ANALYSIS OF GLACIER RECESSION IN THE CORDILLERA APOLOBAMBA, BOLIVIA 1975-2010

A Thesis

by

LADONNA RENÉ LATTERMAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2011

Major Subject: Geography

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Approved by:

Chair of Committee,	Andrew G. Klein
Committee Members,	Anthony Filippi
	John R. Giardino
Head of Department,	Vatche Tchakerian

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ABSTRACT

Analysis of Glacier Recession in the Cordillera Apolobamba,
Bolivia 1975-2010. (December 2011)
LaDonna René Latterman, B.S., Texas A&M University
Chair of Advisory Committee: Dr. Andrew G. Klein

The tropical glaciers in the Bolivian Andes Mountains are small and respond quickly to changes in their climate. They are also a major source of freshwater year-round for nearby communities. Monitoring the glacial changes taking place in these glaciers has become increasingly important as they have been retreating over the past century. These glaciers are remote and the terrain treacherous making it potentially dangerous to gather data through field work. For this reason and because of advances in remote sensing technologies the use of satellite images has become the primary means to study these tropical glaciers in detail.

This research study focuses on the Cordillera Apolobamba range located on the Peruvian-Bolivian border. It is an example of the methodology applied to assess the area covered by glaciers in this and other regions around the world. Using Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images from 1985 to 2010, as well as the Glacier Inventory of Bolivia, the glacier extents of the Apolobamba are mapped. From 1975 to 2010 the portion of the range located within Bolivia's border lost 110.76 km^2 of surface ice lowering its total area from 240.36 km^2 to 129.60 km^2, a

46.08% reduction. From the 1985 to 2010 the entire Apolobamba range lost 102.72 km^2 of ice lowering its total area from 261.07 km^2 to 158.35 km^2, a 39.35% reduction.

An analysis of atmospheric conditions was conducted at the 500 hPa level for various climate variables using NCEP/NCAR reanalysis data. Between time period one (1975-1986) and two (1987-1995) the climate variables exhibiting a statistically significant change are air temperature with an increase of .165°C and geopotential height with an increase of 2.967 m. Between time period two and three (1996-2005) the climate variables exhibiting a statistically significant change are freezing level with a 50.017 m increase, precipitation with an 60.604 mm/month decrease and wind velocity with an increase of .373 m/sec. According to the analysis conducted using the Oceanic Niño Index, the monthly sea surface temperatures exhibit no statistically significant change from 1975-2005.

DEDICATION

I dedicate this thesis to my loving parents, Larry and Kim Latterman, and to my older brother, Christopher Latterman. It is only because of their love, guidance and support that I have made it this far.

ACKNOWLEDGEMENTS

I would like to thank the Geography Department of Texas A&M University for giving me the opportunity to become a Geographer. I would like to thank my committee chair, Dr. Andrew Klein for agreeing to be my advisor and giving me the skills I needed to succeed in the world of GIS. I would like to thank my committee members, Dr. Anthony Filippi and Dr. Rick Giardino for teaching me the ways of Remote Sensing and Geomorphology, and for their time and patience. I would also like to thank Dr. Vatche Tchakerian for being my first advisor when I transferred from another department as an under-graduate. It is fitting that he should be the first to invite me into this world of Geography and one of the last to send me on my way as a graduate.

I would also like to thank my friends and fellow graduate students Joni Kincaid, Iliyana Dobreva, Zhaohui Chi, Panshu Zhao and Billy Hales Jr. for working with me. They gave me a group to belong to and an audience to use as test subjects when practicing my horrible presenting skills.

Last but not least, I would like to thank Serena Aldrich for giving me a priceless gift, her wrist rest bean bag. I don’t think I could have finished my thesis without it. My wrist would not have lasted much longer under such intense pressure and constant abuse. Thank you from the bottom of my heart.

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1. INTRODUCTION

The vast majority of the world's tropical glaciers are located in South America, mainly in Peru and Bolivia. Tropical glaciers must meet these certain criteria: the glacier must be within the astronomical tropics; they should be in the region where the daily temperature variation exceeds the annual temperature variation; they should be in the region covered by the Inter Tropical Convergence Zone (ITCZ) (Kaser, 2001; Kaser and Osmaston, 2002). According to these criteria tropical glaciers occur in Indonesian New Guinea, on Mt. Kenya, Mt. Kilimanjaro and Rwenzori in Africa, and in South America between Venezuela and Bolivia. The glaciers that exist in Peru and Bolivia meet these criteria and are therefore defined as tropical glaciers (Kaser, G. 1999). In his addition to the World Glacier Inventory, J. Graham Cogley recorded 5,075 total tropical glaciers with a total area of approximately 2,807 km^2. From this total number of tropical glaciers 4,985 are located in South America. Of these 3,044 are in Peru and 1,701 are located in Bolivia (Cogley 2008, 2009). Altogether, the glaciers in Peru and Bolivia have an area of approximately 2,589 km^2 which is 92% of the total area of tropical glaciers worldwide (Fig 1).

There are technically three glacier regimes of the low latitudes; the inner tropics, the outer tropics, and the subtropics (Kaser, 2001). The inner tropics are characterized by stable humidity and temperature that cause glacier accumulation and ablation to occur

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This thesis follows the style of *Annals of Glaciology*.

simultaneously throughout the year as occurs in the Ruwenzori Mountains, East Africa, Irian Jaya, New Guinea and the northern Andes (Kaser et al., 1996; Kaser, 2001). In the outer tropics accumulation occurs only during the wet season and both the accumulation and the ablation are reduced during the dry season because much of the energy is used for sublimation and very little is left for melting (Kaser, 2001). The Cordilleras Blanca, Apolobamba, Real and Tres Cruces are located within the outer tropical regime of South America. In the sub-tropics nearly all ablation is the result of sublimation while accumulation is the result of infrequent precipitation distributed over the year and related to the Inter-Tropical Convergence Zone (ITCZ) or the westerly frontal zone (Kaser, 2001). Therefore, the two main characteristics that distinguish the low latitude tropical regimes from the mid-latitudes is their ratio of melting to sublimation and the duration of their ablation periods (Kaser, 2001).

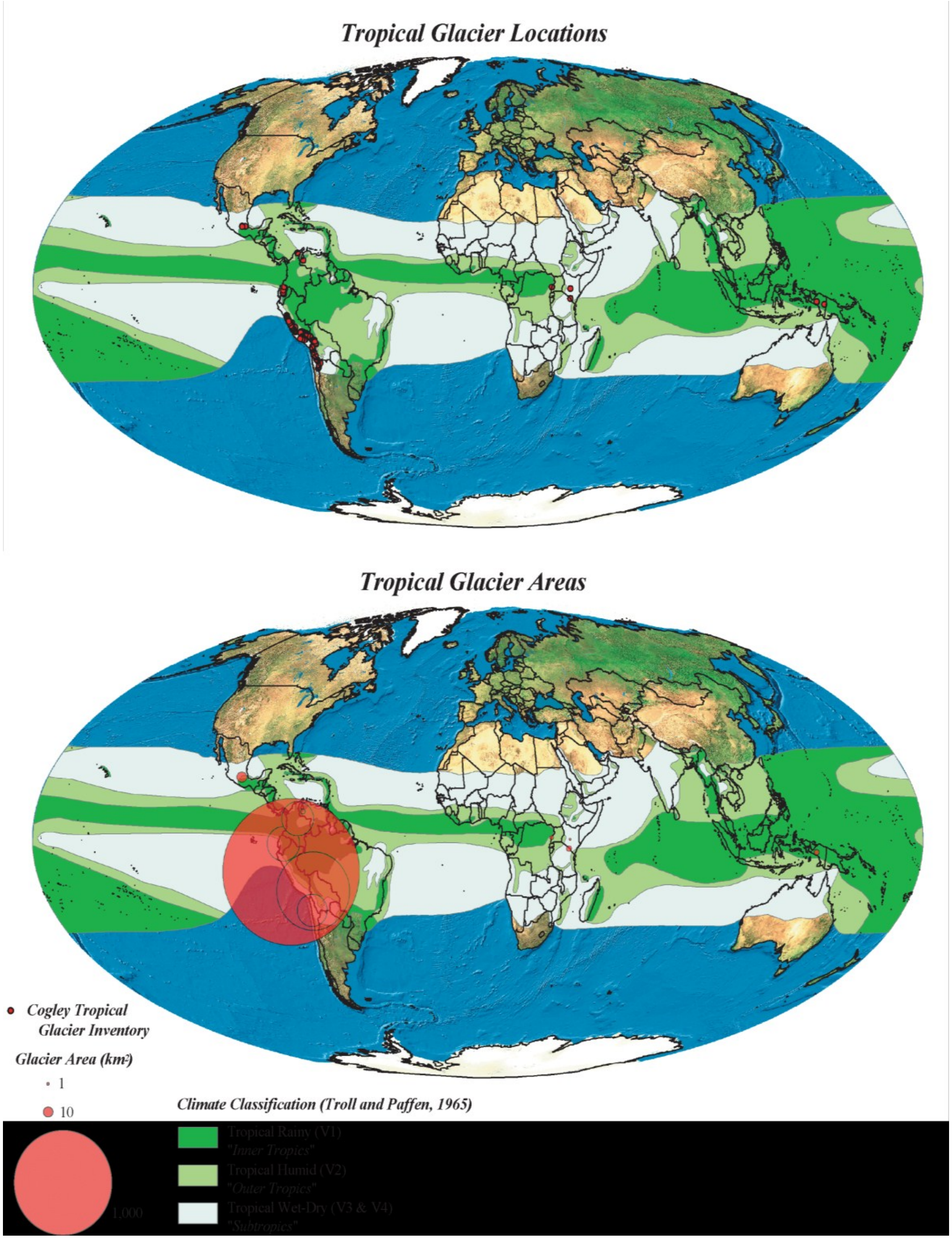


Fig 1. Map of locations and proportional areas of tropical glaciers. From the J. Graham Cogley glacier inventory, as well as the global locations of the tropical zones indicated by Troll and Paffen, 1965.

The large majority of South American tropical glaciers are located in the outer tropics. According to the J. Graham Cogley inventory, of the tropical glaciers in Peru there are 1,070 in the outer tropics, 1,974 in the sub-tropics and zero located in the inner tropics. Of the tropical glaciers in Bolivia there are 1,679 in the outer tropics, fourteen in the sub-tropics and eight in the inner tropics (Fig 1). As previously stated, the outer tropics are characterized by homogenous annual temperatures causing ablation to occur year round with accumulation only occurring in the wet season. Therefore, these tropical mountain glaciers are different from other glaciers not only in their geographic location but in their response to climate change. If a glacier experiences a negative mass balance over a prolonged period of time it is out of equilibrium and will retreat. While a glacier that experiences a positive mass balance over a prolonged period of time is also out of equilibrium but will advance (Andrews, 1975). The glaciers of the inner and outer tropics are more sensitive to certain climate variables such as albedo which is controlled by the occurrence and amount of solid precipitation, incoming long-wave radiation which is related to cloudiness and to air humidity that influences the energy partitioned between melting and sublimation (Favier et al., 2004). Changes in temperature and precipitation cause a tropical glacier to be out of equilibrium; therefore, if the annual temperature increases and the annual precipitation decreases tropical glaciers will most likely experience retreat (Kaser et al., 2005).

El Niño Southern Oscillation (ENSO) events, or anomalies are classified as either El Niño (warm) events or La Niña (cold) events. El Niño events are reported in several studies to have a much greater impact on tropical glaciers than La Niña events. Sicart et al. (2005) state in their study conducted on the Zongo glacier that ablation on outer tropical glaciers is closely related to accumulation and the high albedo of fresh snowfall during the wet season interrupts the glacier's period of greatest solar energy gain. Therefore, any delay in the wet season causes a negative balance due to low accumulation and higher ablation. Such as the delays caused by an El Niño event. Glaciers located in the outer and inner tropics react rapidly to El Niño events. In the outer tropics an induced precipitation deficit is the primary driver while in the inner tropics an increase in temperature is key. Both of which lead to a rise in the snowline altitude in these tropical glaciers which lowers albedo and increases melt (Favier et al., 2004). Therefore, El Niño conditions typically cause tropical glaciers to have a negative mass balance by increased ablation along with decreased sublimation which causes rapid retreat if these conditions prevail over long periods of time (Favier et al., 2004; Wagnon et al., 2001).

Tropical glaciers in Peru and Bolivia are not only important indicators of climate change but are vital sources of freshwater for that region (Arnaud et al., 2001). Approximately 69.9% of the Earth's freshwater is stored in glacial ice and mountain glaciers in particular are important as they allow for large volumes of water to be stored and then released into river networks during warm and dry seasons (Coudrain, 2005). More than 80% of the freshwater supply in the arid and semiarid regions of the tropics and subtropics originates in mountain regions and affects populations downstream (Messerli, 2001).

In the Andes, the runoff from glacierized basins is an important element of water budgets assuring year-round flows that are used for agriculture, drinking water, hydroelectric power generation as well as maintaining the integrity of the ecosystem (Vergara et al., 2007). Peru alone accounts for approximately 4% of the world's yearly renewable water resource most of which is located on the eastern side of the Andes where there is very little agricultural activity and the population density is low (Vergara et al., 2007). This makes the regular runoff from the cordilleras even more important to those on the western coastal side of the Andes. The two major urban centers of La Paz and El Alto in Bolivia receive 30-40% of their potable water from the Cordillera Real (Vergara et al., 2007). Therefore, changes in the amount or frequency of the annual flows from these glacier systems would have not only an ecological impact but an economic impact on the neighboring civilizations (Vergara, et al., 2007).

Despite the importance of these tropical glacier systems there is a substantial lack of information in the current body of research concerning the Cordillera Apolobamba in particular. This is in part due to the remoteness of this mountain range located approximately 200 km northwest of the Bolivian capital of La Paz high in the Andes Mountains. Difficult access limits the amount of field data conducted on this particular group of glaciers which in turn limits the amount of research conducted. Another hindrance is the fact that the Cordillera Apolobamba stretches across the Peruvian-Bolivian border. This requires the cooperation of both of these governments when making travel arrangements and obtaining the approval necessary to gather field data over the entire glacier range. Because of its remote location as well as the rough terrain and the difficulty gaining access to both the Peruvian and Bolivian sides of the range, the Cordillera Apolobamba remains one of the least studied tropical glacier ranges of South America.

One of the most thorough studies of the Apolobamba was conducted by Ekkehard Jordan and others in the 1970's. An inventory was constructed of the glaciers in Bolivia to be added to the World Glacier Inventory (Jordan et al., 1980) using satellite imagery as well as terrestrial and aerial photography. This particular study offers one of the best historical resources for area measurements of the Cordillera Apolobamba glaciers, but unfortunately the inventory only covers the portion of the glacier range located in Bolivia (Fig 2).

The Ekkehard Jordan et al. (1980) Bolivian tropical glacier inventory is used in this study as a historical reference of the area measurements of the Cordillera Apolobamba glacier range in 1975. The area delineated as the Cordillera Apolobamba is also depicted in this study and is shown in Figures 3 and 4 as a modified computer drawn map and a Landsat 5 TM false-color composite image acquired on August 21, 1991. This is the total area covered by glacier and referred to as the Cordillera Apolobamba glacier range in this previous study by Jordan, and is therefore used in the analysis of glacier recession in this study.

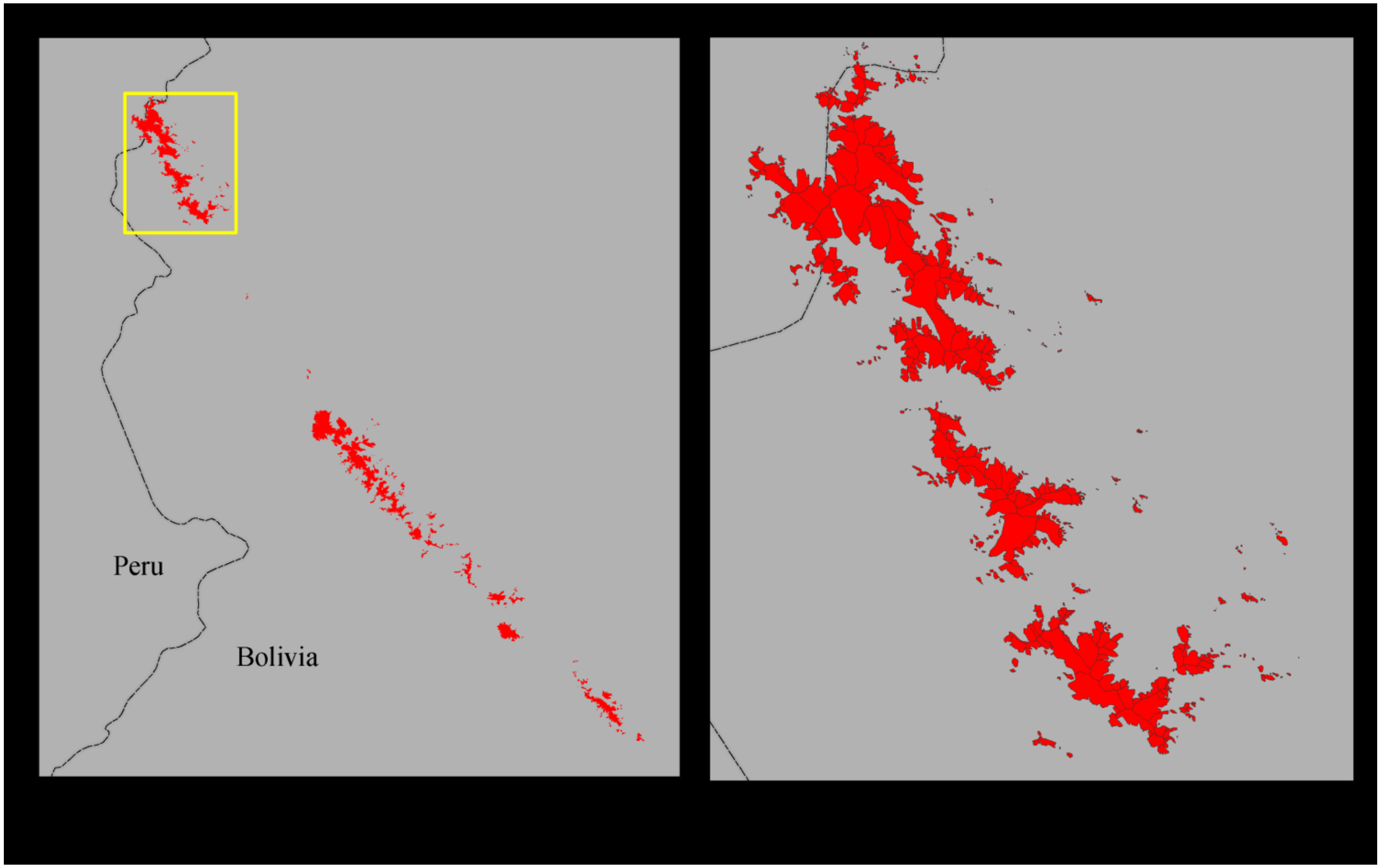


Fig 2. Image of the Glacier Inventory of Bolivia. The frame on the left depicts the total glacierized area included in the Glacier Inventory of Bolivia including the Cordillera Apolobamba, Cordillera Real, and Tres Cruces glacier ranges. The frame on the right depicts only the section of the Cordillera Apolobamba range inside the yellow box that lies within Bolivia used in this study to represent the Bolivian Glacier Inventory of 1970's.

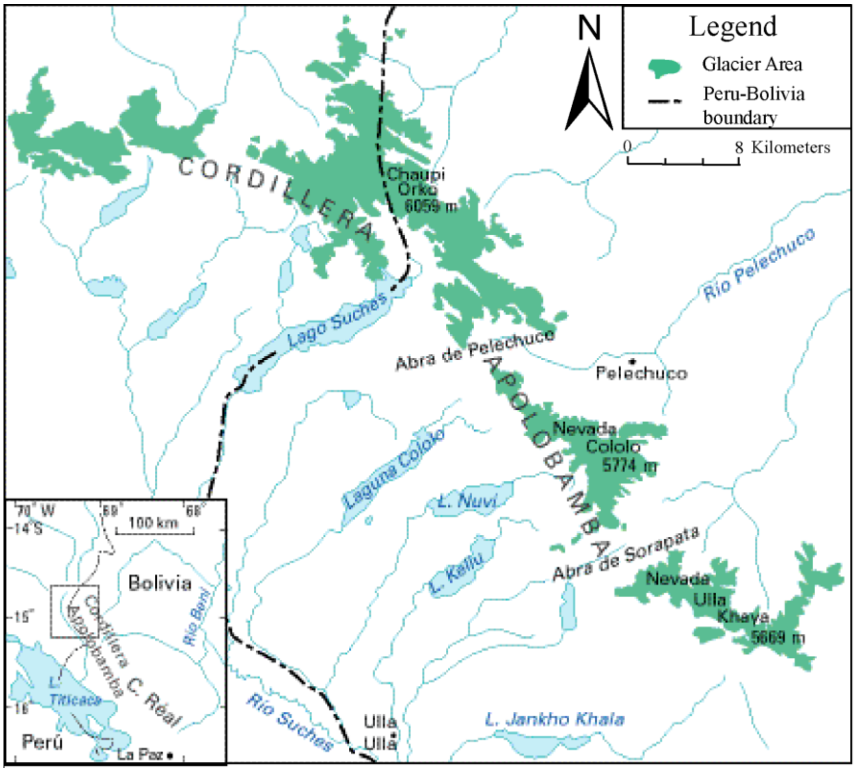


Fig 3. Map depicting the glacierized areas of the Cordillera Apolobamba. This map was modified from Figure 4 of USGS article, Jordan, E., "Satellite Image Atlas of Glaciers of the World: Glaciers of South America-Glaciers of Bolivia", (Jordan, 1999); http://pubs.usgs.gov/pp/p1386i/bolivia/html.

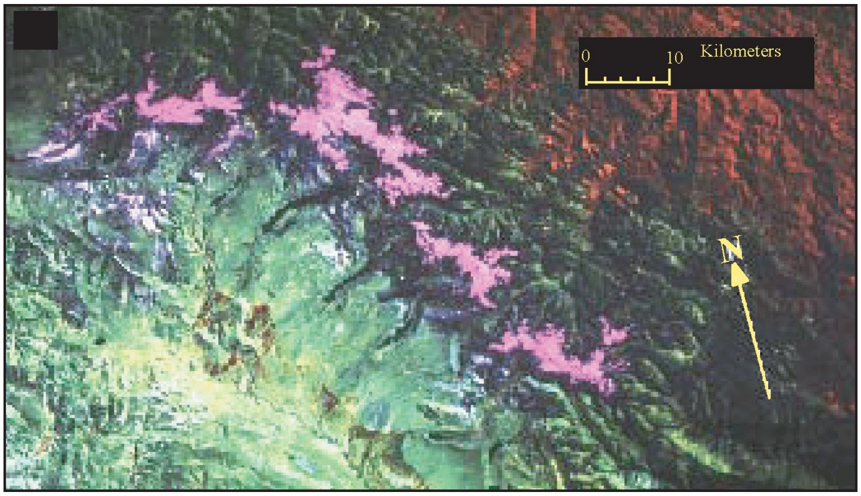


Fig 4. Landsat 5 TM false-color composite image of the Cordillera Apolobamba. (Acquired 21 August 1991) Bands 3, 5, glacierized areas in pink. A modified image of Figure 4 (B) of USGS article, Jordan, E., "Satellite Image Atlas of Glaciers of the World: Glaciers of South America-Glaciers of Bolivia", (Jordan, 1999); http://pubs.usgs.gov/pp/p1386i/bolivia/html.

To construct a complete global glacier inventory it is necessary to gather information concerning the Cordillera Apolobamba as well as other remote glacier ranges through other means besides *in situ* data collection. Advances that have been made in the fields of remote sensing technologies and Geographic Information Science (GISci) now make it possible for this information to be obtained, analyzed and recorded (Bishop et al., 2004). It is also necessary to gather and record climate data for these remote glacierized regions as glaciers are sensitive to changes in their climate. Understanding the way climate and glacier changes have fluctuated over time will give us more insight into the potential impact global climate change could possibly have on these glacier systems. Also it will aid in our understanding of which climate variables have a greater impact on these glaciers. This will further our understanding of regional glacier-climate dynamics (Zhen and Zeng, 1997).

1.1 Thesis Purpose

This study measures and documents the area change of tropical glaciers in the Cordillera Apolobamba mountain range located in the Eastern Cordillera of Bolivia. The secondary purpose of this study is to assess the climate changes that have taken place from 1975 to 2005 in this same region. This study adds to the current knowledge base of glacier monitoring methods and technologies and its results will further extend the historical database of glacier measurements.

One such database that will benefit from this research is the Global Land Ice Management from Space (GLIMS) project which began as an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Science Team project and is designed to monitor the world's glaciers. The GLIMS initiative also includes the continual monitoring of global change detection as well as hazards detection and assessment. Together with a network of international satellite image analysts, the GLIMS project works to develop and maintain a Global Glacier Database. The results of their efforts are archived with the National Snow and Ice Data Center (NSIDC). The GLIMS project works to develop an understanding of glaciers and how they are connected to the Earth's climate system, climate change, the formation of ice ages and the effects of global warming. The goals of this project is the long-term monitoring of the world's glaciers in order to build a base of historical data, to detect climate change in advance and to predict and possibly avoid hazards to communities living near glaciers (Raup et al., 2008).

1.2 Thesis Objectives

To depict how the Apolobamba glaciers have changed over the past thirty-five years, a time series of Landsat images is used to document the changes in the glacier area from 1975 to 2010. This is accomplished by first identifying the area covered by the glaciers in the Cordillera Apolobamba by gathering Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) satellite images of this region of the Andes. To identify glacierized area it is necessary to distinguish the ice from the surrounding rock and snow using remote sensing and satellite image analysis software. Second, satellite image software is used to map the total area of the glacier ice. Third, a time-series of area change maps consisting of successive years of satellite images is created to further identify the short and long term changes that have occurred from 1975-2010.

