Time-evolving inventory of tropical glaciers in Southern Peru, Bolivia, and Northern Chile

Analysis of the Risks of Glacier Shrinkage

Abstract Glaciers have been drastically changing in size for the past few decades. In the areas of Southern Peru, Bolivia, and Northern Chile, the eastern cordilleras (wet tropical glaciers) and western cordilleras (dry tropical glaciers) are shrinking at an alarming rate. Since many populations depend on them for water supply and other societal, economic, and cultural regions, this is a concerning issue for several communities. Using remote sensing and passive remote sensing, the retreat of glaciers have been tracked and recorded in glacier inventories for years. I used satellite and model data as well as the Randolph Glacier Inventory to record the evolution of glaciers for several years while also predicting their future conditions. Applying these techniques/technology, here I show that wet tropical glaciers, eastern cordilleras, have lost the greatest areal coverage while dry tropical glaciers, western cordilleras, have the greatest rate of loss. It was not previously known that these cordilleras were disappearing so fast. In the 4 regions studied, all glaciers showed some loss between 2000-2016. These results signify an issue that is present throughout the world and may be troubling for societies. With further research into the conditions/evolution of these glaciers and taking crucial steps to prevent their shrinkage, we may be able to slow it down while preventing any adversities that may occur.

Introduction Tropical glaciers (or cordilleras) located at low latitudes and high peaks have been studied in the regions of Southern Peru, Bolivia, and Northern Chile for years. Their size, shape, boundaries, location have been measured and collected in inventories like the Randolph Glacier Inventory by researchers for decades (Lynn, T. X. 2015). Satellites have aided researchers in creating images and accurate dimensions of the Earth surface (specifically glaciers in this case) which have helped me understand their past, present, and future conditions (Kelly, J. Z. 2016). After studying the South American cordilleras, I can conclude that glaciers have been decreasing

in area greatly, with one of the regions experiencing a very high rate of disappearance (Sal, K. T., et al 2017). The RGI's analyzed areas vary a lot from the actual values attained over the years. This discrepancy calls for further investigation with more data that will accurately predict what these glaciers will be like in the future.

I will discuss how these values were attained in the later sections. I will go through the technology/techniques utilized to make these specific measurements and create the images used to study the glaciers. After the analysis of the programs, the quantitative data will be discussed along with an interpretation of what the numbers imply. Connecting the past and present states of the glaciers will help forecast their future conditions. Many populations around the world benefit from this since they rely on ice/snow packs as resources (Rick, A. C., Finnick M. S., et al 2015). This is also examined and investigated (although more data is needed globally) so conclusions can be made to understand the effect the glaciers will have on communities in other countries.

Methods As discussed earlier, tropical glaciers in the South American regions of Peru, Bolivia, and Chile are retreating at a very high rate. Remote sensing, active and passive, was used to classify land surface features. The Landsat Program, which is the longest running satellite observing program still being used, can differentiate between land surfaces by using infrared radiation and the NDSI (Normalized Difference Snow Index). The Landsat satellites receive natural light and thermal radiation from the earth's surface which manipulates optical properties to create images that discern various land surfaces. This sort of Passive Remote Sensing is what I utilized to see where glaciers are located. On the other hand, Digital Elevation Models (DEM) are an Active Remote Sensing technology that I worked with to get a three dimensional picture of the Earth's surface. Shuttle Radar Topography Mission (SRTM) is a database that includes

DEMS from latitudes 56°S to 60°N. Using the satellite data and information from the SRTM, I was able to record where/how large the glaciers were every year.

Examining the images from 2000-2016, I observed a decrease in the area of all four glacier regions being studied. Regions 1-3 had a 20%-25% decrease while Region 4 had a decline of 45% in its Western Cordillera. The area lost was more than the RGI forecasted for every glacier. Region 2 Cordillera Real lost the most area (44 km^2) while Region 4 Western Cordillera lost at the greatest rate (1.8x faster). The 2016 areas are about ¼-½ the size of the RGI areas. Despite the inventories being out of date, the Landsat program, DEMs, and SRTM have shown that generally, the rate of glacier shrinkage has increased dramatically in some regions while other regions have experienced a great loss of area.

