Lecture 10: Planetary Atmospheres

Earth’s atmosphere seen from space

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Astro 18: Planets and Planetary Systems
UC Santa Cruz
Topics for Today

• Part 1: Introduction to Class Projects

• Part 2: Lecture on Planetary Atmospheres
Why projects?

• **Reading, homework, lectures: “content”**
  – What we know about our Solar System and others, and the scientific tools used to discover this knowledge

• **Class Projects: “enterprise of science”**
  – The way we really do science – starting with hunches, making guesses, making many mistakes, going off on blind roads before hitting on one that seems to be going in the right direction

• **You will choose a general topic. Then you will formulate your own specific questions about the topic, and figure out a strategy for answering them**

• **We will provide structure via “milestones” along the way, so you won’t get lost**
Projects: Getting started

• Today:
  – Brainstorming about potential topics
  – Topic selection
  – Group formation
  – First meeting of your group

• Weekly e-mails to Claire and Jenn from each of you: how are things going? (be sure to put “Astro18” in subject line)

• Final project outcomes: last two days of class
  – Presentation in class
  – Written report
Topics chosen in the past (just a taste of what’s possible)

• Life elsewhere in the universe

• Hazards from Outer Space: Killer asteroids and comets

• New theories of Solar System formation

• Global warming on Earth: What’s the evidence? Are people causing warming? How are predictions made?

• Were Mars and Venus more hospitable in the past?

• Mars exploration by humans (or by robots)

• Moons of Jupiter and Saturn
First task today

- Brainstorm about potential project topics

- How to “brainstorm”:
  - One person serves as scribe
  - Everyone suggests ideas
  - Scribe writes each one down
  - No criticisms allowed! Just put all the ideas down
  - Later you’ll decide which questions are most important, most interesting, etc. DON’T do that now.

- Split into groups of 2 or 3 (your nearest neighbors?)

- Spend 10 minutes brainstorming about project topics
  - Toss around as many questions as you can, write them down
  - What are you curious about?
Brainstorming, continued

- Main point of brainstorming is to build on each others’ ideas

- Keeping the discussion positive (no criticisms allowed) encourages creativity.
  - Nobody should feel “turned off” or discouraged

- Brainstorming a generally useful method
  - Used in businesses, arts, as well as science
When 10 minutes have passed, we’ll try to categorize the topics

• Make groupings of related topics

• Write them on board or on sign-up sheets

• Ask each of you to sign up for your first choice
  – Include your name and email address

• Form groups for each topic, get together in class
Next task: today in your groups

- Once you’ve chosen a topic:
- What specific questions can you ask (and later answer) about your topic?
Example of brainstorming list for “Pluto” questions

• Why is Pluto so small?
• What is Pluto made of? How do we know?
• How come Pluto’s orbit is so elliptical?
• Did Pluto used to be an asteroid? How do we know?
• Are there other Plutos?
• Does Pluto have an atmosphere?
• What could we learn from sending a spacecraft to Pluto and Charon?
• How long would it take to get there? Could it go into orbit around Pluto?
• Does Pluto have seasons? What are they like?
Next task: each group work on narrowing down your questions

- Think about which of your questions are most interesting or important

- Think about how you would address each one

- Using these criteria, narrow down your list of questions to 3 – 5

- Take 10 minutes now

- Hand in your list at end of class today (be sure to keep copies for yourselves!)
By Thursday November 4th (1 wk)

- Each group look into their 3-5 questions enough to get an idea:
  - Does each question still make sense?
    - Flesh it out: use reference books (in Science and Engineering Library), websites (links on class web page)
  - Why is each question important?
  - How are they related to each other?
  - What resources are available to address each question
    - Textbooks or reference books? Articles in magazines such as Science or Scientific American or Sky and Telescope? Websites? Journal articles?
    - Which group members is most interested in which questions?

