Past climate from ice cores
North and South

Valérie Masson-Delmotte
Laboratoire des Sciences du Climat et de l’Environnement (CEA-CNRS-UVSQ/IPSL)
Gif-sur-Yvette, France

valerie.masson@cea.fr
Outline

I- Polar regions in the climate system

II- Climate archives in ice caps

III- Climate reconstructions from deep ice cores
    Focus on temperature changes

IV- Perspectives
I- Polar regions in the climate system
Polar regions in the climate machine

- Annual mean surface air temperature - 30°C at Greenland summit
- Annual mean surface air temperature - 55°C in the central Antarctic Plateau

Source: CRU
http://www.ncl.ucar.edu/Applications/cru.shtml
Polar regions in the climate machine

Distribution of solar energy (orbit of the Earth)

Atmosphere (greenhouse gases, aerosols, clouds)

Albedo of the surface

Polar regions
= areas where the Earth is losing energy towards space
= areas where the ocean and the atmosphere transport heat
Polar regions in the climate machine

Global ocean circulation

Courtesy of Sabrina Speich (LPO) : http://www.ifremer.fr/lpo/speich/
A view of ocean circulation
The Arctic Oscillation

Source: University of Washington
Modes of Antarctic atmospheric circulation variability

http://jedac.ucsd.edu/ACW/index_description.html
Links between climate change in the polar regions and global changes
Amplification mechanism: change in surface albedo

- change in surface albedo
- effect of water vapour content of the atmosphere
- effect of the type of clouds formed

Climate forcing:
- Warming
  - Reduced snow or ice cover
  - Change in surface albedo
  - More solar radiation absorbed at the surface

Temperature change:
- More infra-red heat loss

+ effect of water vapour content of the atmosphere
+ effect of the type of clouds formed

...
Climate change now

Take home messages

- Polar regions : key climate areas
  ⇒ cold point of the climate system
  ⇒ ongoing large temperature changes
  ⇒ amplifying mechanisms (Ex: albedo of snow and ice)

- Global relevance
  ⇒ ocean and atmosphere circulations (« teleconnections »)
  ⇒ polar ice caps : risks of sea-level changes
II- Climate archives in ice caps
Polar ice caps

Greenland
~ 2.8 millions of km$^3$
~ 7 meters of global sea-level

Antarctica
~ 29.3 millions of km3
~ 70 meters of global sea-level
70% of the Earth’s freshwater
90% of its ice
Antarctic ice sheet: ~12 million years ago
Greenland ice sheet: ~3 million years ago

Source: Zachos et al, Nature 2005
From ice caps to ice cores

Source: B. Ruddiman

Accumulation in central Greenland: 30 cm of water equivalent per year
Accumulation in central Antarctica: 3 cm of water equivalent per year
Sampling the cold point of the global climate system
Hidden inside the ice
Water stable isotopes

Main forms of the water molecule:
$H_2^{16}O$, $H_2^{18}O$, $HD^{16}O$

In ocean water:
$^{18}O/^{16}O \approx 2005$ ppm et $D/H \approx 155$ ppm

Analytical precision $\approx 0.1$ ppm

\[ \delta^{18}O(\text{‰}) = \left( \frac{\frac{^{18}O}{^{16}O}_{\text{ech}}}{\frac{^{18}O}{^{16}O}_{\text{SMOW}}} - 1 \right) \times 1000 \]

Deuterium excess
$\text{d} = \delta^{18}O - 8 \delta D$

Molecular mass ➔ Saturation vapour pressure ➔ Fractionation during equilibrium phase changes

Molecular symmetry ➔ Molecular diffusivity ➔ Fractionation during kinetic processes
Paleothermometry

Compilation of Antarctic locations where the isotopic composition of surface snow has been measured
Possibility to quantify site and source temperature changes

Simple isotopic model

- $\delta^{18}O$ (%) vs. Site temperature (°C)
- Excess (%) vs. Site temperature (°C)

- Physical proxies
- Transfer function: spatial and temporal approach
- Distillation models
- Climate models
- Integrated tracers of the water cycle
Modelling stable isotopes of water in climate models

Courtesy of G. Hoffmann (LSCE)
Stability of the isotope-temperature slope for past periods in Antarctica (left) and Greenland (right).

Antarctica: validity of the isotopic thermometer within 20 to 30%.

Greenland: underestimation of past temperature changes in stable isotopes due to changing seasonal snowfall.

Courtesy of G. Hoffmann (LSCE)
Climatic information preserved in the ice

Water isotopic composition

- Past local temperature changes
  *Antarctic climate change*

Ice chemistry

- Impurities transported by the atmosphere
  Dust, aerosols, pollution…
  *Volcanism, solar activity (climate forcings)*

Air trapped in the ice

- Atmospheric composition
  *Greenhouse gases*
Dating of ice cores

- **Layer counting**
  ⇒ Seasonal cycles of physical or chemical properties of ice layers
  ⇒ Back to 60,000 years in Greenland with an estimated uncertainty of less than 1,200 years

- **Age markers**
  ⇒ Identification of events dated elsewhere (volcanic signals, magnetic field changes)
  ⇒ Cross dating of ice cores because atmospheric signals are global (typical uncertainties of 50 to 1,000 years)

- **Modelling**
  ⇒ Ice mechanics
  ⇒ Requires to estimate past changes of snow accumulation and flow properties
Take home messages

• Chemical, physical analyses of ice cores provide local to global climatic and environmental records

• All ice core records can be placed in a common age scale owing to their records of atmospheric composition

