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Northern Great Plains Water Resources II

Utilizing NASA Earth Observations to Detect Changes in Annual Snowpack Coverage in Intermountain National Parks

**Technical Report** 

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# 1. Abstract

National Parks in the Intermountain region of the United States Northern Great Plains are experiencing changes in Persistent Ice and Snow Cover (PISC) due to changes in climate. Part of the mission of the National Park Service is to discover and protect cultural heritage sites, therefore, mapping changes in PISC is a crucial step in identifying archaeological sites exposed by the receding ice and snow. This project focused on three National Parks in the Intermountain region: Glacier, Grand Teton, and Yellowstone. Multispectral, 30 m resolution imagery from Landsat 5 TM and Landsat 8 OLI were classified to identify areas of PISC during the months of August and September from 1995 to 2016. The resulting composite, cloud-free images were further used to highlight areas where PISC had decreased during the study period.

**Keywords**

National Parks Service, snow and ice, glaciers, climate change, Landsat, remote sensing.

# 2. Introduction

* 1. ***Background Information***

As global climate continues to shift, the mean global temperature is at its highest in 1000 years (Crowley, 2000). In 2016, *The Bulletin of the American Meteorological Society* released the “State of the Climate in 2015,” which specified twenty-three states in the US with recorded annual temperatures within the 10th percentile of historical documentation (Blunden and Arndt, 2016). Furthermore, temperatures in 2015 from September to November were the warmest recorded in the contiguous United States (Blunden and Arndt, 2016).

Glaciers are sensitive to variations in temperature and serve as strong indicators of the global progression of climate change (Paul et al., 2013). Worldwide reports to the International Glacier Commission detailed that all monitored glaciers had significantly ablated or completely disappeared (Haeberli et al. 1989). Currently, Global Land Ice Measurement from Space (GLIMS) uses satellite imagery to compile a record of existing glaciers for research and monitoring. Such measurements can be incorporated into researching glacial advances or retreat.

Furthermore, land uncovered by retreating glaciers has the potential to contain cultural heritage and archeological sites (Andrews et al., 2012). In the interest of protecting these rare areas for their invaluable multidisciplinary research potential, the National Park Service (NPS) strives to discover cultural heritage sites within the border of Glacier, Grand Teton, and Yellowstone National Parks by assessing glacial recession from August 1984 to October 2016.

The Northern Great Plains Water Resources team from the summer 2016 term took an initial look at glacial recession in Rocky Mountain National Park. Analysis of satellite imagery showed a 51% and 69% decrease in area covered by glaciers and other Persistent Ice and Snow Cover (PISC), respectively, in the park between January 1998 and December 2015. A map depicting spatial change showed a trend in glaciers located on the southern ridges of the mountains as more susceptible to change than those located in higher elevations. The previous Northern Great Plains Water Resources team based much of their methodology off of research conducted by David J. Selkowitz of the US Geological Survey, Alaska Science Center and Richard R. Forster from the University of Utah’s Department of Geology. Selkowitz and Forster used available Landsat TM and ETM+ scenes to track PISC and glacial recession in his areas of interest. They also used cloud and shadow masks along with Normalized Difference in Snow Index (NDSI) thresholding to map the ice and snow cover for each scene and year of their study period. For the current project, the methods used by Selkowitz and Forster were slightly modified. The team mainly focused on comparing and validating the results with the results from the Selkowitz and Forster research. The current term will focus on changes in PISC and glacier recession within Glacier National Park, Grand Teton National Park, and Yellowstone National Park.

***2.1.1 Glacier National Park***

Located in northern Montana, along the front range of the Rocky Mountains, Glacier National Park covers over 1 million acres of forest, alpine meadows and lakes (National Parks Conservation Association, 2016; Finklin, 1986). Historically, the region was heavily utilized for fishing, hunting, and timber by the Native American Blackfoot and, in 1895, the US government negotiated a deal with the tribe to purchase over 200 square miles of land for $1.5 million (Keller and Turek, 1998).

