Pleistocene records from polar ice cores:
the atmospheric perspective

Valter Maggi

Environmental Sciences Dept. - University of Milano Bicocca
INFN - Milano Bicocca
The reconstruction of the pattern and tempo of Quaternary climatic changes is essential to understand the present-day climate and foresee its future developments.

The Earth’s paleoclimatic history is preserved in natural materials accumulating progressively over time and responding to environmental and climatic conditions.
“solid” water on the Earth: The Cryosphere

- Ice clouds
- Sea ice (~10% oceanic sur.)
- Glaciers (~10% continental sur.)
- Snow mantle (max 33% continental sur.)
- Permafrost (~24% continental sur.)
- Lake ice and river ice.
Polar glaciers
(\sim 99.8 \% \text{ vol.})

Mountain glaciers
(\sim 0.2 \% \text{ vol.})
Ice cores from the low-accumulation sites of East Antarctica offer a unique archive for long-term climatic and atmospheric history.

Longest ice core climatic sequences available today:

- **Dome Fuji** ice core (Watanabe et al., 2003) 330,000 years
- **Vostok** ice core (Petit et al., 1999) 420,000 years

The recent extension of the **EPICA-Dome C** ice core to 3200 m depth (February 2003) allowed to obtain the longest climatic sequence from polar ice cores (ca. 800,000 years B.P.)
Several proxies can be investigated in ice cores:

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable isotopes of water</td>
<td>$\delta^{18}O$, $\delta D$, d excess</td>
</tr>
<tr>
<td>Soluble components</td>
<td>marine (Cl, Na, K, Mg, SO$_4$,...), terrestrial (NO$_3$, Ca, K, organic acids), biological from oceans (SO$_4$, MSA, ...) volcanic (H$_2$SO$_4$, HCl, HF, ...)]</td>
</tr>
<tr>
<td>Gas in air bubbles</td>
<td>CO$_2$, CH$_4$, N$_2$O, ...</td>
</tr>
<tr>
<td>Ice crystals</td>
<td></td>
</tr>
<tr>
<td>Heavy Metals</td>
<td>Pb, Cd, Ni, Zn, Rh, Pa, ...</td>
</tr>
<tr>
<td>Insoluble microparticles</td>
<td>minor amounts of volcanic material, soot, micrometeorites, mainly <strong>dust</strong></td>
</tr>
</tbody>
</table>

**Dust = Windblown mineral aerosol of continental origin**
Two ice cores in the East Antarctic Plateau:
- Dome C (Pacific sector), for reconstruct the last 500 ky of climatic history
- Dronning Maud Land (Atlantic Sector), for the climatic comparison with the Greenland ice cores (northern Hemisphere)
Ice cores in Antarctica and Greenland

- Talos Dome: 1387 m
- Dye 3: 3037 m
- Camp Century: 1387 m
- GISP2 GRIP: 3085 m
- NGRIP: 3029 m
- Byrd: 2163 m
- Vostok: 3623 m
- Dome F: 3026 m
- DML: 2774 m
- Dome C: 3270 m
- Taylor Dome: 3029 m
- Talos Dome: 3037 m
Sketch of polar glacier with the different geometry and ice flow.
EPICA at Dome C, close to the Concordia Station

Drilling tent

Laboratory

Main Lab.
How the air should be trapped in the ice

Legrand, Jouzel and Raynaud (1995)
How the air should be trapped in the ice

Legrand, Jouzel and Raynaud (1995)
Drilling operations at EPICA–DC
ice core after drilling operations
Main lab for ice core processing
Electrical conductivity measurements
Crystal structure of ice. Polarized thin section
A preliminar dating allows to estimate an age of **730-750 kyr B.P.** at ca. 3138 m depth 
*(7 Climatic Cycles)*

---

**New EPICA Dust Record**

**Global ice volume** *(Bassinot et al., 1994)*

**Chinese Loess deposit** *(Bassinot et al., 1994)*
The last 8 cycles: $\delta D$ and dust EPICA DC in comparison with marine $\delta^{18}O$ and insolation records. Change in amplitude at $\sim 430$ kys “Mid Bruhnes Event”
Histogram of $\delta$D, before (green) and after (cyan) the MBE

