Glaciers and Climate Change in Latin America
What is a glacier?

- A glacier is an immense field or stream of ice, formed in the region of perpetual snow, and moving slowly down a mountain slope or valley, as in the Alps, or over an extended area, as in Greenland.
- Glaciers are most common in polar regions but can also be found at all latitudes, including near the equator.
- The number of glaciers in the world is not well known, but the best estimates are that there are about 80,000 glaciers.
Components of a glacier

http://www.homepage.montana.edu/~geol445/hyperglac/systems1/
Glacial ice currently covers 10 percent (16 million km$^2$) of the Earth's surface. Most glacial ice is tied up in the Greenland (2 million km$^2$) and the Antarctic (13.5 million km$^2$) ice sheets. The remaining 500,000 km$^2$ of glacial ice is found in sub polar to polar regions and in high mountains in the Himalayas, Andes, Alps, and Africa.  http://www.homepage.montana.edu/~geol445/hyperglac/space1/
Snowline in the Americas

Thompson et al., 2000 J Quaternary Sci.
Glaciers in México are restricted to its three highest mountains, all stratovolcanoes. Pico de Orizaba or Citlaltépetl and Popocatépetl have historic volcanism and Iztaccíhuatl is extinct. The total area of the 24 glaciers is 11.44 square kilometers. All are small except for Gran Glaciar Norte on Citlaltépetl, which has an area of 9 square kilometers. The glaciers on all three volcanoes have been receding during the 20th century.
(Williams & Ferrigno USGS Prof. Paper 1386-J-3)
Popocatepetl

The Aztec name of Popocatepetl means "Smoking Mountain." This shows the NE side of the massive stratovolcano, which is the second highest peak in Mexico (5465 m) and towers more than 3200 m above the Valley of Mexico to the right. 20 million people live within 80 km of Popo. Popo has erupted at least 36 times since the Spanish conquest in 1522. http://www.volcano.si.edu
Popo Glaciers

(Williams & Ferrigno USGS Prof. Paper 1386-J-3)
Popocatepetl and Iztaccihuatl

Photo of Iztaccihuatl (right) and Popocatepetl (from Volcano World)
Iztaccihuatl (White woman)

- 5286m tall and is the third-highest peak in Mexico.
- Can be seen from Mexico City (64 km away).
- Iztaccihuatl is an extinct volcano.

(Williams & Ferrigno USGS Prof. Paper 1386-J-3)
Itzaccihuatl Glaciers
El Pico de Orizaba or Citlaltépetl

- Highest point in Mexico (5700m) and the third highest peak in N. America.
- Pico de Orizaba last erupted in 1687.

http://www.phoenix.k12.or.us/orizaba/
Citlaltepetl glaciers

(Williams & Ferrigno USGS Prof. Paper 1386-J-3)
Pico de Orizaba is a hazardous volcano

Several eruptions in the last 13,000 years erupted nuee ardentes. The last large eruption with pyroclastic flows was 3,400 years ago. The black arrows show the paths of older nuee ardentes. The white arrow shows the path of the Chocoman nuee ardente. Dark stars mark dacite domes. Dark areas were covered by nuee ardentes. Major streams shown in blue.

http://volcanoworld.org/vwdocs/volc_tour/mex/19Pico_de_Orizaba.html
No Glaciers in Central America

- Volcan Tajumco, Guatemala, is the highest point in Central America
- 4220 m
- Receives some snowfall
Glaciers of the Andes

- The Andes Mountains of South America, from the Sierra Nevada de Mérida, Venezuela, to Tierra del Fuego, Chile and Argentina, have glaciers depending on latitude, altitude, and annual precipitation.

- The largest area and volume of glacier ice occurs in the Patagonian Andes in the far south.

- The Southern Patagonian Ice Field (~13,000 km²) is the largest glacier outside Antarctica in the Southern Hemisphere. The Northern Patagonian Ice Field (~4,200 km²) is the second largest ice field in Latin America and the third is the glaciarized Cordillera Darwin in Tierra del Fuego (~2,300 km²).
Glaciers in South America are found in the high Andes and in Patagonia:

- Venezuela (2 km²)
- Colombia (104 km²)
- Ecuador (97 km²)
- Peru (2600 km²)
- Bolivia (560 km²)
- Chile and Argentina (19,400 km²)
Venezuela has five glaciers with a total area of 2 square kilometers on three separate peaks in the Sierra Nevada de Mérida. A rapid loss of glacier ice has taken place during the last century, a process that has accelerated since 1972. (Schubert in USGS Prof. Paper 1386)
Colombia Glaciers