The secondary purpose is accomplished by analyzing climate variables for 1975 to 2005 including precipitation, temperature, solar radiation and specific humidity as well as others. This climate variable data is provided by the National Centers for Environmental Prediction (NCEP) National Center for Atmospheric Research (NCAR) reanalysis dataset that is available free to the public through the National Oceanic and Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL) (http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml).

Following the mapping of the area measurements of the glacier ice the changes that have occurred will be compared to climate changes of this region. To have a more complete understanding of all the climate factors affecting this region it is also necessary to analyze the changes taking place in the monthly temperature means of the Oceanic

Niño Index (ONI). By comparing the statistical significance of the climate variables with measurements of the area of these glaciers will determine if there is a correlation between the climate in the Bolivian tropics and the area fluctuations of its glaciers.

2. BACKGROUND

Advancements in remote sensing methods and technologies have made it possible for researchers to gather and analyze information concerning tropical glaciers with limited need for *in situ* data collection. This information is necessary because the retreat that is taking place in glaciers at present is reported as being rapid and monitoring their retreat can benefit from the increased use and application of the available remote sensing techniques (Vuille, 2008). The advances involve the use of digital elevation models (DEM) and global positioning system (GPS) measurements, as well as satellite data obtained from remote sensing platforms such as Landsat, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Satellite Pour l'Observation de la Terre (SPOT) and high resolution satellites such as Ikonos and QuickBird. These give researchers the opportunity to obtain a more large-scale and detailed analysis of changes taking place in the cryosphere as well as the atmosphere. The need for such technologies is evident when monitoring the remote high-elevation glacier ranges of the tropical Andes.

The first Symposium on Mass Balance of Andean Glaciers was held in Valdivia, Chile in March 2003 to present the advances and current knowledge related to the mass balance and area changes of South American glaciers. Topics such as mass balance measurement techniques and monitoring programs, recent glacier variations and their relation with climate change, and the relationship of glacio-hydrological studies and mass balance were discussed in the symposium. At this same time the first Mass Balance

Workshop on Andean Glaciers was held with the main goal of planning a future mass balance network for all Andean glaciers on a continental scale. A review of the advances in Andean glaciology was presented based on a collection of twenty papers written on this subject. These two activities were conducted with the sole purpose of presenting the current knowledge base concerning glaciers in South America and to further the advancement of future methods and technologies used to measure the conditions of these glaciers.

The Intergovernmental Panel on Climate Change (IPCC) states in their 2007 Synthesis Report on Climate Change that from 1995-2006 eleven of these years are ranked in the top twelve warmest years since 1850 which marks the current instrumental record of global surface temperature (IPCC, 2007). It is also reported that the fifty year linear trend from 1956 to 2005 of 0.13 [0.10 to 0.16] °C per decade is almost twice that of the one hundred year (1906-2005) linear trend of 0.74 [0.56 to 0.92] °C (IPCC, 2007). It is predicted that along with heat waves and temperature extremes the twenty-first century will experience increases in heavy precipitation in high latitudes but decreases in most subtropical land regions (IPCC, 2007). Widespread mass loss is predicted for all glaciers along with reductions in snow cover which will reduce the availability of freshwater runoff in regions that rely on these continual sources year-round such as the Hindu-Kush, the Himalayas and the Andes where a reported one-sixth of the world's population lives (IPCC, 2007).

Many studies have been conducted with the purpose of determining the correlation between climate change and the retreat of glaciers. In one such study of the energy balance and runoff seasonality of the Zongo glacier, Wagnon and others (1999) concluded that humidity is the main input control for the seasonality of proglacial stream flow in the outer tropics. This is mainly due to the fact that humidity is responsible for dividing the energy available at the surface between sublimation and melting. It was determined that tropical glaciers, especially in the outer tropics, are not only affected by greenhouse warming but by any increase in specific humidity. These increases in specific humidity reduce the latent heat flux and make more energy available for melting which is the main reason why tropical glaciers have exhibited dramatic increases in retreat since the nineteen-eighties (Wagnon et al., 1999). On the Zongo glacier, it was determined that sublimation is reduced because of low vapor pressure and the energy supplied by radiation is directly consumed by melting during the accumulation season. This explains why discharge is high at this time. During the dry season, a large portion of the energy supplied by incoming radiation is used to sublimate snow or ice. Therefore, energy available for melting is low which in turn leads to low melting rates. Due to the important role that humidity plays in their energy balance, tropical glaciers are climatic indicators and are most sensitive to climate changes such as the greenhouse effect (Wagnon et al, 1999).

It has been reported in several studies that El Niño events have a larger impact on tropical glaciers. In a study of the Zongo Glacier, Bolivia, Wagnon et al. (1999) examined the ENSO event of 1997/1998 under outer-tropical conditions at the Zongo Glacier's mean equilibrium line (EL). This year experienced an El Niño event which resulted in a noticeably higher ablation due to low surface albedo during the wet season.

This in turn caused markedly lower precipitation as well as almost non-existent sublimation due to high air humidity during the dry season.

In a study conducted on the Chacaltaya glacier located in the Cordillera Real, Bolivia by Ramirez and others (2001), it was determined that this small tropical glacier had experienced dramatic shrinkage since the early 1980's with an average deficit of 1 m a^{-1} water equivalent. The mass balance deficit of this glacier was moderate from 1940 to 1963 but this deficit greatly increased in 1983 to ≥ 1 m a^{-1} in water loss (Ramirez et al., 2001). This mass balance deficit was greatly amplified during 1997/1998. The mass loss of 1996/1997 was only 0.66 m whereas the mass loss of 1997/1998 was 3.58 m (Ramirez et al., 2001). It is believed that this was due to the fact that the 1997/1998 year experienced one of the strongest El Niño events of the century. The results of this study report that from 1992 to 1998 the Chacaltaya glacier lost 40% of its ice thickness and two-thirds of its volume as well as >40% of its surface area. It is also predicted that if the climate conditions of that time continued the Chacaltaya glacier would completely disappear within fifteen years.

The remoteness of the Cordillera Apolobamba has led to the lack of information concerning the glaciers in this mountain range compared to other nearby ranges such as the Cordilleras Real, Bolivia and the Cordillera Blanca, Peru. Many studies conducted for the tropical glaciers of the Andes provide a broad overview of the past and present conditions in this region of South America. Some such studies go into detail concerning a particular region, however, none have conducted the research required to give an in depth and complete analysis of the past and present conditions of the Cordillera

Apolobamba in particular. The few past studies including research conducted on the Cordillera Apolobamba include “The Glacier Inventory of Bolivia” written by Ekkehard Jordan (1980) to be included in the World Glacier Inventory. This inventory is a survey of the dimensions and locations of the glaciers in Bolivia focusing on the special features of mass balance. In the Glacier Inventory of Bolivia it is reported that the area measurements of the Cordillera Apolobamba region of Bolivia were more difficult to complete due to the lack of aerial photography coverage of these glaciers at that time. Table 1 lists the area measurement results for the glaciers of the Cordillera Oriental in which the Cordillera Apolobamba is located as indicated by the shaded portion of the table. According to the analysis conducted by Jordan (1980) using the 1975 and 1977 satellite images as well as aerial and terrestrial photographs, the Cordillera Apolobamba glacier range covered an area of approximately 219.804 km^2 during the mid to late 1970’s.

Table 1. Area of Cordillera Oriental. Table modified from Table 1, of Jordan, E. “Satellite Image Atlas of Glaciers of the World: Glaciers of South America-Glaciers of Bolivia” (Jordan, 1999). List of the area measurement results for the Cordillera Oriental Mountain range in the South American Andes. Shaded cells are results for the Cordillera Apolobamba.

Mountain group	*Latitude (South)*	*Longitude (West)*	*Glacier*				*Highest elevation (meters)*	*Lowest glacier terminus (meters)*
			Area km^2	*Percent*	*Number*	*Percent*		
Cordillera Oriental	14°37'- 17°04'	67°13'- 69°14'	591.600 (including 35.590 in Perú)	100	1826	100	6,436	4,311
Cordillera Apolobamba	14°37'- 15°04'	68°58'- 69°14'	219.804	37.2	652	36	6,059	4,311
Chaupi Orko	14°40'	69°10'	129.357	21.9	346	19	6,059	4,365
Cololo	14°50'	69°06'	43.072	7.3	135	7.5	5,774	4,311
Ulla Khaya	15°00'	69°03'	47.375	8	171	9.5	5,669	4,390
Corillera De Munecas	15°20'- 15°38'	68°33'- 68°55'	.684	.1	16	1	5,237	4,828
Morocollu	15°20'	68°55'	.148	.03	8	.5	5,156	4,828
Cuchu	15°38'	68°33'	.536	.1	8	.5	5,237	4,886
Cordillera Real	15°45'- 16°40'	67°40'- 68°34'	323.603	54.7	964	53	6,436	4,420
North Cordillera Real	15°45'- 16°20'	68°01'- 68°34'	262.766	44.4	784	43	6,436	4,420
Illampu-Ancohuma	15°50'	68°30'	103.099	17.4	147	8	6,436	4,438
Calzada-Chiaroco-Chachacomani	16°00'	68°20'	94.072	15.9	251	14	6,127	4,676
Nigruni-Condoriri	16°08'	68°15'	40.868	6.9	241	13	5,752	4,420

Table 1 Continued

Saltuni-Huayna Potosí	16°15'	68°08'	14.504	2.5	50	3	6,088	4,804
Zongo-Cumbre-Chacaltaya	16°18'	68°05'	10.223	1.7	95	5	5,519	4,578
South Cordillera Real	16°20'- 16°40'	67°40'- 67°58'	60.837	10.3	180	10	6,414	4,499
Hampaturi-Taquesi	16°26'	67°52'	11.685	2	70	4	5,548	4,723
Mururata	16°30'	67°47'	17.207	2.9	75	4	5,836	4,592
Illimani	16°38'	67°44'	31.945	5.4	35	2	6,414	4,499
Cordillera Tres Cruces (Quimsa Cruz)	16°47'- 16°09'	67°22'- 67°32'	45.276	7.7	177	9.5	5,760	4,708
Choquetanga	16°54'	67°22'	6.992	1.2	21	1	5,541	4,812
High region of Tres Cruces	16°56'	67°24'	38.284	6.5	156	8.5	5,760	4,708
Nevado Santa Vera Cruz	17°03'- 17°04'	67°13'- 67°14'	2.233	.4	17	1	5,560	4,853

Recent glacier studies of the Andes Mountains include monitoring the volume change taking place in twenty-one glaciers located in the Cordillera Real mountain range. It was concluded that there has been a marked downtrend of glacier volume in the Cordillera Real since 1975 (Soruco, et al, 2009). Through a thorough review of the available knowledge base, Vuille et al. (2008) offer an evaluation of the past and present conditions of the glaciers located in Ecuador, Peru and Bolivia along with the climate changes that occurred in these same regions. According to their findings the Andean glaciers have been experiencing rapid retreat since the Little Ice Age. This review also gives projections into future climate changes and the implications for future water resources. It is predicted that by the end of the twenty-first century the tropical region of the Andes will experience a rise in temperature of 4.5-5°C. Precipitation is projected toincrease during the wet season and further decrease during the dry season. It is predicted that the temperature changes will have a more negative effect on the glaciers located in the inner tropics while precipitation changes will have a more negative effect on those located in the outer tropics. As these glaciers are reduced due to such climate changes their supply of freshwater to the surrounding communities will also be reduced. Already a 410 mm annual deficit has been recorded for the Zongo glacier on the Cordillera Real from 1973 to 1993 (Ribstein et al., 1995).

The glacier systems in South America are vital for the generation of hydroelectric power supplying major urban areas in Peru and Bolivia as well as other neighboring countries (Vergara et al, 2007). It was determined that hydropower provides 50% of the total energy in Ecuador and 80% in Peru. The results of their analysis of the hydrology data provided by 12 watersheds in Peru’s Rio Santa basin indicate that approximately 220 mm per year of water-equivalent, (measured at the La Balsa station) is contributed by glacier runoff representing approximately 60% of the total glacier runoff. At this same station, the inter-annual average discharge of 592 ± 3.4 mm per year over the length of a 48 year historical record would be reduced to 482 mm per year as a result of a 50% decrease of glacier runoff. This would further reduce to 371 mm per year once the glaciers have completely receded and ceased to contribute runoff (Vergara, et al., 2007).

This study further examines the energy costs that would result from the recession of these tropical glaciers using data provided by Peru’s power system; they estimated that with a 50% reduction in glacier runoff the average annual energy output for the Canon del Pato hydropower plant would drop from 1540 gigawatt hours to 1250 gigawatt hours and would reduce to 970 gigawatt hours once the glaciers have completely receded and ceased to contribute runoff. It is estimated that at the rate the tropical glaciers of this region are currently receding the average annual incremental costs to Peru’s power system will be $1.5 billion US should they choose to ration energy, or $212 million US should they choose to implement a gradual adaptation scenario. If Peru decides to invest in additional power sources such as thermal based energy the cost will be approximately $1 billion US per gigawatt hour (Vergara et al., 2007). This study concludes that the further recession of the Andean tropical glaciers will have serious economic consequences on their neighboring urban and agricultural centers.

3. THE STUDY SITE: CORDILLERA APOLOBAMBA LOCATED IN BOLIVIA

3.1 Characteristics of the Andes Mountains

The Andes Mountain range separates the continent of South America into a larger eastern portion and a narrow strip along the western coast consisting mainly of the country of Chile. The Andes Mountains are not a continuous line of peaks but rather they are broken into parallel and transverse ranges with intermediate plateaus and depressions. The main continental-scale feature of the central Andes is the broad Altiplano plateau located between 15°S and 27°S. North and south of this plateau the mountains narrow but continue along the high Andean cordilleras of Peru and along the Chile-Argentine border (Isacks, 1988). The Andes Mountain range separates into two branches oriented north-to-south in Bolivia. The western branch is named the Cordillera Occidental and the eastern branch is the Cordillera Oriental. The Cordillera Oriental rises from the eastern side of the Altiplano to form the eastern spine of the Bolivian Andes before it slopes eastward into the Amazon Basin. This eastern branch of the Andes is also known as the Eastern Thrust Belt as it is formed by the major thrust belts of the eastern cordilleras. The edge of the Oriental that merges with the Amazon Basin is called the Subandes and it is currently believed that this area is the most tectonically active part of the Andes Mountains (Isacks, 1988; Kennan et al., 1995). The Cordillera Oriental consists mainly of deformed Paleozoic-Tertiary strata and igneous rocks (Kennan et al., 1995).

3.2 Characteristics of the Cordillera Apolobamba

The Cordillera Apolobamba mountain range is located just north of Lake Titicaca in the eastern Cordillera Oriental. This mountain range covers an area approximately 1,500 km^2 between latitude 14°35´S to 14°35´S and longitude 69°14´W to 69°34´W. The Cordillera Apolobamba is divided roughly in half by the Peruvian-Bolivian border and is located in a remote region northwest of the Cordillera Real as shown in Figures 5 and 6. The glaciers located in Bolivia as well as Columbia, Ecuador, Peru and Venezuela are mainly mountain glaciers which exist in tropical climate conditions (Casassa et al., 1998). The Cordillera Apolobamba is no exception to this and consists mainly of valley and mountain glaciers as well as ice caps (Vuille, 2008). As shown in Figure 7, the highest of the Cordillera Apolobamba peaks is the Chaupi Orco exceeding 6,000 m in elevation while the second tallest peak is the Cololo which exceeds 5,000 m (Jordan, 1999).

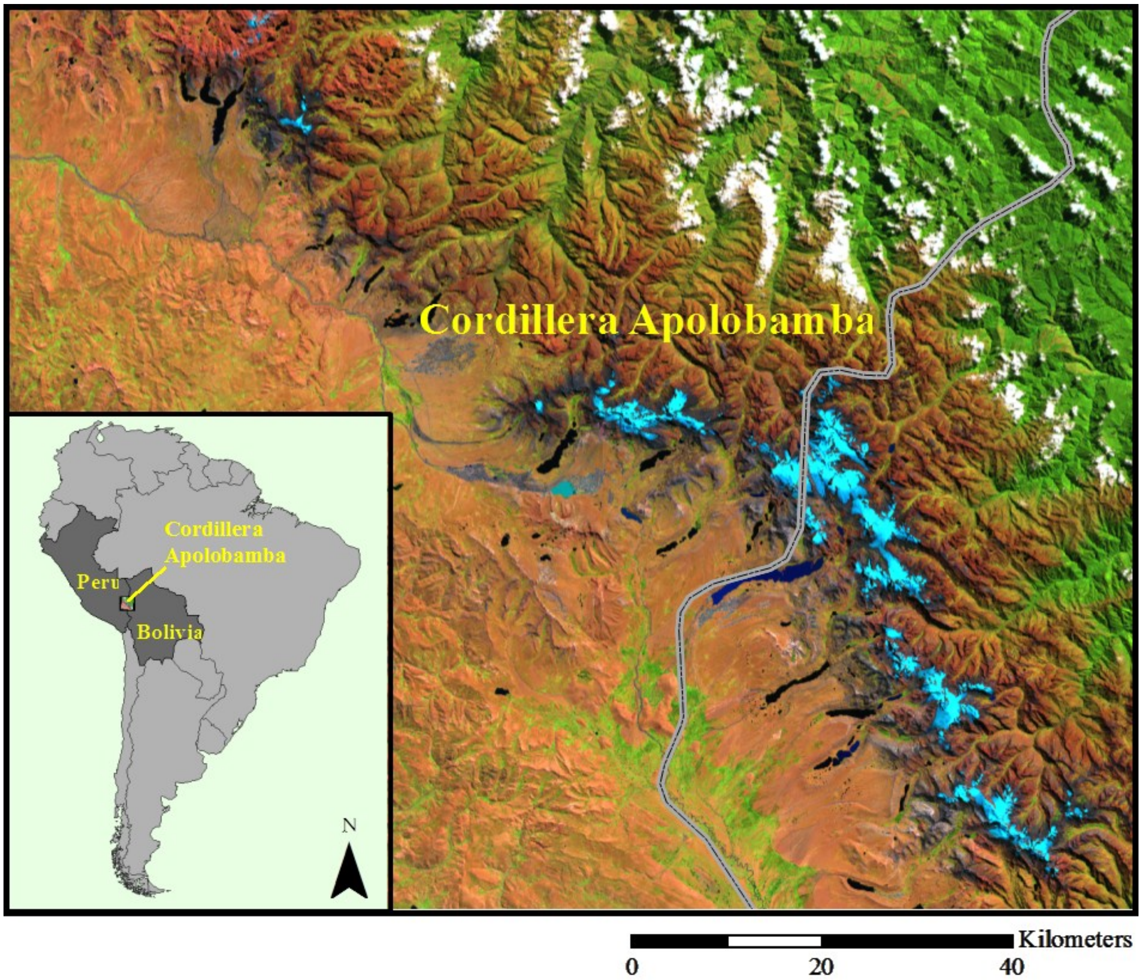


Fig 5. Study site map of the Cordillera Apolobamba glacier range. Located on the western border between Peru and Bolivia. This map was created using a filled 2010 Landsat ETM+ image.

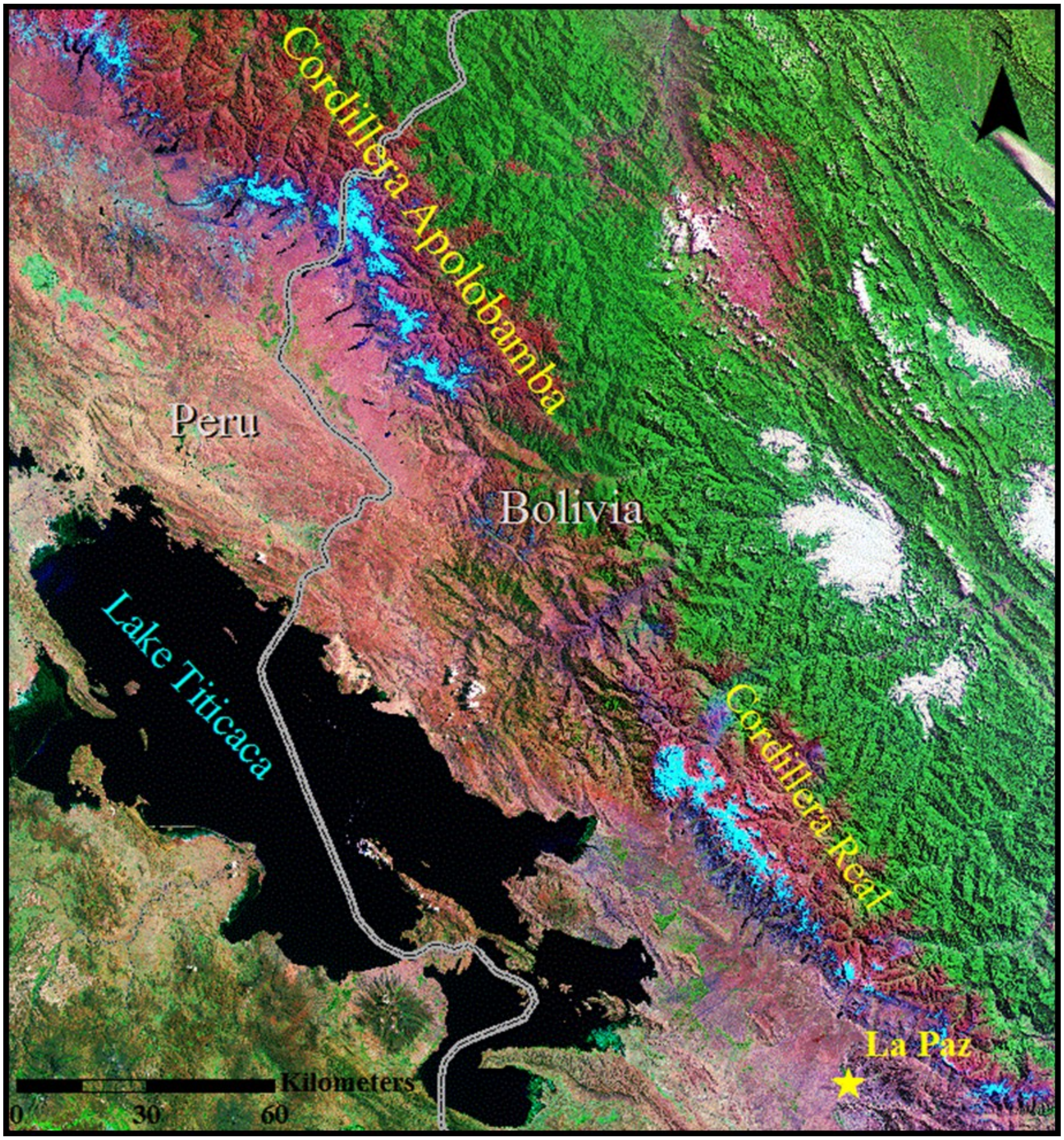


Fig 6. False color composite mosaic created from 2010 Landsat ETM+ images. This mosaic uses bands 5, 4, 2 as RGB. This depicts the Location of the Cordillera Apolobamba in relation to the capital city of La Paz and the Cordillera Real.

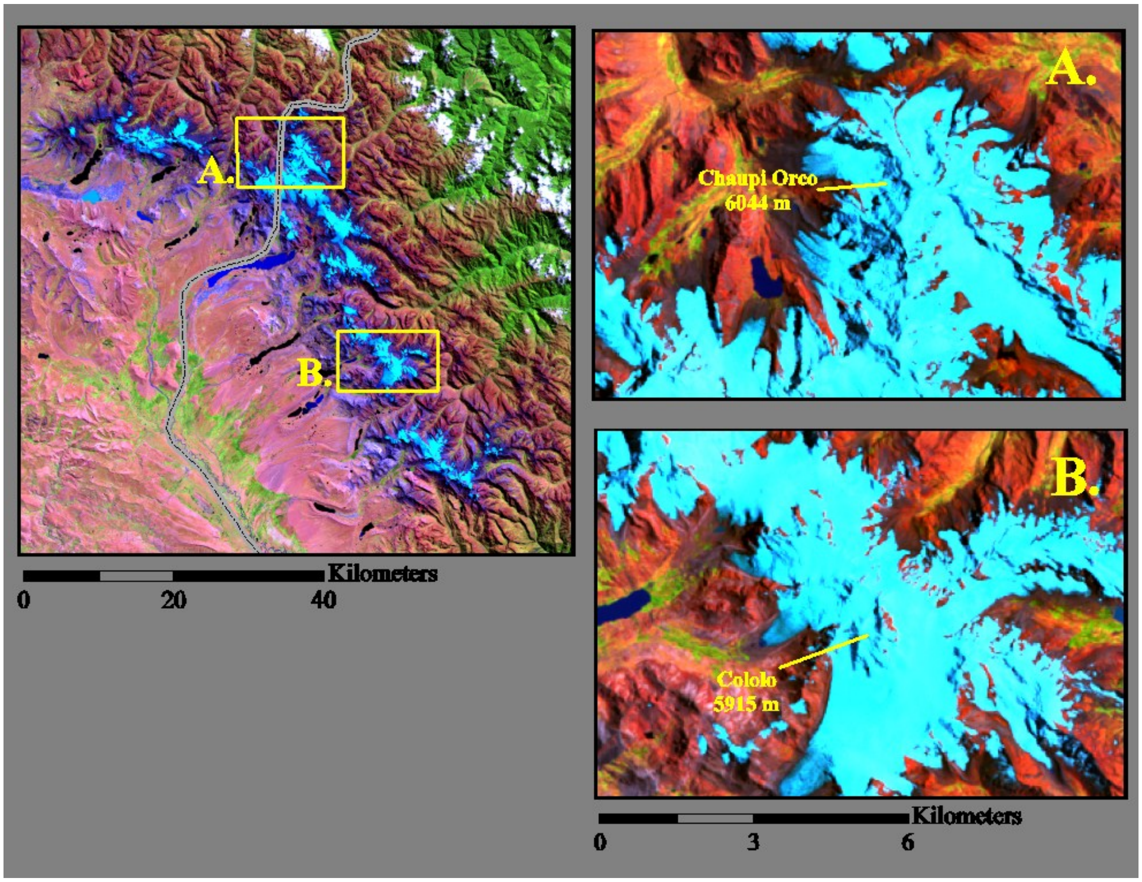


Fig 7. The location of the tallest peaks of the Cordillera Apolobamba. (A) Chaupi Orco at 6,044 meters, and (B) Cololo at 5,915 meters. This map was created using a gap-filled 2010 Landsat ETM+ image.