Results The tropical glaciers located at the low latitudes, but high peaks, of Southern Peru, Bolivia, and Northern Chile, have been decreasing in area for the past several years. This data has been recorded in inventories like the Randolph Glacier Inventory for decades. The longest running satellite observing program, the Landsat Program, uses infrared radiation to differentiate various land surfaces (lakes, snow, etc.). I further applied the Normalized Difference Water Index and Normalized Difference Snow Index to pinpoint the exact areas of ice/snow cover. Compared to 2000, the Landsat satellites detected less snow/ice cover in 2016 at the cordilleras of the 4 regions being studied. The images visibly show that these glaciers are not as extensive as they used to be years ago.

Additionally, Shuttle Radar Topography Mission (SRTM) is a near-global surface elevation model that aided in creating a three dimensional map of the Earth to find the higher elevations which may have glaciers. These Digital Elevation Models helped identify the 4

regions in between 56°S to 60°N latitudes that have glaciers on mountains or volcanoes. Together, the total study area covered in glaciers was measured by the RGI to be 623.7 km^2. After visually assessing the areas, I examined and quantitatively assessed the differences over the years. I determined the average to be 44.6 km^2 (Region 2) loss of ice and snow per decade. This is quite significant because the previous forecasts and inventories did not predict a decline in area so large or at a rate so high (1.8x faster at Region 4). This can be seen in Figures 1 and 2 which show the loss of area for each glacier along with the RGI areas (Figure 2). The RGI, and other inventories, reveal antiquated values that do not reflect the current conditions of these glaciers. With additional research, more accurate forecasts and predictions can be made with a better understanding of their evolution.

Discussion With more information on the boundary conditions of the cordilleras in Southern Peru, Bolivia, and Northern Chile, a better understanding of how they evolve can be achieved. For the past couple decades, an overall decrease in area of tropical glaciers has been occurring throughout the regions with one of the regions experiencing a very high rate of decline. With this new data, I was able to learn more about the glaciers and make future predictions about how they will develop in the future. This is very important for communities living near/around these areas that value them as cultural, societal, and economic resources (Rick, A. C., Finnick M. S., et al 2015). Since glaciers provide water buffering, hydroelectric power, supply, etc. to many populations, it will be a great loss if they keep decreasing in size. There needs to be more assessments of current and future water resources as well as an investigation into the causes of decline. Whatever human activities that may be affecting the glacier changes must be analyzed and actions need to be taken to prevent it from getting any worse.

There were some limitations with this study: it was only considering tropical glaciers and low latitudes and high peaks. Other glaciers around the world need to be studied extensively to make conclusions about the magnitude of this issue. If other areas around the world with populations that depend on these ice/snow packs for resources are being affected in the same way as the populations in South America, it may be a global concern that can have implications not yet foreseen (Fizzle, M. P. 2018). With an improvement in the current inventories, like the RGI, and more data collection from remote sensing, accurate models can be created which will help us understand the conditions/evolution of glaciers (Lynn, T. X. 2015). This can in turn help sustain communities that depend upon them as essential resources.

References

Fizzle, M. P. (2018). Glacier retreat effect on populations in the Andes Mountains. Proc Natl Acad Sci USA, 132(19), 6358-6397. https://doi.org/10.1059/pnas.1639217046

Sal, K. T., et al (2017). Changing boundary conditions of South American Cordilleras. Nature Communications, 9, 8562. https://boi-org.proxy.cc.edu/10.1045/ncomms8562

Kelly, J. Z. (2016). Use of remote sensing in tracking glacier movements. Proc Natl Acad Sci USA, 125(18), 7224-7272. https://doi.org/10.1099/pnas.182837251

Lynn, T. X. (2015). Shuttle Radar Topography Mission and Digital Elevation Models in creating three dimensional surface maps. Nature, 533, 562-587. https://doi-org.proxy.cc.uic/10.1044/nature22814

Rick, A. C., Finnick M. S., et al (2015). Spatial-temporal glacier changes in Peru. Proc. R. Soc. B, 278, 20153194. https://doi-org.proxy.cc.uic/10.1031/rspb.2015.3194