Colombia has many small glaciers with a total area of 104 square kilometers in four areas within the Sierra Nevada de Santa Marta, Cordillera Oriental, and Cordillera Central. The largest glacier is on the Nevado del Ruiz volcano. Loss of glacier area has been noted since the late 1800's, and many glaciers have disappeared during the 20th century. (Williams Jr. and Ferign in USGS Prof. Paper 1386I).
Ecuador glaciers

Ecuador has more than 100 small glaciers with a total area of 97 km². They are located on 4 high summits of the Cordillera Occidental and 13 mountains of the Cordillera Orientale. Since the 1800's, the glacier area has shrunk. USGS Prof. Paper 1386I
SRTM image of Cotopaxi, Ecuador. More than 50 eruptions since 1738. 5900 meters tall, more than 3,000 meters higher than the surroundings. Volcano base ~ 23 km.
The ice cap of Cotopaxi, Ecuador. Cotopaxi lies almost on the Equator (0.7°S 78.4°W). Notice how the ice cap extends to a lower altitude on one side of the mountain because of a precipitation shadow effect. The side of the mountain facing the dominant moisture-bearing winds experiences higher snowfall and hence more extensive glaciation. Also notice the deep channels carved by meltwater and by lahars. The 1877 eruption produced lahars that traveled 100 km from the volcano.
http://www.petergknight.com/glaciers/glaciersphotos.html
Peru Glaciers

USGS Prof. Paper 1386i
Peru Glaciers

Distribution of glaciers (shown in green) in the Cordillera Blanca and Cordillera Huallanca. The Cordillera Blanca is the most extensive tropical ice-covered mountain range in the world and has the largest ice concentration in Perú.

http://pubs.usgs.gov/prof/p1386i/peru/index.html

*Huascaran ice core
Cordillera Blanca (Occidental)

Panoramic view in the northern Cordillera Blanca taken from the summit of Nevado Chopicalqui looking from the northwest (left) to the north (right). Photograph by Leigh Ortenburger.
Quelccaya Retreat

Qori Kalis (Quelccaya's main ice tongue) is retreating at 155 meters per year, three times faster than during the last measurement period (1995-1998). Melting ice has formed a large lake at the front of the glacier which did not exist in 1983 but now covers more than 10 acres. (It is four acres bigger than it was in 1998.) Bare earth has been exposed for the first time in thousands of years.

http://www-bprc.mps.ohio-state.edu/Icecore/Quelccaya.html
Bolivia Glaciers

Bolivia has a total glacier-covered area of more than 560 sq.km. Most of the ice is on the highest peaks of the Cordillera Oriental. The southwestern part of the country does not receive enough precipitation to maintain glaciers on even the highest peaks. The location of present glaciers is shown in blue-green. From Jordan, USG Prof. Paper 1386I
Bolivian Glaciers (cont’d.)

Lakes mark ancient extent of glaciers

Glacierized areas of the Cordillera Apolobamba in the Cordillera Oriental of Perú and Bolivia. L. = Lago/Laguna. Jordan in USGS Prof. Paper 1386I
Low Latitude Alpine Glaciation

- Preserve the best record of climate in Latin America
- Shrinking rapidly
- Peru's Quelccaya ice cap has shrunk by at least 20% since 1963.
- Coring of ice is a good way to study this history.
Oxygen Isotopes & Global Change

There are three stable varieties of oxygen atoms called isotopes that have the same number of protons (8) but different numbers of neutrons (8, 9, or 10) and so have different mass 16:17:18. These are written $^1_6$O, $^1_7$O, and $^1_8$O.

99.6% of all oxygen is $^1_6$O.

About 1 in 2000 oxygen atoms contains an extra neutron and is 17/16 times heavier ($^1_7$O).

About 1 in 500 contains two extra neutrons and is 18/16 times heavier ($^1_8$O).
Oxygen Isotopes & Paleoclimate

Water containing $^{16}$O will evaporate more readily than water containing $^{18}$O since it is lighter.

Hence, rain will have relatively less $^{18}$O than the ocean from which the water vapor evaporated since relatively more of the $^{16}$O evaporates.

These variations are very small but can be measured very precisely.