3.3 Climate of Bolivia and the Cordillera Apolobamba Region

The Andes encompass several temperature and precipitation regimes. The Inter-tropical Convergence Zone (ITCZ) is located between 10°N-3°S and receives an annual rainfall exceeding 2 $m \cdot yr^{-1}$ on both sides of the range. The subequatorial region of the Andes is located between 3°S-15°S and is affected by orographic interception of the trade winds receiving >2 $m \cdot yr^{-1}$ of rainfall on the Amazon side and, <0.2 $m \cdot yr^{-1}$ on the Pacific side. However, south of 33°S the westerly winds create the opposite effect in the temperate latitudes. The central section of the range located between 15°S-33°S is in the subtropical desert belts. Here there is little precipitation on either side of the range and on the high plateau of the Altiplano (Montgomery, 2001). Because there is so little precipitation in the southwestern region of the Andes even the highest peaks cannot sustain glaciers south of latitude 18°30´S (Jordan, 1999). All of Bolivia's glaciers are located between 14°37´ and 18°23´S on the southern edge of the tropical zone (Jordan, 1999).

The climate of South America in the region of Bolivia is mainly determined by the seasonal changes of the Inter-tropical Convergence Zone (ITCZ). During the austral winter the ITCZ is located to the north and tropical anti-cyclones create a cold dry season (April to September, low cloudiness) while during the austral summer wet period (October to March, high cloudiness), the ITCZ is in its most southern location (Ribstein, 1995). The summer wet season is influenced by the inter-tropical circulation while the winter dry season is mainly influenced by the southeast trade winds. Because the summer is the wet season and the winter receives little to no precipitation, the tropical glacier snow reserves must be established during the summer. This is important because ablation occurs year round in this region during the inter-seasonal periods, the winter when solar radiation is intense and during the summer dry periods (Jordan, 1999). The tropical glaciers in Bolivia therefore must maintain a delicate balance between the accumulation of snow and the ablation from solar radiation during their warmest summer season which encompasses approximately October to March.

Bolivia, along with the rest of South America, is affected by the El Niño Southern Oscillation (ENSO) events because of its close proximity to the Pacific Ocean. According to the Intergovernmental Panel on Climate Change (IPCC), El Niño events involve warming of the surface waters of the tropical Pacific in the region from the International Date Line to the west coast of the South American continent. This weakens the strong sea surface temperature gradient across the equatorial Pacific and significantly changes the oceanic circulation. Linked to this is the Southern Oscillation (SO) which involves changes in the trade winds and the tropical circulation as well precipitation (Trenberth et al., IPCC 2007). El Niño events occur approximately every three to seven years and alternate with La Niña events of below average temperatures in the eastern tropical Pacific Ocean. Together these ENSO events have global impacts which are manifested most strongly in the northern hemisphere winter months of November to March when the tropics experience large variations in precipitation (Trenberth et al., IPCC 2007).

4. METHODOLOGY

4.1 Acquisition of Satellite Images

The Landsat satellite images used for this study were obtained from the USGS Global Visualization (GloVis) internet site which offers an inventory of satellite imagery that is free to the public (http://glovis.usgs.gov). The specific images chosen were done so based on their location in Bolivia over the Cordillera Apolobamba mountain range and their minimization of cloud and excess snow cover on and around the glaciers. The Landsat series of satellite images was chosen for this study because they offer accessible data coverage of the entire Apolobamba region of the Andes on a regular basis.

The Landsat 5 and 7 satellites were the primary source of the images used in this study. These both have a similar coverage with a repetitive, circular, sun-synchronous and near-polar orbits at a minimal altitude of 705.3 km measured at the equator. These satellites have a descending orbital node time at 9:45 am plus or minus 15 minutes at the equator with an orbit period of 98.9 minutes They complete fourteen orbits each 24 hours and view the entire Earth every sixteen days (NOAA Landsat, http://landsathandbook.gsfc.nasa.gov/). The currently operating Landsat 5 satellite is equipped with both the Multispectral Scanner (MSS) and the Thematic Mapper (TM) instruments while the Landsat 7 satellite is equipped with the Enhanced Thematic Mapper Plus (ETM+) instrument. All the images used in this study have a resolution of 30 meters.

The primary spectral bands utilized in this study are bands 5 (1.55-1.75 µm), 4 (0.77-0.90 µm) and 2 (0.52-0.60 µm). Band 5 is used because of its ability to discriminate between clouds, snow and ice while band 4 is used because of its ability to distinguish between land and water and band 2 is used because ice is highly reflective in this band. Bands 2 and 5 are used in the NDSI (Normalized Difference Snow Index) to classify snow and ice in the images. Together these bands show the distinction between the clouds (white), water (dark blue), ice (light blue) and the vegetation (green) in 5, 4, 2 RGB band false color composite images. An example of this color distinction is given in Fig. 8 of a 2001 Landsat satellite image of the Apolobamba range.

A total of forty-five Landsat images were acquired to meet the objectives of this study and to illustrate the area changes that have occurred in the Cordillera Apolobamba. These images range in dates from 1975 to 2010 in different months of the year and represent a variety of levels of quality in reference to cloudiness and snow cover. Each was processed to the stage indicative of its level of quality and its overall usefulness in completing the objectives of this study. Table 2 is a full listing of these images and their level of processing. Of these forty-five images only five are used in the final analyses and are indicated by the shaded cells of Table 2.

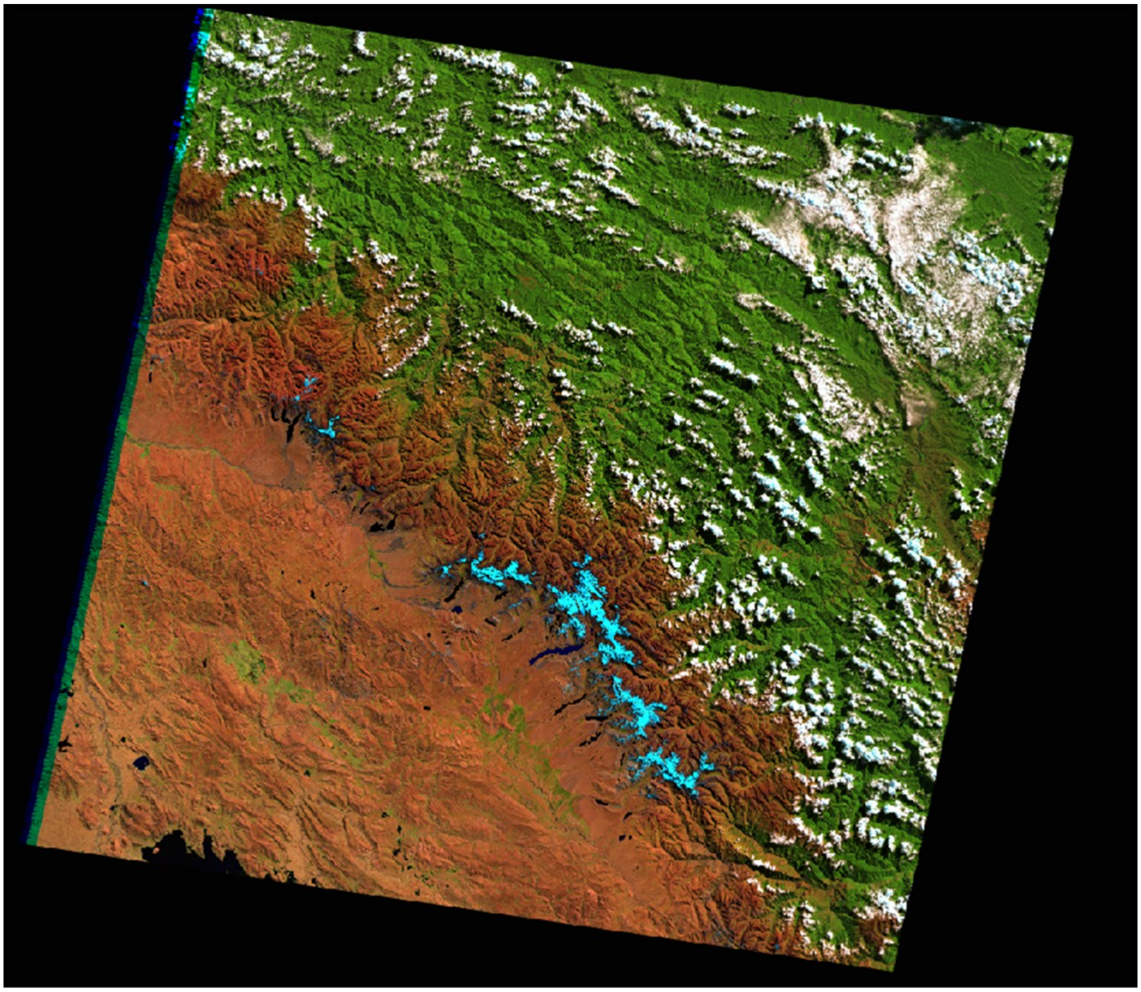


Fig 8. A false color composite 2001 Landsat ETM+ image. This image uses bands 5, 4, 2 as RBG. This illustrates the distinctiveness between clouds (white), ice (light blue), water (dark blue), and vegetation (green).

Table 2. List of all Landsat images used in study. The Landsat satellite images that were acquired for this study, as well as their Landsat satellite sensor and a description of the level of processing each received. Shaded cells indicate images that are used in the final analyses.

Acquisition Date	*Satellite Sensor*	*Level of Processing*
1975-06-22	Landsat 2 MSS	pre-processed only
1985-07-18	Landsat 5 TM	fully processed, area calculations, used in composite 1980's image and final analysis
1986-08-22	Landsat 5 TM	fully processed, area calculations, used in composite 1980's image and final analysis
1987-03-13	Landsat 5 TM	fully processed, area calculations, used in composite 1980's image and final analysis
1995-05-27	Landsat 5 TM	fully processed, area calculations, used in final analysis
1996-06-30	Landsat 5 TM	pre-processed only
1998-06-04	Landsat 5 TM	fully processed, area calculations
1999-09-11	Landsat 5 TM	pre-processed only
2000-06-25	Landsat 5 TM	pre-processed only
2000-07-11	Landsat 5 TM	pre-processed only
2000-08-05	Landsat 5 TM	fully processed, area calculations
2001-07-22	Landsat 7 ETM+	fully processed, area calculations
2002-07-25	Landsat 7 ETM+	fully processed, area calculations
2003-07-28	Landsat 7 ETM+	fully processed, filled, area calculations
2003-09-30	Landsat 7 ETM+	fully processed, used as filler image 1
2003-10-16	Landsat 7 ETM+	fully processed, used as filler image 2
2003-11-17	Landsat 7 ETM+	fully processed, used as filler image 3
2004-05-11	Landsat 7 ETM+	fully processed, filled, area calculations
2004-05-27	Landsat 7 ETM+	fully processed, used as filler image 1
2004-07-14	Landsat 7 ETM+	fully processed, used as filler image 2
2004-08-15	Landsat 7 ETM+	fully processed, used as filler image 3

Table 2 Continued

2005-08-02	Landsat 7 ETM+	fully processed, filled, area calculations, used in final analysis
2005-07-01	Landsat 7 ETM+	fully processed, used as filler image 1
2005-07-17	Landsat 7 ETM+	fully processed, used as filler image 2
2005-08-18	Landsat 7 ETM+	fully processed, used as filler image 3
2006-07-04	Landsat 7 ETM+	fully processed, filled, area calculations
2006-07-20	Landsat 7 ETM+	fully processed, used as filler image 1
2006-05-17	Landsat 7 ETM+	fully processed, used as filler image 2
2006-06-18	Landsat 7 ETM+	fully processed, used as filler image 3
2007-08-24	Landsat 7 ETM+	fully processed, filled, area calculations
2007-08-08	Landsat 7 ETM+	fully processed, used as filler image 1
2007-06-21	Landsat 7 ETM+	fully processed, used as filler image 2
2007-04-18	Landsat 7 ETM+	fully processed, used as filler image 3
2008-08-26	Landsat 7 ETM+	fully processed, filled, area calculations
2008-06-07	Landsat 7 ETM+	fully processed, used as filler image 1
2008-05-06	Landsat 7 ETM+	fully processed, used as filler image 2
2008-05-22	Landsat 7 ETM+	fully processed, used as filler image 3
2009-06-10	Landsat 7 ETM+	fully processed, filled, area calculations
2009-06-26	Landsat 7 ETM+	fully processed, used as filler image 1
2009-11-01	Landsat 7 ETM+	fully processed, used as filler image 2
2009-07-28	Landsat 7 ETM+	fully processed, used as filler image 3
2010-05-12	Landsat 7 ETM+	fully processed, filled, area calculations
2010-04-10	Landsat 7 ETM+	fully processed, used as filler image 1
2010-03-09	Landsat 7 ETM+	fully processed, used as filler image 2
2010-04-26	Landsat 7 ETM+	fully processed, used as filler image 3

In addition to the Landsat scenes used in this study, a glacier inventory created by Ekkehard Jordan (1980) and included in the World Glacier Inventory was used to provide historical extents of the Cordillera Apolobamba glaciers during the 1970's. As previously stated, the glacier extents in this image only encompass the portion of the range that is located in Bolivia. For this reason the area measurements for this study are separated into two categories: (1) the portion of the glacier range that is included in the 1975 Bolivian Glacier Inventory and (2) the complete glacier range shown in the Landsat scenes.

4.2 Satellite Image Pre-Processing

On May 31, 2003 the Scan Line Corrector (SLC) oscillating mirror aboard the Landsat 7 satellite failed creating data gaps in each images taken after this date (USGS, http://landsat.usgs.gov/products_slcoffbackground.php). Therefore, in order to use the Landsat images for the years 2003-2010 it was necessary to fill in these data gaps to obtain an accurate measurement of the glacier size. The frame_and_fill software provided by NASA is the ETM+ gap filling program which was specifically created to fill the data gaps in the Landsat ETM+ SLC-OFF satellite scenes (SourceForge, http://l7gapfill.sourceforge.net/). This software is designed for use with the Level 1 terrain corrected GeoTIFF satellite scenes that are distributed by the USGS Global Visualization Viewer (GloVis) internet site.

The filling process was completed before any atmospheric corrections were done on the images. The frame_and_fill program first aligns multiple Landsat fill scenes to a common anchor scene and then fills the data gaps of the anchor scene with data obtained from the fill scenes. The premise being that the gaps are not always in the same location for each scene leaving an overlap of data that can be transferred from one scene to the gap in another scene. For this study the 2003-2010 images are composites of three fill scenes and one anchor scene obtained over their respective years. A list of the images used as anchor scenes and those used as fill scenes can be found in Table 2.

There were concerns that this method would leave obvious lines, or streaks, of data across the images from pixel with greater snow cover. The main concern being if the four scenes used for each gap-filled image were acquired in different seasons, would there be obvious increases in glacier area measured due to pixels extracted from scenes with greater snow cover. This could potentially create false snow and ice area calculations and compromise the glacier area measurements of the final analysis. Fig. 9 illustrates how this was not the case and the images are in fact filled well, without obvious streaks that would indicate seasonal increases in snow cover.

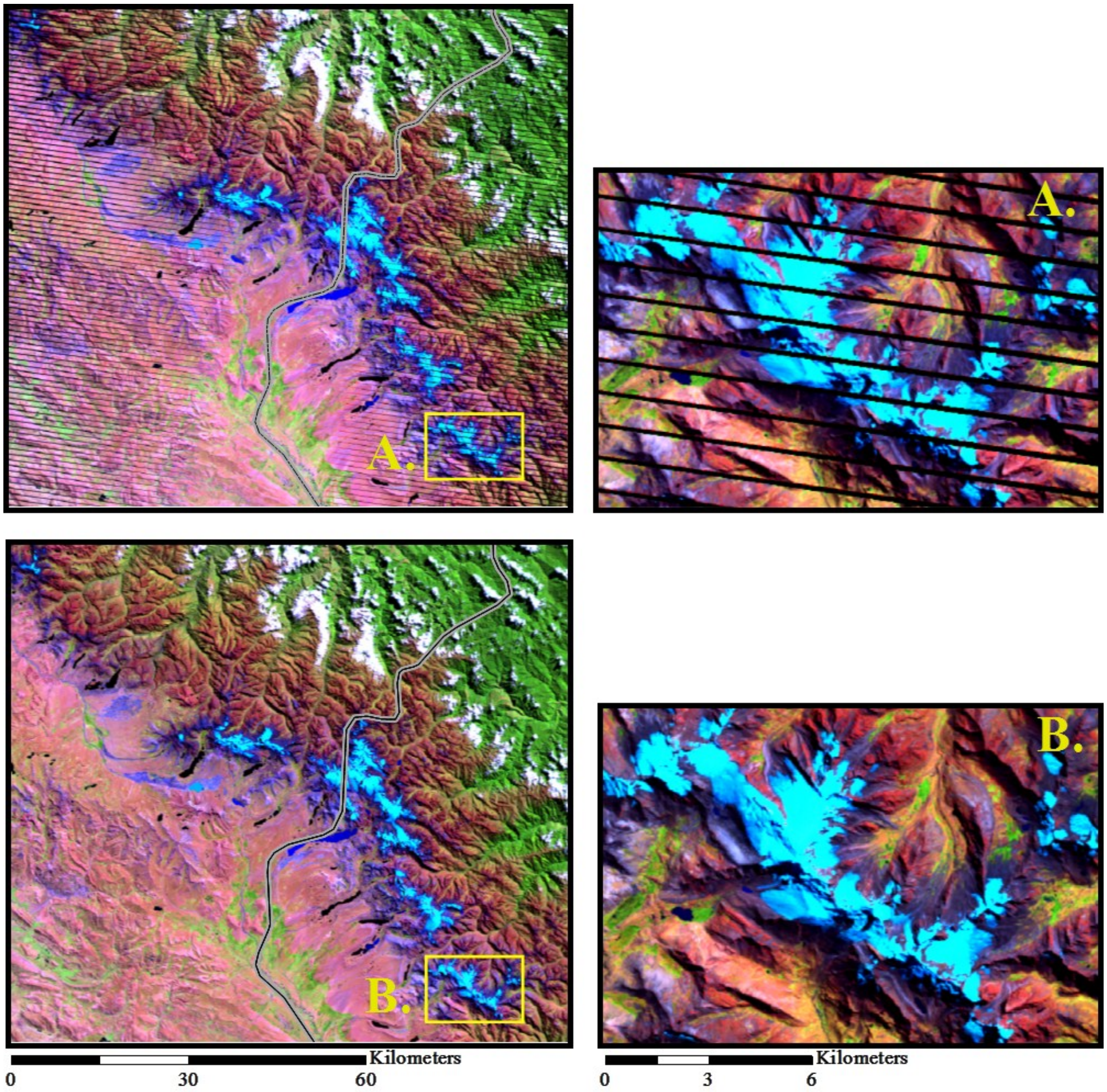


Fig 9. Gap filling process example image. These scenes depict (A) the 2010 image with gaps before the frame_and_fill method was applied and (B) the filled 2010 image after the frame_and_fill method was applied.

Once the images were selected and filled it was necessary to atmospherically correct the Landsat images in order to obtain accurate reflectance measurements. The primary purpose of atmospherically correcting a satellite image is to remove or decrease the influence of the atmosphere on object reflectance (Yuan, 2008). The atmospheric correction for each Landsat image was accomplished in ENVI 4.5 using standard methods to convert the original digital number (DN) values to radiance using the Landsat ETM+ wavelengths. Next the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) method was used to convert the values into reflectance. The FLAASH method is an atmospheric correction method which uses the following equation to correct wavelengths in the visible through the near-infrared and shortwave infrared range of the spectrum (Yuan, 2008).

$$L = \left(\frac{A\rho}{1 - \rho_e S}\right) + \left(\frac{B\rho_e}{1 - \rho_e S}\right) + L_\alpha \qquad \text{Eq. 1}$$

L = sensor pixel

ρ = pixel surface reflectance

ρ_e = average surface reflectance for the pixel and surrounding region

S = spherical albedo of the atmosphere

L_a = radiance back scattered by the atmosphere

A and B = coefficients that depend on both atmospheric and geometric conditions but not on the surface (Kaufmann, 1997)

Unlike other atmospheric correction models, FLAASH incorporates the MODTRAN4 (MODerate resolution atmospheric TRANsmission) radiation transfer code which allows the user to choose the standard MODTRAN model atmosphere and aerosol type that best represents the scene and then a unique MODTRAN solution is computed for each individual scene (Yuan, 2008).

For the gap-filled images, the anchor scene's metadata was used for the FLAASH configuration because it is the outset scene that is filled by the other scenes. Therefore, the majority of the end product composite image is comprised of the anchor scene according to the frame_and_fill program description (SourceForge, http://l7gapfill.sourceforge.net/). It was important that the Landsat images used in this study were pre-processed using similar techniques to ensure comparable glacier mapping results. Each of the scenes had been georectified upon their acquisition from the USGS Global Visualization Internet site (http://glovis.usgs.gov).

4.3 Satellite Image Processing

The Normalized Difference Snow Index (NDSI) was calculated using bands 2 (0.52-0.60 µm) and 5 (1.55-1.75 µm) (Klein et al., 1998) from the atmospherically corrected Landsat image for each year in ENVI with the following equation:

$$\frac{(VIS - NIR)}{(VIS + NIR)} \approx \frac{(band\ 2 - band\ 5)}{(band\ 2 + band\ 5)} \qquad \text{Eq. 2}$$

The NDSI method was chosen because it is less sensitive to illumination variations than non-ratio methods. It also takes advantage of the high brightness values of snow and ice in the visible wavelengths (0.4–0.7 µm) versus low brightness values in the near and mid-infrared (0.75–1.75 µm) to separate them from darker areas such as rock, soil and vegetation (Racoviteanu, 2008; Silverio and Jaquet, 2005). The NDSI method calculates the amount of snow in each pixel and assigns values that fall between -1 and +1.

Following the NDSI calculation, a threshold was created for each image to exclude all erroneous water pixels that were possibly included as snow and ice in the NDSI calculation using the 0.75-0.90 µm band 4 of the atmospherically corrected image and band 1 of the NDSI image. According to Klein et al. (1998), only pixels with a reflectance at 0.9 mm (Landsat band 4), of greater than 11% are considered to be snow which excludes liquid water pixels that may also have high NDSI values. Therefore, the NDSI threshold used in this study was set at 11% for Landsat band 4.

Next, each classified snow and ice raster grid was converted into a vector shapefile containing the glacier area. The World Glacier Monitoring Service, for the purpose of remote sensing, has set a minimal size limit of 1,000 m^2 for identifying glaciers from remotely sensed images (Allison, 1975; Allison and Peterson, 1976).

Because the Landsat image resolution is 30 m this was rounded down to 900 m^2. All the polygons or patches of ice that were not at least 900 m^2 were excluded from the final calculations. This size limit was chosen to ensure that no excess snow or ice around the glacier itself would be included in the area calculations of the glacier.

A combinatorial OR operation was conducted to categorize the change taking place between each successive pair of years. This resulted in identifying glacial ice pixels that were gained, lost and remained the same in both images. The area of ice was then calculated using these pixel counts for each year.

To obtain a more accurate estimate of the total amount of ice for the 1980's decadal period the Landsat 5 TM scenes for the years 1985, 1986 and 1987 were combined into a single scene composed of only the pixels that contain ice in all three images. This was done in order to exclude the excess snow fall that was visibly noticeable in the 1986 and 1987 images as compared to the 1985. Figure 10 illustrates this excess snow cover in the Chaupi Orco peak region of the Cordillera Apolobamba using the 1985 extent outlined (red outline) overlaid onto the 1986 and 1987 scenes. Clearly the latter two exceed the 1985 outline, but more so in 1987. The fourth frame in the lower right corner depicts the glacier extents of these three years overlaid by the 1980's composite image glacier extent (black outline) to illustrate the area used in the analysis of this study. To obtain the 1980's composite image, a combinatorial OR was performed on the 1987 and 1986 images. Following this, another combinatorial OR operation was performed using the resulting image and the 1985 image. The results of this operation yielded the pixels that are only classified as ice in all three images.

