Atmospheric Dynamics: Martian Climate History

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Mars Atmospheric Dynamics
Outline

• Discussion geared towards the scientist/engineer who is familiar with physical principles, but perhaps unfamiliar with properties of the martian atmosphere/atmospheric circulation.

• A slant towards how the atmosphere influences methane production, transport, decay.

• We will address:
  • Temperature
  • Pressure
  • Winds
  • Dust
### The Martian Atmosphere

Comparing Mars and Earth Environments

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td>78% N₂, 21% O₂</td>
<td>95% CO₂</td>
</tr>
<tr>
<td><strong>Atmospheric Water</strong></td>
<td>1-4%</td>
<td>Virtually none</td>
</tr>
<tr>
<td><strong>Surface pressure</strong></td>
<td>1 atm.</td>
<td>~0.01 atm.</td>
</tr>
<tr>
<td><strong>Surface temperature</strong></td>
<td>-85 to 57°C</td>
<td>-128 to 27°C</td>
</tr>
<tr>
<td><strong>Polar Caps</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Days in Year</strong></td>
<td>365</td>
<td>669</td>
</tr>
</tbody>
</table>

- **Surface temperature**
  - Earth: -85 to 57°C
  - Mars: -128 to 27°C

- **Polar Caps**: Yes for both Earth and Mars

- **Days in Year**: 365 for Earth, 669 for Mars
The Martian Atmosphere

EARTH VS. MARS WEATHER
The Martian Atmosphere

EARTH VS. MARS WEATHER

4/30/1999 00:10:10 UTC

MOC2-128 Malin Space Science Systems/NASA
Surface Pressure

• Because of the distance from the Sun, and Mars’ atmospheric composition, the atmosphere itself freezes out.

• This causes substantial variations in martian surface pressure over the course of a year.
Surface Pressure

Pressure (Pa)

Solar Longitude

Sol Number

670 770 870 970 1070 1170 1270 1340

0 100 200 300 400 500 600 670

REMS data through sol 938, from G. Martinez
The Martian Atmosphere

• Energy which drives circulation comes from the Sun
  • Absorption in atmosphere (gas/dust)
  • Absorption by surface
  • Re-radiation from surface/atmosphere
  • Dust scattering
  • Latent heat at poles
Carbon Dioxide Freezes

-128°C

Water Freezes

27°C

-85°C

57°C

TEMPERATURE
Temperature

- Equatorial profile, 1 day, mid-summer
- Rapid surface heating/cooling

Boundary layer, ~10 km
Turbulence

- Energy at small scales is turbulent energy.
- Think of this as convective energy.
Zonal Average Temperatures

from Smith et al., (1999)
Global Circulation

- Hadley Circulation
  - Thermally direct overturning circulation
  - Imbalance of heating at equator and high latitudes
  - Similar to Earth
Global Circulation

$L_s = 0^\circ$

$L_s = 90^\circ$

$L_s = 180^\circ$

$L_s = 270^\circ$

from Forget et al., (1999)
Local Circulation

- Modifiers of general circulation
  - Topography
  - Thermal contrast (poles, albedo/TI variations)
  - Dust

- Topography is responsible for generating waves in the atmosphere, and restricting some wind patterns

- Slope winds
  - Driven on many different scales
  - Familiar to us on Earth, upslope/downslope winds
  - Buoyant air ascends, dense air descends
Local Circulation

- Thermal Contrast Winds
  - Similar in nature to slope winds
  - Also familiar to us, land/sea breezes
  - On Mars, driven by albedo/TI differences
  - Polar cap edge winds
Atmospheric Dust

- At larger scales, most major circulation components are strengthened by increased dust loading in the atmosphere
  - e.g. Hadley circulation

- Circulations forced by solar heating of the ground are generally weakened due to the reduction in insolation at the ground
  - e.g. diurnal slope flows, cap edge circulation, boundary layer convection
Summary (Pt 1)

• Temperature
  • Largely controlled by surface absorption/re-radiation
  • Diurnal cycle (stable vs. unstable); mixing

• Pressure
  • Seasonal condensation cycle, non-condensable enrichment

• Dust
  • Affects strength of global circulation
  • Potential chemistry effects (not discussed here)

• Wind
  • Multiple scales
  • Globally mixes in ~30 days
  • Global circulation strongly affected by local conditions
Mars Climate History
Introduction