Introduce water into mass spectrometer and analyze.
Mass Spectrometers Measure Ratios of Isotopic Abundance, eg. \( \frac{^{18}O}{^{16}O} \)

**“Del” Notation** For Reporting Isotopic Composition of a Sample:

\[
\delta^{18}O = \left[ \frac{\frac{^{18}O}{^{16}O}_{\text{sample}} - \frac{^{18}O}{^{16}O}_{\text{standard}}}{\frac{^{18}O}{^{16}O}_{\text{standard}}} \right] \times 1000 \%
\]

Standard is seawater; by definition has \( \delta^{18}O = 0 \); water with more \(^{18}O\) (heavier) than seawater will have \( \delta^{18}O > 0 \).
Coring Peru Glaciers: Huascaran & Quelccaya

Five glaciers in the Cordillera Blanca (Occidental) of Peru were studied to identify the best sites for acquiring longer-term paleoclimatic and environmental records. Huascaran (9°06' S), the highest (6048 m) and coldest of the sites, was selected for drilling. In 1993 two ice cores were drilled to bedrock. Core 1 (C1), 160.4 m long and Core 2 (C2), 166.1 meters long.

Quelccaya is located at 13°56'S and has a summit elevation of 5670m. Annual accumulation (precipitation minus evaporation and sublimation) averages 1.15 m of water equivalent (snow is largely made up of air, often containing less than 10% water; think of water equivalent as the amount of liquid water produced when snow is melted). Two ice cores were drilled to bedrock, one 155 m long covering the last 1350 years, and the other 164 m long and 1500 years old.

http://www.ngdc.noaa.gov/paleo/slides/slideset/20/index.html
Quelccaya & Huascaran

http://bprc.mps.ohio-state.edu/Icecore/Peru.html
The Quelccaya glacier ends abruptly and spectacularly in a 55 m ice cliff. The annual accumulation layers clearly visible in the photograph are an average of 0.75 m thick. Most snow (80-90%) falls between November and April, and during the rest of the year windblown dust accumulates. The distinct seasonality of precipitation at Quelccaya results in the deposition of dry season dust bands seen in the ice cliff. These layers allow ice core records to be dated accurately by counting annual dust layers in ice records.

http://www.ngdc.noaa.gov/paleo/slides/slideset/20/20_401_slide.html
Huascaran
Sajama Bolivia

The stratovolcano, Sajama (18°S, 6,548 m) is the highest peak in Bolivia and is on the second highest plateau in the world, the Altiplano. A glacier with a depth of about 115 m covers the summit. http://bprc.mps.ohio-state.edu/Icecore/Bolivia.html
Ice Coring

This drill bit is tough enough and sharp enough to slice through meter after meter of solid ice. The bit is fitted onto the core sleeve, a hollow tube into which the ice passes after being cut.

Precipitation and Oxygen isotopes

The colder the temperature, the lighter the oxygen. Rain and snow are always lighter than seawater.
US Rivers & O-isotopes

Oxygen isotopes and Ice Ages

Seawater during an ice age is heavier than seawater during interglacial times ($\delta^{18}O \sim 0\%$ vs. $-1.5\%$)

Variation of seawater $\delta^{18}O$ through time from glacial to interglacial periods

Used with permission from: White, W., Geochemistry, Baltimore: John-Hopkins Univ. Press, in prep.
O- isotopes and the orographic effect

Isotope Fractionation Model involving Amazon Basin hydrology

Schematic showing the oxygen isotopic composition of water vapor along a transect from the Atlantic Ocean to the top of the Andes (Qulccaya glacier). From Thompson et al., 2000
O-isotopes of ice cores

Late Glacial Stage conditions at high elevations were cooler than today. Insoluble dust and anion concentrations in the ice cores reveal that LGS hydrological conditions in the tropics (9°S) were much drier than today, whereas in the subtropics (18°S) LGS conditions were much wetter. This probably reflects the migration of the tropical Hadley Cell in response to a different meridional temperature gradient. Low nitrate concentrations in the LGS ice from both Huascara´n and Sajama suggest that the Amazon Basin forest cover may have been much less extensive. Thompson et al. 2000 JQS
Inferred changes in major vegetation types from the Last Glacial Maximum (~20,000 years ago) to the present. Also shown are selected geomorphological features along with the Quelccaya, Huascara’n, and Sajama ice-core drilling sites. (Thompson et al. 2000 JQS)
In the last three decades, Peruvian glaciers have lost almost a quarter of their area. Patricia Iturregui, head of the Climate Change Unit of Peru's National Council for the Environment, told BBC World Service's One Planet program. "All our estimations on the basis of this data are that in the next 10 years the top tropical glaciers of Peru will disappear if climate conditions remain as the last 10 years." The most immediate threat is coming from the change to water supplies in the area. During the dry season, river water comes exclusively from the glaciers, which melt naturally at that time of year.
Snowline in the Americas