- Each group member sign up to address 1 or 2 questions

- Put “Astro 18” in subject line, send to max@ucolick.org and to jaburt@ucsc.edu
By Tuesday November 9th

• (Group): Together write a 1 - 2 page summary of what your project is:
  – what are your 3 – 5 questions
  – why are they each important (one by one)
  – how are they related to each other
  – what methods might you use to address them
    – Books? Articles in magazines such as Science or Scientific American? Websites? Journal articles?
    – What help can Jenn and I give you

• Put “Astro 18” in subject line, send to max@ucolick.org and to jaburt@ucsc.edu
By Tuesday November 9th, cont’d

• From each individual (each of you): email to us
  – A short email giving me feedback on how your group is going: did everyone participate in your brainstorming session, did you feel included or left out, did you enjoy it?
  – Is someone dominating the group too much?
• Are you finding the work interesting? Here’s a place to ask advice about sources, etc.
  – I’ll ask you to do this each week, for a while at least

• Put “Astro 18” in subject line, send to max@ucolick.org and to jaburt@ucsc.edu
Planetary atmospheres: Outline

- What is an atmosphere? What is its structure?
- Temperature of a planet, if the atmosphere weren’t there ("no-greenhouse temperatures")
- Generic atmospheric structure
- Global climate change
  - Earth
  - Venus
  - Mars

Please remind me to take a break at 12:45 pm!
The Main Points

• **Planetary atmospheres as a balancing act:**
  – Gravity vs. thermal motions of air molecules
  – Heating by Sun vs. heat radiated back into space
  – Weather as a way to equalize pressures at different places on a planet’s surface

• **Atmospheres of terrestrial planets are very different now from the way they were born**
  – Formation: volcanoes, comets
  – Destruction: escape, incorporation into rocks, oceans
  – Huge changes over a billion years or less

• **Prospect of human-induced global warming on Earth is a serious issue. Can be approached scientifically.**
Earth’s Atmosphere: Thin blue line

- About 12 km thick
- Earth’s diameter
  12,000 km, 1000 times bigger
- Consists mostly of molecular nitrogen (N₂) and oxygen (O₂)
- Fractions:
  - 78% Nitrogen
  - 21% Oxygen
  - 0.04% CO₂
**Atmospheric Pressure**

a. A balloon stays inflated when the inside and outside pressures are balanced.

b. Adding air molecules temporarily increases the pressure inside the balloon, so the balloon expands until pressure balance is restored.

c. Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

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Gas pressure depends on both density and temperature.

Adding air molecules increases the pressure in a balloon.

Heating the air also increases the pressure.
Atmospheric Pressure

a. A balloon stays inflated when the inside and outside pressures are balanced.

b. Adding air molecules temporarily increases the pressure inside the balloon, so the balloon expands until pressure balance is restored.

c. Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

Mathematically: \( \gamma = \frac{EF}{n} \). Units: energy per unit volume or force per unit area. 

\( n \) = number density (molecules per cubic cm), 

\( F \) = temperature (deg Kelvin), \( k \) = Boltzmann constant. Units of \( EF \) : energy
Atmospheric Pressure: variation with altitude

- **Pressure and density decrease with altitude because the weight of overlying layers is less**

- **Earth’s pressure at sea level is**
  - 1.03 kg per sq. meter
  - 14.7 lbs per sq. inch
  - 1 bar
In an atmosphere in equilibrium, pressure gradient balances gravity.

Pressure = Net Force / Area

Force = \([P(h) - P(h + dh)] \times Area = \Delta P \times A\)

Gravitational force = \(-Mg = - \left( \frac{mass}{volume} \right) \times (A \Delta h) \times g = -\rho g \times (A \Delta h)\)

\[
\frac{\Delta P}{\Delta h} = -\rho g \quad \text{or, in calculus language,} \quad \frac{dP}{dh} = -\rho g
\]
Profile of density with altitude (a calculus-based derivation)

\[ P = nkT = \left( \frac{\rho}{m} \right) kT \]

\[ \frac{dP}{dh} = \frac{d}{dh} \left( \rho \frac{kT}{m} \right) = -\rho g \]

If temperature \( \approx \) const, \( \frac{d}{dh} \left( \rho \frac{kT}{m} \right) = \frac{kT}{m} \frac{d\rho}{dh} = -\rho g \)

Divide both sides by \( \frac{kT}{\rho m} \):

\[ \frac{1}{\rho} \frac{d\rho}{dh} = -\frac{mg}{kT} = \text{const} \]

Solution: \( \rho = \rho_0 e^{-\left( \frac{h}{h_0} \right)} \) where \( h_0 = \frac{kT}{mg} \)

- Pressure, density fall off exponentially with altitude
- Higher temperature \( T \) \( \Rightarrow \) larger “scale height” \( h_0 \)
- Stronger gravity \( g \) \( \Rightarrow \) shorter “scale height” \( h_0 \)
How big is pressure scale height?

