Ice Cores

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EPSC 510
Fall 2016
Presentation Summary

- Introduction to Ice Coring
- Historical Significance
- Ice Cores in Antarctica
  - Ice Core Interpretation
  - Applications of Recent Ice Core Data
  - Future Innovation
Introduction – Why look at ice cores?

- Ice cores are among the few naturally occurring climate archives.
- Seasonal temperature variations pronounce layering in an annual fashion.
- Ice sheets have the potential to preserve paleoclimate indicators corresponding to time of deposition.
- Ice cores have yielded reliable data dating back 800 Ka.
Structure of Ideal Ice cores

- **Long time scales (Ka-Ma)**
  - Ice sheet flow is dominated by gravitational forces
  - Ideal archiving core sites are referred to as “Domes”
  - These are regions where gravity acts in only the z direction

- **Short time scales (<ka)**
  - Three primary structures
  - Snow cover results from precipitation and win currents
  - Over time, older snow layers compact to firn
  - After sufficient burial ice begins to form, and is considered to be isolated from the atmosphere
  - Ice can be isolated with relict atmospheric air, or with clathrates
Geographic Context

- Ice cores have been collected from a variety of glaciated locations.
- These regions primarily consist of the Antarctic and Greenland ice sheets.
- Secondary regions include “tropical glaciers” (South American Andes) and other land glaciers (Northern Canada).
- This presentation will focus on coring efforts in Antarctica.
- Less notable coastal core sites will be discussed later.
How did we get to Antarctica?

- The first notable attempt to probe an Ice sheet was by Ernst Sorge in the 1930's.
- His findings were published in 1935, showing ice density increase as a function of depth.
- It wasn’t until 20 years later that ice cores were collected.
- Ice core collection quickly became an international effort, with the United States and Europe confined to Arctic regions.
- Russian ice coring was the first in Antarctica, with a 377m core sampled in 1957.

Fig. 1. Greenland and Antarctic deep drilling sites synthesised for the International Partnership for Ice Core Science (from http://www.pages-igbp.org/sparc/).
Early ice cores

- The early 1960’s were an innovative time for Ice core collection sites reached depths on the order of several kilometres in this decade.
- Major inhibitors include drill capability, site accessibility, and bedrock depth.
- (Dansgaard and a team of researchers in Copenhagen conducted research that would pave the way for paleoclimate research with respect to ice cores).
- Publications by Dansgaard’s team in 1953 and 1964 established the close link between the isotopic composition of snow, and the temperature of the precipitation site.
- \(\delta D\) and \(\delta^{18}O\) ratios in snow were an effective proxy for finding atmospheric temperature over periods of snow deposition.
Deep-ice cores

- The early 1970's marked the start of drilling at the Vostok site in Antarctica.
- Over decades, the Vostok site continued to grow in depth, and is now the deepest ice core site (3623m).
- Research has continued in the Vostok site, with the penetration on lake Vostok in 2012.
- The first example of ideal “Dome” drilling was at the inland site of Dome C (Lorius et al., 1979).
- The initial depth of Dome C was 905 m.
- Drilling in this site progressed until bedrock was reached in 2005, at a depth of 3620m.
- Dome C has provided scientists with an analog of paleoclimate indicators for the past 800 Ka.

![Deep drilling at the Vostok site.](image)
Where to look for ice core data?

- Isolated air pockets within the glacial ice preserve the depositional atmosphere.
- Ice without air bubbles (melting) may contain air clathrates.
- Impurities within the ice act as markers for climate cycles/events.
- Lower layers contain older records, but with reduced resolution.
- Accreted layers above glacial lakes (Lake Vostok) provide additional data sources.
Ice Core Interpretation

- Isotopic Properties that infer atmosphere composition:
  - Oxygen16, 18, and Deuterium
  - Carbon-14
  - Beryllium-10
  - Pb-207

- Unique Chemical Signatures:
  - Sea salt
  - MSA's
  - Biological sequences

- Atmospheric Records:
  - Wind
  - PO2
Isotopes: O-16, o-17, and h-2

- Due to the linear relationship between δD and δ18O, both isotopes are able to analog precipitation temperature.
- This principle has been well understood for decades, but only recently applied over long time intervals (800Ka).
- Recent research suggests that these three isotopes can be used to infer humidity as well (Landais et al., 2008; Winkler et al., 2012).
- The figure shows deuterium variations which are very closely linked to greenhouse gas concentrations.