Glacier National Park was opened on May 11, 1910 and quickly became known as the Backbone of the World. With elevations ranging from 3,110 to 10,466 ft., the park is famous for its mountainous topography carved by an estimated 150 glaciers (Finklin, 1986). However, by 1980, over two-thirds of the park’s original glaciers had completely disappeared and continue to ablate at an alarming rate (Hall and Fagre, 2003; Johnson, 1980). The recession of these glaciers translates into a decrease in fresh water availability, which will become problematic as the park is currently home to variety of plants and wildlife, including one of the largest remaining grizzly bear (*Ursus arctos*) populations in the lower 48 states (National Parks Conservation Association, 2016).

***2.1.2 Grand Teton National Park and John D. Rockefeller Jr. Memorial Parkway***

Northwest Wyoming’s Teton Mountain range is home to Grand Teton National Park and the John D. Rockefeller, Jr. Memorial Parkway. Grand Teton National Park was established in 1929 and was joined with the Jackson Hole National Monument to create the present-day Grand Teton National Park in 1950 (Skaggs, 2000). The combined area consists of 310,000 acres (485 mi2) of mountainous terrain with elevations ranging from 6,320 to 13,770 ft. (U.S. Department of Interior, National Park Service. 2016). The John D. Rockefeller, Jr. Memorial Parkway was established in 1972 in commemoration of Rockefeller’s donations of land to the National Park Service. The Parkway connects Grand Teton and Yellowstone National Parks via U.S. Highway 89 and contains 23,700 acres (U.S. Department of Interior, National Park Service. 2016).

The landscape of Grand Teton National Park was formed primarily by movement of the Teton Fault. This fault runs north to south along the east side of the Teton Mountain Range. The Teton Range is the upthrown fault block while Jackson Hole is situated on the downdropped hanging-wall block (KellerLynn, 2010). The landscape has been shaped by periods of glaciation, particularly the Pinedale glaciation (30,000 to 12,000 years ago) (KellerLynn, 2010). As recently as 2011, there were 10 active glaciers within Grand Teton National Park (Reynolds, 2011).

The John D. Rockefeller, Jr. Memorial Parkway consists of a blend of geologic features from Grand Teton and Yellowstone National Parks. It is influenced by the Teton Fault zone but has also been covered by layers of lava and ash from Yellowstone volcanic activity (KellerLynn, 2010). Glaciers completely covered the Parkway during the Pleistocene Epoch, creating gouged valleys and rounded mountains (Rodman et al, 1992), but are now currently absent within the Parkway.

***2.1.3 Yellowstone***

Yellowstone National Park was established on March 1, 1872, making it the first national park in the United States. The park contains approximately 2,221,766 acres with elevations from 5,282 to 11,358 ft. and, while it is predominantly located in Wyoming, the park extends into parts of Idaho and Montana. This park is unique to other National Parks because it contains one of the world’s largest calderas and is seismically active with 1,000-3,000 earthquakes annually (National Park Service U.S. Department of the Interior1, 2016).

Yellowstone National Park has extensive geological and anthropogenic histories. There have been several glaciations during the previous 2.6 million years evident in the large U-shaped valleys, moraines, and erratics within the park (Renkin, 2016). Yellowstone has documented human presence for more than 11,000 years (Park, 2016); with more than 1,800 documented archeological sites, the entire park is an invaluable cultural heritage site (National Park Service U.S. Department of the Interior2, 2016). There are currently no glaciers within Yellowstone National Park, though there are several areas of persistent ice and snow cover.

***2.2 Project Partners & Objectives***

The National Park Service was established in 1916 and currently has eighteen locations in the Intermountain Region. Recent changes in climate have resulted in ice and snow melt in the National Parks in the Intermountain region of the Northern Great Plains and, as a result, areas that were previously covered by persistent ice and snow, have been exposed.