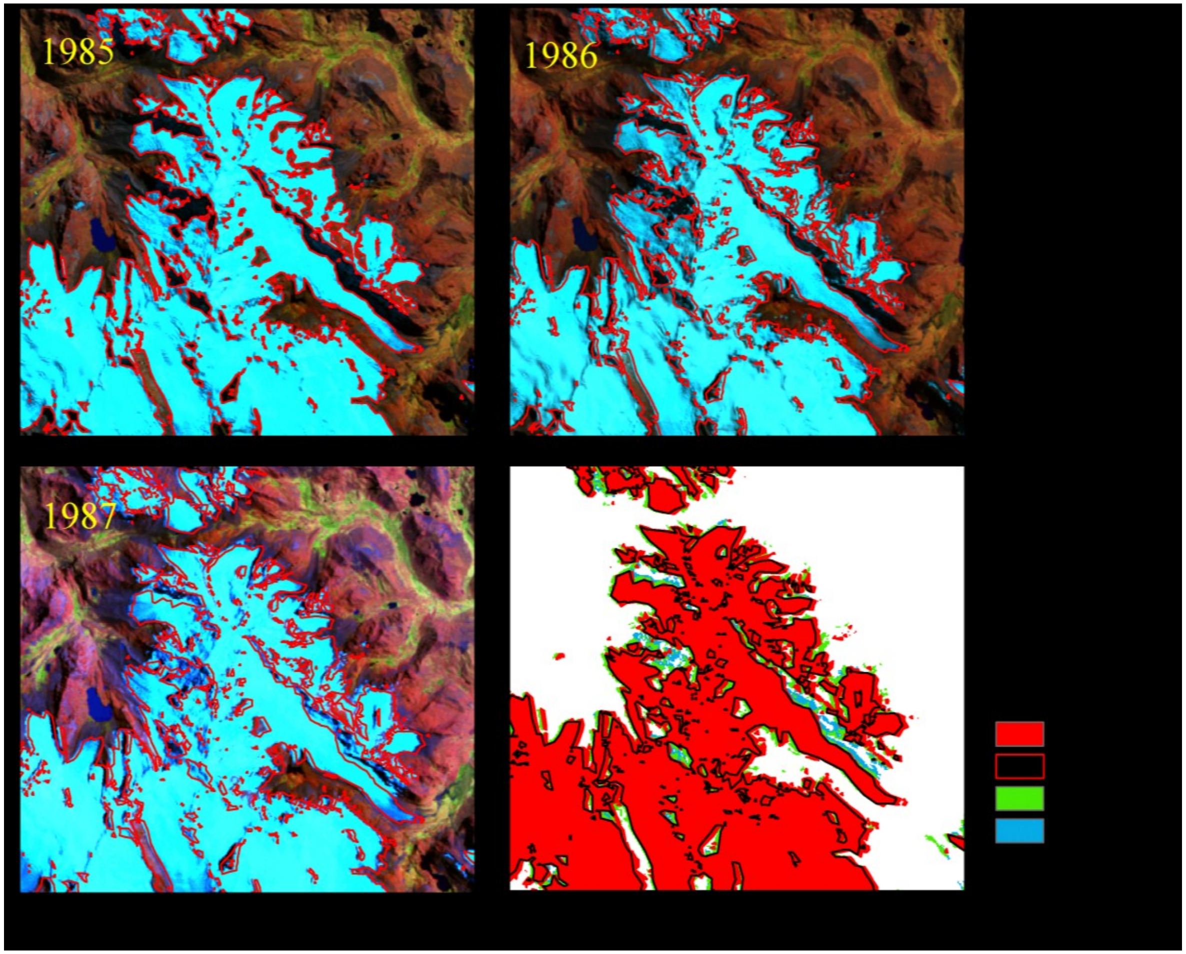


Fig 10. Landsat TM 1985, 1986 and 1987 glacier extents. Scenes from 1985 (upper left), 1986 (upper right) and 1987 (lower left) of the Chaupi Orco peak region of the Cordillera Apolobamba. It is overlaid by the 1985 extent (red line) to exhibit the excess snow cover in the 1986 and 1987 scenes as compared to the 1985 scene. The final frame (lower right) is a map of this same region depicting the glacier area extents of 1985 (red), 1986 (green) and 1987(blue) as compared to the glacier area measured in the 1980's composite image (black line).

Various measurement techniques were applied to the satellite images to calculate not only the area of the glacier ice, but the slope, aspect, and glacier hypsometry as well. The slope and aspect were calculated using a geographic information system and the results are presented graphically in the following section. Hypsometry is the measurement of the elevation of land relative to sea level. A hypsometric curve is shown as a continuous function and graphically displayed as an x-y plot with the elevation on the vertical y-axis and the area above sea level on the horizontal x-axis (Brocklehurst and Whipple, 2004).

For this study the hypsometry was calculated for the Glacier Inventory of Bolivia of 1975 as well as the Landsat 1980's composite, 1995 and 2005 images. This was done to depict the change in area at each elevation zone for each decade. Beginning with the HydroSHEDS (**Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales) DEM of the Cordillera Apolobamba clipped to just the area over the glacier ice, the hypsometry was calculated by reclassifying the DEM into 100 meter zones. Then a zonal statistic operation was performed using the reclassified DEM and the raster extract of the glacier area. The resulting values represent the area of glacierized land above sea level in 100 meter intervals from 4300 to 6000 meters.

4.4 Acquisition of Climate Data

The climate data used for this study was obtained from the National Centers for Environmental Prediction (NCEP) National Center for Atmospheric Research (NCAR) reanalysis dataset that is freely available to the public through the National Oceanic and

Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL) (http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml). This data was obtained with help from Dr. Kenneth Bowman, professor and head of the Department of Atmospheric Sciences in the College of Geosciences at Texas A&M University.

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) provides El Niño Southern Oscillation (ENSO) and monthly sea surface temperature (SST) datasets online at their Climate Prediction Center (CPC) website (http://www.cpc.ncep.noaa.gov/). The Niño 3 (upper) and Niño 3.4 (lower) SST indices depict five month running means using the data from NOAA relative to the base period climatology from 1950-1979. The Niño 3 dataset is bounded by the region 90°W-150°W and 5°S-5°N with a ±0.5°C threshold set on its values while the Niño 3.4 dataset is bounded by the region 120°W-170°W and 5°S-5°N with a ±0.4°C threshold. The threshold for these datasets determines what is considered to be El Niño and La Niña events (i.e., anomalies). Typically, El Niño events are warm phases when the SSTs are above average while La Niña events are cold phases when the SSTs are below average. The Oceanic Niño Index (ONI) has become the standard used by NOAA for identifying warm and cold ENSO phase anomalies (NOAA, http://www.cpc.ncep.noaa.gov/). It is a three month running mean SST index for the Niño 3.4 region with a threshold of ±0.5°C for identifying warm and cold phases. To be considered an El Niño or La Niña event the temperature trend must continue over five consecutive months. These events are further broken down into weak (0.5 to 0.9°C SST anomaly), moderate (1.0 to 1.4°C SST anomaly) and strong (≥ 1.5°C SST anomaly) events For an event, or anomaly, to be considered in any of these categories the temperatures must not exceed these thresholds for three consecutive months (NOAA, http://www.cpc.ncep.noaa.gov/).

4.5 Analysis of Climate Data

The climate data was gathered for 1975-2008 and then divided into three shorter time periods; 1975-1986, 1987-1995, and 1996-2005. Dividing the total thirty year span into three shorter time periods provides a more detailed account of how these factors have fluctuated from one period to the next. These time periods were chosen because they coincide with the years of the four images chosen for the analysis of this study; 1975, 1980's, 1995, and 2005. It is essential to have the climate analysis coincide with the dates of the satellite images analysis to assess the correlation between the climate conditions and the area changes of the glaciers. The monthly means were used from the reanalysis datasets for the climate variables air temperature, freezing level, specific humidity, precipitation, solar radiation, geopotential height and wind velocity at the 500 hPa atmospheric level for the three time periods. This pressure level was chosen because 500 hPa is about 5,500 meters (18,000 feet) above sea level which is approximately at the height of the tallest peaks of the Apolobamba range.

Statistical software (SPSS) was used to conduct an independent samples t-test at the 95% confidence level for periods 1-2 and periods 2-3. The t-test method is used to determine if there was a statistically significant change in the climate variables between each of the three time periods. The variable was considered to be statistically significant if the t-test significance value was less than 0.05 ($\alpha = 0.05$ level). This identified the variables that could potentially have the greatest impact on the retreat of the Apolobamba glaciers. After the results of the area calculations and the climate variables analysis were recorded for each time period the correlations observed between the area changes of the glaciers and the changing climate conditions were depicted both graphically and statistically.

5. RESULTS

5.1 Glacier Mapping

The Landsat TM and ETM+ images as well as the Glacier Inventory of Bolivia used in the analysis of this study cover the thirty-five year span from 1975 to 2010. The glacierized areas of all the Landsat images that were fully processed for this study are shown in Figure 11. When plotted in their entirety the glacierized area of the Cordillera Apolobamba appears to have increased in 1986 and 1987 as well as from 1998 to 2005 and again from 2005 to 2010. These apparent increases in area are erroneous and are associated with excess snow cover in these images. Therefore, these images were excluded from the final area analysis.

The images included in the final area analysis of the retreat of the glacier ice were 1985, 1986, 1987, 1995 and 2005 as well as the Glacier Inventory of Bolivia from 1975 for the Cordillera Apolobamba. The 1985, 1986, and 1987 images were, as previously mentioned, combined into a 1980's composite image here after referred to and labeled as the 1986 image because this is the average of these three years. The final images used in the area analysis of the retreat of the glacier ice of the Cordillera Apolobamba provide an accurate depiction of the rate of change.

For the further analyses of hypsometry, slope and aspect an image was chosen from each decade. Those chosen were the 1975 Glacier Inventory of Bolivia as well as 1986, 1995 and the 2005. They are evenly spaced at ten years apart and can be associated with the three time periods used in the climate analysis. Period 1 covers the years 1975-1986 and includes the Glacier Inventory of Bolivia and the 1980’s composite image. Period 2 covers the years 1987-1995 and includes the images 1980’s composite and the 1995 image. Period 3 covers the years 1996-2005 and includes the 2005 image.

The further analyses of hypsometry, slope and aspect are conducted for the complete range and the Bolivia segment of the 1975 Glacier Inventory of Bolivia separately. This is done because the Glacier Inventory of Bolivia encompasses a smaller region than the images covering the entire Cordillera Apolobamba. Therefore, the results for the Bolivia segment of the Cordillera Apolobamba included in this study represent only the change in the area that was covered by E. Jordan in the Glacier Inventory of Bolivia of the 1970’s.

The outputs of the area calculations for the glacier range exhibit a recessional trend that has continued from 1975 to 2010 as indicated by a simple linear regression (Fig 12). In total, the Cordillera Apolobamba glacier range has decreased in area over the past thirty-five years. The portion of the Cordillera Apolobamba located within Bolivia’s border, as shown in the Glacier Inventory of Bolivia, has lost 110.76 km^2 of surface ice decreasing its total area from 240.36 km^2 to 129.60 km^2. This represents a 46.08% reduction for the area of the Cordillera Apolobamba included in the Glacier Inventory of Bolivia from the 1970’s. From the year 1985 to 2010 the entire Apolobamba range lost 102.72 km^2 of ice decreasing its total area from 261.07 km^2 to 158.35 km^2. This represents a 39.35% reduction for the entire glacier range. The linear regression calculated for the glacier area change was used to ascertain the glacier area loss per year. Following is the simple linear regression equation calculated for the entire Cordillera Apolobamba glacier range:

$$y = -2.000 * x + 4179.224 \quad \text{Eq. 3}$$

According to these calculations, the entire Cordillera Apolobamba has receded at a pace of approximately 2.00 km^2 per year. The simple linear regression equation calculated for the Bolivia segment of the Cordillera Apolobamba is as follows.

$$y = -2.925 * x + 5996.784 \quad \text{Eq. 4}$$

According to these calculations the Bolivia segment of the Cordillera Apolobamba has recede at approximately 2.93 km^2 per year.

The time period from 1975 to 1986 exhibits the greatest area loss in Bolivia decreasing from 240.36 km^2 to 165.78 km^2 (-74.58 km^2) while the time period from 1995 to 2005 exhibits the greatest area loss for the entire range decreasing from 193.20 km^2 to 171.62 km^2 (-21.58 km^2) (Table 3). These are the same time periods exhibiting the greatest percent area loss at 31.03% glacier area from 1975 to 1986 for Bolivia and 11.17% glacier area from 1995 to 2005 for the entire range.

Figures 13 and 14 further illustrate the reduction of the glacierized area of the Cordillera Apolobamba. Figure 13 depicts the area of the entire glacier range for 1986, 1995 and 2005. Figure 14 depicts the area of the Bolivia segment for 1975, 1986, 1995 and 2005. Each of these figures uses the 2010 Landsat ETM+ scene as a base and has two insets depicting the region of the two tallest peaks of the Cordillera Apolobamba, the Chaupi Orco and the Cololo, for closer reference of the glacier retreat.

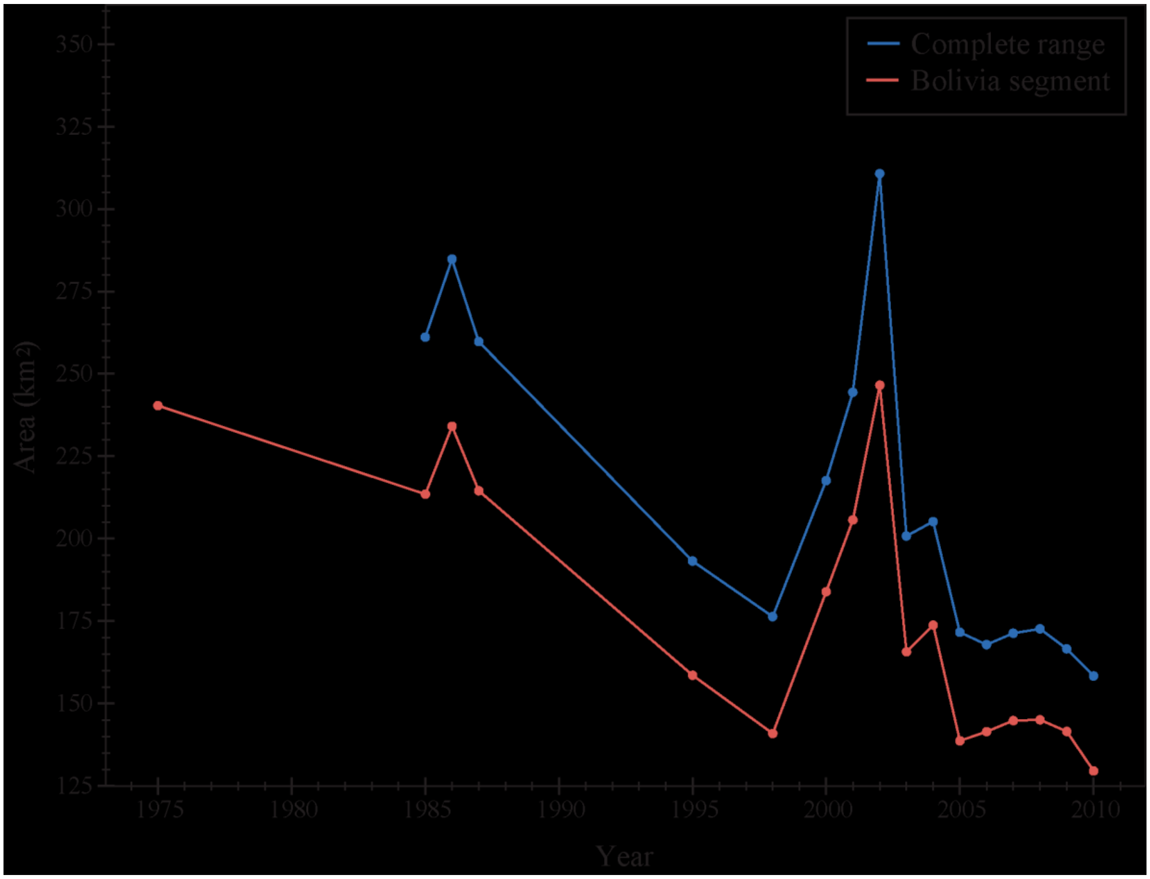


Fig 11. Glacier area of Cordillera Apolobamba. Line graph depicting the glacier area (km^2) of all the Lansdat satellite images that were fully processed for this study as well as the Glacier Inventory of Bolivia.

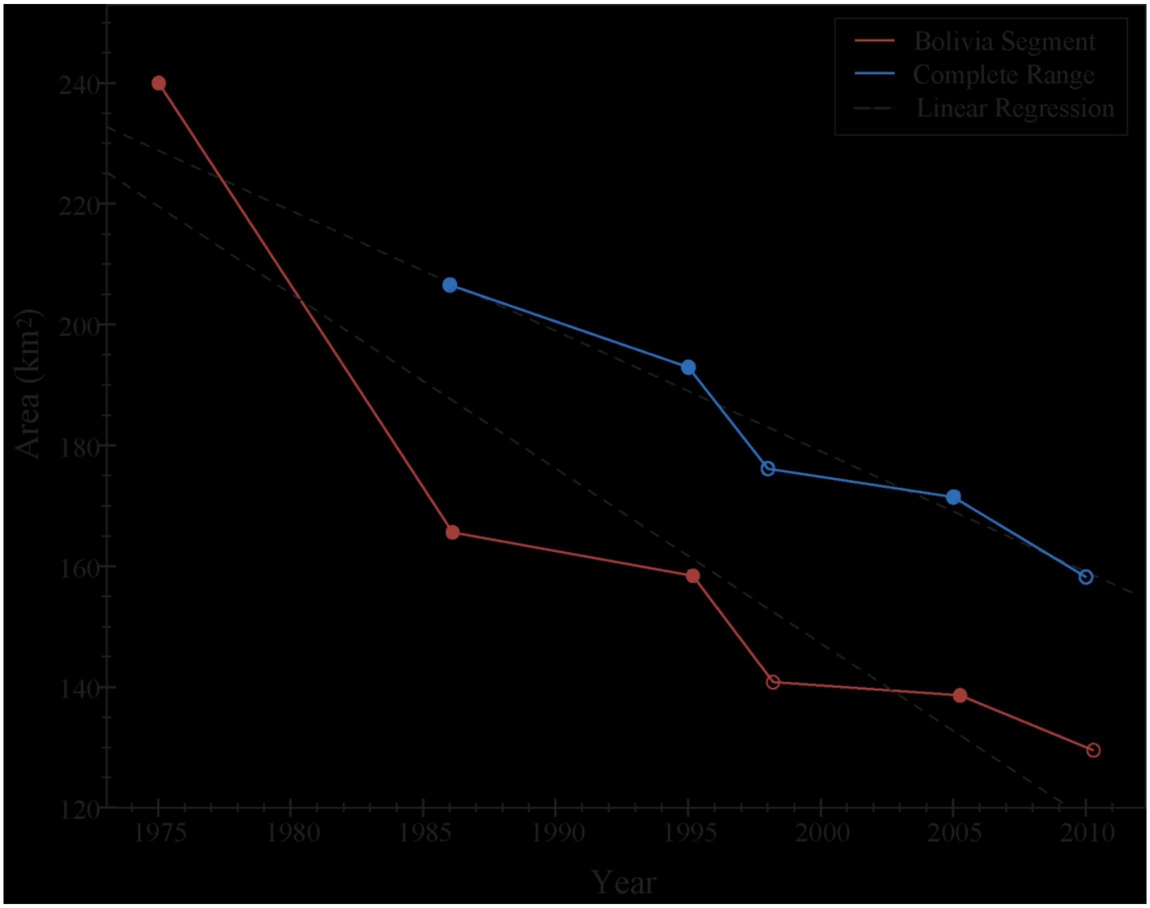


Fig 12. Glacier area of Cordillera Apolobamba with linear regression. Line graph depicting the area changes for both the portion of the Cordillera Apolobamba located in Bolivia and the complete glacier range with a linear regression trend line. The years with filled markers are used in further analyses of hypsometry, slope and aspect.

Table 3. The glacier areas for 1975, 1986, 1995, 1998, 2005 and 2010. Also the total area loss and percent area loss for the portion of the Cordillera Apolobamba located in Bolivia and the complete glacier range.

	Complete Range	*Bolivia Only*
Year	**Total Area (km^2)**	
1975	NA	240.36
1986	206.87	165.78
1995	193.20	158.56
1998	176.34	140.92
2005	171.62	138.70
2010	158.35	129.60
	Total Area Loss (km^2)	
1975 to 1986	NA	74.58
1986 to 1995	13.67	7.22
1995 to 2005	21.58	19.86
	Percent Area Loss	
1975 to 1986	NA	31.03
1986 to 1995	6.61	4.35
1995 to 2005	11.17	12.52

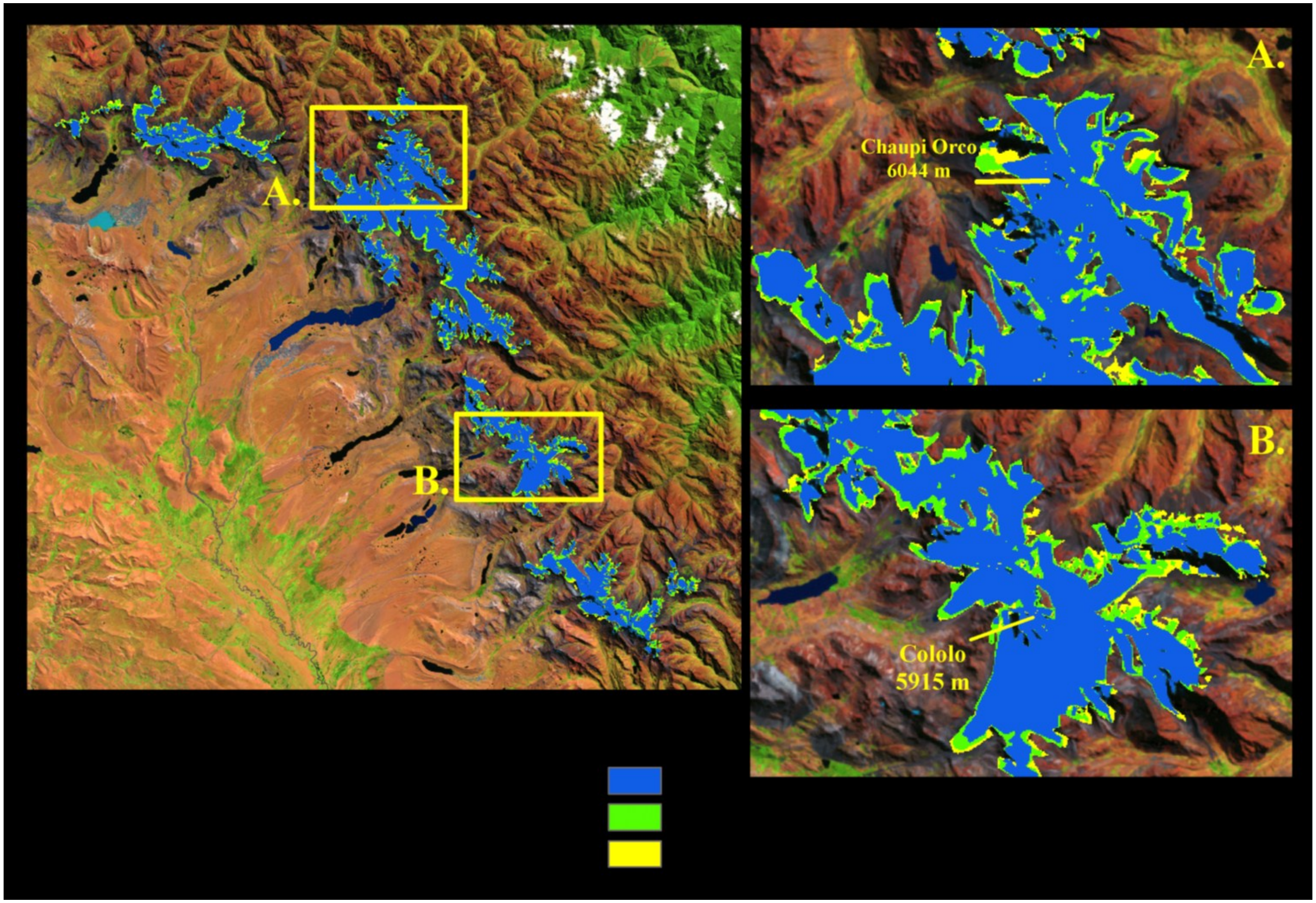


Fig 13. Glacier recession 1986-2005. Image depicting the recession of glacier ice from 1986 to 2005 for the entire Cordillera Apolobamba over a 5 ,4, 2 (RGB) false color composition of the 2010 Landsat ETM+ image. The frames on the right depict the tallest peaks (A) Chaupi Orco and (B) Cololo for closer reference of glacier retreat.

