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REMOTE SENSING APPLICATIONS IN CRYOSPHERE: A REVIEW OF MONITORING THE RECEDING GLACIERS

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Abstract— **Cryosphere is a term representing all the frozen places on earth. They include snow and ice on land as well as in water, glaciers and permafrost. Snow and ice helps in regulating Earth's temperature as they reflect a significant amount of radiations back into space. Thus, all the components of the cryosphere have a great impact on climate; moreover it influences almost every region on the planet due to interaction between warm equatorial oceans and cold polar latitudes via transfer of heat. As the cryospheric components are generally located in very remote areas, thus the remote sensing techniques are well suited to acquire all relevant data required to study and understand the factors that govern the evolution of cryosphere. This paper aims at describing the importance of cryosphere and remote sensing applications associated with it. A review of receding glaciers as one of the application of remote sensing in cryosphere is also depicted in the paper.**

Keywords— **Cryosphere, Remote Sensing, Receding, Glaciers, Climate Change, ASTER, Terra, Landsat.**

I. INTRODUCTION

A major portion of Earth's land and ocean surface is covered by cryosphere. The spatial extent of permanent, relatively stable and seasonal global snow cover is shown in figure 1. The cryosphere not only stores almost 77% of Earth's freshwater, it also plays a vital role in the functioning of global climate system. Snow and ice have a high albedo as compared to that of vegetation and thus is an important cooling factor in the global climate system. As snow and ice cover are reducing, the darker land and oceans are getting exposed which retains the solar radiations rather than reflecting them, hence increasing the warming and resulting in further reduction of snow and ice covered areas. Sea ice considerably reduces the heat transfer between ocean and atmosphere. Sea ice layer acts as an insulating layer and keeping the Earth's climate cooler. With the reduction of sea ice the heat in form of warm water is getting transferred from equatorial regions to the poles which are resulting in warming the polar atmosphere and further reduction of cryospheric area in polar regions. The oceanic conveyor belt is highly affected due to increasing amount of icebergs, ice sheets and ice shelves joining the ocean and reducing the salinity of ocean water. Terrestrial permafrost and frozen sediments beneath oceans support an important reservoir of organic carbon and gas hydrates [1]. Melting of permafrost is resulting in emission of methane which contributes to the greenhouse gas in the atmosphere [2].

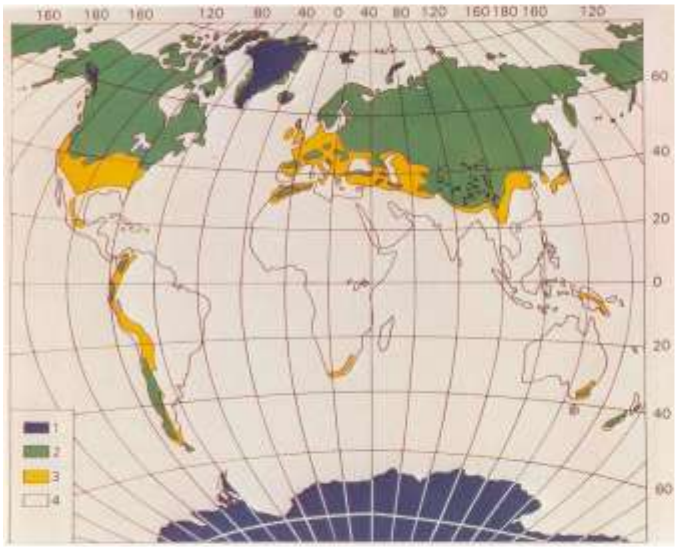


Fig. 1: Map of permanent (blue), relatively stable (green), and seasonal (yellow) global snow cover (Martinec, 1985).