- $h_0 = \frac{kT}{mg}$
  - height at which pressure has fallen by $1/e = 0.368$

- Earth $h_0 = 8$ km
  - the thin blue line

- Venus $h_0 = 15$ km
  - ($g$ a bit lower, $T$ higher)

- Mars $h_0 = 16$ km
  - (both $g$ and $T$ lower)

Hence the “thin blue line”
Effects of Atmospheres

- Create pressure that determines whether liquid water can exist on surface
- Absorb and scatter light
- Create wind, weather, and climate
- Interact with solar wind to create a magnetosphere
- Can make planetary surfaces warmer through greenhouse effect
**Equilibrium atmospheric temperature (no atmosphere)**

Some sunlight is reflected away by surface and atmosphere.

Incoming energy from sunlight

Absorbed sunlight heats the surface.

Planet emits thermal radiation in all directions.
Equilibrium temperature: balance solar heating against cooling

Equilibrium or steady state: balance $W/m^2 = \text{joules/sec per m}^2$

$W/m^2$ absorbed from sunlight = $W/m^2$ emitted in thermal radiation

Scale to Earth: incident power from Sun = $1.360 \frac{W}{m^2}$ at top of atmosphere

$1.360 \frac{W}{m^2} \times \left( \frac{1 \text{ AU}}{\text{dist. from Sun}} \right)^2 \times \pi \left( R_{\text{planet}} \right)^2 \times (1 - \text{albedo}) = \sigma T^4 \times 4\pi \left( R_{\text{planet}} \right)^2$

Solve for $T$:

$$T = \left[ \frac{1.360 \ W/m^2 \times (1 - \text{albedo})}{4\sigma (\text{dist. from Sun}/1 \text{ AU})^2} \right]^{1/4} = 280K \left[ \frac{1 - \text{albedo}}{(\text{dist. from Sun}/1 \text{ AU})^2} \right]^{1/4}$$

\textbf{albedo} = fraction of sunlight that is reflected by a surface

“No-greenhouse” temperature
# “No-greenhouse” temperatures

## Table 10.2 The Greenhouse Effect on the Terrestrial Worlds

<table>
<thead>
<tr>
<th>World</th>
<th>Average Distance from Sun (AU)</th>
<th>Reflectivity</th>
<th>“No Greenhouse” Average Surface Temperature*</th>
<th>Actual Average Surface Temperature</th>
<th>Greenhouse Warming (actual temperature minus “no greenhouse” temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>12%</td>
<td>163°C</td>
<td>425°C (day), 175°C (night)</td>
<td>—</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>75%</td>
<td>−40°C</td>
<td>470°C</td>
<td>510°C</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>29%</td>
<td>−16°C</td>
<td>15°C</td>
<td>31°C</td>
</tr>
<tr>
<td>Moon</td>
<td>1.00</td>
<td>12%</td>
<td>−2°C</td>
<td>125°C (day), 175°C (night)</td>
<td>—</td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>16%</td>
<td>−56°C</td>
<td>−50°C</td>
<td>6°C</td>
</tr>
</tbody>
</table>

* The “no greenhouse” temperature is calculated by assuming no change to the atmosphere other than lack of greenhouse warming. Thus, for example, Venus ends up with a lower “no greenhouse” temperature than Earth even though it is closer to the Sun, because the high reflectivity of its bright clouds means that it absorbs less sunlight than Earth.

- **Conclusion:** for Venus and Earth, at least, something else is going on! (not just radiation into space)
**Light’s Effects on the Atmosphere**

- **Ionization:** Removal of an electron
- **Dissociation:** Destruction of a molecule
- **Scattering:** Change in photon’s direction
- **Absorption:** Photon’s energy is absorbed
How do different energy photons interact with atmosphere?