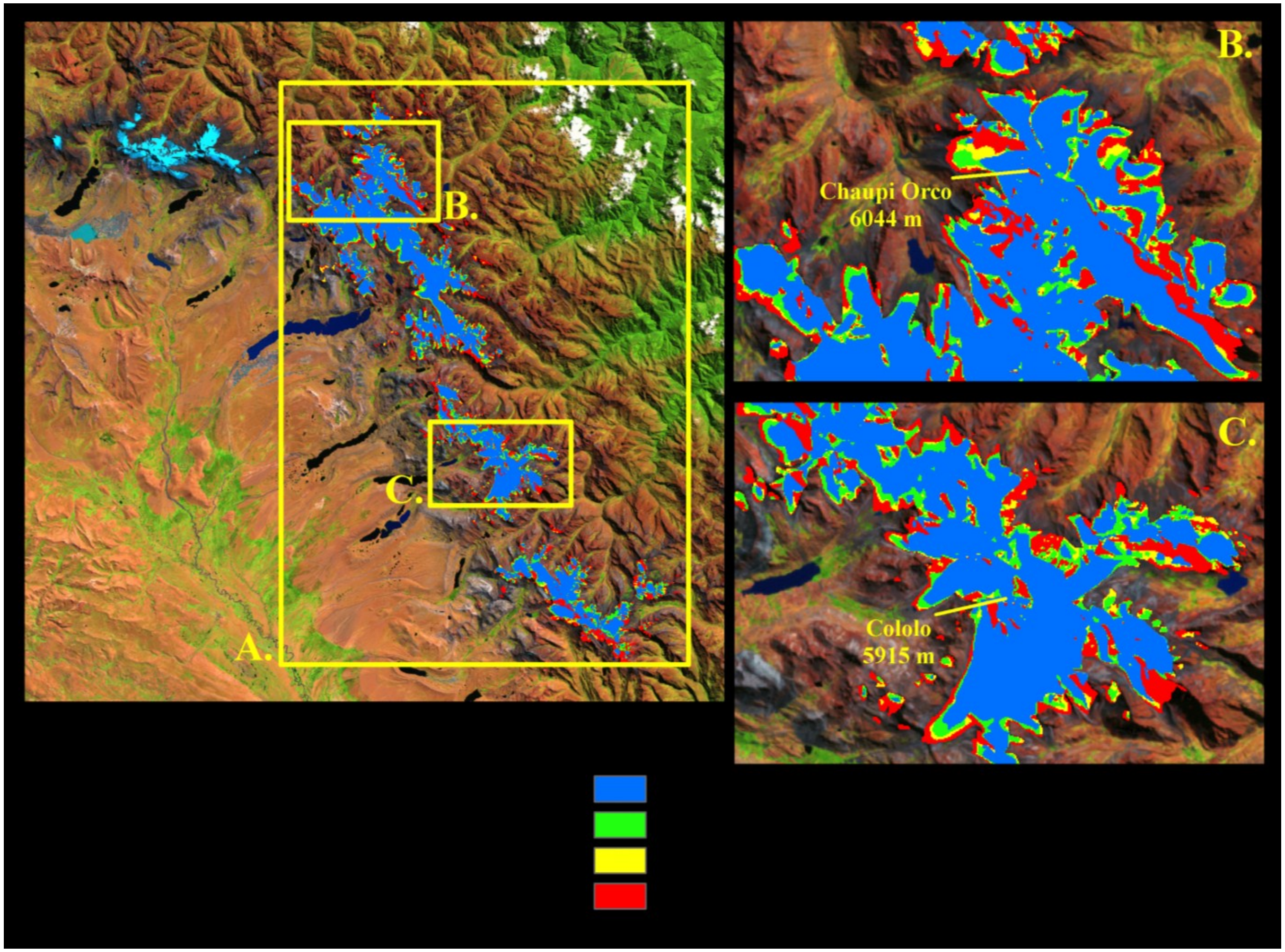


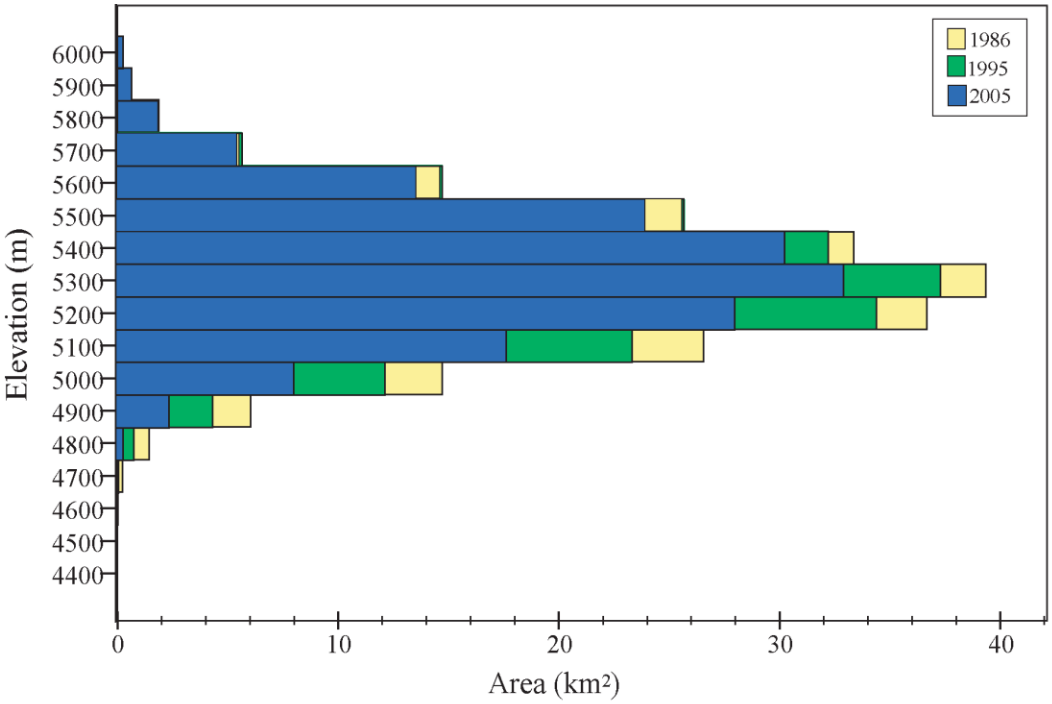
Fig 14. Glacier recession 1975-2005. Image depicting the recession of glacier ice from 1975 to 2005 for the portion of the Cordillera Apolobamba in Bolivia that is included in the Glacier Inventory of Bolivia (A). The base image used is a 5, 4, 2 (RGB) false color composition of the 2010 Landsat ETM+ image. The frames on the right depict the tallest peaks (B) Chaupi Orco and (C) Cololo for closer reference of glacier retreat.

5.2 Hypsometry Results

According to the hypsometry calculations, the Cordillera Apolobamba’s lowest glacierized elevation has changed by aproximately 100 m each decade from 1975 to 2005; 4,384 m in 1975, 4,493 m in 1986, 4,556 m in 1995 and 4,604 m in 2005. The highest glacierized elevation of the Cordillera Apolobamba has remained constant at 5,998 m.

Between 1975 and 1986 the glacierized area of the segment of the Cordillera Apolobamba range in Bolivia decreased by 100% between 4,300 and 4,400 m in elevation and by 93.75% between 4,400 and 4,500 m. From 1986 to 1995 this segment decreased by 100% between 4,400 and 4,500 m, and then from 1995 to 2005 it additionally decreased by 100% between 4,500 and 4,600 m in elevation. The segment of the Cordillera Apolobamba within Bolivia lost all the glacier ice from its three lowest elevation zones of 4,400 as well as 4,500 and 4,600 m above sea level from 1975 to 2005. The results for the entire range are similar exhibiting a loss of 100% of the glacierized area between 4,400 and 4,500 from 1986 to 1995 and then a loss of 100% of the glacierized area between 4,500 and 4,600 m from 1995 to 2005. From the pattern of this retreat it is evident that the recession of the Cordillera Apolobamba’s glacier ice is proceeding from the lowest toward the highest elevations. This is expected as the lowest portion of a glacier is the ablation zone where most of the loss of glacier ice takes place while most of the gain in ice takes place in the accumulation zone in the upper regions of the glacier (Andrews, 1975).

The highest elevations from 5,500 to 6,000 m exhibit small increases or apparent gains in elevation of approximately 5 % of the glacierized area of the Cordillera Apolobamba between the 1986 and 2005 images. From 1986 to 1995 both the Bolivia segment and the complete range exhibit increases in elevation varying from 0.24 % to 6.8 %, the highest increase being in the highest elevation zones of 5,800 as well as 5,900 and 6,000 m. There are also small increases of approximately 1 % in the 5,800 to 5,900 elevation zones for the Bolivia segment and the complete range between the 1995 and 2005 images. This can be seen in the percent area loss (Fig 15, Fig 16) as an increase in percent area for the 5,800 to 6,000 m elevation zones between 1986 and 2005 for the entire glacier range. However, the 1975 to 2005 results for the percent area loss in the Bolivia segment do not exhibit any gain at higher elevations (Fig 16). This could possibly be explained by several scenarios that will be further explained in the following discussion section.



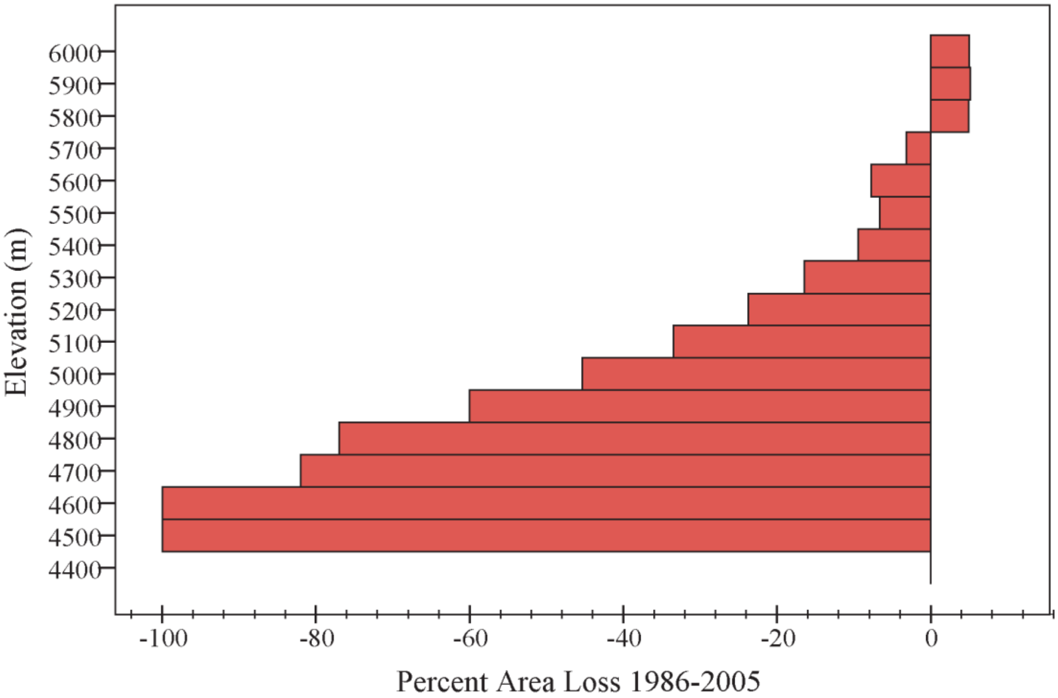


Fig 15. Hypsometry of entire Cordillera Apolobamba. Graphs depicting the hypsometry for the glacierized area of the complete Cordillera Apolobamba; (top) Area of land (km^2) above sea level for each elevation bin, (bottom) the Percent Area Loss from 1986-2005 for each elevation bin.

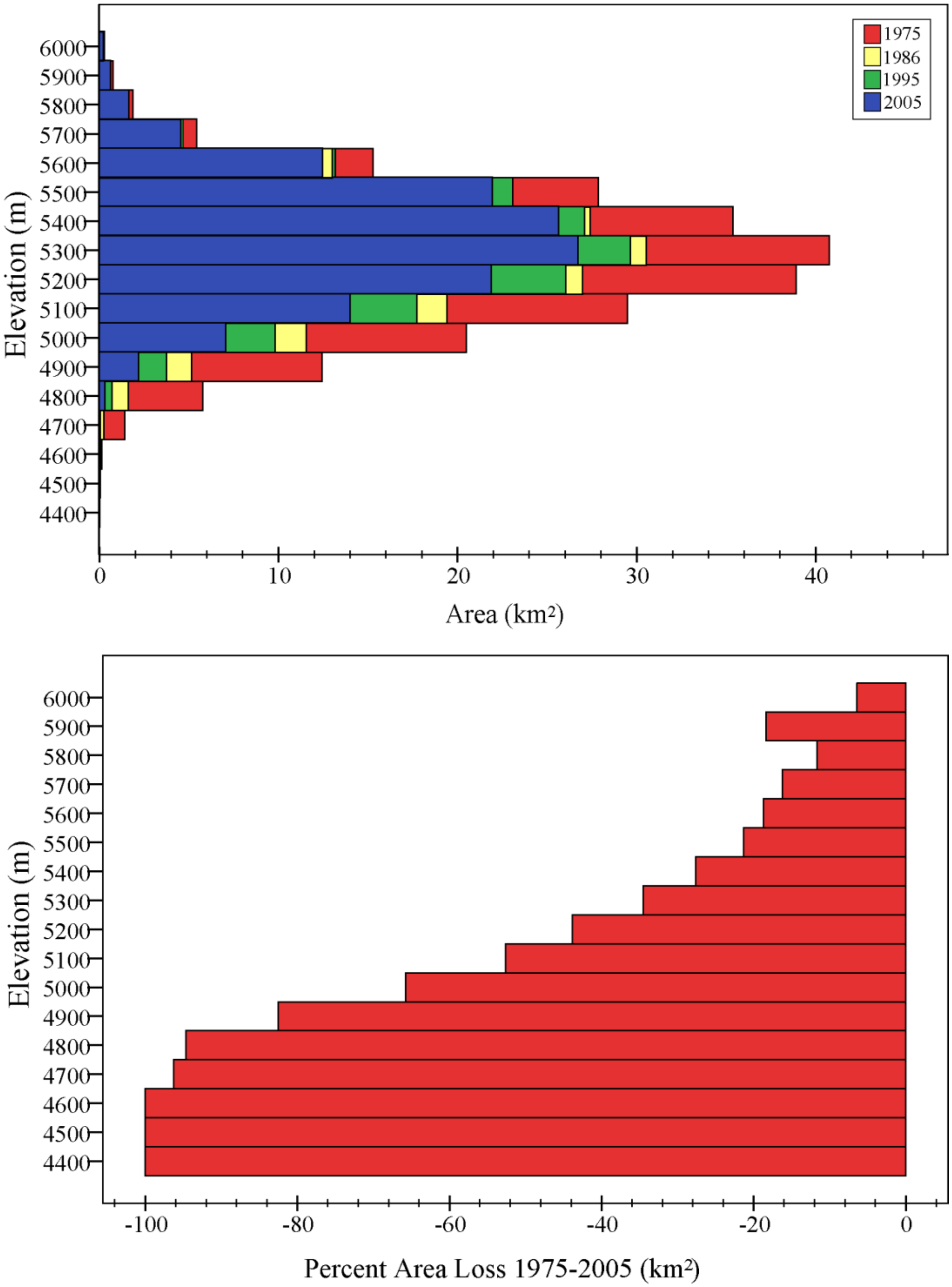


Fig 16. Hypsometry of Bolivia segment of Cordillera Apolobamba. Graphs depicting the hypsometry for the glacierized area of the Bolivia segment of the Cordillera Apolobamba; (top) Area of land (km^2) above sea level for each elevation bin, (bottom) the Percent Area Loss from 1975-2005 for each elevation bin.

5.3 Slope and Aspect Results

Both the slope and aspect results in this study were calculated using a HydroSHEDS DEM which is a void filled version of the high resolution elevation dataset obtained during the flight for NASA's Shuttle Radar Topography Mission (SRTM). This mission obtained elevation data on a global scale in order to generate the most complete high resolution digital topographic database of the Earth and consisted of a specially modified radar system onboard the Space Shuttle Endeavour during an 11 day mission in February of 2000 (NASA, http://www2.jpl.nasa.gov/srtm/). Slope calculations depict the ratio of change in elevation from 0 - 90°, or simply how steep is the ground. The results are obtained by calculating the difference between a pixel's elevation value and those of its adjacent pixels (DeMers, 2002).

The results of the slope calculations are similar for both the entire Cordillera Apolobamba range and the Bolivia segment. The Cordillera Apolobamba's glacierized area has predominately gentle sloping faces between 10-20° (Fig 17, Table 4, Fig 18, Table 5). The steepest slopes of this area are 40-50° with a very small area being between 50-60°. At the 90 m resolution of the HydroSHEDS DEM, there are no slopes steeper than 60° within the glacierized area of the Cordillera Apolobamba.

From 1975 to 1986 the greatest losses for the Bolivia segment at the lower degree intervals particularly the 20-30° interval which suffered a -23.72 km^2 loss in area. From 1995 to 2005 the greatest area losses for the entire range were -10.13 km^2 from 10-20° and -8.06 km^2 from 20-30°.These losses also occurred in the lowest degree interval.

In the analysis of both regions there are apparent increases in area during the 1986 to 1995 results in the 40-50° and 50-60° intervals.

The greatest percent area loss was between 1975 to 1986 for the Bolivia segment of the Apolobamba and between 1995 and 2005 for the complete range. For the Bolivia segment there was a decline in percent area loss during the 1986 to 1995 decade resulting in percent area gains for the 40-50° and 50-60° intervals. Also for this segment the 1995 to 2005 decade exhibits consistant percent area losses for all degree intervals ranging from 10% to 26%. However, there are apparent gains in percent area for the 1986 to 1995 decade in the 40-50° (5.61%) and 50-60° (4.55%) intervals. This is similar to the complete range which exhibits a 2.81% gain in area in the 40-50° interval during the 1986 to 1995 decade. The possible causes of these small increases in area will be further analyzed in the following discussion section.

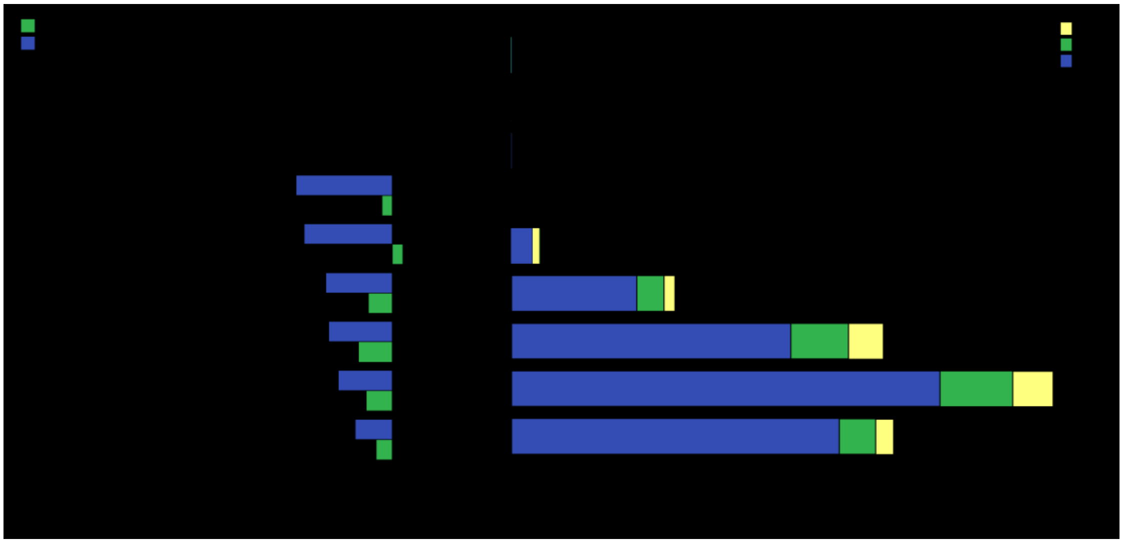


Fig 17. Slope area change of entire range. Graphs depicting the slope of the entire Cordillera Apolobamba range from 1986-2005. Also the percent area loss on the left and the total slope in area (km^2) on the right each separated into degree zones from 0-90° shown between the two graphs.

Table 4. Slope area change of entire range. The slope calculations for the entire Cordillera Apolobamba range. Included are the total area, area loss, and percent area loss, 1986-2005. Bold values represent an increase in area.

Slope Degree Interval	***Area (km^2)***			***Area Loss (km^2)***		***Percent Area Loss***	
	1986	**1995**	**2005**	**1986-1995**	**1995-2005**	**1986-1995**	**1995-2005**
0-10	53.14	50.81	45.74	2.32	5.07	4.38	9.98
10-20	75.23	69.93	59.80	5.30	10.13	7.04	14.49
20-30	51.72	47.04	38.98	4.69	8.06	9.06	17.13
30-40	22.78	21.31	17.51	1.47	3.81	6.47	17.86
40-50	3.84	3.95	3.01	**+0.11**	0.93	**-2.81**	23.67
50-60	0.16	0.16	0.12	**+0.00**	0.04	2.79	25.86
60-70	0	0	0	0	0	0	0
70-80	0	0	0	0	0	0	0
80-90	0	0	0	0	0	0	0

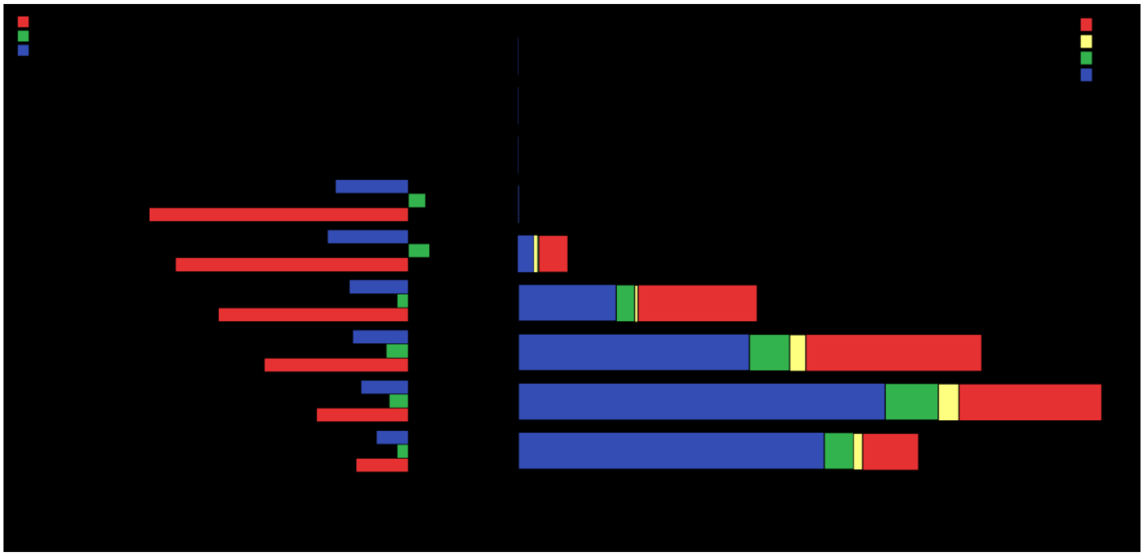


Fig 18. Slope area change of Bolivia segment. Graphs depicting the slope of the Bolivia segment of the Cordillera Apolobamba range from 1975-2005. Also the percent area loss on the left and the total slope in area (km^2) on the right each separated into degree zones from 0-90° shown between the two graphs.

Table 5. Slope area change of Bolivia segment. The slope calculations for the Bolivia segment of the Cordillera Apolobamba range. Included are the total area, area loss, and percent area loss, 1975-2005. Bold values represent an increase in area.

Slope Degree Interval	***Area (km^2)***				***Area Loss (km^2)***			***Percent Area Loss***		
	1975	**1986**	**1995**	**2005**	**1975-1986**	**1986-1995**	**1995-2005**	**1975-1986**	**1986-1995**	**1995-2005**
0-10	54.42	47.00	45.61	41.78	7.42	1.39	3.83	13.64	2.95	8.40
10-20	79.22	60.15	57.14	50.07	19.07	3.01	7.07	24.07	5.00	12.37
20-30	62.96	39.24	36.94	31.55	23.72	2.29	5.39	37.68	5.84	14.59
30-40	32.53	16.33	15.85	13.40	16.20	0.48	2.45	49.80	2.94	15.48
40-50	6.85	2.68	2.83	2.23	4.18	**+0.15**	0.60	60.92	**-5.61**	21.22
50-60	0.31	0.10	0.10	0.08	0.21	0.00	0.02	67.84	**-4.55**	19.13
60-70	0	0	0	0	0	0	0	0	0	0
70-80	0	0	0	0	0	0	0	0	0	0
80-90	0	0	0	0	0	0	0	0	0	0

Aspect is the horizontal direction in which a slope faces and calculates the steepest downslope direction from each pixel to its neighboring pixels which is then expressed clockwise from 0 - 360°; 0° represents north, 90° represents east, and so on clockwise back to north at 360° (DeMers, 2002).

According to the aspect analysis conducted for this study the slopes of the glacierized area of the Cordillera Apolobamba, both the Bolivia segment and in its entirety, are predominately oriented in a south to southwestern facing direction (Fig 19, Fig 20). From 1986 to 1995 the aspect percent area loss exhibits a similar pattern in the four cardinal directions with the majority (approximately 9%) between 180°-195° (south). The 1995 to 2005 decade exhibits an aspect percent area loss with a clear north-eastern orientation the majority (approximately 36%) between 15-30°.

During the 1975 to 1986 decade the majority of the area loss for the entir glacier range was between 210-225° at approximately 46% (Fig 21). From 1986 to 1995 the majority of the area loss was between 195-210° at approximately 7.5%. This decade experienced considerably less area loss in all directions compared to the 1975-1986 decade. The aspect percent area loss of the glacierized slopes for the Bolivia segment of the Cordillera Apolobamba exhibits a majority orientation in the south-western direction from 1975 to 1986 and 1986 to 1995 (Fig 22). From 1995 to 2005 the aspect percent area loss for the Bolivia segment changes to a north-eastern direction the majority (approximately 36%) being between 15-30°.

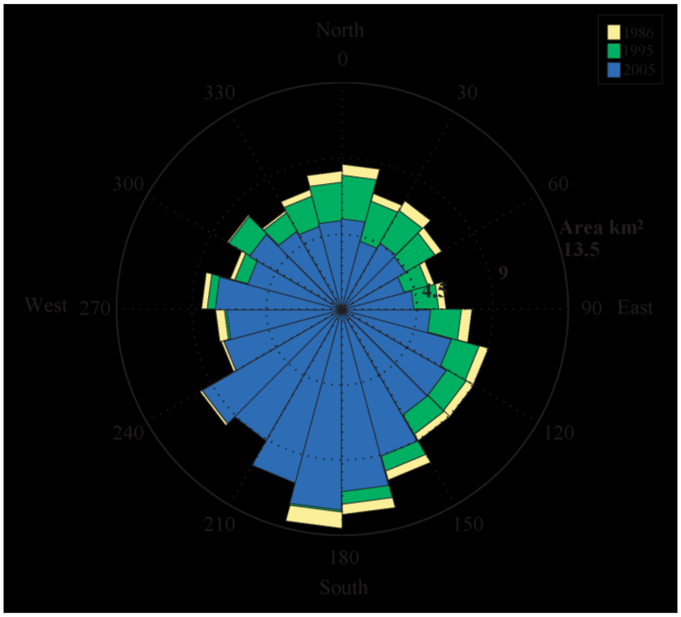


Fig 19. Aspect of entire range. Rose diagram depicting the aspect area calculations for the entire Cordillera Apolobamba range for the years 1986, 1995 and 2005.

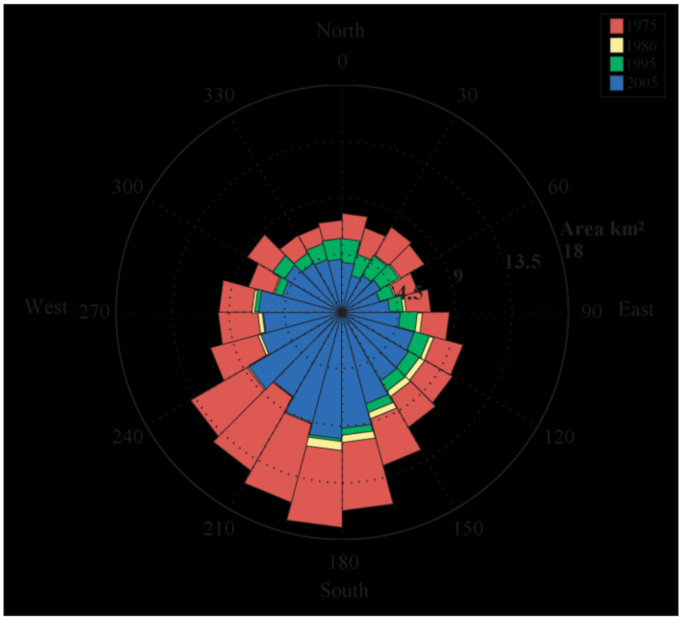


Fig 20. Aspect of Bolivia segment. Rose diagram depicting the aspect area calculations for the Bolivia segment of the Cordillera Apolobamba range for the years 1975, 1986, 1995 and 2005.

