5. Radiative forcings and feedbacks

Definitions
Radiative forcing is an energy imbalance imposed on the climate system either naturally or by human activities.

Radiation and climate change
"Unperturbed base state" or "Reference" 1750 (Pre-industrial):
Atmospheric CO\(_2\): 280 ppm

"Perturbed state" 2016 (Present state):
Atmospheric CO\(_2\): 404.83 ppm

* March 2016 https://www.co2.earth/

Typically determined as difference between a radiatively perturbed state and an unperturbed base state (e.g. present state – preindustrial)

Radiative forcings and feedbacks
Provides a measure of the influence that a climatic factor (e.g. albedo, solar emission, greenhouse gases) has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system.
**Definitions**

Positive **forcing** tends to warm the surface while negative forcing tends to cool it. Forcing values are expressed in Wm-2.

- **Radiative forcing**, RF, net change (down – up), at the tropopause: \[ \Delta T_s = \lambda \times RF \]
- RF > 0 Wm\(^{-2}\) → Positive forcing (tends to warm the surface)
- RF = 0 Wm\(^{-2}\) → Radiative balance
- RF < 0 Wm\(^{-2}\) → Negative forcing (tends to cool the surface)

**Radiative forcings and feedbacks**

- Radiative forcings are internal climate processes that amplify or dampen the climate response to a specific forcing.
- Process amplified? Positive feedback, as here.
- Process dampened? Negative feedback.

**Radiative forcing of climate: 1750 - 2011**

<table>
<thead>
<tr>
<th>Forcing agent</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Mixed Greenhouse Gases</td>
<td>Very high</td>
</tr>
<tr>
<td>Other WMO/GO</td>
<td>High</td>
</tr>
<tr>
<td>Ozone</td>
<td>High</td>
</tr>
<tr>
<td>Stratospheric water vapour from CH(_4)</td>
<td>High</td>
</tr>
<tr>
<td>Surface Albedo</td>
<td>High</td>
</tr>
<tr>
<td>Black Carbon on snow</td>
<td>High</td>
</tr>
<tr>
<td>Clouds</td>
<td>Medium</td>
</tr>
<tr>
<td>Total anthropogenic</td>
<td>High</td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>Medium</td>
</tr>
</tbody>
</table>

**Components of climate change process**

- Non-Radiative influences (e.g., land use change, volcanic eruptions, aerosols, aerosol-cloud interactions, solar variability, stratospheric ozone)
- Radiative forcing
- Non-Radiative influences
- Climate forcing

- E.g., human activities, deforestation, land use change, and fossil fuel combustion.
Feedback example (+): water vapour

For a doubling of CO₂

ΔT > 0

Latent heat release

Humidity Δq > 0

IR emission ΔIR > 0

Evaporation and sensible heat flux > 0

ΔTₕ = 0

CO₂ direct tropospheric heating ~ 3 Wm⁻²

ΔR (CO₂) ~ 1.2 Wm⁻²

→ Dominant mechanism for greenhouse feedback to warm surface

1 = Tropospheric temperature

Δₜ = Mixed layer temperature

Δₚ = Downward IR emission

q = Specific humidity

ΔR = Radiative flux (IR + Solar): CO₂ only

Radiative forcings and feedbacks

Adapted from Ramanathan

Feedback example (+): Ice/snow albedo

1. Initial state

2. +ΔT perturbation

3. Ice/snow cover decreases

4. Less sunlight reflect: more sunlight absorbed

Radiative forcings and feedbacks

Radiation & Climate Change over Earth’s history

4.5 Gyr

10⁷ Years: Climate change on Geological Timescales

10⁵ Years: Ice age cycles

10⁴ Years: Holocene climate change

1 Kyrs

10⁴ Years: Milennial climate change

250 yrs

10³ Years: Multidecadal climate change

Present

Extrinsic

Intrinsic

Solar irradiance changes

e.g. Orbital eccentricity

100,000 year period

Extrinsic

Intrinsic

Astrophysics – Astronomy – Geology

Chemistry – Palaeobiology

Radiative forcings and feedbacks
Solar changes: timescales

- 5-minute oscillations
- Solar minimum to maximum (11-year cycle)
- 5-minutes
- 27-days
- 11-years
- Centuries
- 10-Million-years+

Radiative forcing...

since the beginning
(5 Gyr ago)

