Past and Future Climates
Astronomical, Solar, and Anthropogenic Forcing Strategies for Future Space and Modeling Research

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• Climates of the past
• Solar variability and climate
• Future Climate(s)
• Future strategies
• Conclusion(s)
The Earth Climate

The Earth climate is one of the most difficult phenomenon to understand (and of course model and forecast (if ever possible) because it is determined by the influence of a variable Sun on an unstable planet involving a large number of interacting phenomena. It is a chaotic concept!

This is illustrated by the increasingly overabundant literature on global warming and its causes, not all self-consistent, even though peer reviewed and apparently intelligent!

Climate science is typically an interdisciplinary field that includes nearly all fields of modern science from astronomy to life science and sociology through chemistry, aerodynamics, fluid physics, magnetism, solid state physics, thermodynamics and geophysics.
The Earth-Sun System

![Diagram showing the Earth-Sun System with planets and habitable zone]

- Mass of star relative to Sun
- Radius of orbit relative to Earth's
- Habitable Zone
- Venus
- Earth
- Mars
A variable water planet

Generalized model of thermohaline circulation: "Global Conveyor Belt"

- High salinity water cools & sinks in the North Atlantic
- Deep water returns to surface in Indian & Pacific Oceans through the process of upwelling

Warm shallow current
Cold & deep high salinity current
The Earth atmosphere

- **Magnetosphere**
- **Thermosphere**
- **Ionosphere**
  - Mesopause
  - Mesosphere
  - Stratosphere
- **Stratosphere**
  - Tropopause
  - Troposphere

**Radiation**
- X-rays
- Extreme UV
- Ultraviolet
- Visible Light
- Infrared
- Galactic Cosmic Rays
- Auroral Particles
- Solar Protons

**Temperature (°K)**
- 200
- 300
- 500
- 1000
- 2000
- 3000
Ocean/atmosphere interactions
PDO/ENSO
Among these we find:

- Solar radiation forcing
- Volcanism and the outgassing of Earth interior modifying the atmosphere
- Astronomical parameters: obliquity of the Earth with respect to the ecliptic plane
- Plate tectonics
- The albedo of the solid Earth, the oceans ice sheets and the atmosphere (clouds and aerosols),
- The greenhouse effect
- Oceanic and atmospheric circulation
Long-term solar forcing

A 0.7% increase per each 100 million years

Freezing point of water

(300 ppm CO₂)

A 0.7% increase per each 100 million years
Astronomical and Orbital Forcing
Milutin Milankovitch
1879-1958

[Diagram showing various astronomical forcings over time, including:
- Precession
- Obliquity
- Eccentricity
- Solar Forcing
- Stages of Glaciation]
Plate tectonics

$\text{CO}_2 + \text{CaSiO}_3 \rightarrow \text{CaCO}_3 + \text{SiO}_2$

- Plate tectonics map showing the distribution of continents.
- Cratons and 1.1 Ga belts highlighted.
- CO2 + CaSiO3 → CaCO3 + SiO2 chemical reaction.
Crucial role of CO₂, CH₄, O₂ in paleoclimate change

CH₄ (mostly of biogenic origin) is destroyed by O₂ (mostly of biogenic origin)

\[ CH₄ + 2O₂ \rightarrow CO₂ + 2H₂O \]

CO₂ sink is due to methanogenic archaea and to the weathering (water rain and formation of silicates)

Weathering resulting from Rodinia breakup
Forcing factors since 1 My
Zooming on the Holocene Climate
Solar variability and climate

Reconstructed temperature over last millennium

The Earth is getting warmer

Global Land–Ocean Temperature Index

- **Annual Mean**
- **5–year Running Mean**

Temperature Anomaly (°C)

1880 1900 1920 1940 1960 1980 2000
Glacier length records
Global mean surface temperature and its main regression components as of 1880 (Solanki et al)

- a: Global surface temperature
- b: ENSO
- c: Volcanic aerosols
- d: Solar irradiance
- e: Anthropogenic forcing
Cosmic rays and formation of clouds/aerosols

The “CLOUD” experiment at CERN
Future climate
Near-term future
Anthropogenic Forcing (W/m²)