- Infrared photons are absorbed, causing molecules to vibrate and rotate.
- Most visible-light photons are simply transmitted, though some are scattered.
- Ultraviolet photons can dissociate (break apart) molecules.
- X rays can ionize gases (tear off electrons) as well as dissociate molecules.
How does the greenhouse effect warm a planet?

Visible light passes through the atmosphere.

Some visible light is reflected by clouds, haze, and the surface.

The surface absorbs visible light and emits thermal radiation in infrared.

Greenhouse gases absorb and reemit infrared radiation, thereby heating the lower atmosphere.
Greenhouse gases

- carbon dioxide \( \text{CO}_2 \)
- water vapor \( \text{H}_2\text{O} \)
- methane \( \text{CH}_4 \)
- others too \( (\text{NO}_2, \ldots) \)

- More greenhouse gases in atmosphere can lead to higher surface temperatures
Concept Question

What would happen to Earth’s temperature if Earth’s surface were less reflective?

a) It would go up.
b) It would go down.
c) It wouldn’t change
Concept Question

- What would happen to Earth’s temperature if Earth’s surface were less reflective?
  
a) It would go up.
b) It would go down.
c) It wouldn’t change
Melting sea ice lowers reflectivity, so Earth heats up more

- This is one of the factors exacerbating global warming.

- As more arctic ice melts in summer, arctic ocean absorbs more light, temperature rises.
Generic atmospheric structure

- **Exosphere**
  - Heated by solar UV and X rays; region of greatest escape

- **Thermosphere and Ionosphere**
  - X rays heat and ionize gases

- **Stratosphere**
  - Heated by UV light; no convection

- **Troposphere**
  - Greenhouse gases trap infrared radiation; convection important

- **Ground**
  - Infrared

- **X** rays
  - UV
  - Visible
Temperature structure of Earth’s atmosphere
Compare Earth, Venus, Mars

The curves show how temperature varies with altitude, starting from the ground (altitude 0 km).

Arrows indicate planet's surface temperature if there were no greenhouse effect.
History of atmospheres on Venus, Earth, Mars

- Huge changes took place over the 4.6 billion years since planets formed!

- Early atmospheres didn’t resemble current ones at all

- Question: why are atmospheres of Venus, Earth, Mars so different?
Sources of atmospheric gases

How Atmospheres Gain Gas

Outgassing from volcanoes

Evaporation of surface liquid; sublimation of surface ice

Impacts of particles and photons eject small amounts
Kilauea volcano outgassing

NOV, 24, 1992
Losses of Atmospheric Gases

How Atmospheres Lose Gas

Condensation onto surface

Chemical reactions with surface

Large impacts blast gas into space
**Thermal Escape of atmospheric gases**

\[ v_{\text{thermal}} = \sqrt{\frac{2kT}{m}} \]

The most common speed is the peak thermal velocity.

Although most atoms do not have escape velocity . . .

. . . a small fraction of the atoms can and do escape permanently into space.
Components of atmospheres on Venus, Earth, Mars

- Why are they so different?
- Were they always this different from each other?
The three atmospheres of Earth: “First Atmosphere”

- First Atmosphere: Primordial elements
  - Composition - Probably H$_2$, He

- Today these gases are relatively rare on Earth compared to other places in the universe.

- Were probably lost to space early in Earth's history because
  - Earth's gravity is not strong enough to hold lightest gases
  - Earth still did not have a differentiated core (solid inner/liquid outer core) which creates Earth's magnetic field (magnetosphere = Van Allen Belt) which deflects solar wind. Magnetosphere protects any atmosphere from the solar wind.

- Once the core differentiated, gases could be retained.
“Second atmosphere”: produced by volcanic outgassing

- Gases similar to those from modern volcanoes (H\textsubscript{2}O, CO\textsubscript{2}, SO\textsubscript{2}, CO, S\textsubscript{2}, Cl\textsubscript{2}, N\textsubscript{2}, H\textsubscript{2}) and NH\textsubscript{3} (ammonia) and CH\textsubscript{4} (methane)

- No free oxygen (O\textsubscript{2} not found in volcanic gases)

- Ocean Formation - As Earth cooled, H\textsubscript{2}O produced by outgassing could exist as liquid

- CO\textsubscript{2} could then dissolve in ocean, be sequestered in marine sediments
“Third atmosphere”: Free oxygen, lower CO$_2$

- Today, atmosphere is ~21% free oxygen. How did oxygen reach this level?