The primary NASA Application Areas for this project are Water Resources and Climate, as this project measures glacial recession and the ensuing vegetative cover due to an increase in global temperatures. The data will help the National Park Service to locate and preserve previously covered sites of archaeological interest which are now accessible due to glacial retreat in the intermountain region. The project also aims to allow the National Park Service in Yellowstone, Grand Teton, and Glacier National Parks to restore areas where vegetative cover and fire regime have been altered by glacial ablation.

# 3. Methodology

***3.1 Data Acquisition***

The Northern Great Plains Water II team assessed changes in PISC through the Google Earth Engine (GEE) platform. Surface reflectance imagery from Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) for the study period of January 1964 through October 2016 was processed within GEE (Table 1). The resulting images were downloaded in GeoTiff format for further manipulation in ArcGIS. Additionally, the team accessed U.S. Department of Agriculture National Agricultural Imagery Program (NAIP) imagery for its ability to discern surface features at high resolution.

**Table 1.** *Landsat path and row numbers for Glacier, Grand Teton, and Yellowstone National Parks.*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| National  Park | Scene 1 | | Scene 2 | |
| Path | Row | Path | Row |
| Glacier | 41 | 26 | N/A | N/A |
| Grand Teton | 38 | 29 | 38 | 30 |
| Yellowstone | 38 | 29 | N/A | N/A |

The team used the University of Idaho’s GRIDMET climate data to look at relevant climate variables on a park-by-park basis from January 1979 to October 2016. GRIDMET was chosen because of its 4 km spatial and daily temporal resolution, in addition to being native to the GEE platform. Daily average precipitation during the months of November to March, as well as daily average high temperature from April to September were calculated on a yearly basis from 1979 to 2015.

The NPS provided the team with shapefiles of the parks as administrative boundaries, as well as shapefiles of the most up-to-date record of glacial cover in each park. Additionally, data was obtained from the Randolph Glacier Inventory (RGI), a globally complete inventory of glaciers, from its most recent iteration in 2015. Glacier shapefiles from the parks and RGI were used as comparison for the final products produced in GEE.

***3.2 Data Processing***

The Landsat surface reflectance acquired from GEE was filtered to the melting season, August through September of a given year, and scenes in Table 1. Given the cloudy environment of the Parks, steps were taken to ensure the most cloud-free images were used for analysis. The Landsat surface reflectance scenes from a melting season were condensed into a single image by taking the median value of each pixel. The team inspected each of the median images for persisting cloud cover. Images that showed less than ten present cloud cover were used for further analysis. Two different ice cover identification techniques were applied: supervised classification and index thresholding illustrated in Figure 1.

**Figure 1.** *Flowchart of different techniques applied in Methodology.*

**PISC**

**Condensed Melting Season**

Mask Clouds and Ice

Landsat Imagery

Landsat Imagery

**Landsat Imagery**

**Create Mask Water**

**Condensed Melting Season**

**Water-Free Melting Season**

**Supervised Classification**

**Extract Ice Cover**

**Apply Index Threshold**

**Calculate Decadal Difference**

Mask Clouds and Ice

**Mask Clouds and Ice**

Initially the team implemented a GEE supervised classification technique. Four classes were used to analyze the Landsat imagery: vegetation cover, water, ice/snow cover, and bare earth/soil. Training points were manually collected by team members in these class types. Over 1,000 unique training points were collected per year of analysis per park. Team members selected vegetation points in forests, grasslands, and vegetation covered in shadow. Water values were selected from large lakes and small glacial lakes. Snow and ice cover points were collected in the center and edges of large snow bodies, and in areas covered in shadow. Finally, points for bear earth/soil were collected on different soil types, exposed rock faces, and in areas of shadow. Ninety percent of the training points from a year were used to train the supervised classification model in GEE. The remaining ten percent were used to test the classification accuracy. Glacier National Park was classified for the years of 1995, 2001, 2006, 2011, and 2015. Yellowstone National Park and Grand Teton National Park were classified for the years of 1995, 1999, 2005, 2011, and 2016.

