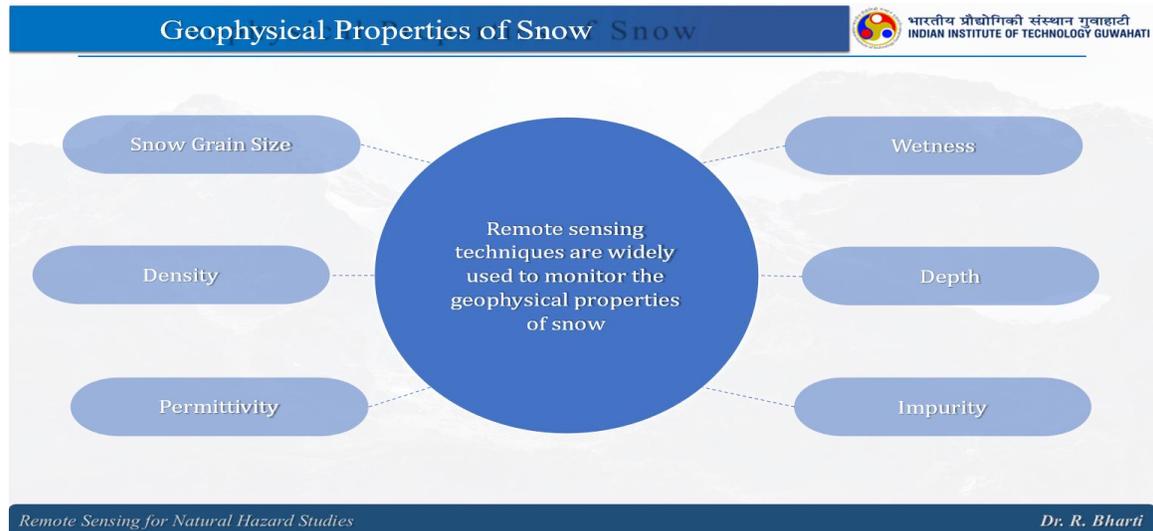
The thermal properties of snow, particularly its low thermal conductivity and high insulation capacity, govern the heat exchange between the atmosphere and the ground. So, remember that I talked about the surface. So, from here, you have geothermal energy, and from here, you have solar radiation.

So, if you have glacial ice or snow, it is basically a very good insulator, and it has low thermal conductivity; because of that, it restricts temperature changes in this system so drastically. That is why, when you have any foreign material here, that will lead to changes in its thermal properties, and then you will have major changes in this glacial system that are not ideal for our survival. So, that is why these thermal properties are very, very important when we talk about the stability of a glacial system. In avalanche science, these properties affect snow metamorphism, bonding between layers, and weak layer formation. All of these are critical for avalanche forecasting.

In permafrost modeling, snow acts as a thermal buffer, delaying or preventing ground freezing and thawing, thus influencing permafrost degradation. Understanding the thermal insulation properties of snow is essential for engineering design in snow-covered regions. So, if you want to construct a building or maybe a warehouse, then you need to have complete information about this snowpack, where subsurface thermal dynamics directly influence the structural stability of that area. The heat capacity of snow and freshwater ice at constant volume is about 3 percent less than that at constant pressure at the melting point, and the difference between C_p and C_v , which is nothing but your constant volume and constant pressure, decreases with decreasing temperature. So, I hope you understand the implications of thermal properties at higher altitudes.

So, the snow exhibits fascinating thermal properties that play a crucial role in its behavior and its impact on the environment. These properties are largely influenced by snow's highly porous structure, which traps air in between. So, I hope you remember this. So, when you have a liquid, it is liquid water. So, from here, if we are going towards this freezing, then what will happen is that there will be a release of energy, and the energy will be 334 joules per gram. When it goes from solid to liquid, it absorbs the same amount of energy, and then when we talk about the transition from liquid to gas, evaporation occurs, and here the energy absorbed is 2500 joules per gram. Similarly, when gas is converted to liquid, 2500 joules per gram of energy will be released, and there is also a direct conversion from gas to solid. So, here's what you must do: you must add this energy plus this energy. So, together it will be 2834 joules per gram that energy will be released, and we will call it deposition. It is being converted from solid to gas. So, we call it sublimation. So, this sublimation will absorb 2834 joules per gram. So, this is very interesting, and that explains the thermal properties of this snowpack. This relationship can be easily understood, and it can be directly linked to the snowpack properties. So, when we talk about the remote sensing techniques, especially those used

in the geophysical properties of snow. So, here we have the different parameters that we talked about.



So, starting from snow grain size, density, permittivity, wetness, depth, and impurities, these properties are used to define the geophysical properties of snow. We will try to understand this one at a time. So, when we talk about the snow grain size, grain size refers to the typical size of an individual snow crystal or ice particle that makes up the snowpack. So, here you can see some examples of different types of snow grains. So, here it is very smooth; here it is again coarser; this is again much coarser than that.