- **Oxygen Production**
  - Photochemical dissociation - breakup of water molecules by ultraviolet light
    - Produced O$_2$ levels 1-2% current levels
    - At these levels O$_3$ (Ozone) could form to shield Earth surface from UV
  - Photosynthesis: CO$_2$ + H$_2$O + sunlight = organic compounds + O$_2$ - Supplied the rest of O$_2$ to atmosphere.

- **Oxygen Consumers**
  - Chemical Weathering - through oxidation of surface materials (early consumer)
  - Respiration of plants and animals (much later)
  - Burning of Fossil Fuels (much, much later)

- Once rocks at the surface were sufficiently oxidized, more oxygen could remain free in the atmosphere
Why does Earth’s climate stay relatively stable?

The Carbon Dioxide Cycle

1. Atmospheric CO₂ dissolves in rainwater
2. Rain erodes minerals which flow into ocean
3. Minerals combine with carbon to make rocks on ocean floor
Why does Earth’s climate stay relatively stable?

4. Subduction carries carbonate rocks down into mantle

5. Rocks melt in mantle and outgas CO₂ back into atmosphere through volcanoes

6. Note that Plate Tectonics is essential component of this cycle
Earth’s Thermostat

- Cooling allows CO₂ to build up in atmosphere
- Heating causes rain to reduce CO₂ in atmosphere
Cyanobacteria and stromatolites made early oxygen for atmosphere

- The first photosynthesis
  - Consumes CO\(_2\), release O\(_2\)

Cyanobacteria: colonies are called stromatolites
Earth: hydrological cycle

1. Water evaporates into atmosphere

2. Convection carries vapor higher, to cooler regions.

3. Water vapor condenses into droplets or flakes, forming clouds.

4. Drops and flakes grow larger.

5. Rain and snow fall to surface.
Did Earth get its water from comets?

- Some water from outgassing volcanoes

- Second potential source of the Earth's ocean water is comet-like balls of ice.

- Enter atmosphere at rate of about 20/second.

- Four billion years of such bombardment would give enough water to fill the oceans to their present volume.

- Possible problems: isotope ratios don’t match. Under active research.
What factors can cause long-term climate change?
Solar Brightening

- Sun very gradually grows brighter with time, increasing the amount of sunlight warming planets
Changes in Axis Tilt

- Greater tilt makes more extreme seasons, while smaller tilt keeps polar regions colder
Changes in Reflectivity

- Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming
Changes in Greenhouse Gases

- Increase in greenhouse gases leads to warming, while a decrease leads to cooling
Global Warming on Earth

- Global temperatures have tracked CO₂ concentration for last 500,000 years
- Antarctic air bubbles indicate current CO₂ concentration is highest in at least 500,000 years
Intergovernmental Panel on Climate Change (IPCC)

- International scientific consensus
  - The majority of atmospheric scientists agree
  - A few do not agree

- Series of important reports based on scientific method (not infallible, but high quality)

- Nobel Peace Prize

- Look for yourselves: Good website http://www.ipcc.ch/
The atmospheric concentration of $\text{CO}_2$ and $\text{CH}_4$ in 2005 exceeds by far the natural range of the last 650,000 years.
Global mean surface temperatures have increased

Variations of the Earth’s surface temperature for...

Departures in temperature in °C (from the 1961-1990 average)

the past 140 years (global)

Departures in temperature in °C (from the 1961-1990 average)

the past 1000 years (Northern Hemisphere)
Glaciers and frozen ground are receding

Increased Glacier retreat since the early 1990s

Area of seasonally frozen ground in NH has decreased by 7% from 1901 to 2002
The Chacaltaya Glacier and Ski Lift, Bolivia
Global temperature will keep rising even after CO₂ emissions are reduced.