II. REMOTE SENSING IN CRYOSPHERE

Studying and monitoring of cryosphere is a very challenging task due to remote locations of cryospheric components and also due to the global span of cryospheric processes and great daily to seasonal variations in the snow and ice extent [3]. Presence of different forms of ice and snow makes it impossible for any single observing system to make adequate and relevant observations. Therefore many techniques must be agglomerated to fully study and monitor the cryosphere and its interaction with other Earth systems. Use of various observing tools, direct field measurements is highly hindered by many factors including inhospitable climatic and physical conditions in the areas. Thus, the best suited method to study cryosphere is remote sensing. Using remote sensing is also a challenging task as it has to overcome various hindering factors such as cloud cover, forest, geocoding accuracy, influence of topography and atmospheric effects. However all the factors can be accounted for by using different sensors and different remote sensing techniques.

Cryospheric remote sensing is in use from the time of World War I [4]. It began with the 1923 Junkers expedition to Spitzbergen by Mittelholzer and others [5] followed by Wilkins who documented ice cover in Antarctica during the first flight by using hand held Kodak 3A camera [6], Mckinley became third in the league who operated his Fairchild K-3 mapping camera during Byrd's 1929 flight to south pole [7]. After about 32 years, during early 1960's space borne cameras came into action. CORONA, ARGON and LANYARD were the first three operational imaging satellite reconnaissance systems and they acquired data for both detailed reconnaissance purposes and for regional mapping [8-9].

Remote sensing can be air borne or space borne, both uses almost similar kinds of instruments however space borne systems can provide global scale, pole to pole observations on daily basis ([2]. Due to different electromagnetic, gravitational and magnetic force fields present, different amount of radiations are reflected from earth's surface. Hence there are several instruments aboard various satellites for different conditions like Electrically Scanning Microwave radiometer (ESMR), Scanning Multichannel Microwave radiometer (SMMR), Advanced Very High Resolution radiometer (AVHRR), Moderate Resolution Imaging Spectrometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS), Satellite Pour l'Observation de la Terre (SPOT). Various other satellite instruments that measure different properties of cryosphere can be found at http://globalcryospherewatch.org/satellites/vars-sats.php .The satellite observing system for the cryosphere is as shown in figure 2.

III. GLACIERS

Glaciers are one of the most important components of cryosphere. About 32% of total land area is covered by glaciers [10]. They are formed where the snow is deposited for a long time and gets transformed into ice. This huge mass of ice flows under the influence of its own weight to the areas of lower altitudes, where it melts again. Accumulation and ablation areas are separated by the equilibrium line, where the balance between gain and loss of mass is exactly zero. Glacier distribution is thus primarily a function of mean annual air temperature and annual precipitation sums modified by the terrain which influences the amount of incoming net radiation or the accumulation pattern [10]. Studying glaciers is very important as they have significant impacts on human livelihoods, economy of a country and climate as well. Glaciers acts as freshwater reservoirs for many countries (stores about 75% of total freshwater), it is also of considerable economic importance for nations as they provide water during drier summer days for irrigation purposes. Glacier ice itself has proved to be a profitable export commodity for some countries (monitoring glaciers). Countries like Switzerland enhance electric power generation from the water that is released of the glaciers. Tourism and habitat for species are some other important aspects of glaciers. Along with many benefits there are some hazards created due to glaciers like ice-bergs and surging (remember the titanic). From the past years, it is a well-known fact that glaciers are receding. Studying and monitoring glaciers is a very important but challenging task for the scientists worldwide.