=> Possibility to analyse the sequence of events during climate changes
A model of ice caps covering the northern hemisphere at the Last Glacial Maximum, 21,000 years ago (Joussaume, 1995).
Recent completion of drilling projects

**EPICA Kohnen Station**
- Jan. 2006
- 2774 m
- 500 000 years?

**Byrd**
- 1968
- 2164 m
- 80 000 years

**Dome F**
- Jan. 2006
- 3029 m
- 1 000 000 years?

**Vostok**
- 1996
- 3623 m
- 400 000 years

**EPICA Dome C**
- Dec. 2004
- 3270 m
- 800 000 years
Deep drilling projects: need for intense operational support

The example of EPICA Dome C

- Climatic and geographic constraints: 3233 m elevation, -54.5°C, 75°S, 123°E
- Transport by traverses: 1200 km from DDU
- Window for summer field work: 8 to 10 weeks
- Drilling capability: 0 to 250 meters per week
- Equipment required: 1000 tons, 7 convoys
- Personnel required: 8 drillers, 20 scientists

European Project for Ice Coring in Antarctica
Support by 10 national programs (Belgium, Denmark, France, Germany, Italy, The Netherlands, UK, Norway, Sweden, Switzerland), the European Commission (5th and 6th PCRD) and European Science Foundation
EPICA deep drilling

EDC99

1996/1997 : casing 130m
1997/1998 : 364m
1998/1999 : 781m
1999/2000 : casing
2000/2001 : 1459m
2001/2002 : 2864m
2002/2003 : 3201m
2004/2005 : 3270m

EDC96
Climate records in Dome C deep ice
Temperature history at Dome C
(as a function of time)

Ice ages each 100 000 years

Changes in the intensity of warm periods: why?

Very long warm period ~400 000 years ago
Ice ages: orbital theory

A. Eccentricity: 400 ka and 100 ka

B. Obliquity: 41 kyr

C. Axial precession: 23 kyr
Orbital theory: our past and our future
Our future: a « super-interglacial » period
Evolution of greenhouse gases

Climate and Greenhouse Gases during the last 650 Kyrs

EPICA Dome C
Indermuehle et al (submitted)
EPICA project members (2004)
Spahni et al (submitted)

Vostok
Pépin et al (2001)

1700 ppbv
382 ppmv
Greenland deep ice cores

Camp Century
1966
1391 m
~ 50 000 years

NorthGRIP
2004
3085 m
~125 000 years

Summit (GRIP, GISP2)
1992 and 1993
3029 m
~100 000 years

Dye 3
1981
2037 m
~ 30 000 years
Greenland records:
Summit (GRIP) versus NorthGRIP

NorthGRIP community members, Nature, 2004
Rapid climate changes in Antarctica

![Graph showing Greenland and Antarctic temperature changes with age in ky BP and δ¹⁸O in ‰ /SMOW](image)

- Greenland temperature change
- Antarctic temperature change

Age (thousand of years ago)
« See-saw effect »

Source: Voelker et al 2002
NorthGRIP ice core record

- Intensity of abrupt increases (°C)
- 75°N JJA insolation (W.m²)
- NorthGRIP δ¹⁸O (pmil)
- Sea level (m)

Age (years BP):
- 16
- 12
- 8
- 4
- 0

Sea level (m):
- -120
- -80
- -40
- 0

NorthGRIP δ¹⁸O (pmil):
- -44
- -40
- -36
- -32
NorthGRIP ice core: a detailed view of the last glacial inception

Landais et al. Climate Dynamics 2006
Constraints on the Greenland ice sheet reaction to climate change

Modelling the response of the ice sheet to warming hypotheses

NorthGRIP: last interglacial period, about 5°C warmer than now at both poles
Greenland responsible for 2 to 3 meters of sea level rise
Antarctica responsible for the rest of the observed 4 to 7 meters

Cuffey and Marshall, 2000; Steffen and Huffs, 2005
Simulated climate change
Take home messages

- Antarctic ice cores cover the past 800,000 years.

- Greenland longest climate record covers about 123,000 years (not the full last warm period).

- Temperature reconstructions are used to test climate models for their capability to simulate large past climate changes.

- Global relevance of temperature changes in polar regions.

- Glacial-interglacial temperature changes comparable to those expected in the case of 4xCO$_2$. 
III- Perspectives
International Polar Year and beyond
Past polar climate changes: key uncertainties

- Current and past evolution of ice sheet mass balance
- Climate history in Greenland and West Antarctica during the past interglacial (warm) period
- Evolution of Antarctic climate at time scales of decades
- Regional changes in Greenland and Antarctica
- Antarctic climate change prior to 800,000 years
Perspectives

- 2007-2009: International Polar Year
  Coordinated traverses: surface and bedrock characteristics, recent climate change

- IPICS: International Partnership for Ice Core Science
  http://www.nicl-smo.unh.edu/IPICS/
  sponsored by NSF/OPP and European Polar Board.
IPICS

- **The oldest ice core**: A 1.5 million year record of climate and greenhouse gases from Antarctica.

- **The last interglacial and beyond**: A northwest Greenland deep ice core drilling project.

- **The IPICS 40,000 year network**: a bipolar record of climate forcing and response.

- **The IPICS 2kyr array**: a network of ice core climate and climate forcing records for the last two millennia.
Ongoing and future projects

- Existing ice cores
- In preparation
- Future projects
- Lack of information
Why look for climate change prior to 1 million years?

Past climates are essential to test and improve the understanding of climate change mechanisms including feedbacks between the global carbon cycle and climate.

Need understanding of the shift from small ice ages with periodicities of 40,000 years to large ice ages with periodicities of 100,000 years: natural carbon cycle?