Once CO₂ gets into atmosphere, it stays there for hundreds of years!
Projections of Future Changes in Climate

Best estimate for low scenario (B1) is 1.8°C (likely range is 1.1°C to 2.9°C), and for high scenario (A1FI) is 4.0°C (likely range is 2.4°C to 6.4°C).
The greenhouse effect: What about Venus and Mars?

Visible light passes through the atmosphere.

Some visible light is reflected by clouds, haze, and the surface.

The surface absorbs visible light and emits thermal radiation in infrared.

Greenhouse gases absorb and reemit infrared radiation, thereby heating the lower atmosphere.
**Venus Climate**

**If Earth moved to Venus’s orbit**

*More intense sunlight…*

*…would raise surface temperature by about 30°C.*

**Runaway greenhouse effect**

*Higher temperature increases evaporation, and warmer air holds more water vapor.*

*Additional water vapor further strengthens the greenhouse effect.*

**Result:** Oceans evaporate and carbonate rocks decompose, releasing CO₂…

*…making Earth hotter than Venus.*
Venus tectonics

- No evidence for plate tectonics on Venus
  - No mid-ocean rifts
  - No subduction trenches

- Volcanos spread evenly across surface instead of at plate boundaries, as on Earth.

- Lithosphere not broken into plates; probably because heat at surface slightly softens the lithosphere.
No carbon-silicate cycle on Venus

Earth’s carbon-silicate cycle
Resurfacing on Venus

- Venus has far fewer impact craters than Moon & Mercury, but more than Earth (dense atmosphere protects it)
- Geologic activity (volcanic resurfacing) has erased most small craters
- Surface age is only about a billion years.
- Rather uniform age implies that Venus was "resurfaced" by lava flows during a recent, relatively short period
- This differs profoundly from Earth's crustal history. What is it telling us?
  - Could Venus' present crust only have formed that recently?
  - Could there have been a growing crust before 1 billion years ago that "turned over" as heat built up underneath, to lead to a new era of major lava flows?
  - Why?
There was once liquid water on Mars

- **Geomorphological evidence (**lots** of it)
  - River and flood channels, alluvial fans, slumps, canyons, ...

- **One more piece of evidence: shape of ocean basins**

TOPOGRAPHIC MAPPING of Mars has recently revealed remarkable similarities to the ocean basins on Earth. For example, the western Atlantic near Rio de Janeiro (left) presents a similar profile to that of the northern polar basin on Mars (right).
Why did Mars’ climate change?

- Evidence of previous era when liquid water was plentiful
- Today: Evidence for ice mixed with soil in top meter of ground
Climate Change on Mars

- Mars has not had widespread surface water for 3 billion years
- Greenhouse effect probably kept surface warmer before that
- Somehow Mars lost most of its atmosphere (no more Greenhouse)
Mars’ atmosphere affected by both volcanoes and B fields?

- Shortly after Mars formed, its surface temperature was ~ equal to its blackbody temperature (around -55 C).

- As volcanoes dumped CO₂ and H₂O vapor into atmosphere, greenhouse effect increased temperature above 0 C (freezing) so liquid water could exist.

- Two competing effects determined amount of CO₂ in atmosphere: volcanoes adding CO₂, and rocks absorbing CO₂. Result: moderate level of CO₂.

- Greenhouse effect could keep surface T > 0 C, as long as volcanoes kept erupting.

- Eventually Mars' core cooled and solidified (Mars is small). Volcanic activity subsided. Magnetic field went away, solar wind particles eroded atmosphere.

- Once rate of eruptions tapered off, CO₂ in the atmosphere started to fall.

- As the atmosphere thinned out, the greenhouse effect weakened. Eventually the average surface temperature dropped, and surface water froze.
The Main Points

- **Planetary atmospheres are a balancing act:**
  - Gravity vs. thermal motions of air molecules
  - Heating by Sun vs. heat radiated back into space
  - Weather as a way to equalize pressures at different places on Earth’s surface

- **Atmospheres of terrestrial planets are very different now from the way they were born**
  - Formation: volcanoes, comets
  - Destruction: escape, incorporation into rocks, oceans
  - Huge changes over a billion years or less

- **Prospect of human-induced global warming on Earth needs to be taken seriously**