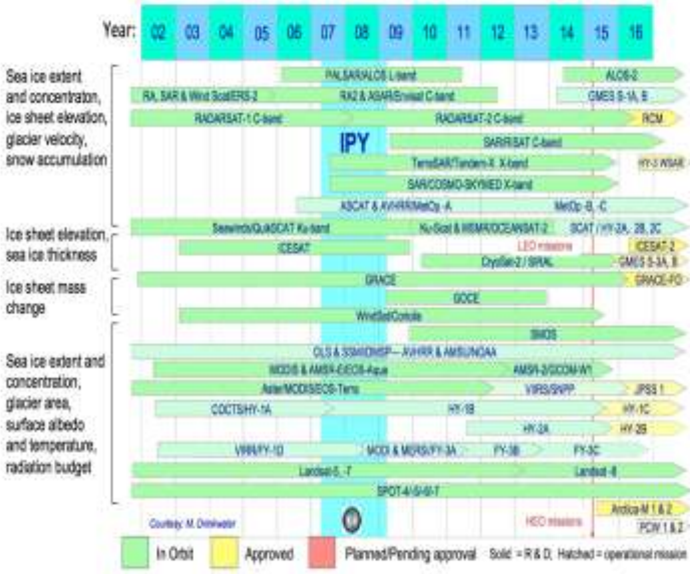


Fig 2: Cryospheric satellite missions (Source: <http://globalcryospherewatch.org/satellites/overview.html>)

IV. REMOTE SENSING TO MONITOR GLACIERS

Remote sensing, be it air-borne or space-borne is a better technique than the field methods to monitor changes occurring in glaciers. Many studies have been carried out using different sensors to measure various glacial parameters. Terra ASTER, SPOT [11], ALOS [12], Landsat [13] and IRS [14] are some of the successfully used sensors. IKONOS and Quickbird data have also been used to study glaciers [15-16]. Stereoscopic images acquired by satellites are used to develop a digital elevation model which acts as a tool to measure volumetric and mass balance changes in glaciers.

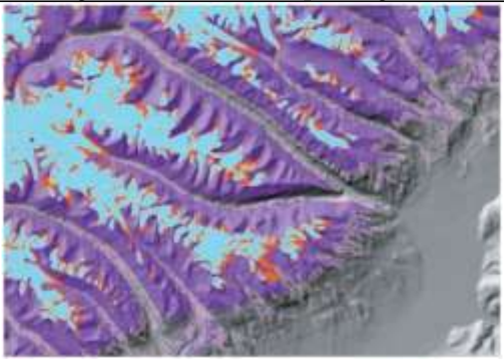
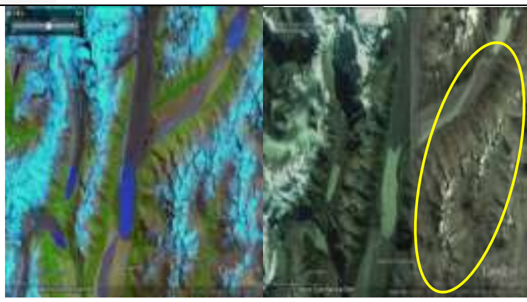
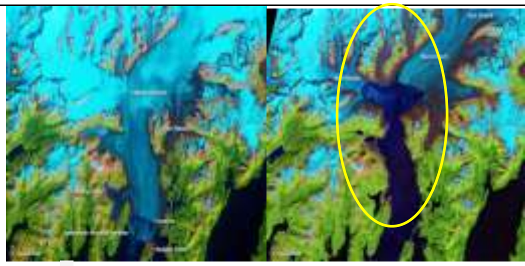
Glacial mapping, Digital elevation models for glacier mapping and the geodetic method of measuring glacier mass balance are most important features that comprise remote sensing application to study glaciers.

Terminus position and changes in glaciers can be easily extracted from multispectral satellite images. Calculated glacier areas when combined with a DEM, the glacier outlines

so generated are useful to derive other glacier parameters such as hypsometry, minimum/median elevations and equilibrium line altitude (ELA) (Klein A.G., 1996).
With high advantages of use of remote sensing to study glaciers there are few challenges also that remain in order to use the proposed methods at larger scales, such as, i.) The lack of standardized image analysis methods for delineation of debris-covered ice; ii) Limited field validation data (GPS measurements and specific mass balance measurements); iii) lack of accurate elevation data for remote glacierized areas; and iv) algorithms for automatically discerning debris-covered ice from non-ice areas with debris [17].