The second technique used to identify ice cover from the condensed melting season Landsat images was index threshold. Unlike the Supervised Classification technique, index thresholding was not able to bias out any additional cloud contamination. Condensed melting season Landsat images with more than ten percent cloud cover were removed. However, NDSI values for ice and water are similar so the team created a cloud free water mask.

The surface reflectance CF-mask was used to remove cloud cover more thoroughly. Consequently, ice cover was removed because clouds have similar spectral qualities as snow. The CF-mask applied to the condensed images removed the ice and cloud cover from the scenes. Then, thresholding was used to create a water mask. The water mask threshold values were NDVI < 0.3 and the Normalized Difference Water Index (NDWI) > -0.75. The water mask was applied to the condensed melting season Landsat images and a threshold NDSI greater than 0.4 was set to capture the ice cover. The resulting ice cover data were exported from GEE as images and shapefiles. The data was imported into ArcMap along with the National Hydrography Dataset (NHD) waterbodies data. The NHD waterbodies file was used as an additional mask to remove more falsely identified water pixels.

The team grouped the processed ice cover areas into decades by adding the rasters in ArcMap. Those rasters were then divided by the number of years measured within that decadal period. The resulting raster showed the percent likelihood of a pixel having snow within the decadal period. The team then used the Reclassify Tool in ArcMap to remove areas with less than 30% likelihood of snow cover in the decadal period to account for years of high snowfall. These remaining ice cover areas were classified as PISC. The difference in PISC was calculated by subtracting the total area of PISC from sequential decadal periods.

The NDVI Difference Maps were generated using data from GEE NDVI calculations and the Area of Exposed Land maps. The team gathered Landsat surface reflectance images within the melting season and tiles in Table 1 in two consecutive decades. Scene with more than 10 percent cloud cover were removed. NDVI values were calculated for each year of available data. The decadal representation of NDVI was calculated by taking the median NDVI value for each pixel within the decade. The previous median decade NDVI was subtracted from the most recent median decade NDVI. Area of exposed land was used as a mask to remove any NDVI data values outside of PISC area change.

Climate analysis was also completed in GEE script. The GRIDMET data was first subset to each park. The daily average precipitation was averaged over November to March. The daily average high temperature was averaged over April to September. The output of this script was a table of the data in comma separated value format. The data were input into Microsoft Excel for further analysis of yearly and decadal trends and their relationship to PISC.

***3.3 Data Analysis***

In each park, the measured ice cover areas from the supervised classification and index thresholding were compared by total area difference in ArcMap. Table 2 shows the differences in ice cover area detected by both methods.

**Table 2.** *Difference in ice cover measurements in supervised classification and index thresholding in acres.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Year | Glacier Ice Cover Area Difference (Acres) | Glacier Percent Difference | Grand Teton Cover Area Difference  (Acres) | Grand Teton Percent Difference | Yellowstone Cover Area Difference (Acres) | Yellowstone Percent Difference |
| 1995 | 17,732 | 0.77% | 2,906 | 0.45% | 1,433 | 0.03% |
| 1999 | NA | NA | 4,720 | 0.74% | 3,580 | 0.08% |
| 2005 | NA | NA | 551 | 0.09% | 363 | 0.01% |
| 2006 | 8,896 | 1.31% | NA | NA | NA | NA |
| 2011 | 38,770 | 1.49% | 4,499 | 0.70% | 6,581 | 0.15% |
| 2015 | 18,790 | 0.82% | NA | NA | NA | NA |
| 2016 | NA | NA | 2,152 | 0.34% | 345 | 0.01% |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Glacier National Park | | Grand Teton National Park | | Yellowstone National Park | |
| Years | Area (acres) | Years | Area (acres) | Years | Area (acres) |
| 1984-1995 | 16578.2 | 1986-1996 | 3292.0 | 1986-1996 | 24.0 |
| 1996-2005 | 28229.5 | 1997-2006 | 1419.2 | 1997-2006 | 90.7 |
| 2006-2015 | 10954.1 | 2007-2016 | 1912.3 | 2007-2016 | 19.6 |