<table>
<thead>
<tr>
<th>Emitted Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂ H₂Oₘₙ O₃ CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Nitrogen gases</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂ CH₄ O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂ CH₄ O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate CH₄ O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Cloud Adjustments due to Aerosols</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td>Short-lived gases and aerosols</td>
<td>Albedo Change due to Land Use</td>
<td>-0.15 [-0.25 to -0.05]</td>
<td>M</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in Solar Irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

Total Anthropogenic RF relative to 1750

- 2011: 2.29 [1.13 to 3.33] - H
- 1980: 1.25 [0.64 to 1.86] - H
- 1950: 0.57 [0.29 to 0.85] - M
Atmospheric CO₂

For 650,000 years, atmospheric CO₂ has never been above this line ... until now.
Anthropogenic Forcing

Atmospheric CO₂ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

PARTS PER MILLION


YEAR

December 2013
History of growth in world population and environmental impact of *Homo sapiens*, indicated by its surrogates, per capita and total human energy use.

Cosmic evolution and Biogenic forcing

\( \Phi_m (\text{erg s}^{-1}\text{g}^{-1}) \)

- society
- brains
- animals
- plants
- planets
- stars
- galaxies

- society
  - industrialized
  - agriculture
  - hunting and gathering
- plants
  - sugarcane
  - pina
  - corn
- stars
  - Sun
  - red giant
  - red dwarf
- epigenomic

\[ t(y) \]

\[ 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \]
IPCC

future Earth surface temperatures

AR4 2007

AR5 2013

421 ppm

936 ppm
Uncertainties

Total solar irradiance database

Monthly sunspot number

Ts (W m^{-2})

Sun
Uncertainties

![Graph a](image)

![Graph b](image)
Anomalies

Has global warming stopped?

GLOBAL TEMPERATURE

Anomaly with respect to 1961–90 (°C)


Global average
Adjusted global
Trend 1999–

Energy (10²¹ joules)

1980 1990 2000 2010

Upper ocean
Deep ocean
Above 700m
Below 700m
Ice
Land
Atmosphere
Future strategies

- Many more observations,
- Much more improved modeling,
- Ensured continuity in data gathering over time scales which are meaningful to climate science, i.e. decades.
Modeling the climate
Principle of error reduction in data assimilation

• Prediction is not just very difficult,
• Exact predictions are impossible.
• Individual weather systems 3 - 12 days
• General weather situation 7 - 30 days
• Climate anomalies (El Nino) 3-12 months
Evolution of weather forecast skill

Anomaly correlation (%) of ECMWF 500hPa height fields
Importance of satellites for weather forecasting

Satellite data used by ECMWF

- MeghaTropiques
- Sentinel 3
- GOSAT
- ADM Aeolus
- SMOS
- TERRA/AQUA AMV
- GMS/MTSAT Rad
- GOES Rad
- METEOSAT Rad
- FY-2C/D AMV
- GOES AMV
- HY-2A
- METEOSAT AMV
- Oceansat
- QuikSCAT
- FY-3A/B
- AURA
- AQUA
- TRMM
- GCOM-W/C
- CHAMP/GRACE
- TERRASAR-X/SAC-C
- COSMIC
- ENVISAT
- ERS-1/2
- METOP
- DMSP
- NOAA
Conclusions

Global Land–Ocean Temperature Index

- Annual Mean
- 5–year Running Mean

Atmospheric CO₂ at Mauna Loa Observatory

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Energy per capita (kW)
Total energy consumption (TW)

Energie dissipée (en watts/kg)

Age de l’univers (en années)
Conclusion

Reducing the present uncertainties affecting our evaluation of climate evolution can only come through much expanded, internationally coordinated observational assets, both at the small-scale process level, and at large-scale circulation changes. It involves:

• The design and deployment of new instruments on the ground, at sea and in space;
• The maintenance of crucial in-situ and satellite observing systems.
• These should be accompanied by rigorous approaches to synthesize the heterogeneous data streams into a coherent dynamic framework.
Conclusion

Sustaining such observations over sufficiently long periods to provide records of useful quality for climate research is a serious inter-generational challenge.
But who is in charge?
Thank you!