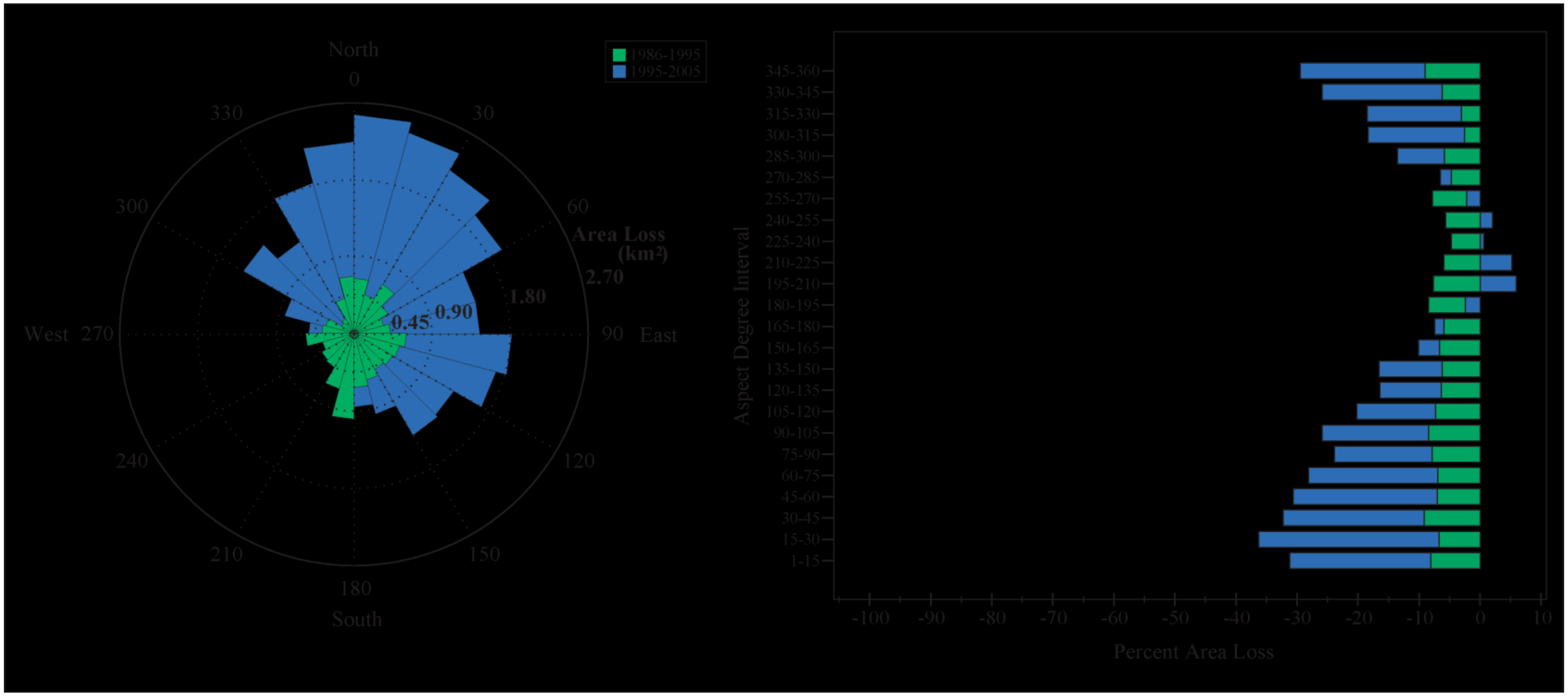


Fig 21. Aspect area loss of entire range. Rose diagram (left) depicting the aspect area loss for the entire Cordillera Apolobamba range for the years 1986-1995 and 1995-2005. Bar graph (right) depicting the percent area loss in aspect for each degree interval for the years 1986-1995 (green) and 1995-2005 (blue).

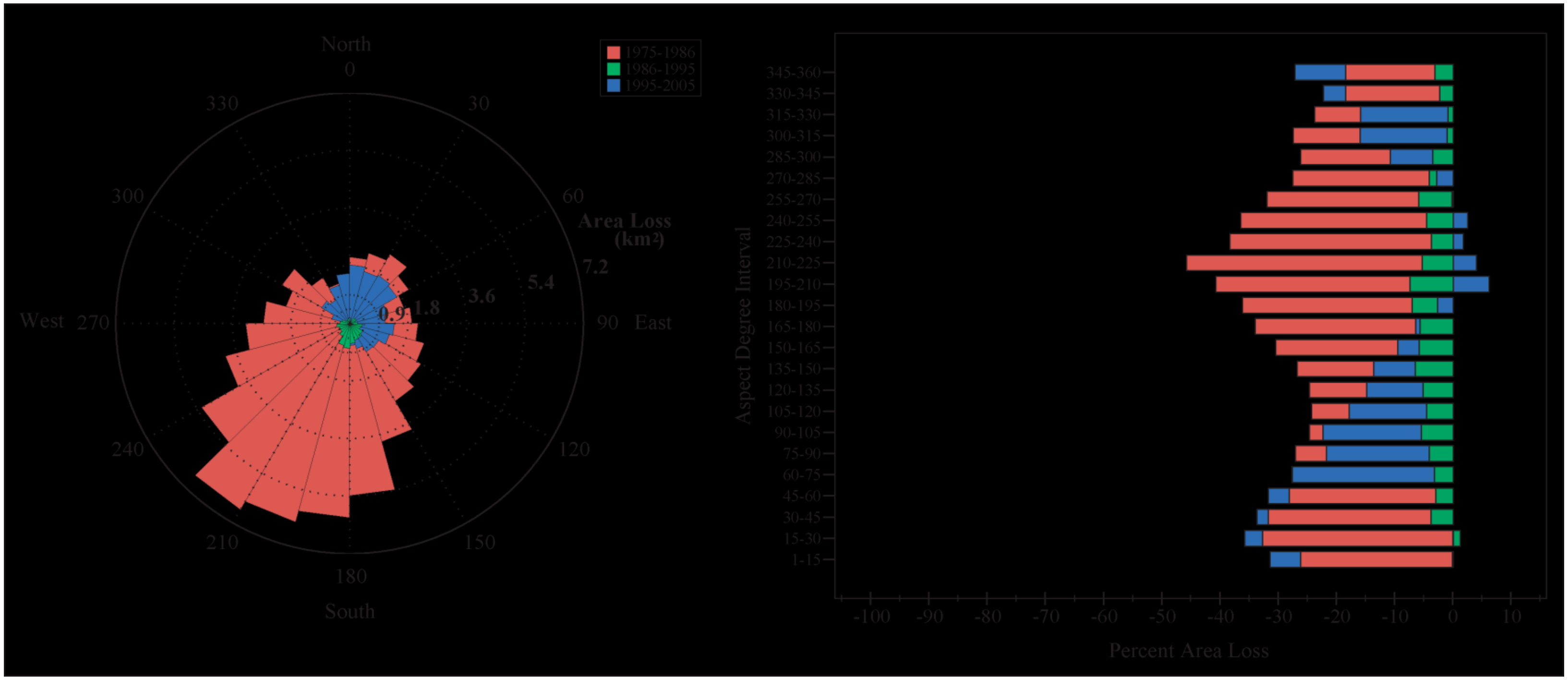


Fig 22. Aspect area loss of Bolivia segment. Rose diagram (left) depicting the aspect area loss for the Bolivia segment of the Cordillera Apolobamba range for the years 1975-1986, 1986-1995 and 1995-2005. Bar graph (right) depicting the percent area loss in aspect for each degree interval for the years 1975-1986 (red), 1986-1995 (green) and 1995-2005 (blue).

5.4 NCEP Climate Variables Results

The climate variables used in this study were extracted from the monthly NCEP re-analysis datasets at the 500 hPa level from 1975-2008 in the Bolivia-Peru region of South America. This atmospheric level was chosen because surface pressure at sea level is approximately 1000 hPa (1000 mb) which represents the total weight of the atmosphere. The 500 hPa (500 mb) level cuts the atmosphere approximately in half vertically and is also significant because the it is roughly 5,500 meters above ground level. The tallest peaks of the Cordillera Apolobamba range reach 6,044 meters (Chaupi Orco), and 5,915 meters (Cololo) which is within the 500 hPa atmospheric level. This ensures that the results of the climate variable analysis are recorded at the approximate height of the glaciers themselves providing an accurate depiction of the conditions in which these glaciers exist.

Figure 23 depicts the temporal trends in the annual mean of each of the studied climate variables from 1975 to 2008. Included in each graph is a linear regression trend over this thirty year span. Air temperature, solar radiation, freezing level, geopotential height and wind velocity each exhibit an increasing trend. Only the precipitation exhibited a decreasing trend and specific humidity had no temporal trend.

The mean annual air temperature increased from -6.62°C in 1975 to -6.06°C in 2008, representing a 8.38% increase. Downwelling solar radiation increased from 249.72 W/m^2 in 1975 to 259.48 W/m^2 in 2008, representing a 3.91% increase. Freezing level height increased from 4687.81 m in 1975 to 4824.02 m in 2008, representing a 2.91% increase. Geopotential height increased from 5861.50 m in 1975 to 5872.51 m in 2008, representing a 0.19% increase. Wind velocity increased from 6.18 m/sec to 7 m/sec in 2008, representing a 13.22% increase. Precipitation is the only variable exhibiting a decrease in value from 266.34 mm/month in 1975 to 182.86 mm/month in 2008, representing a 31.35 % decrease. Specific humidity remained relatively constant through the periods with 0.0014 kg/kg in 1975, 0.0015 kg/kg in 1986, 0.0014 kg/kg in 1995, and 0.0017 kg/kg in 2005.

To conduct a more detailed analysis of the NCEP climate variables, the thirty year time span from 1975 to 2005 was subdivided into three shorter time periods. These coincide with the dates of the Landsat satellite images used in the glacier area calculations. The three time periods are; (1) 1975-1986, (2) 1987-1995, and (3) 1996-2005. In addition to the total change of each climate variable over the entire thirty year span, the change in the variables between each time period is also considered in the climate analysis.

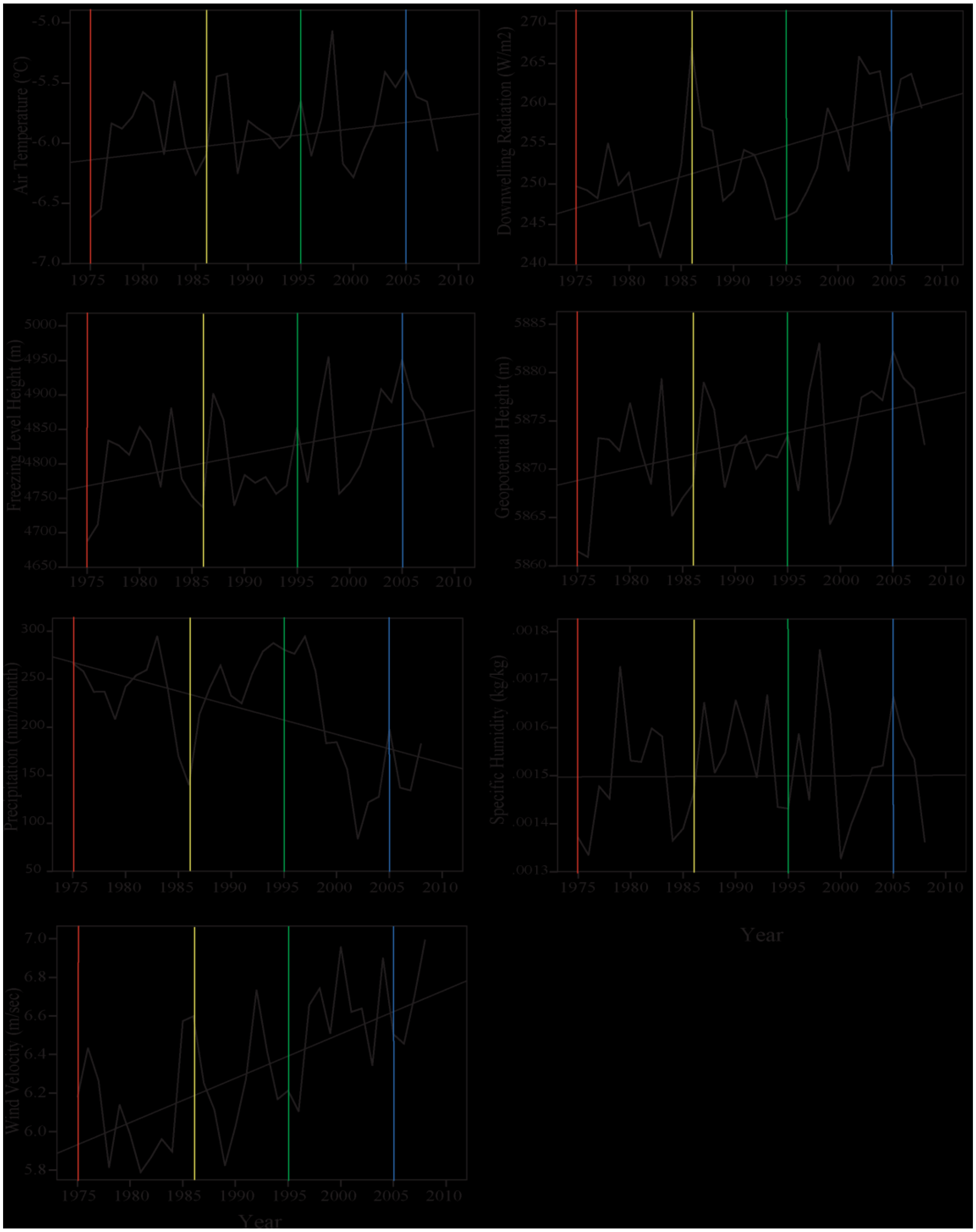


Fig 23. Graphs depicting the temporal trends in the NCEP variables. These graphs depict the annual average of each variable: air temperature, radiation, freezing level height, geopotential height, precipitation, specific humidity, and wind velocity. They are measured at the 500 hPa level for the Bolivia-Peru region of South America from 1950-2008. Included in each graph is a linear trend of the studied variable. The years of the scenes used in the analysis are indicated by vertical lines; (red) 1975, (yellow) 1986, (green) 1995, (blue) 2005.

The statistical significance of each variable between the three time periods was calculated to determine which variables experienced the most significant change (Table 6). Statistical significance is determined to be equal to or less than the α = 0.05 level of the Student's two tailed t-test. In Table 7, the positive numbers indicate a decrease in the variable's value and the negative numbers indicate an increase in the variable's value. The bold values in the table indicate that the variable exhibited a statistically significant measure of change between the two periods. Between periods one (1975-1986) and two (1987-1995) air temperature and geopotential height exhibit statistically significant changes. Air temperature increased by .165°C with an α value of 0.032 and geopotential height increased by 2.967 m with an α value of 0.031. Between time period two and three (1996-2005) the climate variables exhibiting a statistically significant change are freezing level with a 50.017 m increase and an α value of 0.002, precipitation with an 60.604 mm/month decrease and an α value of 0.000 and wind velocity with an increase of .373 m/sec and an α value of 0.023.

Table 6. T-test results. Table of the climate analysis results for the mean difference and the Student's two-tailed t-test α values for the NCEP climate variables. These are calculated between the three time periods: 1 (1975-1986), 2 (1987-1995), 3 (1996-2005). The bold values exhibit a statistical significance change.

Climate Variable	***Mean difference between period 1-2***	***T-test period 1-2***	***Mean difference between period 2-3***	***T-test period 2-3***
Air Temperature	-.165 °C	**0.032**	-.057 °C	0.499
Downwelling Radiation	-1.197 W/m2	0.678	-5.337 W/m2	0.099
Freezing Level	-12.520 m	0.384	-50.017 m	**0.002**
Geopotential Height	-2.967 m	**0.031**	-1.746 m	0.249
Precipitation	-16.966 mm/month	0.283	60.604 mm/month	**0.000**
Specific Humidity	-.000068 kg/kg	0.237	.000022 kg/kg	0.719
Wind Velocity	-.099 m/sec	0.518	-.373 m/sec	**0.023**
Oceanic Niño Index	-.340 °C	0.243	.195 °C	0.548

5.5 El Niño Southern Oscillation and Oceanic Niño Index (ONI) Results

For the purposes of this study the Oceanic Niño Index (ONI) was chosen as the dataset used to distinguish El Niño Southern Oscillation (ENSO) El Niño and La Niña events. According to the thresholds set by the ONI, El Niño events are warm phases when the sea surface temperatures (SSTs) in the tropical Pacific from the International Date Line to the west coast of the South American continent are above the threshold of 0.5°C while La Niña events are cold phases when the SSTs are below -0.5°C. To be distinguished as one of these events, the observed temperature trend must continue over five consecutive months. These events are further broken down into weak (0.5 to 0.9°C SST anomaly), moderate (1.0 to 1.4°C SST anomaly) and strong (≥ 1.5°C SST anomaly) events (Table 6) (http://www.cpc.ncep.noaa.gov/).

Period one experienced four El Niño events and three La Niña events, period two experienced three El Niño events and two La Niña events and period three experienced three El Niño events and three La Niña events. Table 7 indicates the ENSO events that occurred from 1950 to 2008 divided into their relative strengths (weak, moderate, strong) provided by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) monthly sea surface temperature (SST) datasets online at their Climate Prediction Center (CPC) website (http://www.cpc.ncep.noaa.gov/) confirms these results.

During period one (1975-1986) there were two weak La Niña events in 1984 and 1985 and one strong La Niña event in 1975 as well as two weak El Niño events in 1976 and 1977, one strong El Niño event in 1982, and one moderate in 1986. Period two experienced one weak La Niña event in 1995 and one strong La Niña event in 1988 as well as two moderate El Niño events in 1987 and 1994 and one strong El Niño event in 1991. Period three experienced two moderate La Niña events in 1998, 1999, and one weak La Niña event in 2000 as well as one strong El Niño event in 1997, one moderate El Niño event in 2002 and one weak El Niño event in 2004 (Fig 24).

The Oceanic Niño Index recorded from 1950 to 2008 (Fig 25) exhibits considerable increases and decreases in mean annual sea surface temperatures over this time period. However, similarities can be drawn between this graph and the recorded ENSO events. For instance, the year 1975 is indicated by a sharp decrease to -1.14°C in mean annual SSTs which coincides with the strong La Niña event recorded for this year. The strong El Niño events of 1982, 1991 and 1997 can be seen in the Oceanic Niño Index graph as well with increases in mean annual SSTs to 0.95°C, 0.80°C and 1.26°C respectively.

Table 7. ENSO events and their relative strength per year (1950-2008). These are recorded by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) monthly sea surface temperature (SST) datasets online at their Climate Prediction Center (CPC) website (http://www.cpc.ncep.noaa.gov/). All years not listed are Neutral.

ENSO Event	***El Niño***			***La Niña***		
Strength	***Weak***	***Moderate***	***Strong***	***Weak***	***Moderate***	***Strong***
	1951	1986	1957	1950	1954	1955
	1963	1987	1965	1956	1964	1973
	1968	1994	1972	1962	1970	1975
	1969	2002	1982	1967	1998	1988
	1976		1991	1971	1999	
	1977		1997	1974	2007	
	2004		2009	1984		
	2006			1985		
				1995		
				2000		

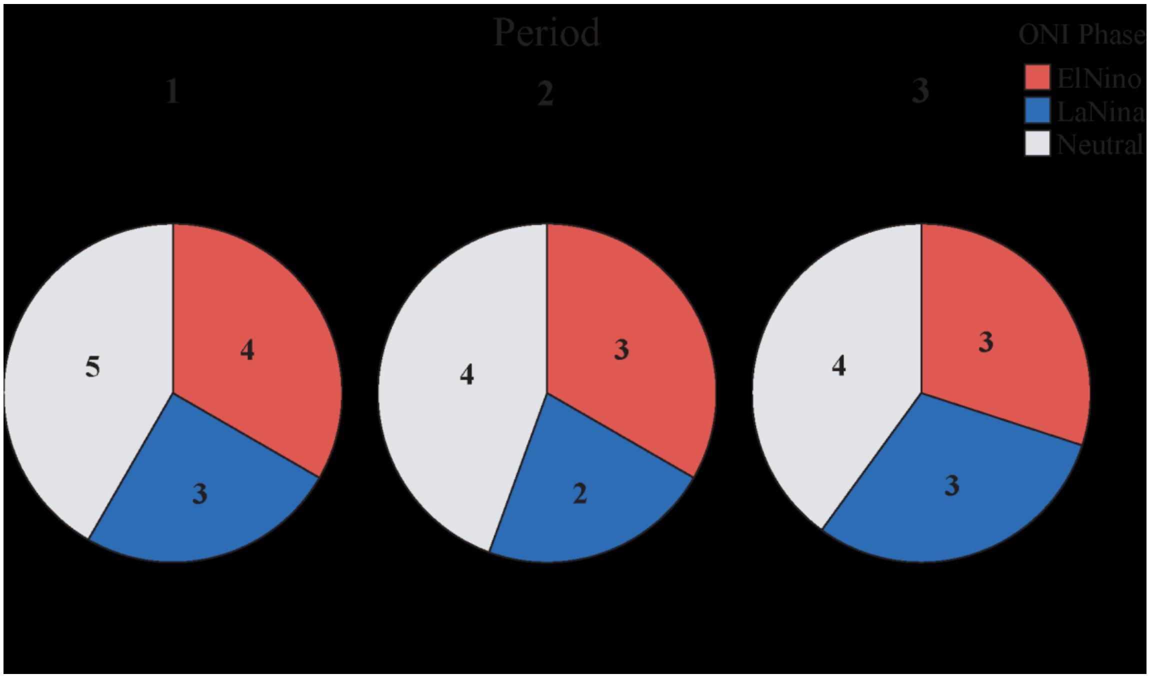


Fig 24. Charts depicting the number and type of ENSO events 1975-2005. These are recorded by the National Oceanic and Atmospheric Administration’s (NOAA) National Weather Service (NWS) monthly sea surface temperature (SST) datasets online at their Climate Prediction Center (CPC) website (http://www.cpc.ncep.noaa.gov/).

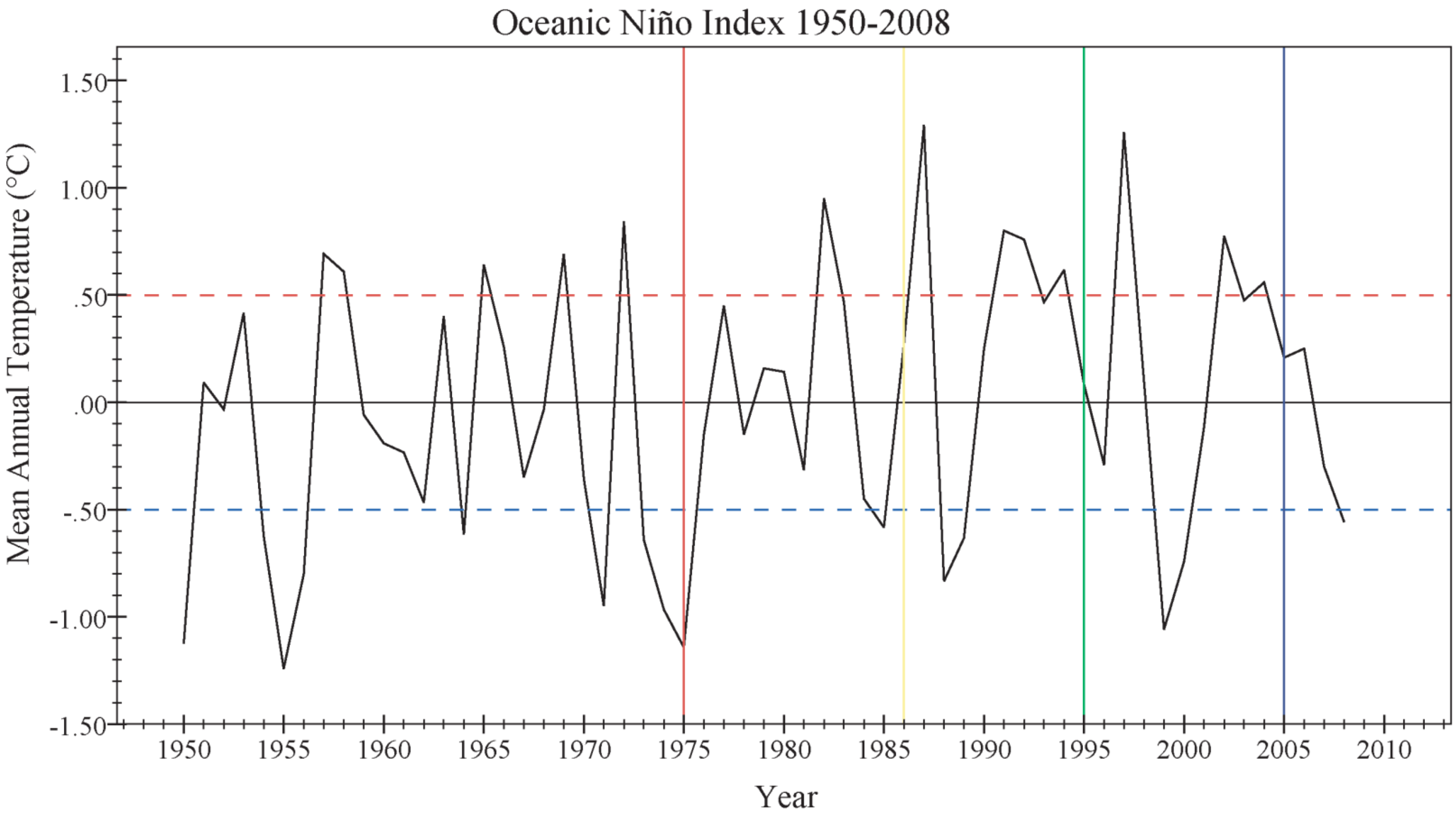


Fig 25. Graph depicting the Oceanic Niño Index, 1950-2008. Recorded by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) monthly sea surface temperature (SST) datasets online at their Climate Prediction Center (CPC) website (http://www.cpc.ncep.noaa.gov/). The four years of the images used in the analyses are indicated by colored lines.