**Table 3**. *Average* *decadal PISC*

|  |  |
| --- | --- |
| Decadal PISC Comparison | Percent Change |
| 1986-1995 to 1996-2005 | 37% |
| 1996-2005 to 2006-2015 | -24% |
| 1986-1995 to 2006-2015 | 4% |

**Table 4.** *Difference in PISC measurements in supervised classification and index thresholding for Glacier National Park.*

|  |  |
| --- | --- |
| Decadal PISC Comparison | Percent Change |
| 1986-1996 to 1997-2006 | -57% |
| 1997-2006 to 2007-2016 | 35% |
| 1986-1996 to 2007-2016 | -42% |

**Table 5.** *Difference in PISC measurements in supervised classification and index thresholding for Grand Teton National Park.*

|  |  |
| --- | --- |
| Decadal PISC Comparison | Percent Change |
| 1986-1996 to 1997-2006 | 278% |
| 1997-2006 to 2007-2016 | -78% |
| 1986-1996 to 2007-2016 | -19% |

**Table 6.** *Difference in PISC measurements in supervised classification and index thresholding for Yellowstone National Park.*

# 4. Results & Discussion

***4.1 Analysis of PISC Results***

The index thresholding method misidentified ice cover in Glacier and Grand Teton National Park, shown in Table 4. The missing ice cover in these parks is less than 2% of the parks total area. The mountainous terrain in the parks results in large swaths of area to be shadow covered, and the missing ice cover area in these parks falls within these shadow covered areas. PISC in Glacier National Park increased from 1986-1995 to 1996-2005.

Table 2 shows that the parks have various differences in ice cover area between the two techniques. Yellowstone National Park’s supervised classifications show the most difference compared to the index thresholding. Investigating the areas of ice cover lead to the discovery that the supervised classification was incorrectly mapping areas of bright soil as snow. This resulted from the small sample size of training points collected over these areas. Table 6shows an overall decrease of PISC in Yellowstone National Park. The increasing percent change from 1986-1996 to 1997-2006 was due to high snow precipitation and fewer years for measurement.

Compared to Selkowitz and Forster’s thresholding data, the GEE thresholding technique proved to be far more conservative in its estimates of where PISC was located. In Glacier National Park, the percent difference in area of PISC identified ranged from 85% in 2009, to 193% in 2014 and 2015. One of the reasons for this discrepancy in total PISC can be attributed to the fact that Selkowitz and Forster did not use a water mask, which is not easily applied on the continental scale of their study; any water (from large lakes to small glacial pools) was automatically classified as perennial ice and snow cover, inflating the reported total PISC area. Another contributing factor to this discrepancy is due to the GEE thresholding technique underrepresenting PISC in shaded areas.

In Grand Teton National Park, Selkowitz and Forster’s total area of PISC again was higher than the data collected for this project. There was much more fluctuation of percent difference than in Glacier National Park. In 1995, the percent difference between this project and Selkowitz and Forster’s data was 36%, compared to 195% difference in 2009. Much of the land that GEE categorized as bare ground was considered to be PISC by Selkowitz and Forster.

Analysis of the PISC data from Glacier National Park on a decadal basis revealed some trends that run counter to the steadily decreasing PISC that has been experienced in other areas. From 1986 to 1995 the average area covered by PISC was 16,599.3 acres, between 1996 and 2005, PISC averaged 28,927.8 acres, and between 2006 and 2015 PISC averaged 17,548 acres (table 3). This is believed to be due to a combination of climatological factors. During the 1986-1995 period, melting-month temperatures were average, but precipitation was lower than average; during the 1996-2005 period, melting-month temperatures were lower than average and precipitation was average; during the 2006-2015 period, melting-month temperatures were higher than average and precipitation was average (figs. 2, 3).