The Sun in a Stellar Context

- Hertzsprung Russell Diagram (HRD)
  - Used to understand and explain stellar evolution; location governed by mass
  - Main sequence: where stars spend most of their lifetimes and are generally stable (the Sun sits on this today)
  - Red giant branch: late stage, high mass stars
  - Red giant branch: late stage, low mass stars

The Sun in a Stellar Context

- Luminosity, L/L_
- Surface Temp., K
- 10^-4
- 10^-2
- 10^-1
- 1
- 10
- 10^1
- 10^2
- 10^3
- 10^4
- 30000
- 6000
- 3000
Earth forms ~4.5 Gyrs ago

Today 4.6 Gyrs ago

Radiative forcings and feedbacks

Sun & Earth formed 4.6 billion years ago

Stellar nebula collapses under gravitation

Formation of Sun and Earth

Planets form in disk by accretion (dust to planetesimals)

Angular momentum conservation prevents complete collapse

Rotating disk forms; origins of planets

4 H + He

Nuclear fusion

Solar Luminosity 100% → today 90% 80% 70%

Actual temperature:
- 25°C
- 0°C
- 25°C
- 50°C

Faint Young Sun Paradox

Radiative zone

Convection zone

Core (nuclear fusion)

→ Sun gets brighter with time because...
→ p-p chain more efficient with as more He accumulates
→ Core density increase; Temp. increases → reactions increase

→ Geological evidence suggests T > 0°C

Hydrological cycle; marine biota; sedimentary rocks

Radiative forcings and feedbacks

Early Earth: bombarded by meteors → kept surface molten, delivered water to Earth
4 Gyr ago

- Oceans condense
- CO₂ atmosphere remains
  + N₂, H₂O, CH₄
  For O₂ accumulation, wall 2 Gyr

→ Accretion slows; planet cools
(Add: Radiative forcings and feedbacks)

4 Gyr ago

- CO₂ spewed from volcanoes
- Lack of continents to remove CO₂
- Build up of CO₂ higher than today

→ Vigorous seafloor spreading
(Add: Radiative forcings and feedbacks)

Faint Young Sun Paradox

- CO₂ partial pressure vs. Solar Luminosity
  - Karling et al., 1988
  - Englert & Sofia (1981)

→ Early Earth: warmed by high GHGs
  CO₂ ~ 100~1000 times present atmospheric levels

The Long-term Carbon cycle

- CO₂ volcanic outgassing
- CO₂ hydrolysis...
  ... chemical weathering of silicate materials by positively charged cations (Na⁺, K⁺, Fe³⁺, Mg²⁺, Al³⁺, and Ca²⁺) with silicate structures (SiO₂)
  Rainwater + CO₂
  = H₂CO₃
  +CO₂ mid-ocean ridge outgassing

100,000 year timescale
Continental crust
Lithosphere
Athenosphere
**without life, precipitation of high ions, subduction..."
The Long-term Carbon cycle

- Many factors affect chemical weathering rates; controlled by:
  - Temperature: chemical weathering ↑ by 2x for each 10K
  - Precipitation: more precip. → more groundwater in soil → CaCO₃
  - Vegetation: plants deliver CO₂ from atmosphere to the soil → CaCO₃

- Negative feedback cycle operating over millions of years
- Cycle may have acted as a thermostat to moderate Earth’s climate through geologic time

Faint Young Sun Paradox

- So... hypothesis:
  - Solar luminosity increased...
  - ... and CO₂ decreased
  - ... because...
  - ... temperatures rose
  - and continents grew...
  - ... which led to more weathering and carbon sequestration

- Negative feedback may have prevented permanent freezing early on and excessive GHG later

Continental growth

- Land coverage: 0% to 30%
- Continent building > Continent erosion

Earth today

- But...
  - ... evidence for planet-wide glaciation 2.2 and 0.7 Gys ago
  - ... carbon cycle failure?
  - ... natural thermostat: so how could the entire planet freeze?
750 Myr ago
1. Most land in tropics
2. Hot/moist conditions favour weathering & CO₂ removal
3. Earth cools → glaciation at poles

750 Myr ago
4. Continents ice-free → weathering continues → Earth cools
5. Once ice exceeds 30° → runaway ice-albedo effect
6. Ice may have been 1 km thick on average

>700 Myr ago
High silicate weathering may have been enhanced by...
1. 830 ± 200 Myrs, break up Rodinia supercontinent
   a. Dry interior far from ocean → low weathering
   b. Break up: dry regions become wetter → enhanced weathering leads to decrease in atmospheric CO₂
2. 723 Myrs, massive eruption of basalt lava near equator
   a. Rich source of Ca²⁺ ions
   b. Fast weathering

Together these are sufficient to cause a snowball Earth in models

**750 - 580 Myr ago**

1. Volcanoes continue to erupt
2. No rainfall to wash out CO₂
3. CO₂ increases x1000 present levels

![Graph showing solar flux and log pCO₂](image)

How do we get out of this?