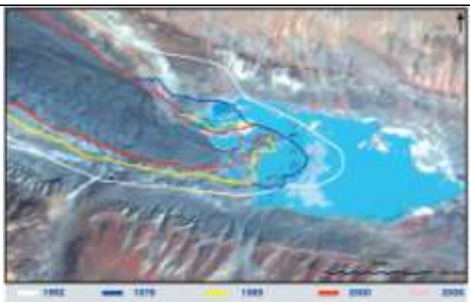
V. DATA ACQUIRED BY REMOTE SENSING WHICH ENSUE RECEDING OF GLACIERS

Table-1: Some Retreating Glaciers Studied Using Remote Sensing

Image/Remark/Data Capturing Source
 The study depicts a total area loss of the order of 13% per decade since the 1970s, or volume loss of 7 km^3 per year (0.02 mm yr^{-1} sea level equivalent) for glaciers in the **Lhasa river basin**. The basin has lost roughly 20% of their water-equivalent ice reserves during the last 20–30 years. *Instrument/Satellite:* Blue: Landsat data of 2000. Red: Glacier areas lost since 1970, CGI data. Light and Dark Violet: Probable permafrost distribution modelled by Keller (1992). Hillshade in background: SRTM DEM. Source: Adina E, et al.
 Over the last 25 years**, Gangotri glacier** has retreated more than 850 m, with a recession of 76 m from 1996 to 1999 alone. (Please note that the blue contour lines drawn here to show the recession of the glacier's terminus over time are approx.) *Instrument/satellite: (*NASA image by Jesse Allen, Earth Observatory; based on data provided by the ASTER Science Team. Glacier retreat boundaries courtesy the Land Processes Distributed Active Archive Centre.) SOURCE Terra- ASTER gangotri.kml
 NIWA scientists stated that **Tasman glacier** had retreated by 5 kilometres over the previous three decades. They also stated that New Zealand glaciers on the whole had lost 5.8 cubic kilometres over the same time period. *Instrument/satellite:* Google Earth(in this paper); for study taken by Terra –ASTER. (Image on left is of 2003 and on right is of the year 2013.) SOURCE tasmanglcr.kml
 Tree-ring records of precipitation anomalies and of temperature allowed them to reconstruct a 500-year history of snow water equivalent in the **Sierra Nevada**. The researchers found that the low snowpack of April 2015 was "unprecedented in the context of the past 500 years." *Instrument/Satellite:* Terra-MODIS. SOURCE sierranevada.kml
 Experimental results by Ryan Casotto show that both the West Branch and the East Branch (which feeds into the Main Branch) are now moving between 5 and 10 meters (16 and 33 feet) per day. *Instrument/Satellite:* Image on left (1986): TM sensor on Landsat 5 satellite; Image on right (2014): Operational land imager on Landsat

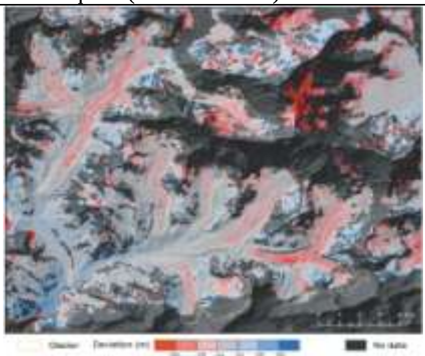
8 satellite. SOURCE

columbia.kml



An area loss of 16% over the 40- year period (0.4% yr^{-1}) in this area of the western Himalaya (**Samudra Tapu Glacier**), with rates per individual basin ranging frm 0.2 to 0.7% yr^{-1}.

Instrument/Satellite: Maps from 1962 for baseline glacier dataset. Then, compared with new glacier outlines from 2001/2002/2004 LISS-II/LISS-IV images. Remote sensing-based glacier outlines were derived using standard VIS–NIR band combinations (bands 2, 3, 4) from LISS-II and IV images, respectively, combined with visual interpretation techniques. (Adina E et. al.)