EPICA community members, 2004
Change in flux of some chemical compounds in the last 750 kys over the Antarctica

Na
SO$_4$
Fe
Ca

Wolff et al. 2006
$\text{CO}_2$ record of the last 650 ka

black EPICA DC
blue Vostok
green Taylor Dome

Siegenthaler et al., 2005
EPICA DC: CH$_4$ and N$_2$O records for the last 650 kys

The methane over the Antarctica, in the pre-industrial era, never grew above 773 ppbv. Before 430 kys, with mild interglacials, the CH$_4$ concentration reached a maximum of 600 ppbv. (minimum Holocene value).

Spahni et al., 2005
Methane 2006
1780 ppb + 130% in 200 years

CO₂
2006
380 ppm + 35 % in 200 years

EPICA DC GHG’s and T° in the last 650 kys.

(Brook, 2006)
Dome B (DB) (77° 05' S, 94° 55'E; 3650 m a.s.l.)
The site is located 320 km upflow from Vostok, 870 km far from Dome C. Core drilled during the 1987/88 season (33rd Soviet Antarctic Expedition)
**Dome B (DB) (77° 05' S, 94° 55'E; 3650 m a.s.l.)**
The site is located 320 km upflow from Vostok, 870 km far from Dome C. Core drilled during the 1987/88 season (33rd Soviet Antarctic Expedition)
**EPICA-Dome C ice core (EDC)** (75°06’ S, 123°21’ E; 3233 m a.s.l.)
Drilled in the framework of the *European Project for Ice Coring in Antarctica* (joining 10 European Nations)
The ice core reached the depth of 3,200 m during the field season 2002/03, and preserves the longest climatic memory from polar ice cores (about 750,000 years).

**Dome B (DB) (77° 05’ S, 94° 55’E; 3650 m a.s.l.)**
The site is located 320 km upflow from Vostok, 870 km far from Dome C. Core drilled during the 1987/88 season (33rd Soviet Antarctic Expedition)
**EPICA-Dome C ice core (EDC)** (75°06' S, 123°21' E; 3233 m a.s.l.)
Drilled in the framework of the **European Project for Ice Coring in Antarctica**
(joining 10 European Nations)
The ice core reached the depth of 3,200 m during the field season 2002/03, and preserves the longest climatic memory from polar ice cores (about 750,000 years).

**Dome B (DB) (77° 05' S, 94° 55'E; 3650 m a.s.l.)**
The site is located 320 km upflow from Vostok, 870 km far from Dome C. Core drilled during the 1987/88 season (33rd Soviet Antarctic Expedition).
**EPICA-Dome C** (EDC) (75°06’ S, 123°21’ E; 3233 m a.s.l.)
Drilled in the framework of the *European Project for Ice Coring in Antarctica* (joining 10 European Nations)
The ice core reached the depth of **3,200 m** during the field season 2002/03, and preserves the longest climatic memory from polar ice cores (about **750,000 years**).

**Dome B** (DB) (77° 05’ S, 94° 55’ E; 3650 m a.s.l.)
The site is located 320 km upflow from Vostok, 870 km far from Dome C. Core drilled during the 1987/88 season (33rd Soviet Antarctic Expedition)

**Komsomolskaia** (KMS) (74° 05’ S, 97° 29’ E; 3500 m a.s.l.)
Core extracted in 1983 (28th Soviet Antarctic Expedition)
EPICA-Dome C ice core (EDC) (75°06’ S, 123°21’ E; 3233 m a.s.l.)
Drilled in the framework of the European Project for Ice Coring in Antarctica (joining 10 European Nations)
The ice core reached the depth of 3,200 m during the field season 2002/03, and preserves the longest climatic memory from polar ice cores (about 750,000 years).