In Grand Teton National Park, PISC was at its maximum of 3,292.0 acres during the 1986 to 1996 time period (table 3). It decreased to an average of 1,419.2 acres 1,419.2 acres from 1997 to 2006. In the final decade of the study, from 2007-2016, PISC in Grand Teton National Park increased slightly to 1912.3 acres in area. The overall trend of decreased PISC followed the climate trends of increasing temperatures and steady precipitation (figs. 4, 5).

Yellowstone National Park has very sparse PISC due to lower elevations throughout the park. There are no glaciers, so PISC swings from year-to-year depending on the date and intensity of late-season snowfall (table 3). As temperatures continue to rise, the average PISC should decline (figs. 6, 7).

***4.2 Analysis of Climate Results***

Analysis of temperature during the melting months of April through September, and precipitation during the winter months of November through March, was conducted on a park-by-park basis. The variables were averaged over each year so overall trends could be monitored. Though temperature and precipitation are highly variable on a yearly time frame due to El Niño Southern Oscillation (ENSO) and other factors, overall trends for the last 36 years can be observed.

From 1979 to 2015 in Glacier National Park, average melting-month high temperatures increased by almost 1° C shown in Figure 2. There was considerable variability from year-to-year that was independent of any standard climatic indices. Precipitation during the winter each year increased during the study period by nearly 1 mm/day. Precipitation was variable as well (Figure 3). However, years of higher precipitation tended to occur during a La Niña cycle while lower precipitation occurred during El Niño years.

**Figure 3.** *Average monthly precipitation of Glacier National Park in November through March.*

**Figure 2.** *Average temperature of Glacier National Park in melting season, April through September.*

Within Grand Teton National Park and the John D. Rockefeller Jr. Memorial Parkway, average melting-month temperatures increased by approximately 0.5° C as shown in Figure 4. Figure 5 shows the winter precipitation during the study period remained nearly constant on average. There was considerable year-to-year variability in both temperature and precipitation. Temperature showed little correlation to climatic indices, but precipitation was higher during La Niña years and lower during El Niño years.

**Figure 5.** *Average monthly precipitation of Grand Teton National Park in November through March.*

**Figure 4.** *Average temperature of Grand Teton National Park in melting season, April through September.*

Yellowstone National Park showed similar trends in climate to Grand Teton National Park, which was expected given the parks’ proximity to one another. Figure 6 shows melting-month temperature increased by almost 1° C. Winter precipitation remained nearly steady on average at 3.0 mm/day as shown in Figure 7. Average melting-month temperature did not appear to follow any trends in the climatic indices, but precipitation roughly followed the Southern Oscillation Index with higher precipitation occurring during La Niña years and lower precipitation usually occurring during year with a strong El Niño.

***4.3 Future Work***

There is room for further refinement of PISC detection in the Intermountain Region. As with all remote sensing projects, detecting PISC can benefit from utilizing higher resolution imagery, such as Sentinel-2a. Furthermore, both methods only monitor changes in PISC area. To fully understand the retreat of PISC and glaciers future work should include monitoring the volume change of PISC. Currently, the GEE supervised classification is too time consuming and memory intensive to analyze all of the available years for PISC. Future PISC studies may benefit from solely using GEE supervised classification of snow cover because of its higher accuracy.

**Figure 7.** *Average monthly precipitation of Yellowstone National Park in November through March.*

**Figure 6.** *Average temperature of Yellowstone National Park in melting season, April through September.*

Additionally, future expansion or refinement can be applied to the index thresholding approach. The NDVI, NDWI, and NDSI values are conservative to preserve more ice area. This leaves some water pixels to be falsely identified as ice cover. Refinement to the water mask would remove more of the water pixels from the image before NDSI thresholding was applied. There are some ice cover pixels that are not identified in the NDSI threshold because they are in shadowed areas. Finding a method for subtracting shadows from the Landsat surface reflectance while preserving ice cover may improve further monitoring of retreating PISC.