6. DISCUSSION

6.1 Changes in Glacier Extents in the Cordillera Apolobamba, Bolivia

Mapping the glacierized area of the Cordillera Apolobamba through remote sensing provides the opportunity to gather information about this otherwise inaccessible range of tropical glaciers. Very little has been published concerning this particular glacier range and even less is known about the rate of these tropical glaciers' retreat. Since so few studies have been conducted for this region there is very little historic data to use in computing the rate of the Cordillera Apolobamba's recession. For this study, the past area measurements collected for several tropical glaciers is presented to give a global reference to which the Cordillera Apolobamba can be compared (Hastenrath, 2005; Ramirez, 2001; Klein, unpublished).

The glacierized area of the entire Cordillera Apolobamba has decreased by 39.35% from 1985 to 2010 while the segment included in the Glacier Inventory of Bolivia has decreased by 46.08% from 1975 to 2010. This percent area decrease is consistent with that of other tropical glaciers over roughly the same time periods (Table 8, Table 9). The largest decrease in glacierized area of the Cordillera Apolobamba is exhibited between the 1975 and 1986 images for the segment included in the Glacier Inventory of Bolivia. This segment of the glacier decreased from 240.36 km^2 in 1975 to 165.78 km^2 in 1986 indicating a 74.58 km^2, or 31.03% reduction. The glacier recession between the following images were less significant; 7.22 km^2 or 4.36% reduction between 1986 and 1995, 17.64 km^2 or 11.13% reduction from 1995 to 1998, 2.22 km^2 or

1.58% reduction from 1998 to 2005, and 9.10 km^2 or 6.56% reduction from 2005 to 2010.

The Chacaltaya glacier, in the Cordillera Real, and the Cordillera Tres Cruces glacier range are located in Bolivia. However, these two are considerably smaller than the Cordillera Apolobamba. The Chacaltaya glacier was 0.53 km^2 in 1860 and disappeared in the year 2009. In 1975, the total glacier area of the Cordillera Tres Cruces was 55.38 km^2 and was recorded to be only 27.34 km^2 by the year 2000, representing a 50.64% reduction. In Venezuela, the Pico Boland experienced a reduction of 75.20% from 1985 to 2007. In Africa, the Kilimanjaro glaciers decreased in area by 55.62% from 1976 to 2007, the Mt. Kenya glaciers decreased by 46.06% from 1987 to 2004, and the glaciers of the Rwenzori Mountains decreased by 57.64% from 1987 to 2006. The glacier range that has experienced the greatest reduction in area is the Mt. Jaya glaciers in Papua Indonesia which decreased by 80.47% from 1974 to 2007.

The percent area loss per year was calculated by dividing the percent area loss by the number of years in each time span. In addition, the area loss per year was calculated using simple linear regression for each of the glaciers listed in Table 8 (Fig 26). The entire Cordillera Apolobamba range has receded by approximately 2.00 km^2, or 1.57%, per year from 1985 to 2010. The Bolivia segment of the Cordillera Apolobamba has receded by 2.93 km^2, or 1.32%, per year from 1975 to 2010. These percent area decreases per year measurements are similar to those of the other tropical glaciers listed. However, the Cordillera Apolobamba has receded by 1 to 2 km^2 more per year than these other tropical glacier examples.

Table 8. Area loss and percent area loss of other tropical glaciers worldwide. These are recorded during roughly the same time periods used for the Cordillera Apolobamba in this study.

Glacier	*Time Span*	*Area Loss (km^2)*	*Area Loss per year (km^2)*	*Percent Area Loss*	*Percent Area Loss per year*
Mt. Jaya, Papua Indonesia	1974-2007	5.15	0.12	80.47	2.44
Kilimanjaro, Tanzania	1976-2008	2.32	0.11	55.62	1.79
Mt. Kenya, Kenya	1987-2004	0.23	0.01	46.06	2.71
Rwenzori, Uganda	1987-2006	1.43	0.05	57.64	3.03
Tres Cruces, Bolivia	1975-2000	28.04	1.15	50.64	2.03
Pico Boland, Venezuela	1985-2007	0.50	0.03	75.20	3.42
Chacaltaya, Bolivia	1983-2009	0.14	0.003	100	3.85
Cordillera Apolobamba, Bolivia (Bolivia segment)	1975-2010	110.76	2.93	46.08	1.32
Cordillera Apolobamba, Bolivia (entire range)	1985-2010	102.72	2.00	39.35	1.57

Table 9. Area measurements of other tropical glaciers worldwide.

Jaya, Papua Indonesia		*Chacaltaya, Bolivia*		*Pico Boland, Venezuela*		*Kilimanjaro, Tanzania*		*Mt. Kenya, Kenya*		*Rwenzori, Uganda*		*Tres Cruces, Bolivia*	
Date	**Area (km^2)**	**Date**	**Area (km^2)**	**Date**	**Area (km^2)**	**Date**	**Area (km^2)**	**Date**	**Area (km^2)**	**Date**	**Area (km^2)**	**Date**	**Area (km^2)**
1850	19.30	1860	0.53	1952	2.03	1913	12.06	1899	1.56	1906	6.50	1975	55.38
1936	13.00	1940	0.22	1981	0.95	1954	6.68	1947	0.87	1955	3.81	1986	35.74
1942	9.90	1963	0.20	1985	0.67	1976	4.17	1963	0.77	1987	2.49	1992	29.72
1962	8.10	1983	0.14	1988	0.61	1990	3.31	1987	0.50	1990	1.68	2000	27.34
1972	7.30	1992	0.10	2000	0.36	2000	2.52	1993	0.41	2005	1.08		
1974	6.40	1993	0.10	2001	0.35	2006	1.93	2004	0.27	2006	1.05		
1987	5.00	1994	0.10	2002	0.32	2008	1.85						
2000	2.25	1995	0.09	2003	0.28								
2002	2.10	1996	0.08	2004	0.28								
2003	1.89	1997	0.08	2005	0.22								
2004	1.91	1998	0.06	2007	0.17								
2005	1.72	2009	0.00										
2007	1.25												

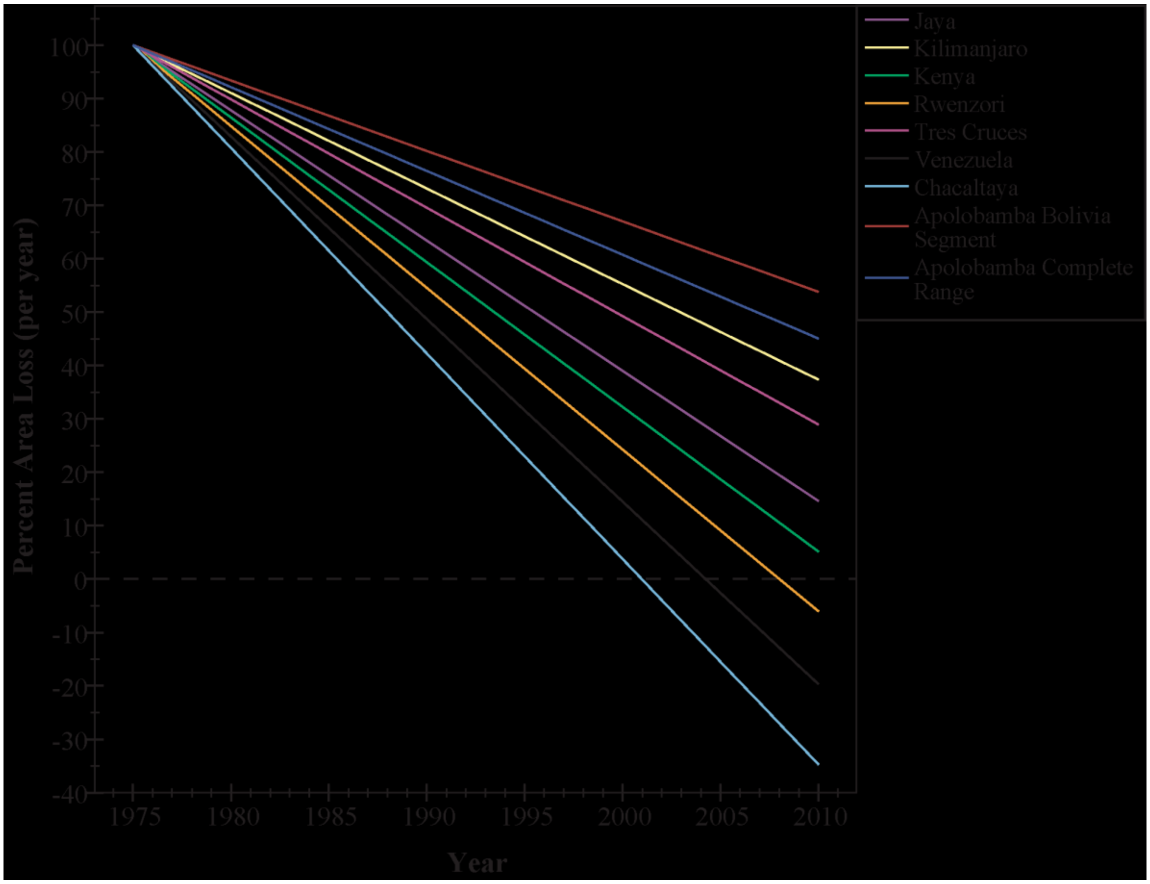


Fig 26. Graph of the percent area loss per year of various tropical glaciers. This graph depicts the percent area loss of each of the glaciers in Table 9. The year 1975 was chosen as the initial starting point (representing 100%). From this point the annual percent area loss is subtracted from each glacier to depict the rate of glacier retreat per year.

Although, the Cordillera Apolobamba has experienced a similar percent area decrease in the past several decades it differs from these other tropical glacier ranges in size. Table 10 is a listing of the Cordillera Apolobamba's area (km^2) for each year from all sixteen of the Landsat satellite images that were gathered for this study as well as the area measurements from the Glacier Inventory of Bolivia in 1975. As of 2010, the Apolobamba has not yet decreased in area below 100 km^2 which is in stark contrast to even the largest of the tropical glaciers listed in Table 9, the Tres Cruces also located in Bolivia. The Cordillera Tres Cruces was recorded to be 35.74 km^2 in 1986. If we consider the 1980's composite image (referred to as 1986 in previous tables and graphs) area measurement of 206.87 km^2 for the entire Cordillera Apolobamba, this range stood a total of 578.82% larger than the Tres Cruces. As of the year 2000, the Cordillera Apolobamba was 217.59 km^2 which was 795.87% larger than the Tres Cruces at 27.34 km^2.

Table 10. Glacier areas of all Landsat images. This table lists the area measurements (km^2) for each of the Landsat (TM and ETM+) satellite images obtained for this study.

Year	***Complete range Area km^2***	***Bolivia Segment Area km^2***
1975	NA	240.36
1985	261.07	213.51
1986	284.73	234.13
1987	259.75	214.55
1980's composite	206.87	165.78
1995	193.20	158.56
1998	176.34	140.92
2000	217.59	183.91
2001	244.38	205.72
2002	310.71	246.55
2003	200.77	165.72
2004	205.20	173.78
2005	171.62	138.70
2006	167.84	141.51
2007	171.33	144.87
2008	172.64	145.10
2009	166.58	141.58
2010	158.35	129.60

The tropical glaciers listed in Table 9 are small compared to the Cordillera Apolobamba but there are others that match its size. Mainly there is the Cordillera Real located just southeast of the Apolobamba. The Cordillera Real represents 11% of all tropical glaciers worldwide and includes 55% of all glaciers in Bolivia (Soruco, 2009), and as of 1975 it had a surface area of 324 km^2 (Jordan, 1999). In their study of the Cordillera Real, Soruco et al. (2009) measured the volume and area changes of 376 glaciers in this range and determined that from 1975 to 2006 they lost 48% ±5% of their surface area. The Cordillera Blanca, Peru had a glacierized area of approximately 721 km^2 in 1970 which decreased to 643±63 km^2 in 1987 and then to 600±61 km^2 in 1996 representing a 15% recession in 25 years (Siliverio, 2005). As of 2003, the Cordillera Blanca was estimated to be 569±21 km^2 (Racoviteanu, 2008). Assuming the results of both of these studies are accurate, the Blanca decreased by approximately 152 km^2 from 1970 to 2003 representing a 21.08% area. The percent area loss found in these two studies matches well with that of the various tropical glaciers and that of the Cordillera Apolobamba found by this research study. This implies that all tropical glaciers worldwide have experienced similar rates of retreat regardless of their size or location.

6.2 Hypsometry

The hypsometry analysis indicates that the Cordillera Apolobamba has exhibited area loss of 100% at its lowest glacierized elevations of zones of 4400, 4500 and 4600 m above sea level from 1975 to 2005. This includes the calculations for both the entire range and the Bolivia segment. It is apparent from this analysis that the glacier recession of the Cordillera Apolobamba's is proceeding from the lowest toward the highest elevations. This is expected as the highest elevations of glaciers are typically the accumulation zone and the lowest elevations are typically the ablation zone (Andrews, 1975).

Also exhibited in the hypsometry analysis is the apparent gain in area in the higher elevation zones from 5500 to 6000 m of approximately 5 % of the glacierized area of the Cordillera Apolobamba between the 1986 and 2005 images. During the 1986 to 1995 decade both the Bolivia segment and the complete range exhibit increases area varying from 0.24 % to 6.8 %, the greatest increases in area being in the highest elevation zones of 5800, 5900 and 6000 m. There are also small increases in the 5800 to 5900 elevation zones for the Bolivia segment and the complete range between the 1995 and 2005 images. This is exhibited as an increase in percent area for the 5800 to 6000 m elevation zones between 1986 and 2005 for the entire glacier range. This pattern is not evident in the 1975 to 2005 results for the Bolivia segment which do not exhibit any apparent gain in percent area in the higher elevation zones.

These results are believed to be an error in the 1980's composite image as the problem is the apparent gain in percent area in the higher elevation zones between the 1986 and the 2005 images. In Figure 27 the images from 1985, 1986 and 1987 are depicted over the Chaupi Orco peak of the Cordillera Apolobamba. Overlaid on these is the area of ice that is evident in the 2005 image but not in the 1980's image representing the apparent gain in glacier ice area. These pixels were extracted through a combinatorial OR operation using the 1980's composite and the 2005 images.

The total glacier area of each of the three 1980's images exceed that of the 2005 image which represents the recession of the glacier over this twenty year time span. However, the 1986 and 1987 exhibit greater snow cover as compared to the 1985 image. This is believed to be the main cause of the apparent gains in area at the higher elevation zones. The excess snow cover of the 1986 and 1987 images misrepresented the average snow and ice covered pixels in the combinatorial OR operations that were used to calculate the average glacier area of this time period.

As this is one possible explanation of this gain in area at the higher elevation zones of the Cordillera Apolobamba there are others. This error could be the result of image shadowing or possibly an error in the operations used to calculate the total number of pixels containing ice. However, it is also possible that this is not an error but these measurements are true and there was a gain in glacier ice area at these higher elevations. Further analysis is required to accurately explain this phenomenon.

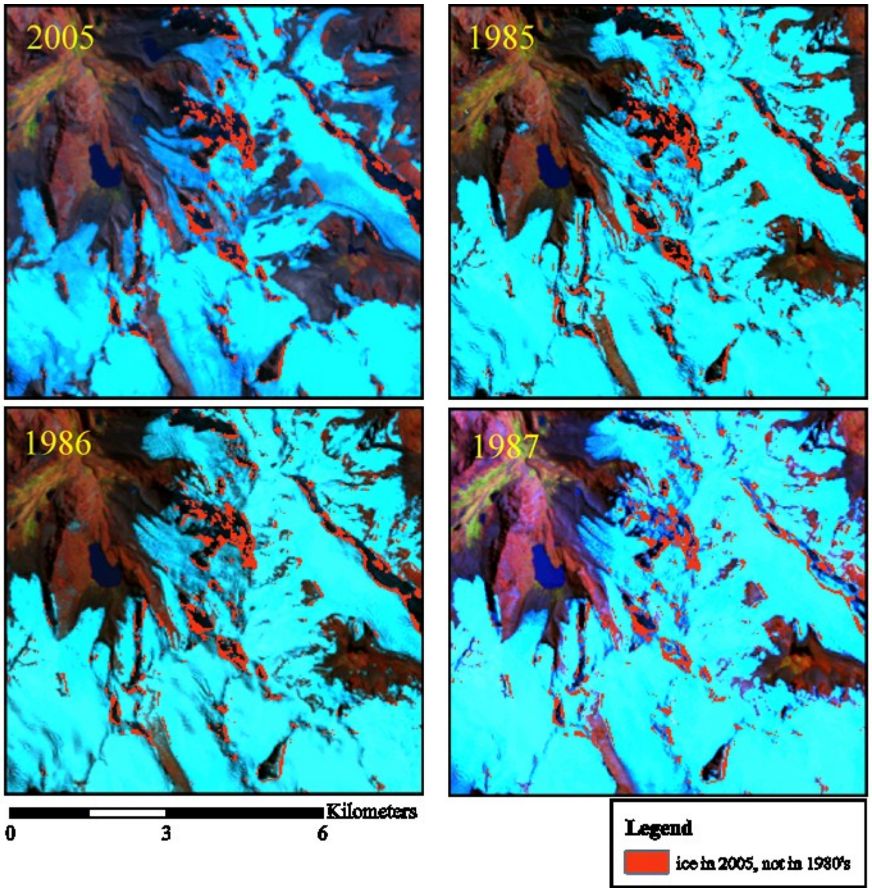


Fig 27. Landsat TM images 1985, 1986, 1987 and Landsat ETM+ image 2005. These are overlaid with the pixels classified as ice in the 2005 image to illustrate the excess snow cover in the 1987 image as well as the shadowing in the 1985 and 1986 images. This is used to explain why there is apparent gain in area in the higher elevation zones of the hypsometry analysis results.

6.3 Slope and Aspect

Slope and aspect are important factors to include in the analysis of glaciers as these two characteristics greatly influence a glacier's orientation which in turn influences the glacier's mass balance (Evans, 2006). As stated before, the mass balance of tropical glaciers is sensitive and directly related to several climate variables such as the amount of solid precipitation, the amount of incoming solar radiation penetrating the cloud cover and air humidity all of which drive the sharing of energy between melting and sublimation (Favier, 2004). The impact these factors have on the glacier is greatly influenced by the slope and aspect of the glacier's faces.

Evans (1977, 2006) and Evans and Cox (2005) have conducted studies to determine global slope aspect tendencies on glaciers and the reasons behind their dominance at certain latitudes and altitudes. These studies have determined that in most regions glaciers favor poleward (north-south) aspects. North-south contrasts in glacier altitude are greatest in the mid-latitudes, approximately 30°–70°, at high altitudes and for glaciers with steeper gradients of at least 30° overall (Evans, 2006). There are also east-west contrasts in glacier altitude that are greatly dependent on variations in cloud cover and temperature before and after mid-day. That is, if the cloud cover is uniform there should be greater melting on the westward slopes of the glacier which receive sun in the afternoon when the air temperature is warmer (Evans, 2006).

In contrast to the majority of glaciers worldwide, westward tendencies are found in the tropics where convection over the mountains gives rise to cloud cover which in turn reduces the amount of solar radiation reaching the western slopes giving the glacier a westward aspect (Evans, 2006). Glaciers in Peru and the lower altitudes of the tropics indicate southward and westward tendencies that are thought to be due to afternoon cloudiness and winds from the east (Evans and Cox, 2005, Evans, 2006). Wind is an important factor as typically the windward side of mountain ranges often receives more precipitation.

The Cordillera Apolobamba glacier does not have an overall steep slope of more than 30° as the majority (98%) of its glacierized area has a slope within or less than the 30°-40° slope interval. In the past thirty five years, the greatest slope area loss has occurred within 20°-30° in the 1975-1986 decade and within 10°-20° during the following two decades. It is not surprising that these gentle slopes should lose the greatest area as they represent the majority of those of the glacierized area of the Apolobamba. Considering its relatively gentle slopes, and the previous mentioned study, we would expect that the Apolobamba does not have a north-south contrast in glacier altitude.

Analysis of the glacier aspect of the Cordillera Apolobamba indicates a clear south to south-westward orientation in the aspect of its glacierized slopes which coincides with the previously mentioned studies. What is interesting is the change in the direction of the aspect area loss between the three decades. The aspect total area loss from 1975 to 1986 (-74.6 km^2) and from 1986 to 1995 (-7.2 km^2) for the Bolivia segment exhibits a clear majority loss in the south-western direction, although the loss was far greater during the 1975 to 1986 decade. This orientation of the aspect area loss changes to a north-eastern direction between 1995 and 2005 with a decrease of 19.9 km^2.

As a whole, the entire glacier range exhibits the same north-eastern aspect area loss during this same decade. However, from 1986 to 1995 the aspect area loss exhibits a more uniform pattern in all directions with small anomalies such as less aspect area loss in the north-western direction and a large spike in aspect area loss at 180°-195° (south). The reason for this is unknown as is the reason for the aspect area loss change in direction from the 1970's to the 1980's decade. An examination of the climate conditions during these decades will aid in the understanding of the changes in area loss.

6.4 NCEP Climate Variables

The local surface energy balance of a tropical glacier is dependent on cloud cover and surface albedo which both influence the radiation balance, on the local winds, air temperature and humidity and on the surface and snow pack temperature which provide the upward energy inside the snow and ice (Wagnon et al., 1999). Each of these climate variables is important and their sustained stability leads to the sustained stability, or equilibrium, of the glacier (Andrews, 1975).

Tropical climates are characterized by homogenous temperatures throughout the year, however, there are differences between the inner and outer tropics. The inner tropics experience stable annual humidity causing accumulation and ablation to occur simultaneously throughout the year whereas the outer tropics are characterized by a seasonality of air temperature, specific humidity, precipitation and cloudiness (Kaser, 2001, Favier et al., 2004). Therefore, accumulation in the outer tropics occurs only during the humid months and ablation, which is strong during these wet months, is reduced throughout the rest of the year (Kaser, 2001, Favier et al., 2004).

The outer tropics of the Peruvian-Bolivian region of South America experiences a cold and dry austral winter from approximately April to September with low cloudiness and a wet rainy austral summer from October to March with high cloudiness (Ribstein, 2005). The monthly ranges of these seasons are reported differently in several similar studies. Sicart et al. (2005), state that Bolivia's dry season lasts from May to August and the wet season from September to April while Wagnon et al. (1999) agree on this dry season but report the wet season to be from October to March. However, all agree that the climate of this region of the Andes exhibits a pronounced wet and dry season. This seasonality is made evident in the analysis of the NCEP climate variables for the 500 hPa atmospheric level over the Cordillera Apolobamba glacier range.

Air temperature is an important factor in the energy balance of a tropical glacier. However, it has been recorded in previous studies that air temperature does not play as vital a role as other climate variables. The dry atmosphere of high altitude tropical glaciers causes cloud cover to increase the long-wave radiation received at the surface by more than 50%, whereas this increase remains less than 30-40% at the mid latitudes (Kimball et al., 1982). Therefore, changes in the atmospheric temperature have smaller effects on the net long-wave radiation received by tropical glaciers than on mid latitude glaciers, but the change in cloud cover has a much greater effect (Sicart et al., 2005). Whereas Alpine glaciers are very sensitive to changes in air temperature, the negative mass balances observed in tropical Andes glaciers are more often related to the amount of solid precipitation received which influences their albedo (Vincent et al., 2005). According to these findings it is not likely that the atmospheric air temperature over the Cordillera Apolobamba has as great an impact on glacier area changes as other climate variables such as precipitation and radiation.

The outer tropics experience a warm, wet summer and a cold, dry winter season which most studies agree are approximately within the ranges of October to April (summer) and April to September (winter). The analysis presented in this study indicates the annual temperature cycle of the Apolobamba region experiences an annual increase in air temperature. This increase in atmospheric air temperature occurs approximately from October to April fitting with the before mentioned warm austral summer season (Fig 28).

The annual average air temperature of the 500 hPa level over the Apolobamba has increased from -6.62 °C in 1975 to -5.39 °C in 2005. The air temperature has remained between -4 °C and -7 °C with very few months deviating from this norm. The t-test conducted in this study indicates that air temperature exhibited a statistically significant change between periods one and two ($\alpha = 0.032$) but not between periods two and three ($\alpha = 0.499$). Therefore, the analysis if this study has indicated that between periods one (1975-1986) and two (1987-1995) the mean air temperature difference of -.165 °C was statistically significant while the mean air temperature difference of -.057 °C between periods two and three (1996-2005) was not statistically significant according to the Student's t-test.