Thompson et al., 2000 J Quaternary Sci.
Chile & Argentine Glaciers

The ice fields and glaciers of Patagonia are akin to those of southern Alaska. This map of Chile and Argentina shows the occurrence of glaciers in the Dry Andes (Desert Andes and Central Andes) and in the Wet Andes (Lakes Region and Patagonian Andes) and location of towns and cities near the glacierized areas that have airports. Liboutry in http://pubs.usgs.gov/prof/p1386i
Patagonia

This MODIS image from April 12, 2002, shows the dramatic impact the Andes Mountains have on rainfall and vegetation. At left is southernmost Chile, which appears quite lush, while Argentina is dry and brown. Note the two large ice fields; these are the N. and S. Patagonian ice fields.
Fig. 1. Location of the 63 surveyed glaciers, labeled in white, overlaid on the topography of (A) NPI and (B) SPI, derived from SRTM of February 2000. Drainage boundaries between glaciers are indicated in red. Elevation contours in gray lines are separated by 100 m between 100 and 2000 m, and by 200 m above 2000 m elevation. Ice-covered areas are shown in white shaded relief. Non-ice areas are shown in colored shaded relief with illumination from the west. (C) Location of the icefields in South America.
S. Chile Lakes

Shuttle photograph (STS060-085-0AE) of Andes and lakes of Southern Chile February 1994. The west-east distribution and species of vegetation and physiography vary from the well-watered Pacific Ocean coastal range of low mountains to the volcanic, snowcapped summits of the Andes Mountains to the arid, leeward side of the Andes in Argentina. The relatively low, forested coastal mountains, with elevations of 2000 to 3000 feet (610 to 915 meters) above sea level, receive an average of 80 inches (200 centimeters) of precipitation annually. Eastward the landscape becomes a broad valley where cattle raising predominates, but agricultural products such as fruits, vegetables, grains, and other food crops are changing the agricultural specialization.

A north-south alignment of lakes along the western flank of the Andes Mountains provides a flourishing tourism industry in this "lakes region" of Chile. The elevations of a north-south-trending string of snowcapped volcanic peaks vary from 6000 feet (1830 meters) to more than 11 000 feet (3350 meters) above sea level. Most of the volcanoes are in Chile, but some are located on the border between Chile and Argentina. Several glacier lakes are visible on the Argentine side of the border, and an elongated reservoir stands out in marked contrast to the arid conditions in the Argentine region of Patagonia.
Southern Patagonia

Green areas are ice fields. Red and purple lines are Caldenius' "third" and "fourth" systems of end moraines, which are dated at 18-19 ka and 10-13 ka. The three largest ice fields are the Northern and Southern Patagonian Ice Fields and the ice field of Cordillera Darwin (modified from Lliboutry, 1956, 1965). Abbreviations: Ba., Bahía; Co., Cordillera; I., Isla; L., Lago; Pen., Peninsula; Pta., Punta; R., Río; Sta., Santa.

http://pubs.usgs.gov/prof/p1386i/chile-arg/wet/historic.html
N. Patagonian Ice Field

The Northern Patagonian Ice Field is centered near 47°S, 73.5°W. The NPIF is a vestige of an extensive ice sheet that covered much of Patagonia just over a million years ago. Today, its glaciers are largely in retreat and has only an area of 4,200 sq km (Dallas County ~ 2500 sq km). The ice sheet persists because of its elevation (1,100 to 1,500 m), favorable terrain, and a cool, moist, marine climate. The ice field has 28 exit glaciers, the largest two—San Quintin and San Rafael—nearly reach sea level to the west at the Pacific Ocean. Smaller exit glaciers feed numerous rivers and glacially carve valleys now filled with lakes to the east. This photo was taken by the crew of STS-108 in December, 2001. Arms of Lake General Carrera are visible on the right of the image.
Landsat mosaic of N. Patagonian Icefield, draped on DEM and viewed from SW
Southern Patagonian Ice Field

The Southern Patagonian Ice Field has an area of about 13,000 square kilometers, a length of ~ 360 km (over three degrees of latitude), and an average width of about 40 kilometers. To the west of the ice field, nearly fifty significant outlet glaciers reach sea level in rugged fiords on the Pacific coast. Brüggen is the largest of these. East of the ice field, several of the larger glaciers on the eastern flank form large piedmont lakes (such as Lago Argentino).