# 5. Conclusions

The PISC within the Intermountain National Parks is undoubtedly decreasing. There are ground observations and photographic evidence that prove some glaciers have significantly reduced in volume, if not melted entirely. Monitoring the retreat of PISC area with satellite observations has provided an insightful look at year-to-year trends in PISC. While the index thresholding method is faster than utilizing a supervised classification, it has some drawbacks. At this time, index thresholding cannot completely remove falsely- identified water pixels. Furthermore, areas of ice cover in shadows are not reliably measured because of the differences in spectral value.

Parks may benefit from reducing the study to individual or groups of glaciers and preforming a smaller-scaled supervised classification. The smaller study area would reduce sampling bias while still mapping ice cover in shadows. Furthermore, the smaller study area my increase the number of measurable years because of the reduced chance of cloud contamination. Differentiation of PISC between glacial and non-glacial areas using remotely-sensed data could not be verified using the methods outlined in this study.

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# 8. Content Innovation

**Content Innovation #1**

**Glossary Viewer**

***Ablation:*** removal of ice and/or snow through melting or evaporation.

***Earth Observation (EO):***umbrella term used that includes all airborne and flight missions that study the Earth.

***Earth Observing System (EOS):***a subset of the full suite of NASA Earth observing missions focused on long-term global observations of the long-term global observations of the land surface biosphere, solid Earth, atmosphere, and oceans to improve understanding of the Earth as an integrated system.

***El Nino & El Nina (El Nino-Southern Oscillation) (ENSO):*** the warm and cool phases of a cyclic climate pattern in the tropical Pacific. Shifting back and forth every two to seven years, the pattern results in swings in temperature, precipitation, and wind in the tropics as well as triggering a host of global side effects.

***Erratics:*** A piece of rock that greatly differs type and size to the native rock around it. Such rocks were carried by glaciers over great distances and deposited when the glacier receded.

***Global Land and Ice Measurements from Space (GLIMS):***Project utilizing satellite data to monitor glaciers across the globe.

***Google Earth Engine (GEE):***collection of satellite imagery and geospatial datasets with large-scale analysis capabilities available for developers to quantify differences on the Earth’s surface.

***Landsat 5, Thematic Mapper (TM):***NASA EO launched on March 1, 1984.

***Landsat 7, Enhanced Thematic Mapper Plus (ETM+):***NASA EO launched on April 15, 1999.

***Landsat 8, Operational Land Imager (OLI):***NASA EO launched on February 11, 2013.

***Moderate-resolution Imaging Spectroradiometer (MODIS):***NASA EOS consisting of two satellites, Aqua and Terra, whose orbits run perpendicular to one another across the earth.

***Moraine:*** Ridge of debris material such as pebbles and boulders deposited when glaciers retreat.

***National Park Service (NPS):*** Federal government agency that manages all national parks, monuments and other historical properties in the US.

***National Hydrography Dataset (NHD):*** The National Hydrography Dataset contains information about lakes, rivers, wetlands, glaciers, and other water features. Generated from the US Geological Survey.

***Normalized Difference in Snow Index (NDSI):*** a graphical indicator used to analyze remotely-sensed data on snow on the earth.

***Normalized Difference in Vegetation Index (NDVI):*** a graphical indicator used to analyze remotely-sensed data on live green vegetation on the earth.

***Normalized Difference in Water Index (NDWI):*** a graphical indicator used to analyze remotely-sensed data on water across the surface of the earth.

***Persistent Ice and Snow Cover (PISC):*** ice and snow that does not melt over the course of an entire year.

***Randolph Glacier Inventory (RGI):*** a globally complete inventory of glaciers.

***Sentinel-2a:***ESA EO launched June 23, 2015.