So, what is the impact when the sun is illuminating this area? What happens, depending on the grain size of this target, is that the amount of energy released will vary. So, this amount of energy depends on the size of the grains. So, that will influence the total radiative budget, and that will indirectly impact the energy stored or reflected by a snowpack. Then comes the density.

Density

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Snow density is a fundamental property of snow, defined as the mass of snow per unit volume.

It varies significantly depending on the snow's age, condition, and other factors. Fresh, dry snow has a relatively low density, while older or wet snow can be significantly denser.

Factors Affecting Snow Density

- Snow Type (Fresh vs. Old)
- Temperature
- Wind
- Metamorphism
- Compaction
- Liquid Water Content

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So, the snow density is a fundamental property of snow, defined as the mass of snow per unit volume. It varies significantly depending on the snow age, condition, and other factors. Fresh, dry snow has a relatively low density, while older or wet snow can be significantly denser because we are talking about solid precipitation here. So, let us say we have solid precipitation here; then subsequently, we have another layer of solid precipitation. Snowfall is happening, and because of the overburden pressure and the temperature, this layer will be compacted. So, the factors that affect snow density are snow type, whether it is fresh or old snow, which will result in different densities; temperature will also control it, as will wind, because if you have high wind speeds in this area.

From fresh snow to ice, that conversion will be fast. Then metamorphism, depending upon the overlying pressure, will start, and then compaction will take place, leading to a change in density. Then we have liquid water content, which is the fraction of liquid water content in your snow. That will also define the density.

Then we have permittivity. Snow permittivity, which is a measure of its ability to store energy in an electric field, is highly dependent on its state, whether it is dry or wet, and the presence of liquid water can be studied. The first one is the state of whether it is dry or wet snow, and the presence of liquid water in this snowpack. Dry snow is primarily composed of ice and air. has lower permittivity than wet snow, which includes liquid water, because when it is fresh snow, you have more voids in between. So, it is basically ice and air, but subsequently, when it is converted to a particular layer with overlying pressure, what happens is that it will have less space for the air, and liquid water can also be present in between.

So, the factors affecting snow permittivity are snow density, liquid water content, temperature, snow type, and snow microstructure, which is nothing but your crystal size and orientation. That can be studied to learn more about the permittivity. Then comes the wetness. Snow wetness, also known as liquid water content, refers to the amount of liquid water present within a snowpack. So, this is one example; here you can see visually that you can identify this as dry snow and this as wet snow, but this is just for example.

So, it is a crucial factor in understanding snow hydrology, seasonal snow changes, and regional climate variability. The presence of even a small percentage of liquid water significantly alters the physical, thermal, and electromagnetic properties of the snow. So, what are the different factors that control this snow wetness? So, they are temperature, solar radiation, air temperature, snowpack density, precipitation, slope, and aspect. So, this precipitation I am talking about is the normal precipitation, liquid precipitation, not the solid one.

Depth

Snow Depth

Snow depth refers to the vertical distance from the surface of the snowpack to the ground beneath it.



Then comes the snow depth, which is referred to as the vertical distance from the surface of the snowpack to the ground beneath it. So, let us say this is the lowest layer, and here you have a rock surface, or soil, which is present here. So, the depth will be only this much from the surface. But if there is another layer of snow, then this is not the correct depth. So, depth will be further down, and generally, we have some mechanisms to measure. So, there are some automatic ways of measuring. For snow depth measurement, we have different approaches: one is manual, another is automatic, where we can use a scale to measure the annual or seasonal precipitation, and the automatic method uses sensors to identify changes in elevation so that we can determine the precipitation value. Then comes the impurity, which is very, very important.

Impurity

Snow impurities refer to particles that are mixed into the snowpack, affecting its properties and, ultimately, its melting behavior

The presence and concentration of these impurities significantly impact physical, chemical, and radiative properties of snow.

Common Snow Impurities

- Black Carbon / Soot
- Dust (Mineral Dust)
- Biological Impurities (Algae)
- Chemical Pollutants
- Debris



Impacts of Snow Impurities

- Reduced Albedo
- Significantly affect the Earth's energy budget
- Increased Snowmelt

Snow impurities refer to particles that are mixed into the snowpack, affecting its properties and ultimately its melting behavior. The presence and concentration of these

impurities significantly impact the physical, chemical, and radiative properties of the snow. So, here you can see the example; this side is the fresh snow, whereas the surface has some contamination and impurities. So, what is the major difference? If light falls here, more energy will be reflected. Whereas if this particular area receives energy from the sun, less energy will be reflected. So, here the difference between these two is the amount of energy that is being reflected from the surface, which we call albedo. So, if there is a change in the albedo, it will significantly affect how much energy is being stored in the glacier system.