• Geological and geochemical evidence points to a vastly different, early climate on Mars.
  • Fluvial features (rivers, channels, shorelines, aqueous signatures) suggest a planet warmer and wetter than present
  • An atmosphere of 100’s mb pressure
  • Temperatures near or above melting point of water
• What happened?
Introduction

• Early Mars atmosphere had to be thicker
  • Liquid water has pressure and temperature constraints

• Early solar luminosity was ~25% lower than present
  • Starting from a colder place

• The “Faint Young Sun” paradox

• Can it be reconciled?
CO$_2$ Atmosphere

- First Attempt (circa 1980s)
- Thick CO$_2$ atmosphere (1-5 bar)
- Assumes *reduced solar luminosity* (75%)
  - Comparatively easy to reach 273 K at present solar luminosity.
CO₂ Atmosphere

- Add enough CO₂ to make the planet warm (~5 bar)
- But CO₂ will saturate at pressures lower than this.
- Furthermore...as surface pressure increases, planetary albedo rises due to atmospheric scattering (planet gets “brighter”)

In other words, CO₂ is not always a greenhouse warmer.
Trace Gases

- Still assume CO$_2$ was abundant long ago.
- Trace greenhouse species
  - NH$_3$, SO$_2$, CH$_4$, H$_2$S, H$_2$O, etc.
- Each has drawbacks
  - Solubility
  - Redox chemistry
  - Photochemical lifetime
  - Abundance
  - Etc…
Trace Gases

500 mb CO₂ only

500 mb CO₂ + SO₂

500 mb CO₂ + saturated atm.

500 mb CO₂ + SO₂ + saturated atm.

Annual average surface temperatures from Mischna et al., (2013)
Trace Gases

- Greenhouse warming due to CIA by H$_2$ with CO$_2$.
- Significant only for background atmospheres $> \sim 500$ mb.
- Requires 10% H$_2$ atmosphere and saturated atmosphere

work by Ramirez et al. (2014)
Clouds

- Carbon dioxide ice clouds can be effective scatterers of upwelling IR.
- An alternative idea to greenhouse gases

from Forget and Pierrehumbert (1997)
Cloud Cover

• Water ice clouds can also act as warming agents in the atmosphere.

• Even CO$_2$ ice clouds can be warming agents from IR scattering.

Urata and Toon, (2013)

More cloud / Higher cloud / Bigger cloud particles / More warming

More cloud / Higher cloud / Bigger cloud particles / More warming
Impact Warming

- Impact-induced warming:
  - Introduction of significant heat and water to the climate system

- Big impactors (10’s km)
  - Smaller impactors have negligible influence
  - Results in global influence

- Large impacts occur with less frequency later in Mars history
Impact Warming

• Impact climate change is **not** local
  – These are large impacts (~Hellas-forming size)
  – Precipitation could/would be global

• Cratering history limitation on how late in geological time such climate change could be
  – Large impacts occur with less frequency later in Mars history, largely restricting this to early times
Sputtering / Photochemical Escape

- Sputtering and moderate carbonate formation act as the decay process.
- Requires <1 bar CO₂ initially.
- Probably <100 mb since ~3 Ga
- Mostly cold and dry throughout history

From Hu et al., (2015)
Orbital Change

- Orbitally driven climate change
  - Obliquity
  - Eccentricity
  - Perihelion

- Does not modify overall global insolation
  - Only modest change to surface pressure
  - Primary effect is to water cycle/redistribution of surface ice

from Laskar et al., (2002)
Orbital Change

- Rise in obliquity moves ice to tropics → increase in planetary albedo

- Change in eccentricity/precession phasing can control cloud distribution and polar cap size

- As obliquity approaches zero, atmosphere will collapse at poles
Alternatives to pure water melt

Kieserite \((\text{MgSO}_4 \cdot \text{H}_2\text{O})\)

Polyhydrated sulfates \((\text{e.g. MgSO}_4 \cdot 7\text{H}_2\text{O})\)

Gypsum \((\text{CaSO}_4 \cdot 2\text{H}_2\text{O})\)

Other hydrates

Gendrin et al. (2005)
Summary (Pt 2)

- Geochemical and geological evidence suggests a wet early Mars
- Need to significantly warm early Mars (FYS paradox)
- Many mechanisms have been proposed, none wholly satisfactorily
  - Sulfur species, methane, water vapor,
  - CO$_2$/H$_2$O ice clouds
  - Impacts?
  - Brines
- Most prevailing theories estimate 100’s mb initially