Dome B (DB) (77° 05’ S, 94° 55’E; 3650 m a.s.l.)
The site is located 320 km upflow from Vostok, 870 km far from Dome C. Core drilled during the 1987/88 season (33rd Soviet Antarctic Expedition)

Komsomolskaia (KMS) (74° 05’ S, 97° 29’ E; 3500 m a.s.l.)
Core extracted in 1983 (28th Soviet Antarctic Expedition)
EPICA-Dome C ice core (EDC) (75°06’ S, 123°21’ E; 3233 m a.s.l.)
Drilled in the framework of the European Project for Ice Coring in Antarctica (joining 10 European Nations)
The ice core reached the depth of 3,200 m during the field season 2002/03, and preserves the longest climatic memory from polar ice cores (about 750,000 years).

Dome B (DB) (77° 05’ S, 94° 55’ E; 3650 m a.s.l.)
The site is located 320 km upflow from Vostok, 870 km far from Dome C. Core drilled during the 1987/88 season (33rd Soviet Antarctic Expedition)

Komsomolskaia (KMS) (74° 05’ S, 97° 29’ E; 3500 m a.s.l.)
Core extracted in 1983 (28th Soviet Antarctic Expedition)

VOSTOK ice core (VK) (78° 05’ S, 106° 48’ E; 3480 m a.s.l.)
Russia-France-US collaboration
The first 3310 m of the Vostok ice core preserve the climatic memory of the last 420,000 years.
Dust deflated from arid regions of the Southern Hemisphere, injected into the mid-high Troposphere and transported long-distance can reach the interior of the East Antarctic Plateau.

During long-range transport, the dust is graded and a mineralogical selection occurs. The dust plume is progressively enriched in quartz, clays and feldspars.

Minerals entrapped in Vostok ice core (after Gaudichet et al., 1992):

- 40% clays (mainly Illite),
- 15% crystalline silica,
- 15% feldspars
- minor amounts of pyroxenes, amphiboles, metallic oxydes, volcanis glasses.
The regions providing the bigger dust fluxes at present time are primarily associated to little or no ground cover, erodible surfaces and seasonal wetness. (Mahowald et al., 1999)

Global distribution of dust sources identified through TOMS (Total Ozone Mapping Spectrometer) sensor on NIMBUS-7 satellite (Prospero et al., 2002).

Major dust « hot spots » in the Southern Hemisphere for present time (Prospero et al., 2002).
The dust cycle is tightly linked to the climate system:

- Continental Aridity
- Hydrological cycle
- Atmospheric circulation (transport)
- Radiative effect
- Atmospheric reactions
- Fertilization of the oceans and CO$_2$ uptake

The investigation of past changes in atmospheric dust load and transport patterns are an essential tool for paleo-climate and paleo-environmental reconstructions.
In this study, more than 50 samples have been collected from **South America, South Africa, New Zealand, and the exposed areas of Antarctica.**

- **Southern South America (>30°S):** 24 samples
- **Antarctica (Dry Valleys):** 9 samples
- **New Zealand:** 15 samples
- **Northern Victoria Land:** 1 sample
- **Northwest Victoria Land:** 1 sample

No samples from Australia have been analysed in this study.

A Franco-Australian project is in course (Dr. M. Revel-Rolland).

The Antarctic **Dry Valleys** and **New Zealand** have been documented for the first time.

No samples from the **Antarctic Peninsula** have been collected; geologically similar to southern South America.
Dust Variability investigated by **Coulter Counter technique** (physical approach)

**DUST CONCENTRATION** in ice

- Number of particles per ml of ice
- Dust mass ($\text{ng}_{\text{dust}} / g_{\text{ice}}$) estimated assuming average density of 2.5 g/cm$^3$

**DUST SIZE DISTRIBUTION** (particles with diameter 0.7-20 µm)

- 256 Channels of measurement

Particle diameter is equivalent to diameter of a spherical particle
Dust Variability investigated by **Coulter Counter technique**
(physical approach)

**DUST CONCENTRATION** in ice

- Number of particles per ml of ice
- Dust mass \( \text{ppb or } \text{ng}_{\text{dust}} / \text{g}_{\text{ice}} \)

estimated assuming average density of 2.5 g/cm\(^3\)

