The CLOUD Experiment at CERN

Jasper Kirkby, CERN
(representing the CLOUD Collaboration)

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• Scientific motivation; solar/cosmic ray - climate variability
• Physical mechanisms
• CLOUD design and status
I. SCIENTIFIC MOTIVATION
Millennial- and centennial-scale climate change

- Extensive evidence for “sub-orbital” climate change, eg:
  - Persistent ~1470y cycle during last glacial and present interglacial
  - Persistent rapid sea-level changes by 10-20m in previous glacials/interglacials (cf. 0.2-0.6m projected for 21st century)

- Important impact on our future
- ...but no established forcing mechanism
GCR-climate - 2000yr

- Little Ice Age and Medieval Warm Period
- Global observations

<table>
<thead>
<tr>
<th>high GCR flux</th>
<th>cool climate</th>
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<tbody>
<tr>
<td>low GCR flux</td>
<td>warm climate</td>
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Austrian speleothem:

- GCR change (% from 1950 value)
- CO2 (ppm)
- $\delta^{18}$O (‰)
- $1^\circ$C

Mangini et al., EPSL 235 (2005)
- LIA is merely most recent of ~10 such solar/GCR-climate events in last 10 kyr
- Millennial-scale north Atlantic sea surface temperature fluctuations ~2C
- ~1500 y periodicity of ice rafted debris, extending across glacial-Holocene boundary
- Bond cycles confirmed in Alaska, equatorial Africa, south China...
GCR influence on ITCZ in Little Ice Age?

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<td>southerly ITCZ shift</td>
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<td>northerly ITCZ shift</td>
<td>low GCR flux</td>
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- Drier in LIA
- Wetter in LIA

ITCZ displacement during LIA

July ITCZ
- D5
- D7
- D8
- D6
- W0

January ITCZ
- W2
- W4
- W3
- W1
GCRs and Indian Ocean monsoon

- Solar/GCR forcing of Indian Ocean monsoons (ITCZ migration) on 10-100-1000 y timescales
- Confirmation of ITCZ pattern seen in LIA: high GCR => southerly ITCZ shift
2. PHYSICAL MECHANISMS
• **Two aspects to address:**
  - Mechanism for solar magnetic variability?
  - Mechanism for cosmic rays to affect clouds and climate?
Solar orbits around barycentre of solar system

- Barycentre (CoM) of solar system varies with relative positions of outer planets (esp. Jupiter & Saturn)
- Orbit of sun around barycentre repeats ordered trefoil each 179 yr
- Trefoil (~50yr) periods coincide with increasing solar magnetic activity (low GCR/warming climate)
- Disordered periods coincide with solar minima (high GCR/cooling climate)
- Solar (differential) rotation known to be fundamental to solar magnetic activity
- Mechanism to link solar rotation and solar orbit?
- Does present long minimum before cycle 24 indicate a phase shift to long minima of Maunder / Dalton /1878-1913 periods?

**Carbon-14 anomaly (x 10^-3)**

** Galactic cosmic rays**

- increasing GCR
- GCR change (% from 1950 value)

**Year (AD)**

- Wolf
- Spörer
- Maunder
- Dalton
- future?

**Solar maxima**

- symmetrical ‘trefoil’ solar orbits

**Solar minima**

- Jose (1965)
- Landscheidt (1984)
- Fairbridge & Shirley (1987)
- Charvatova (1990)
Why clouds are important for climate change

- Clouds cover ~65% of globe, annual average
- Net cooling of 30 W/m²
- c.f. 1.6 W/m² total anthropogenic
Cloud properties are sensitive to concentration of droplets (which form on cloud condensation nuclei - CCN)

More aerosols/CCN => brighter clouds, with longer lifetimes
• Cloud formation over large areas of ocean is limited by low CCN number
• Additional aerosol (from ships) leads to persistent and brighter clouds, with smaller droplets
Formation of new aerosols in atmosphere

