**Objective**

Introduction to global climate change  
Glaciers as recorders of global climate change  
Examples of how changes in climate impacted past Peruvian cultures  
Evidence for recent acceleration of the rate of glacier loss  
Evidence that some glaciers like the Quelccaya ice cap are smaller than they have been in the last 6,000 years

*Why B.F. Skinner became pessimistic about human beings.*  
“Immediate consequences outweigh delayed consequences”  
“Consequences for the individual outweigh consequences for others”  
*P. Chance, 2007*

Our options  
Our greatest challenges in the 21st Century
Natural mechanisms influence climate

**Natural mechanisms**
- Changes in solar output
- Changes in the amount of volcanic aerosols in the atmosphere
- Internal variability of the coupled atmosphere-ocean system (e.g., ENSO, monsoon systems, NAO)

Human factors also influence climate

**Non-natural mechanisms**
- Changes in the concentrations of atmospheric greenhouse gases
- Changes in aerosols and particles from burning fossil fuels and biomass coal (sulfate aerosols) – cooling; biomass (black carbon) – warming
- Changes in the reflectivity (albedo) of Earth’s surface and the hydrologic cycle

Carbon Dioxide Concentrations

Smoke from fires in Guatemala and Mexico (May 14, 1998)
Climate Responses to Different Forcing Mechanisms

Stratosphere is cooling

Troposphere is warming

This response is expected from GHG forcing & is predicted by climate models. It is not forced by the sun!

The Meteorological Record is Very Short

Globally averaged temperature (land & ocean)

60-month Running Mean
132-month Running Mean

relative to the 1951-1980 mean

data.giss.nasa.gov/gistemp
It's not the Sun!

Source: Solar irradiance from composite satellite-based time series: 1976/01/05 to 2011/02/02 Physikalisch Meteorologisches Observatorium Davos
2011/02/03 to 2012/01/11 University of Colorado Solar Radiation & Climate Experiment

Various archival systems provide paleoclimate records

Ice Cores
Class-100 clean room houses the equipment to analyze dust, isotopes and chemicals.

Freezers for storage and cold rooms for physical property measurements.

Machine shop for fabrication of our drills.

Ice cores are powerful contributors to multi-proxy reconstructions:
1) they provide multiple lines of climatic & environmental evidence
2) ideal for revealing rapid climate changes

Guliya ice cap, Tibet

A  Temperature ($\delta^{18}O$, $\delta^D$)
B  Atmospheric Chemistry
C  Net Accumulation
D  Dustiness of Atmosphere
E  Vegetation Changes
F  Volcanic History
G  Anthropogenic Emissions
H  Entrapped Microorganisms
Ice cores provide unique histories …… from regions where other recording systems are limited or absent

Huascarán, Peru

Dasuopu Glacier Southern Tibet

EPICA Dome C ice core extends back through eight glacial and interglacial stages (800,000 years) recording changes in the composition of Earth’s atmosphere

Lüthi et al., Nature, 2008

Today:

$\text{CO}_2$ is 393 ppmv

$\text{CH}_4$ is 1800 ppbv

Thousands of Years (B.P.)

800 600 400 200 0

393

1800

3700

IPCC Emission Scenarios for 2100 AD

$\text{CO}_2$ remains in the atmosphere for decades to millennia
Today: CO₂ is 393 ppmv
CH₄ is 1800 ppbv

Lüthi et al., Nature, 2008

The fraction of CO₂ remaining in the air, after emission by fossil fuel burning, declines rapidly at first, but 1/3 remains in the air after a century and 1/5 after a millennium (Atmos. Chem. Phys. 7, 2287-2312, 2007).
IPCC 4th Assessment (2007)  
Projection for 2100 AD  
2.0 – 4.5 °C

Northern Hemisphere temperature (°C) for the last 1000 years

Population

1.0 billion in 1850
2.0 billion in 1930
4.1 billion in 1975
6.1 billion in 2000
7.0 billion in 2012
9.0 billion by 2050

In 2012 we also need animals and crops

17 billion Fowl
1.9 billion Sheep and goats
1.4 billion Cattle
1.0 billion Pigs
400 million Dogs
500 million Cats

In contrast, the pre-exploitation number of American Bison: 60 - 80 million
Looking ahead to 2030 you can see sustained growth in global demand for electricity is inevitable. Demand is forecasted to more than double by 2030 (Energy Information Administration).