**580 Myr ago**

1. Volcanoes continue to erupt
2. No rainfall to wash out CO₂
3. CO₂ increases x1000 present levels
4. Extreme warming triggered; rapid ice melt over ~100s of years.
5. Chemical weathering and thermostat resumes

Snowball is still a theory...
... evidence includes:
1. 700 & 2200 Myr ago: glacial sediments everywhere
2. Deposits show embedded equatorial magnetic field
3. Iron deposits found that can only be formed in oxygen depleted oceans (e.g., ice separates ocean/atmosphere)

**Radiative forcings and feedbacks**

**580 Myr ago**

A few Myr later

it has been suggested that perhaps Snowball Earth allowed complex life to emerge
Radiative forcing...

since life flourished
(540 Myrs ago)

Phanerozoic (540 Myr → present)

Current “eon”: greek for “visible life”

1. Period where life starts to spread out...
2. ... animals and plants evolved
3. Dramatic changes in CO₂ levels on the order of 5-10 times present levels...
4. ...maybe related to changes in plate tectonics and biologic activity

Phanerozoic (540 Myr → present)

Generally warmer in the past 540 million years owing to higher CO₂ levels

Two periods of large glaciation correlated with low CO₂

Ice sheets: Crowley 1998; GEOCARB II: Berner & Kothavala, 2001; CO₂ proxies: Royer, 2006; image based on IPCC AR4
Rad. forcing and feedbacks

In the early Phanerozoic the solar constant was 4% less than current levels, which compensates overall decreasing CO₂ forcing during Phanerozoic.

Continental glaciation (terminology)

Mountain building

Last 65 Myrs

Cooling, CO₂ decline

Mountain building, increase in weathering

Mid-ocean ridge expansion slows, less CO₂ from volcanoes and less from plate subduction and subduction zones

*Benthic δ18O proxy for ice volume

Phanerozoic (540 Myr → present)

Phanerozoic (540 Myr → present)

Strong increase in atmospheric oxygen in the carbon period due to large bioplastic growth

Formation of fossil fuel deposits during carbon period

%O₂ in atmosphere

Ice sheets: Crowley 1998; GECCARB II; Berner & Kothavale, 2001; CO2 proxies: Royer, 2004; image based on IPCC AR4

90 Myrs ago

65 Myrs ago

50 Myrs ago

35 Myrs ago
Phanerozoic (540 Myr → present)

Last 65 Myrs

- Cooling, CO2 decline
- Mountain building, increased weathering
- Mid-ocean ridge expansion slows, less CO2 from volcanoes, less from plate subduction and volcanoes at subduction zones
- Antarctica moves polewards
- Antarctic glaciation 33 Myr ago

Phanerozoic (540 Myr → present)

Last 5.5 Myrs

- CO2 decreases
- Antarctica settles at pole
- Gradual cooling
- Ice albedo effect increasingly important
- Settling into 100 Kyr cycles

Radiative forcing...

Ice ages and orbital changes
(100 Kyr timescales)
The last Ice Age (20 Kyr ago)

- Clear 100 Kyr periodicity in Antarctic temperatures and ice volume
- Ice age changes
- EPICA (Antarctica)
- Vostok (Antarctica)

- Low
- High

- 450 400 350 300 250 200 150 100 50 0 Time (Kyr)
- $\Delta T \, (^{o}C)$
- 30 -3 -6

- Ice Volume

- EPICA (Antarctica)

- 100 Kyr periodicity in Antarctic temperatures appears linked to mid-high latitude insolation changes

- Radiative forcings and feedbacks

- The last Ice Age (20 Kyr ago)
- Solar irradiance changes

- e.g. Orbital eccentricity
  - 100,000 year period

- Extrinsic
- Intrinsic
Discoveries...

Louis Agassiz (1807-1873)
1837 talk: “Glaciation of Switzerland”
Led to broad acceptance of ice age theory

Milutin Milankovitch (1879-1958)
astronomical theory, 1940
realized importance of summertime insolation changes in high latitudes for ice sheet melt.