**DUST SIZE DISTRIBUTION**
(particles with diameter 0.7-20 \(\mu\)m)

- 256 Channels of measurement

Particle diameter is equivalent to diameter of a spherical particle

**WHAT INFORMATION?**
Long-range transport = \textit{Size selection} \sim 2 \ \mu m \ \varnothing

\begin{align*}
[Dust]_{\text{ice}} & = f(\text{source strength}) \\
& \quad + f(\text{dry/wet deposition efficiencies}) \\
& \quad + f(t) \\
& \quad + f(\text{accumulation rate in ice})
\end{align*}

Dust size distribution in ice = f(t)
The first (low-resolution) dust record from EPICA-Dome C ice core

**LGM/Holocene dust concentration ratio of ca. 53 (i.e. 26 in flux)**

750 +/- 300 ppb (LGM) 14 +/- 8 ppb (Holocene)

*Previous results:*
- **Vostok** ca. 24 from Petit et al., 1990
- **Dome B** ca. 35 from Jouzel et al., 1995
- **Old Dome C** ca. 28 from Royer et al., 1983

Post-glacial dust fall starts at **18 kyrs B.P.**

**14.6 kyrs B.P. :** Holocene dust levels are reached

*Delmonte et al., 2002a*
New features arising from the first EDC record:

A shallow re-increase of dust during the *Antarctic Cold Reversal* (ACR) phase, not observed in previous studies.

Return to colder conditions in the Southern Hemisphere?

A **pre-Holocene dust minimum** spanning 800-1000 years.

Humid period at the dust source region(s)?

---

**A shallow re-increase of dust**

During the **Antarctic Cold Reversal** (ACR) phase, not observed in previous studies.

Return to colder conditions in the **Southern Hemisphere**?

**A pre-Holocene dust minimum** spanning 800-1000 years.

Humid period at the dust source region(s)?
Slightly smaller particles during the LGM with respect to the Holocene

Modal value of lognormal function fitting the particle volume (mass)-size distribution

First (low-resolution) dust record from EPICA-Dome C (Delmonte et al., 2002a)
High resolution EPICA-Dome C dust record: the last transition and the Holocene

Documentation of the PRE-HOLOCENE DUST MINIMUM (spanning 800-1000 years) that seems synchronous with the CH$_4$ increase after the Younger Dryas

Evidence for MILLENNIAL and SECULAR-SCALE oscillations of dust size from 2 to 13 kyrs B.P.
The **short-term fluctuations** observed during the **deglaciation** remind the variability of dust size characterizing the EDC record during the last 13 kyrs B.P. *(Holocene and late Deglaciation)*

**Holocene dust size variations**

- Dust concentrations are very low
- Size changes very small but significant *(around 0.5 µm)*
The particle size evolution in Komsomolskaia ice core is very similar to Dome C during the deglaciation (while Vostok is more similar to Dome B according to Briat et al., 1982).

Millennial to centennial-scale oscillations are superposed to the main trend of the dust size changes. In correspondence to the Pre-Holocene dust minimum, these short-term oscillations are clearly in antiphase!

REGIONAL VARIABILITY OF DUST TRANSPORT

Delmonte et al., submitted to Clim Dyn
Δ DUST SIZE between Dome C and Dome B during LGM (sharing the same source)

LENGTH OF DUST PATHWAY
[longer pathways enhancing dust grading (finer dust)]

Controlled by the PRESSURE FIELDS over the Antarctic and the Circumantarctic

Horizontal dimension

Zonal and Meridional circulation in the Southern Hemisphere

Vertical dimension

Altitude of transport
**Horizontal Dimension**

**Zonal circulation** (*West to East*) represents the *dominant component* of the atmospheric circulation at the high latitude of the Southern Hemisphere.

The zonal circulation, is embedded at any time with *perturbations* taking the form of *waves*, allowing the *meridional* exchanges of different air masses.

*Wavenumbers 1 to 3 define more-or-less stationary waves associated to longitudinally-positioned structures (highs and lows) distorting the zonal circulation.*

*Wavenumbers 1 to 3 together account for a large percentage of the total variance of the 500 hPa pattern (Tyson, 1986).*