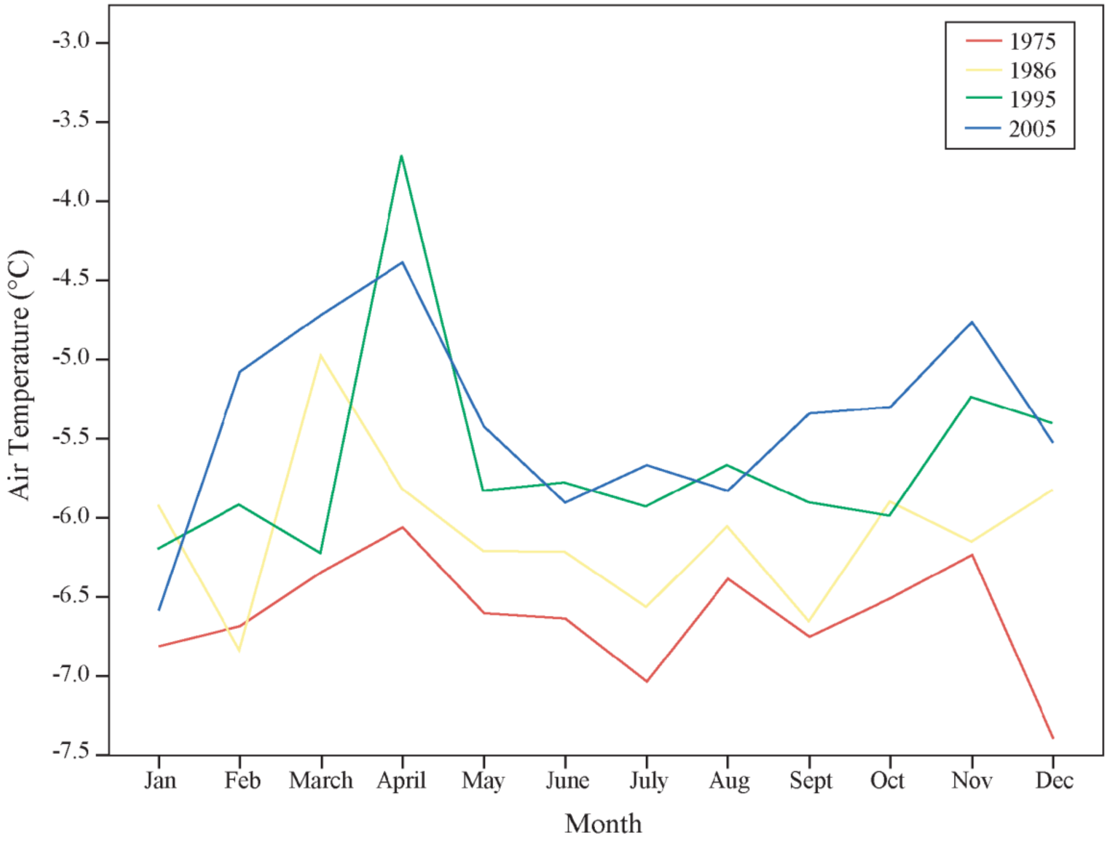


Fig 28. Annual air temperature. Graph of the annual change in air temperature for 1975, 1986, 1995 and 2005 for the Cordillera Apolobamba region

The climate of the inner tropics is distinguished by continuous precipitation throughout the year compared to the outer tropics which are characterized by one dry season, where subtropical conditions prevail, and one wet season, where tropical conditions prevail (Kaser, 2001, Favier et al., 2004). The precipitation pattern for the Cordillera Apolobamba region of South America is similar for each annual cycle exhibiting a pronounced dry season from approximately April to August and a wet season from approximately September to March (Fig 29). This coincides with the before mentioned increase in air temperature indicating a clear seasonal pattern. Within each annual cycle the difference between the highest and lowest precipitation values is approximately 200 to 300 mm/month. Overall, the precipitation over the Cordillera Apolobamba has steadily decreased from 266.34 mm/month in 1975 to 197.94 mm/month in 2005.

The t-test calculation conducted for precipitation indicated no statistically significant change between periods one and two ($\alpha = 0.283$). However, it does indicate that precipitation exhibited a statistically significant change between periods two and three ($\alpha = 0.000$). Therefore, the analysis if this study has indicated that between periods one (1975-1986) and two (1987-1995) the mean precipitation difference of -16.966 mm/month was not statistically significant while the mean precipitation difference of 60.604 mm/month between periods two and three (1996-2005) was statistically significant according to the Student’s t-test.

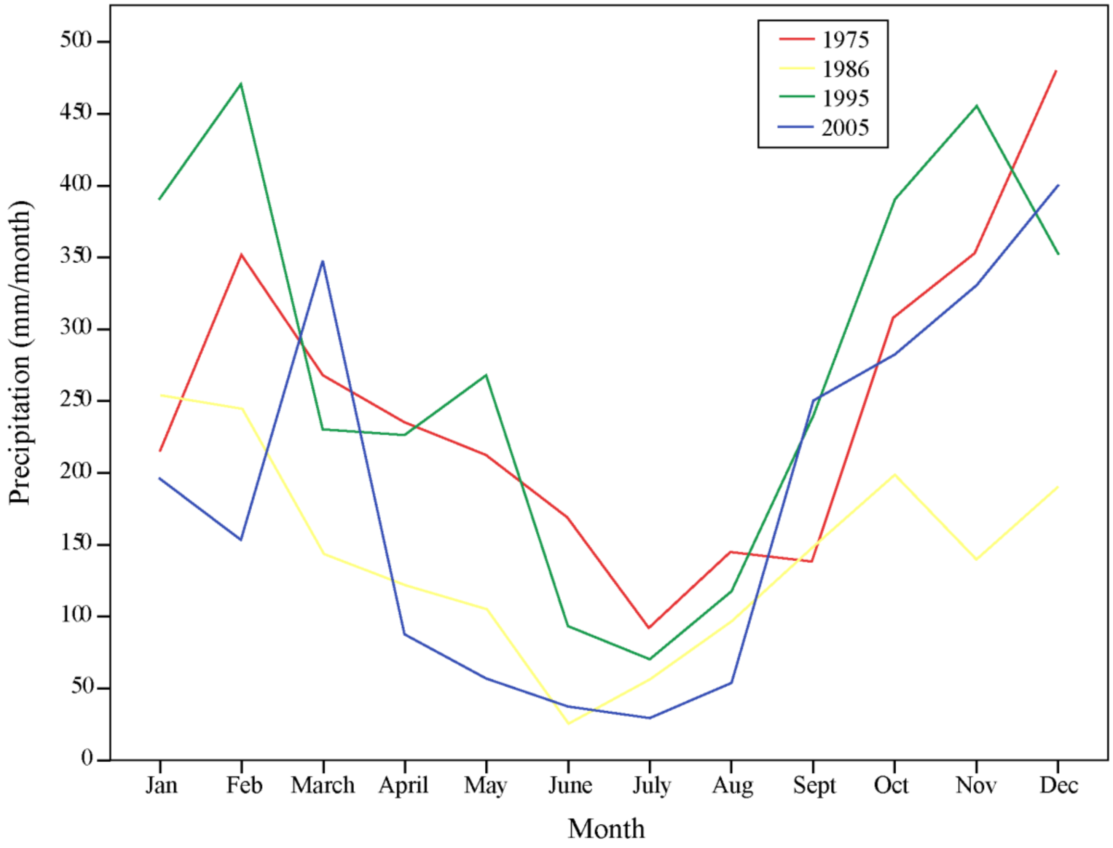


Fig 29. Annual precipitation. Graph of the annual change in precipitation for 1975, 1986, 1995 and 2005 for the Cordillera Apolobamba region.

Incoming solar radiation plays a vital role in the energy balance of tropical glaciers. At any location on Earth, the incident solar radiation received increases with altitude due to the thinning atmosphere except in locations where increased cloud cover counters this effect (Evans, 1977). In the Bolivian outer tropics, outgoing long-wave radiation indicates that melting occurs almost every day while incident short-wave radiation is typically smaller due to the latitude and thick cloud cover during the summer months when these glaciers should receive their maximum irradiance (Favier et al., 2004). The annual cycle of downwelling radiation indicates a large decrease approximately April to August each year (Fig 30). This coincides with the before mentioned austral winter season when this region experiences colder air temperature and less precipitation. Overall, the average annual downwelling solar radiation at the 500 hPa level over the Cordillera Apolobamba region has steadily increased from 249.72 W/m^2 in 1975 to 256.58 W/m^2 in 2005.

The t-test indicates that radiation exhibited no statistically significant change between period one and two ($\alpha = 0.678$), or between periods two and three ($\alpha = 0.099$). The analysis if this study has indicated that between periods one (1975-1986) and two (1987-1995) the mean downwelling radiation difference of -1.197 W/m^2 was not statistically significant while the mean downwelling radiation difference of -5.337 W/m^2 between periods two and three (1996-2005) was also not statistically significant.

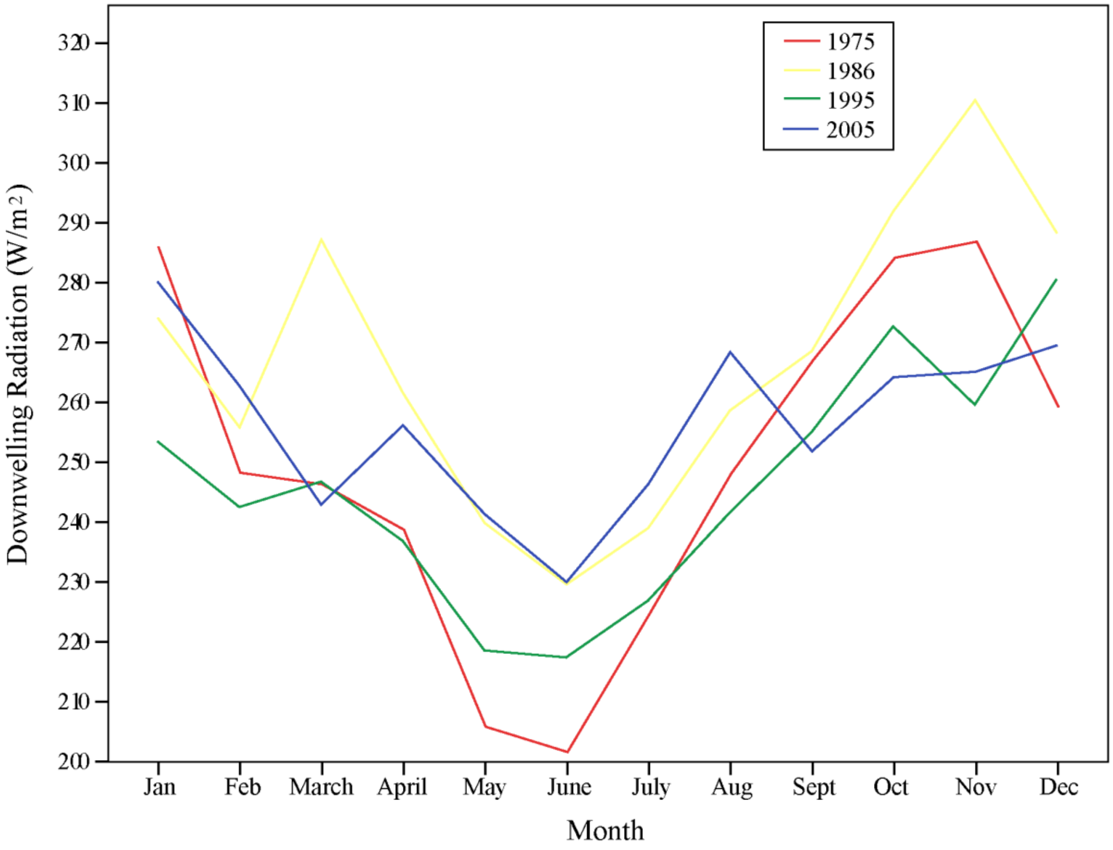


Fig 30. Annual downwelling radiation. Graph of the annual change in downwelling solar radiation for 1975, 1986, 1995 and 2005 for the Cordillera Apolobamba region.

Specific humidity is the ratio of water vapor to dry air in an air mass, it is measured in kg/kg, and it is one of the key climate variables that affect glacier mass balance (Wagnon et al., 1999). Humidity, along with radiation, air temperature and winds, is listed as one of the key climate variables that impact a glacier's energy balance. Significant changes in humidity could lead to significant changes in the glacier's energy balance and thus its mass balance. However, no significant changes in specific humidity were observed for the Cordillera Apolobamba region from 1975 to 2005. Overall, the annual average specific humidity values are neither increasing nor decreasing but remain between 0.0013 kg/kg and 0.00175 kg/kg. There are, of course, fluctuations between the individual years: (1975) 0.00137 kg/kg; (1986) 0.001463 kg/kg; (1995) 0.001432 kg/kg; (2005) 0.00167 kg/kg. The monthly values fluctuate from 0.00073 kg/kg (March 1975) to 0.00269 kg/kg (May 1982).

The t-test conducted for this study indicates that the specific humidity over the Cordillera Apolobamba exhibited no statistically significant change between period one and two ($\alpha = 0.237$) or between periods two and three ($\alpha = 0.719$). The analysis if this study has indicated that between periods one (1975-1986) and two (1987-1995) the mean specific humidity difference of -0.000068 kg/kg was not statistically significant and the mean specific humidity difference of 0.000022 kg/kg between periods two and three (1996-2005) was also not statistically significant according to the Student's t-test.

The Southeasterly Trade Winds prevail over the Peruvian-Bolivian region of South America. It is not surprising that this does not indicate much variability over the decades as these Trade Winds are governed by global climate conditions. For a more accurate depiction of the wind conditions over the Cordillera Apolobamba the velocities must be considered at the regional scale. Wind velocity which has followed an increasing trend from 1975 to 2005. In 1975, the average annual wind velocity measured 6.18 m/sec and in 2005 it measured to 6.50 m/sec.

Wind Velocity exhibited no statistically significant change between periods one and two ($\alpha = 0.518$), but it did exhibit a statistically significant change between periods two and three ($\alpha = 0.023$). The analysis if this study has indicated that between periods one (1975-1986) and two (1987-1995) the mean wind velocity difference of -.099 m/sec was not statistically significant. However, the mean wind velocity difference of -.373 m/sec between periods two and three (1996-2005) was statistically significant according to the Student's t-test.

The wind velocity annual cycle over the Cordillera Apolobamba region does not appear to follow a clear seasonal pattern as each year exhibits differing monthly values (Fig 31). For instance, 1975 experienced increased wind velocity from December to April, and then again from June to August. Whereas, 1986 experienced increased wind velocities from approximately March to May and then again in July with a smaller peak in September, and then increased again from October to December. When considering the other climate variables, wind velocity appears to be more closely associated with the air temperature trends.

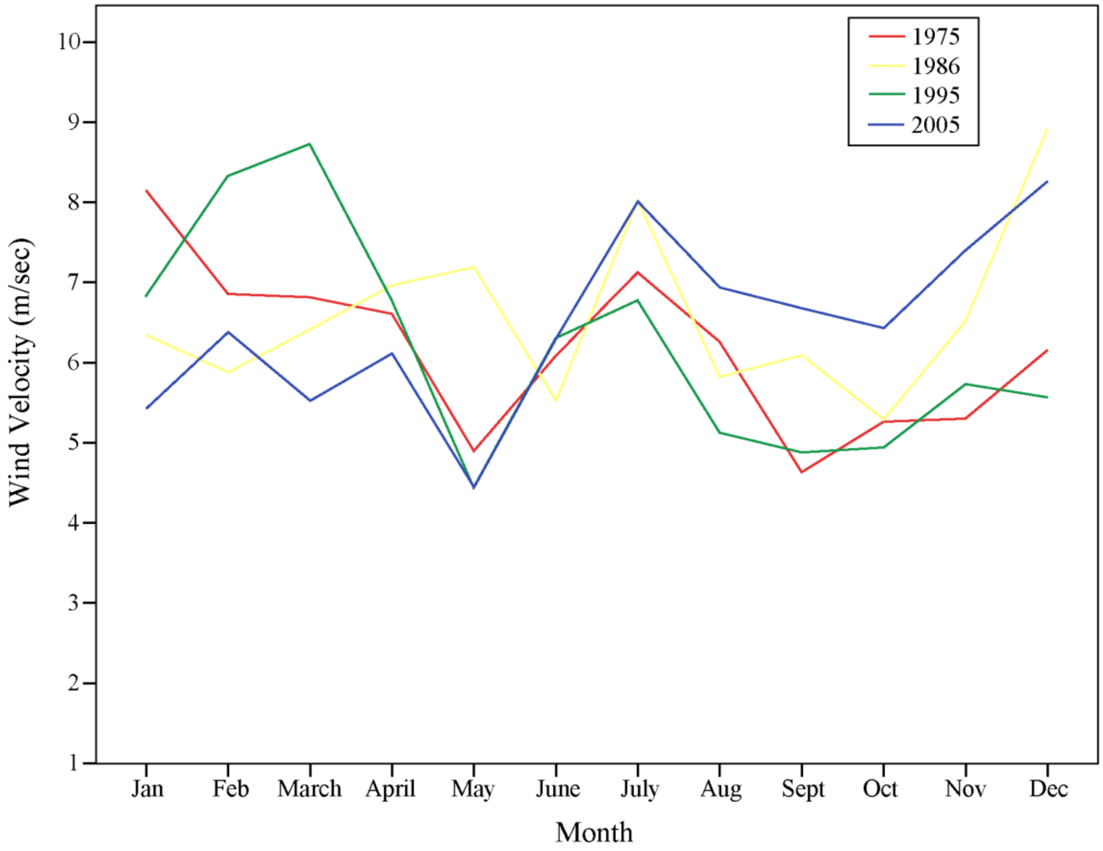


Fig 31. Annual wind velocity. Graph of the annual change in wind velocity for 1975, 1986, 1995 and 2005 for the Cordillera Apolobamba region.

Freezing level and geopotential height are both climate variables that are measured in meters above ground level. The freezing level, also called the zero-degree isotherm, is the altitude at which the temperature is 0°C, the freezing temperature of water. The average annual freezing level of the 500 hPa over the Cordillera Apolobamba region reached its maximum of 4950 m in 1998 and dropped to its minimum of 4737 m in 1986. However, it has steadily increased from 4687.81 m in 1975 to 4951.65 m in 2005. The t-test indicates that the freezing level exhibited no statistically significant change between periods one and two ($\alpha = 0.384$) with an increase of 12.520 m, but did exhibit a statistically significant change between periods two and three ($\alpha = 0.002$) with a 50.017 m increase.

Geopotential height refers to the gravity adjusted height, or elevation, of a pressure level. For any given atmospheric pressure level the geopotential height is the elevation needed to reach that pressure value. Although the average annual geopotential height of the 500 hPa level over the Apolobamba region has fluctuated up and down in the past thirty five years it has followed an increasing trend from 5861.50 m in 1975, to 5882.23 m in 2005. According to the Student's t-test calculations, the geopotential height exhibited a statistically significant change between periods one and two ($\alpha = 0.031$) with a 2.967 m increase, but did not exhibit a statistically significant change between periods two and three ($\alpha = 0.249$) with a 1.746 m increase.

As previously stated, the most significant reduction in glacier area for the Cordillera Apolobamba occurred between 1975 and 1986 in the Bolivia segment. The glacier receded by 74.58 km^2, or 31.03%, during this eleven year span which coincides with time period one. Although this represents the greatest recession of the glacier between any two images, no clear correlation can be measured between this area recession and the climate variables. During period one only air temperature and geopotential height exhibit a statistically significant change. According to previous studies, area changes in tropical glaciers have been associated with changes in air temperature, however, other climate variables such as precipitation, radiation and specific humidity are also indicated to have changed as well. As these variables do not show any statistically significant change during time period one (1975-1986), the glacier-climate analyses of this study have not indicated a clear and statistically measureable correlation between the changes in the glacierized area of the Cordillera Apolobamba and the changes in the climate variables of this region.

6.5 El Niño Southern Oscillation and Oceanic Niño Index (ONI)

During El Niño events tropical glaciers experience strongly negative mass balances (Favier et al., 2004, Wagnon et al., 2001, Francou et al., 2004). Bolivian glaciers in particular experience strongly enhanced ablation due to the precipitation deficit while a decrease in albedo prevails during these El Niño periods (Favier et al., 2004, Wagnon et al., 2001). These conditions result in enhanced melting and the negative mass balance as mentioned before. In their study of the glaciers of the outer and inner tropics, Favier et al. (2004) stated that most tropical glaciers were not at equilibrium during strong El Niño events and it was predicted that if these conditions persisted over prolonged periods of time tropical glaciers would retreat at a rapid rate.

Previous studies report the climate in the Andes is related to sea surface temperature in the Pacific Ocean with both temperature and precipitation departing from the mean during El Niño (warm) and La Niña (cold) events (Vuille et al., 2003, Vuille and Bradley, 2000). This thermal and hydrological response to sea surface temperature changes can act in favor of glacier mass balance as with La Niña events or against it as with El Niño events (Vuille et al., 2003). If acting against the glacier mass balance it is implied that El Niño events promote a negative mass balance within tropical glaciers. Any glacier experiencing a sustained negative mass balance is therefore out of its equilibrium and will retreat (Andrews, 1975).

In period one (1975-1986) there were four El Niño events, three La Niña events and five Neutral years. In period two (1987-1995) there were three El Niño events, two La Niña events and four Neutral years. In Period three (1996-2005) there were three El Niño events, three La Niña events and four Neutral years.

During the years of the four satellite images used in the analysis of this study there were recorded ENSO events, or anomalies, as follows: 1975 (period one) – Strong La Niña; 1986 (period two) – Moderate El Niño; 1995 (period two) – Weak La Niña; 2005 (period three) – Neutral. Only the 1986 (the 1980's composite) Landsat image of the Cordillera Apolobamba was acquired during a time when an El Niño event was occurring in the Pacific Ocean in time period two. During 1986, the annual average downwelling radiation value increased to 266.99 W/m^2 from the 1975 value of 249.72 W/m^2, and then decreased again to 245.94 W/m^2 in 1995. This represents a temporary increase of incoming solar radiation of 6.9%. The annual average precipitation decreased to 139.77 mm/month in 1986 from its previous value of 169.79 mm/month in 1975, and then increased to 280.56 mm/month in 1995. This represents a temporary decrease in precipitation of 17.7%. Although there are smaller anomalies observed in other climate variables these two exhibit the greatest differences during this El Niño period.

Although this particular year offers a unique case in which the conditions that prevail during an El Niño event resulted in minor changes in the climate, this same correlation cannot be applied to any of the three time periods. Time period one experienced the most El Niño events (4), however the climate variables during this time period did not indicate significant changes. The only two variables to exhibit a statistically significant change between periods one and two are air temperature and geopotential height. According to previous studies we would expect to see both temperature and precipitation exhibiting significant changes. As previously mentioned, El Niño events result in the enhanced melting of glaciers caused by a precipitation deficit. This decrease in precipitation, particularly solid precipitation, decreases the albedo, or reflectance, of the glacier's surface. Therefore, more energy is absorbed by the glacier resulting in the before mentioned increase in melting (Favier et al., 2004, Wagnon et al., 2001). However, the analysis conducted in this study did not measure the albedo of the Cordillera Apolobamba glacier ice. Also, it did not take into consideration the possible changes in cloud cover over the Cordillera Apolobamba region. The amount of incoming solar radiation received at the glacier's surface is closely associated with the amount of cloud cover. The correlation between incoming solar radiation and the amount of energy absorbed by the glacier is left for further study.

7. CONCLUSIONS

Remote sensing offers the means for glacier monitoring in remote areas lacking traditional glacier area monitoring methods. The Cordillera Apolobamba on the Peruvian-Bolivian border is one such remote glacierized area which requires remote sensing techniques to monitor and record its area fluctuations. The tropical glaciers in this region of South America are sources of fresh water and hydropower for several major urban centers such as La Paz and El Alto in Bolivia and their recession is the cause of much concern. Because of this, frequent and accurate mapping of these tropical glaciers is important as is maintaining a tropical glacier inventory database. This study is an example of the methodology applied to assessing the changes in the glacierized area in this and other regions around the world.

The analysis conducted in this study on Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images from 1985 to 2010 as well as the Jordan Glacier Inventory of Bolivia of the 1970’s confirms that the glacierized area of the Cordillera Apolobamba on the Peruvian-Bolivian border has receded from 1975 to 2010. From the 1985 to 2010 the entire glacierized area of the Cordillera Apolobamba recede by 102.72 km^2 decreasing its total area from 261.07 km^2 to 158.35 km^2, a 39.35% reduction. From 1975 to 2010 the portion of the Cordillera Apolobamba located in Bolivia that is recorded in the Jordan Glacier Inventory of Bolivia recede by 110.76 km^2 decreasing its total glacierized area from 240.36 km^2 to 129.60 km^2, a 46.08% reduction. The atmospheric analysis was conducted at the 500 hPa level for various NCEP climate variables. Between the time periods one (1975-1986) and two (1987-1995) the climate variables exhibiting statistically significant changes are air temperature with an increase of .165°C and geopotential height with an increase of 2.967 m. Between time period two and three (1996-2005) the climate variables exhibiting statistically significant changes are freezing level with a 50.017 m increase, precipitation with a 60.604 mm/month decrease and wind velocity with an increase of .373 m/sec.

The increase in radiation and decrease in precipitation potentially have the greatest impact on the recession of the Cordillera Apolobamba glacierized area. According to past studies, the glaciers of the outer tropics exhibit sensitivity to certain climate variables such as albedo which is controlled by the occurrence and amount of solid precipitation, incoming long-wave radiation which is related to cloud cover and to air humidity which influences the energy that is partitioned between melting and sublimation (Favier et al., 2004). Interestingly, the specific humidity of the Cordillera Apolobamba region did not exhibit any statistically significant change from 1975 to 2005. While air temperature increased over the thirty year time span, its total annual average increase from -6.62 °C in 1975 to -5.39 °C in 2005 was minimal.

Despite the statistically significant changes that were observed for air temperature and geopotential height between periods one (1975-1986) and two (1987-1995), as well as those observed for freezing level, precipitation and wind velocity between periods two and three (1996-2005), no correlation was found to exist between these changes and the ENSO El Niño events during these time periods. As recorded in previous studies, El Niño events typically cause changes in air temperature, precipitation, cloud cover and albedo which result in the rapid retreat of tropical glaciers. El Niño conditions cause the induced precipitation deficit in the outer tropics as well as increased ablation along with decreased sublimation which will lead to the rapid retreat of tropical glaciers if these conditions prevail over long periods of time (Favier et al., 2004; Wagnon et al., 2001). That is the primary reason El Niño events are reported to have a greater impact on these glaciers than La Niña events. Period one experienced the most El Niño events (4) as compared to periods two and three which each experienced three. Yet the key climate variables radiation, precipitation and specific humidity during period one do not exhibit significant changes. The cloud cover conditions, albedo and energy balance of the Cordillera Apolobamba were not examined in this study and are left for further analysis.

Although the glacierized area of the Cordillera Apolobamba has decreased from 1975 to 2010, and there are recorded changes in the climate, the glacier area and climate variable analyses conducted in this study indicate no clear correlation between the recession of the Cordillera Apolobamba glacier and the change in the climate of that region.

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