- Trace condensable vapours are major source of aerosols in atmosphere
- Poorly understood but H$_2$SO$_4$ and organic vapours are important
- Ions from cosmic rays may stabilise embryonic clusters and accelerate critical early growth period - “ion induced nucleation”
• Cosmic rays ionise atmosphere and control Earth-ionosphere conductivity
• Large aerosol charges at cloud boundaries => unipolar space charge region
• Can be entrained inside clouds and may affect:
  ▸ Rate of aerosol accretion by cloud droplets
  ▸ Ice particle formation
  ▸ Atmospheric dynamics
• Largest ion currents in polar regions (GCRs, geomagnetic disturbances...)

Global electrical circuit
3. CLOUD DESIGN AND STATUS
Way forward

- At present, solar-climate variability is largely ignored or considered insignificant because no physical mechanism is established
  - Key challenge is to establish (or rule out) a mechanism
- Question cannot be answered by continued passionate debate
  - Requires experimental observations & measurements
Solar-climate mechanisms

• Three candidates:
  ▶ Solar irradiance variability
  ▶ Solar UV variability ($\sim 10^{-3}$ of solar irradiance)
  ▶ Galactic cosmic rays (via solar wind modulation)

• Each is considered unlikely - but at least one is responsible!
• All three deserve further study
• Ambiguity between solar irradiance/UV or GCR effect can be resolved by climatic influence of Forbush, geomagnetic or space weather disturbances

Global mean temperature ($^\circ$C)

-0.10 -0.05 0 0.05 0.10 0.15

Year

1600 1650 1700 1750 1800 1850 1900 1950 2000

Lean et al. (1995)

Lean et al. (2002)

solar irradiance estimated forcing (MAGICC GCM)
estimated effect of solar irradiance changes since LIA

estimated effect

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• Quantitative study of cosmic ray - aerosol - cloud microphysical interactions in the laboratory:
  ‣ Aerosol chamber (+ analysing instruments)
  ‣ CERN particle beam → adjustable source of “cosmic rays”

• Simple concept but technically challenging:
  ‣ Wall losses → bigger is better
  ‣ Cleanliness → sub-ppt impurities
  ‣ Temperature stability <0.1°C
CLOUD facility at CERN
Mk2 3m aerosol chamber

- Stainless steel chamber, 3m diameter, 3.5m height
- Ports for sampling probes, optical readout & instrumentation
- Thermal housing and precision temperature control
- Operation range: 1.0 → 1.1 bar absolute
  -90°C → 100°C
- CERN UHV procedures for inner surfaces
- Air supply from cryogenic liquids
Mk2 field cage and UV system

- Field cage: $E < 25$ kV/m
- Clearing field or unipolar field
- Optical-fibre UV system, eg. $O_3 \rightarrow O \rightarrow OH$
CLOUD experimental goals

• Influence of cosmic rays on:
  ‣ Aerosol nucleation and growth:
    ✦ Ion induced nucleation of aerosols from trace gases
    ✦ Aerosol growth to cloud condensation nuclei (CCN)
    ✦ Activation of CCN into cloud droplets
  ‣ Cloud microphysics (global electrical circuit):
    ✦ Ice particle formation
    ✦ Collision efficiencies of aerosols and droplets
    ✦ Freezing mechanism of polar stratospheric clouds

• Evaluation of climatic significance of laboratory measurements by cloud modeling → field studies and GCMs
Conclusions

• Palaeoclimatic studies show that Earth’s climate varies substantially on 100-1000 year time scales
• Causes are not understood but solar/cosmic ray variability may be an important driver
• Detailed physical mechanism is not established - and is not included in any present global climate model
• Suggestive association of solar orbital motion and solar magnetic variability - deserves further study
• CLOUD experiment at CERN aims to provide a quantitative understanding of possible galactic cosmic ray-induced changes in aerosol and cloud formation
• The question of whether - and to what extent - the climate is influenced by solar/cosmic ray variability remains central to our understanding of anthropogenic climate change