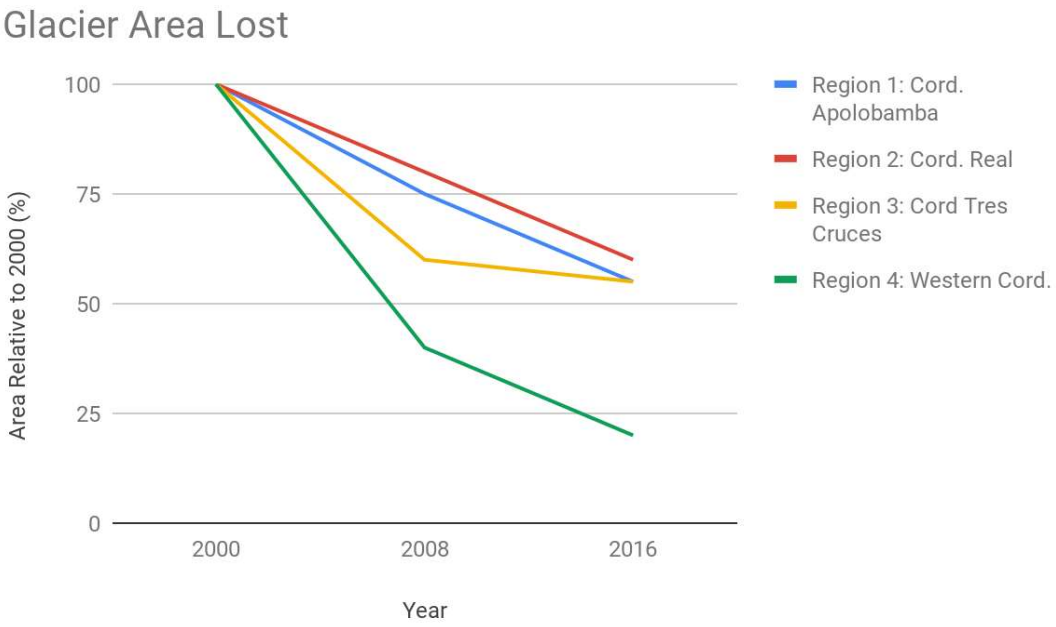

Figure 1. The percentage of glacier/cordillera area that was lost is displayed on the y-axis. The year (on the x-axis) that the data was recorded is from 2000 to 2016. Each of the 4 regions decreased in area over 16 years with Region 4 declining the most and at the fastest rate compared to the other cordilleras.

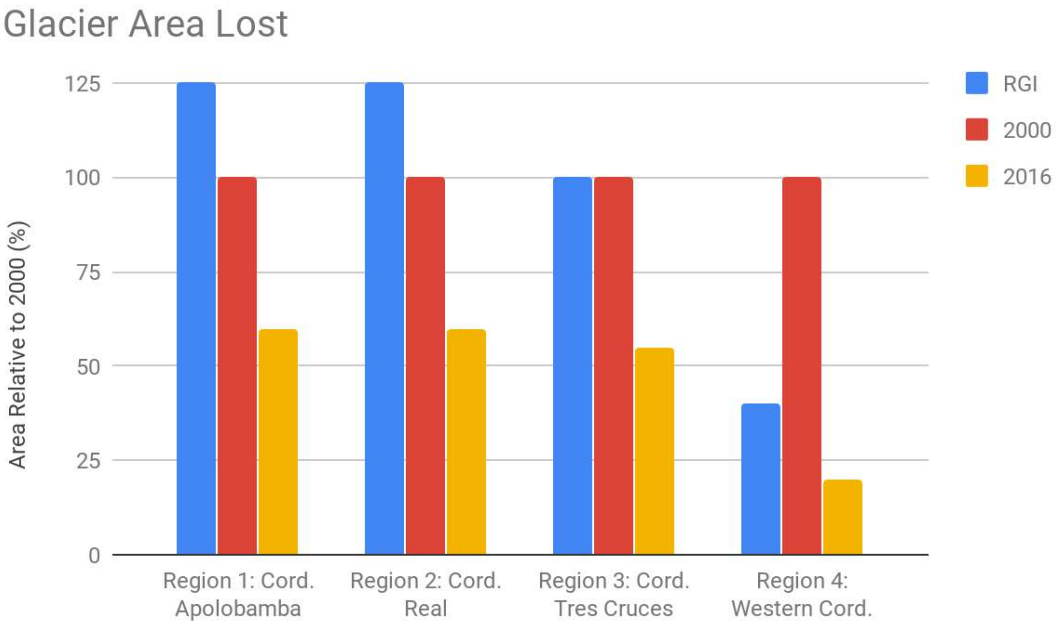

Figure 2. Four different regions in Southern Peru, Bolivia, and Northern Chile have tropical glaciers/cordilleras at high peaks.The red columns show 100% area of the glacier being present in the year 2000. The orange columns show the area in 2016; all of the cordilleras decreased in size, with the Region 4 Western Cordillera experiencing the fastest rate of disappearance. The blue columns indicate the RGI analysis areas.