Source: Mark Little, General Electric Global Research
**Ohio State Ice Core Sites**

- *Ice Cores drilled by the OSU Ice Core Paleoclimatology Group*

As of October 2011

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**a). ECMWF 500 hPa temperature (°K) DJF**

**b). SST (°C) DJF**

**c). Xie-Arkin precipitation DJF**

(Modified after Sobel, 2002)
Annually Resolved Ice Core Records of Tropical Climate Variability over the Past ~1800 Years

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Ice cores from low latitudes can provide a wealth of unique information about past climate in the Tropics, but they are difficult to recover and few exist. Here we report annually-resolved ice core records from the Queleccaya ice cap (5670 m asl) in Peru which extend back ~1800 years and provide a high-resolution record of climate variability there. Oxygen isotopic ratios (δ18O) are linked to sea surface temperatures in the tropical eastern Pacific, while concentrations of ammonium and nitrate, document the dominant role played by the migration of the Intertropical Convergence Zone in the region of the tropical Andes. Queleccaya continues to retreat and thin: radiocarbon dates on wetland plants exposed along its retreating margins indicate it has not been smaller for at least six millennia.

distinct annual layers (fig. S1A) used to reconstruct an ~1800 year climate history. Details about the construction of the timescale, extracting annually-resolved information, and reconstructing the net annual accumulation are provided in the supplementary online text. The δ18O records for the 2003 QSD and QSD core, separated by 1.92 km, are highly correlated (R = 0.995, p < 0.0001, for decadal averages, table S1). In light of their similarity, documented in the supplementary online text, all subsequent discussions are based on the QSD core.

These records (Fig. 2 and fig. S2) based on freshly cut ice samples, are precisely dated and include oxygen isotopic ratios (δ18O) and concentrations of soluble dust and major cations (F, Cl, NO3−, NO2−) and cations (Na+, NH4+, K+, Mg2+, Ca2+). The reproducibility of decadal averages of δ18O (1993 QSD core v. 2003 QSD core) from 1990 to 1992 CE (Fig. S1A) is excellent (R = 0.955, p < 0.0001). Details of the reproducibility of δ18O and net accumulation among the four cores, two in 1993 and two in 2003, over the last 1000 years are in the supplementary online...
Quelccaya ice cap, Peru (2003) Thompson et al., Science (Express), 2013

Spatial correlations $\delta^{18}O$ vs ERSSTs $\delta^{18}O$ vs ERSST NINO4
Reconstructed SST for NINO4 Thompson et al., Science (Express), 2013
Pre-Colonial Cultures

Pre-Historic Andean Civilizations Rose and Fell to the Rhythms of Climatic Change

- Dust conc. (x10^5)
- Ammonium (ppb)
- Year (CE)
- Quelccaya Ice Cap, Peru

Legend:
- Late Horizon
- Late Intermediate Period
- Middle Horizon
- Early Intermediate Period
- Inca Empire
- Chimu Empire
- Northern Coastal Culture
  - AD 650 - AD 1450
- Southern Coastal Culture
  - AD 1000 - AD 1300
- North Coastal Macht
  - AD 1000 - AD 1300
- Coastal Culture
- Highland Cultures
  - Tharuma and Huari Highland Cultures

Data sources:
- After Thompson (1992) and Pudesh (1974)
- Quelccaya ice core from Thompson et al. (1986) in press
Cordillera Vilcanota & Quelccaya

Landsat 5: 04-Aug-2006
1988-2006 recession in yellow

<table>
<thead>
<tr>
<th></th>
<th>Area (km²)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vilcanota</td>
<td>370</td>
<td>28.7</td>
</tr>
<tr>
<td>Quelccaya</td>
<td>52</td>
<td>45</td>
</tr>
</tbody>
</table>

Compton Tucker; NASA

Quelccaya, Peru

1977

2002
Quelccaya Ice Cap, Peru

5177 ± 45 yr. BP

200 - 400 m above its modern range

Distichia muscoides

Plant

2002

2005
Nature’s best thermometer, perhaps its most sensitive and unambiguous indicator of climate change, is ice.

“Ice asks no questions, presents no arguments, reads no newspapers listens to no debates. It is not burdened by ideology and carries no political baggage as it changes from solid to liquid. It just melts.”

From A World Without Ice by Henry Pollack, 2009
Muir Glacier, SE Alaska
August, 1941 (photo by William Field)  August, 2004 (photo by Bruce Molnia)

Kyetrak Glacier, Eastern Himalayas

1921 2009
Ghiacciai della Lobbia e dell’Adamello/Mandrone (102 anni)

Quelccaya Ice Cap (13°56'S, 70°50'W, elev. 5670m)

Sajama (18°07'S, 68°53'W, elev. 6542m)

Huascaran Col (9°07'S, 77°37'W, elev. 6048m)
Retreat of the Qori Kalis Glacier (Peru)

1978 – no lake

2011
lake covers 84 acres

The Third Pole high, cold, remote & threatened by climate change
- Centered on the Tibetan Plateau & Himalayas
- Covers 5 million km²
- One of the largest glacial stores of fresh water over 46,000 glaciers
  (Asia’s water tower)
- Glaciers feed Asia’s largest rivers
- Help sustain 1.5 billion people in 10 countries
Naimona’nyi Glacier, southwestern Himalaya (Tibet)

Recovered three ice cores to bedrock in 2006
157.5, 137.8, 113.7 meters

Photo: Lonnie G Thompson
$^{36}\text{Cl}$ from the Ivy Tests (1952-1958)

Ivy Test

Area Reduction for 7090 glaciers
85% of the ice present in 1912 has disappeared

**Total Area Of Ice On Kilimanjaro**


1912 - 1989 after Hurne's work and Greilich's, J. Glaciol. 1987
1990 - 2007 from Thompson, OSU
From 2000 to 2007
- Northern Ice Field surface lowered 1.9 meters
- Furtwängler Glacier surface lowered 3.1 m
- Southern Ice Field surface lowered 5.1 m