Fig. 9. Variations, over the last 800,000 yr, of deuterium (δD, black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO₂ (green), CH₄ (blue), and nitrous oxide (N₂O, red) derived from air trapped within ice cores from Antarctica (Schultz et al., 2009).
• Entrapped air within ice has been of great scientific interest since the 1960’s
• Correlation between C-14 dating and atmospheric [CO2] took over a decade to reliably measure (Lorius et al., 1968)
• [CO2] data from Dome C showed that carbon dioxide concentrations were around 30% lower during the LGM
• Among the first major evidence to support claims made by Arrhenius at the end of the 19th century
• Can be used as a proxy for cosmic radiation (radionuclide)
• Other greenhouse gasses have been heavily studied in ice cores, including ethane, methane, and nitrous oxide

Isotopes: c-14
Similarly to C-14, Be-10 is a radionuclide that can be found in ice cores.

The majority of cosmic rays reaching Earth are from supernova explosions outside our solar system.

Cosmic rays are mitigated by the solar magnetic field and geomagnetic field.

Until recent research into Be-10, cosmic radiation was only recorded to the 1930's using ionization chambers and neutron monitors.

Using Be-10 as a cosmic radiation proxy has extended this archive to 9.4 Ka.
Be-10 and C-14

- Both radionuclides are produced via nuclear reactions between cosmic rays and nitrogen/oxygen.
- C-14 is a less effective solar radiation proxy, as it enters the carbon cycle which is already enriched with C-14.
- Be-10, however, is an aerosol-borne isotope with a short atmospheric residence time.
- Findings show a huge discrepancy between modern solar radiation and past radiation (Steinhilber, 2012).
Scientists have looked to ice cores for evidence of lead pollution from 20th century mining.

Pb isotope data was recorded at Law Dome between 1500 and 1989 AD. Articles published in the early 2000's concluded that a major Pb pollution event is observed between 1884 and 1908 AD. This spike in anthropogenic lead was attributed to mining at Broken Hill and Port Pirie, Australia. The sparsity of data doesn’t allow for conclusions regarding transport to Antarctica (P. Vallelonga, 2002).
Chemical Signatures: Sea ice proxies

- One of the greatest challenges to climate modelling is the ability to quantify sea ice extent in the past.
- Research has been conducted in recent years to identify proxies within sea ice cores.
- Unlike traditional ice cores (dome oriented, long), coastal regions are drilled to find ice extent proxies.
- Antarctica is an ideal site for observing.
- Antarctic ice cores only contain sea ice information if it can be transported by the atmosphere.

As ice extent increases, sea ice surface area increases, as well as the distance required for aerosol transport.
Salty Blowing Snow:
- Salty blowing snow is a theory which states that snow on sea ice is high in salinity.
- Strong winds have the ability to mobilize snow to the Antarctic interior.
- The sublimation of this snow should result in sea salt aerosols, which are entrapped in glacial ice.

Frost Flowers:
- Delicate crystals that form with new sea ice.
- As brine wicks up, the fresh frost flowers have a rather high salinity.
- Frost flowers are mobile, but are related to seasonal variations in ice formation.
- (N.J. Abram et al., 2013) suggests little seasonal contrast in sodium flux, which undermines the frost flower theory.
Results from various ice core data sets show a strong correlation between sea salt and temperature/ice presence.