Glacier elevation changes from 1970-2007 at Mt. Everest were calculated from the data. Red is indicating the lowering of elevation of glaciers while blue is indicating advancement in elevation of glacier.

Instrument/Satellite: Corona KH-4B DEM and Cartosat-1 DEM (Bolch et al., 2011) Also done ICESMAP processing.

A temporal overview on short term glacier length change is shown in figure 3. The number of advancing glaciers is shown by blue stacks and the number of retreating glaciers by red stacks in the corresponding years of survey. From the figure it can be clearly seen that number of retreating glaciers are far greater than the advancing glaciers.

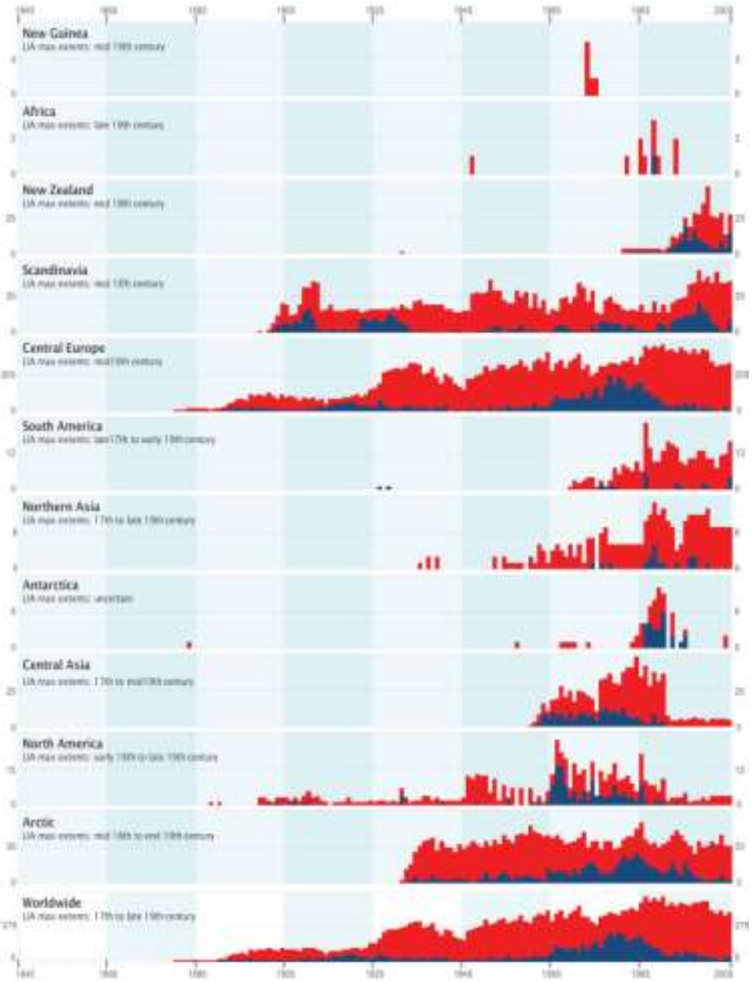


Fig 3: Number of advancing and retreating glaciers. (Source: fig based on data analysis by R. Prinz, University of Innsbruck; data from WGMS).

VI. CONCLUSION

Cryospheric remote sensing has become a very important technique since last five decades. It helps us understand and monitor the cryospheric components and their variations and trends. Moreover it helps in assessing the glaciers situated in the most unfavorable ground and climatic conditions such as the poles, Arctic and Antarctica.

Though there are some limitations and challenges to the use of remote sensing of cryosphere, however better techniques are getting evolved in order to overcome these obstacles. There are many projects launched by space agencies worldwide to monitor the changes occurring in glaciers as they of high importance for providing the evidences of climate change and it also helps in estimating the future water resources and contribution to sea level rise.

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