S. Patagonian Ice Field
STS056-098-026 Southern Andes Mountains, Argentina and Chile April 1993. Numerous glacier lakes can be seen on either side of the north-south axis of the ice- and snow-covered Andes Mountains. The mountains gradually decrease in elevation, from ~ 10 000 feet (3048 meters) in this photograph to 4000 feet (1220 meters) and less above sea level near the horizon. Lake Viedma (northernmost) and Lake Argentino—the two larger light blue lakes at the northern end of the photograph—constantly receive meltwater from the western glaciers. The brownish-tan terrain east of the Andes Mountains is a plateau where the constantly blowing west wind, coupled with very limited precipitation, produces a harsh, barren, almost nonvegetated landscape in this Argentine region of Patagonia.
View of S Pat. Ice Field

View on 11 February 1966 from the summit of Cerro Bertrand looking toward the north and showing the three mountain ranges in the middle part of the Southern Patagonian Ice Field. The west range includes Cordón Risopatrón; the central range includes Cordón Mariano Moreno; the east range includes Cordón Marconi, Monte FitzRoy, and Cerro Huemul. Photograph courtesy of Pedro Skvarca, Instituto Antártico Argentino, División Glaciología, Buenos Aires, Argentina.
The crew of the International Space Station caught a rare glimpse of the massive ice fields and glaciers of Patagonia early in the afternoon on September 25, 2001. This part of the South American coast sees frequent storms and is often obscured from view by cloud cover. Brüggen Glacier is the largest western outflow from the Southern Patagonian Ice Field and, unlike most glaciers worldwide, advanced significantly since 1945. From 1945 to 1976, Brüggen surged 5 km across the Eyre Fjord, reaching the western shore by 1962 and cutting off Lake Greve from the sea. The glacier continued advancing both northward and southward in the fjord to near its present position before stabilizing. The growth covers a distance of more than 10 km north to south, adding nearly 60 square km of ice.

Changes in the position of the terminus of Glaciar Brüggen, 1945-1976

http://pubs.usgs.gov/prof/p1386i/chile-arg/wet/historic.html
Glacier Occidental, Chile

Center Point Latitude: 49°S, Center Point Longitude: 74°W
Glacier Viedma

Oblique aerial photograph (March 1989) looking northwest at Glaciar Viedma in the Southern Patagonian Ice Field as it calves into Lago Viedma. In the background on the right is Nunatak del Viedma at the foot of an extensive mountain range, Cordón Mariano Moreno. Photograph courtesy of Daniel Rivademar, Buenos Aires, Argentina (furnished by Pedro Skvarca, Instituto Antártico Argentino, División Glaciología, Buenos Aires, Argentina).
The San Quintín Glacier is the largest outflow glacier of the Northern Patagonian Ice Field in southern Chile. Its terminus is a piedmont lobe just short of the Golfo de Penas on the Pacific Ocean and just north of 47°S. Like many glaciers worldwide during the twentieth century, San Quintín appears to be losing mass and possibly retreating. Such a change is evident in these two photographs taken by astronauts only seven years apart. The first was taken by the crew of STS-068 in October 1994 and the second by the Increment 4 crew of the International Space Station in February 2002.
Patagonian Glaciers are melting rapidly

Rignot et al 2003 Science 302 434-437
Patagonian Glaciers and Sealevel Rise

Digital elevation models of the Northern and Southern Patagonia Icefields of South America generated from the 2000 Shuttle Radar Topography Mission were compared with earlier cartography to estimate the volume change of the largest 63 glaciers. During the period 1968/1975–2000, these glaciers lost ice at a rate equivalent to a sea level rise of 0.042 millimeters per year. In the more recent years 1995–2000, average ice thinning rates have more than doubled to an equivalent sea level rise of 0.105 millimeters per year. Sealevel is presently rising at a rate of about 2 mm/year Patagonian glaciers are contributing about 0.1 mm/year. Rignot et al 2003 Science 302 434-437