The mechanism of salt transport must be further constrained in order to model sea ice extent with reasonable accuracy.

Using aerosols as a proxy for ice extent is a challenge due to the extreme variability of wind cycles over long periods of time.

Other proxies have been explored that have clearer transport mechanisms...
MSA Production:
- The Southern Ocean is host to a huge biomass of phytoplankton.
- Sea Ice species produce the signature compound dimethylsulphide (CH$_3$)$_2$S.
- This compound is exchanged with the atmosphere, and later oxidised to MSA.
- Recording MSA concentrations in ice cores has the potential to infer collection site proximity to marine biological activity.
- MSA concentrations decrease with increasing proximity and altitude.
Near several of the Vostok drilling sites, a massive subglacial lake was discovered (Lake Vostok). The massive lake has likely been isolated from marine sources for millions of years, with no light penetration through the overlying 3.7km of ice. Using similar ice coring practices as before, scientists hope to analyze accreted ice layers at the bottom of the core. The purpose of this research was to identify compounds and sequences within the accreted layers, giving a possible timeline of activity in the lake.
• With over 231m of accreted ice sampled, a total of 3,507 unique gene sequences were discovered. (94% bacteria, 6% Eukarya)
• Molecular signatures suggest a possible connection to the surrounding ocean, while the lake remains entirely under sea level
• The presence of thermophilic and thermotolerant organism sequences infers the presence of hydrothermal activity near Lake Vostok
• Hydrothermal activity is further supported by the lake’s placement in a graben structure associated with a 35 Ma rift valley.
Using the 800 Ka range of the newest Dome C ice cores, researchers have correlated dust flux to climactic events throughout Earth's history.

An astonishing 25-fold increase in dust flux is observed when comparing glacial to interglacial intervals.

The study covers all 8 large glacial cycles currently recorded by ice cores.

Inferences made from trapped dust during glacial intervals:

- Neodymium signature suggests dust sourced from South America.
- Grain sizes indicate higher wind velocities.
- Reduced hydrological cycles increase atmospheric lifetime of dust particles.

Figure 3 | EDC dust-temperature relationship. Values of δD (ref. 8) are plotted against dust flux (both at 55-cm resolution). Green and blue dots represent data from 0–430 kyr BP and 430–800 kyr BP, respectively. Superposed is a cubic polynomial fit, $\log_{10}(D) = -3.737 \times 10^{-7}(\delta D)^2 + 4.239 \times 10^{-2}(\delta D)^2 - 1.607(\delta D) - 204$, where $D$ is the dust flux (mg m$^{-2}$ yr$^{-1}$), and δD is in ‰ ($r^2 = 0.73, N = 5,164$).
A recent study released in September 2016 by D.A. Stolpher shows how the partial pressure of atmospheric oxygen has decreased over 800 Ka.

The observed decrease of PO2 was recorded to be 0.84% per Ma, which has interesting implications for oxygen sources and sinks on Earth.

The results suggest oxygen sinks are 2% larger than sources, averaged out over 800 Ka.

Over geologic time scales such as this, the theories have been suggested to account for this change.

It is known that there was an increase in continental weathering during the Pleistocene.

Sedimentary carbonate and pyrite weathering is likely a contributor in the oxygen cycling imbalance.

Oceanic cooling may have initiated the oxygen sink anomaly as well. As ocean waters cool, oxygen solubility is increased, and oxygen exposure to marine sediment increased as a result (Oxygen burial).
Future of ice cores

- In collaboration with 10 nations, the EU is funding a project to discover ice as old as 1.5 Ma.
- The BE-OI project hopes to find a topographically suitable region where ice near the bedrock is older than ever recorded.
- The oldest ice cores come from Dome C, but the bedrock was reached back in 2005.
- Because most Antarctic domes have been sampled, researchers face the challenge of dealing with ice cores affected by flow.
- The expected time window for surveying and drilling is 2017/18.
references


Thank you!