Thompson et al., PNAS, 2009
Furtwängler Glacier, 1999
Photo: Lonnie Thompson
January

2012
Photo: Michael O'Toole
September

Ice Fields near Puncak Jaya, Papua, Indonesia drilled 2010

1936

1991

2001
Ice surface area for glaciers near Puncak Jaya, Papua, Indonesia and for the ice fields of Kilimanjaro

\[ R^2 = 0.98 \text{ (P. Indonesia)} \]
\[ R^2 = 0.98 \text{ (Kilimanjaro)} \]

Lonnie G Thompson, unpublished figure, do not distribute.
Recent and rapid melting of glaciers around the world

Climatologically we are in unfamiliar territory, and the world's ice cover is responding dramatically.
How to manage a world with threats from climate change, rising sea levels and rising energy consumption?
**Perfect Storm is Brewing**

**Ingredients for a Perfect Disaster:**
- 1000-year CO₂ Lifetime
- Climate System Inertia
- Positive (Amplifying) Feedbacks
- Fossil Fuel Addiction

**Alternative: A Brighter Future**
- Low Cost Fuels
- Clean Air & Water
- Economic Development, Good Jobs

"Immediate consequences outweigh delayed consequences"  
*P. Chance, 2007*
Tornado approaching Tuscaloosa, April 27, 2011
(source: ABC news)

Aftermath of tornado in Joplin, MO, May 22, 2011
(source: NY times.com)
In 2011, Ohio experienced its wettest year on record.

The cost of extensive repairs to roads and bridges was estimated at almost $40 million. In requesting assistance for disastrous flooding that occurred in April and May, Ohio’s Governor John Kasich said in a letter to President Obama that the impacts in Ohio were "of such severity and magnitude that effective response is beyond the capabilities of the state and local government."

Weather Fatalities

- Weather Fatalities for 2011
- 10 Year Average (2002-2011)
- 30 Year Average (1982-2011)
Pakistan flooding, Sept. 25, 2011, Sindh Province (source: Faisal Mahmood/Reuters)

2011: Overall losses: $148 billion
Insured losses: $55 billion

Fire near Colorado Springs, June 27, 2012
(Source: Sa Blne, Smithsonian.com)

The U.S has endured a near-record wildfire season with the total acres burned roughly the same size as Massachusetts and Connecticut combined:
2006-- 9.8 million acres
2007-- 9.3 million acres
2012-- 9.1 million acres
“Consequences for the individual outweigh consequences for others”  P. Chance, 2007

Waldo Canyon fire west of Colorado Springs, June 26, 2012 (source: RJ Sangosti, The Denver Post)

6 to 7 meters of sea level rise eq.

2012 record summer surface melting

40% 97%
Data: September 17, 2012: Left Panel: sea ice extent (>15% ice), Right: sea ice concentration (%). Pink Line: climatological extent (1979—2000). Source: National Snow and Ice Data Center, Boulder, Colorado. Sea ice cover in September, 2012 was 3.42 million square kilometers (1.32 M sq. mi.) which is 18% smaller than in 2007 record low of 4.17 million square kilometers (1.61 M sq. mi.)

Climate System Models Did Not Predict This!

Model runs: Stroeve et al., 2007
Hurricane/Superstorm Sandy
Death toll: 110
Estimated cost: $60 Billion

Illustrates: the conditions and events and scenarios that we can expect from climate change. In New York and New Jersey there are 45 superfund toxic waste sites within half a mile of the coast.

Gov. Cuomo of New York to President Obama “we have a 100-year flood every two years now” In fact, three of the 10 biggest floods in Lower Manhattan since 1900 have occurred in the last 3 years.

Rising seas create a higher baseline for future storm surges. Current estimates are that coastal waters will rise by two feet by 2050 and four feet by the end of the century.
Summer 2013, Australia

Summer 2013, Smoke from Australia’s Fires
It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change. *Evolutionary Theory*

Individuals, groups and nations, in contrast to evolution, can understand their circumstances and deliberately make the appropriate changes in polices in order to improve their outcome.

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**So Society has Three Options!**

- **Mitigation**, means taking measures to reduce the pace & magnitude of the changes in global climate that are caused by human activities.
  
  Examples of mitigation include reducing emissions of GHG, enhancing “sinks” for these gases, and “geoengineering” to counteract the warming effects of GHG.

- **Adaptation**, means taking measures to reduce the adverse impacts on human well-being that result from the climate changes that do occur.
  
  Examples of adaptation include changing agricultural practices, strengthening defenses against climate-related disease, and building more dams and dikes. But it’s a moving target!

- **Suffering**, the adverse impacts that are not avoided by either mitigation or adaptation.
Our greatest challenges of the 21st Century will be:
(1) learning how to get along with each other and
(2) learning how to get along with our Planet.

These two challenges deal with human behavior and are closely related!

For Global Climate Change --- Nature is the Time Keeper!