So, here, if you see, less energy will be stored because maximum energy is getting reflected, but here, more energy will be stored, and that will change the status of this glacier system. So, more melting is expected here. So, the common snow impurities that we see in the glacier system or snow are black carbon or soot and dust, which is nothing but mineral dust. Biological impurities, such as algae, chemical pollutants that come through the air circulation, and debris that comes from the surrounding hills during landslides and other geological processes. So, the impact of snow impurities can be seen in terms of reduced albedo, which significantly affects the Earth's energy balance and increases snow melt, which is ultimately a result of snow impurities.

So, the increased snowmelt that we can see occurs if we have more snow impurities in a snowpack. As we all know, these snowpacks are situated at higher altitudes where field investigations and in-situ measurements are very difficult. So, that is why we have to find an alternative way, and remote sensing is one of the very important sources of information in estimating or measuring snow properties. So, the geophysical properties of snow. So, it helps to overcome the challenges in in-situ measurements of snow properties.

Then, particularly microwave remote sensing overcomes the problem of cloud cover, as observed in optical remote sensing, especially in higher altitude areas. It also provides data or products for a larger aerial extent. So, these are the major advantages of why we are discussing the remote sensing application in geophysical property estimation. So, now we will observe the snow grain size. Snow grain size is a fundamental property of snow and is directly proportional to its surface area.

Here you can see an example of snow grain size; estimating snow grain size is crucial for understanding and monitoring the Earth's radiation balance, particularly in the context of the cryosphere. The size of the snow grains plays a key role in determining snow albedo. It impacts the reflection of sunlight by the snow-covered surfaces. So, here we have some references; if you are interested, you can refer to them, and you can read more details about this basic topic. The snow grain size, which represents this course of snow metamorphism, has been identified as one of the most valuable snow physical parameters. The snowpack stability has frequently been examined in snow avalanche studies utilizing information derived from snow grain size and snow shape.

Snow grain size is a fundamental property of snow and is directly proportional to its surface area.

Estimating snow grain size is crucial for understanding and monitoring the Earth's radiation balance, particularly in the context of the cryosphere (Jin et al., 2008).

The size of snow grains plays a key role in determining snow albedo, impacting the reflection of sunlight by the snow-covered surface (Marshall & Oglesby, 1994; Gelman Constantin et al., 2020).



https://www.esa.int/ESA_Multimedia/Images/2011/04/Snow_grain_size_chart

Due to the rough topography of the Himalayas, particularly in the Himalayan region, many geophysical parameters are poorly sampled because of accessibility and support. Developing sophisticated remote sensing techniques is critical for obtaining timely information on the spatio-temporal variability of snow cover and snow grain size. According to the IAHS international classification for seasonal snow on the ground. The observer should select a homogeneous snowmass and record the mean size of its predominant grains, focusing on measuring the diameter of the grains, which is its grain size, and it is typically measured in millimeters.

So, although this approach might work well for field research, in the case of remote sensing-based research, characterizing the average grain size over a wide range is necessary. Surface feature extraction and mapping based on spectral signatures are popular hyperspectral remote sensing applications. So, here we will try to see how hyperspectral remote sensing is being used in snow grain size studies. Snow surface features such as snow grain size, snow wetness, and snow albedo have all been studied through hyperspectral remote sensing. The hyperspectral images and advancements in radiometric isometric models have led to the emergence of more precise snow grain size inversion models.

And, here we will try to understand how hyperspectral remote sensing is used for snow grain size. So, in this paper, they have used the Hyperion sensor to retrieve snow grain size and spectral albedo for the snow cover in the western Himalayas, which is from India. In contrast, Singh et al. (2022) employed PRISMA data for the snow grain size estimation. In another study, the inversion methods for snow grain size, called the absorption band area method, which is hardly affected by topographic error, solar illumination angle, and noise, are being used. So, the physical sense of the method is that

the absorption feature is directly proportional to the amount of energy absorbed by the ice particles in the spectral region. So, we have seen in hyperspectral remote sensing how particular characteristic wavelength absorption features arise because of the presence of the chemical composition and its internal atomic structure. The same fundamental has been used here in a different way to identify the snow grain sizes. SID is used to map snow grain size, and then the absorption band area method is utilized to validate the trend of energy absorbed by each snow grain size.

The grain size mapping method is applied to PRISMA data using the GHU snow spectral library, and for this, the South Lhonak Glacial Lake region has been selected because there was recently a GLOF event. So, it highlights the advancement in remote sensing technologies for snow research using hyperspectral data from PRISMA Level 2. This is level 2, so that is basically the bottom of the atmosphere reflectance. In the absence of in situ data, this study sheds light on the possible use of snow grain size mapping to evaluate snowpack conditions and dangers.

So, with this, I will try to explain to you the basic details. So, with this, I will end part 1 of this lecture. We will continue this in the next lecture.

Thank you.