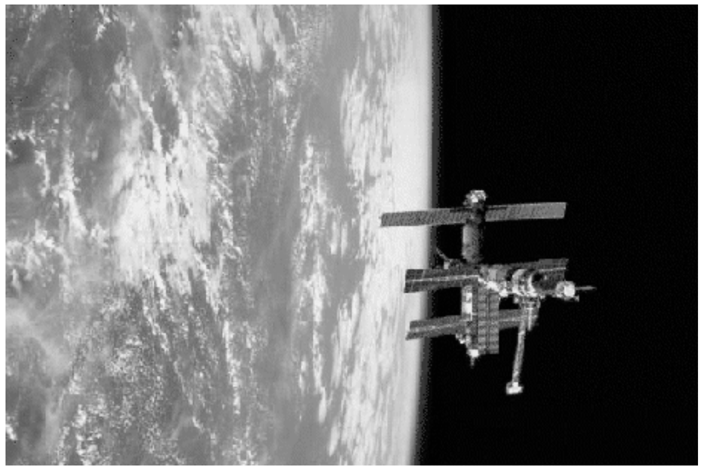
# Lecture 10: Planetary Atmospheres



Earth's atmosphere seen from space

Jenn Burt

October 28th, 2010

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 <u>max@ucolick.org</u> and to <u>jaburt@ucsc.edu</u>**

# *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!**

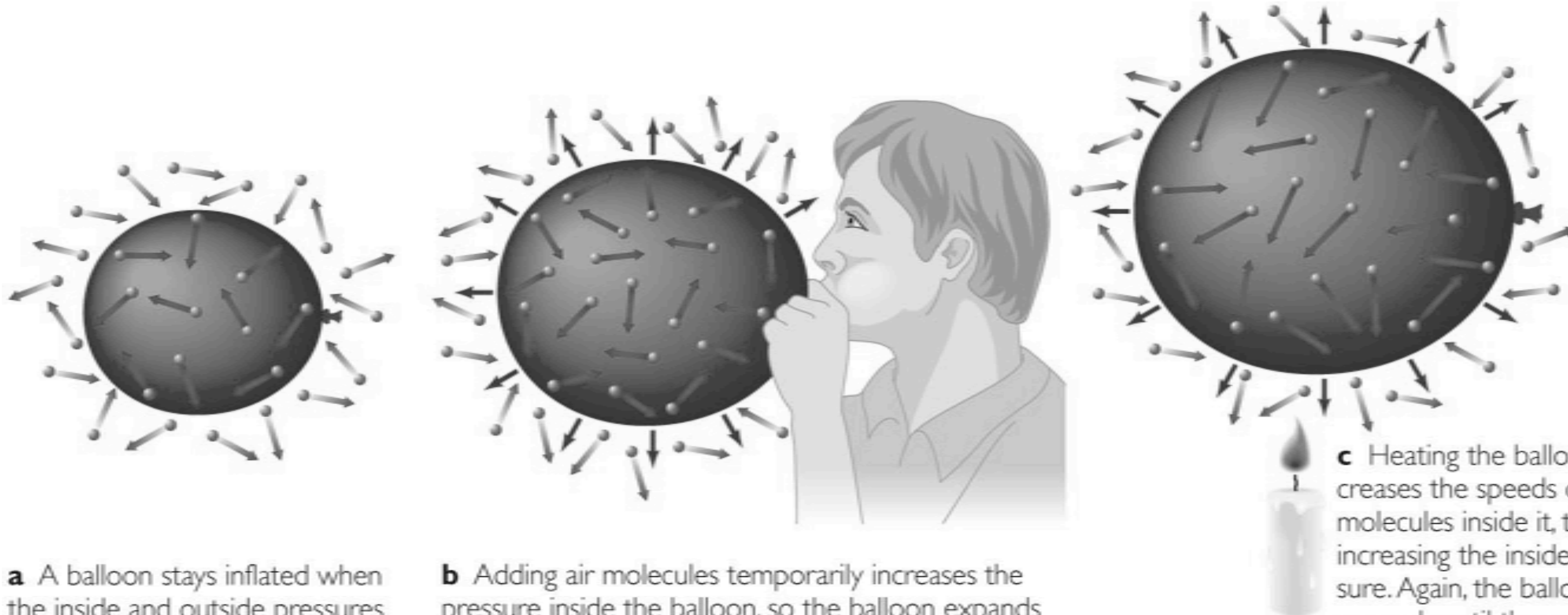
# The Main Points

- 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 ($N_2$) and oxygen ($O_2$)**
- **Fractions:**
  - **78% Nitrogen**
  - **21% Oxygen**
  - **0.04% $CO_2$**

# 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.

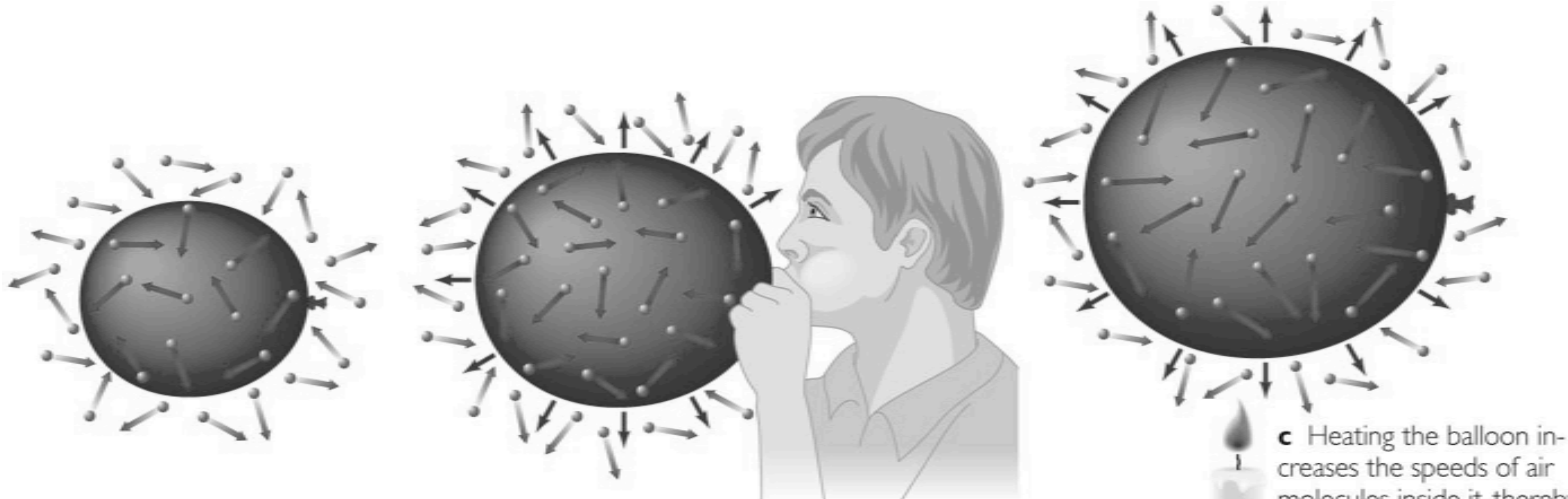
c Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

**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.

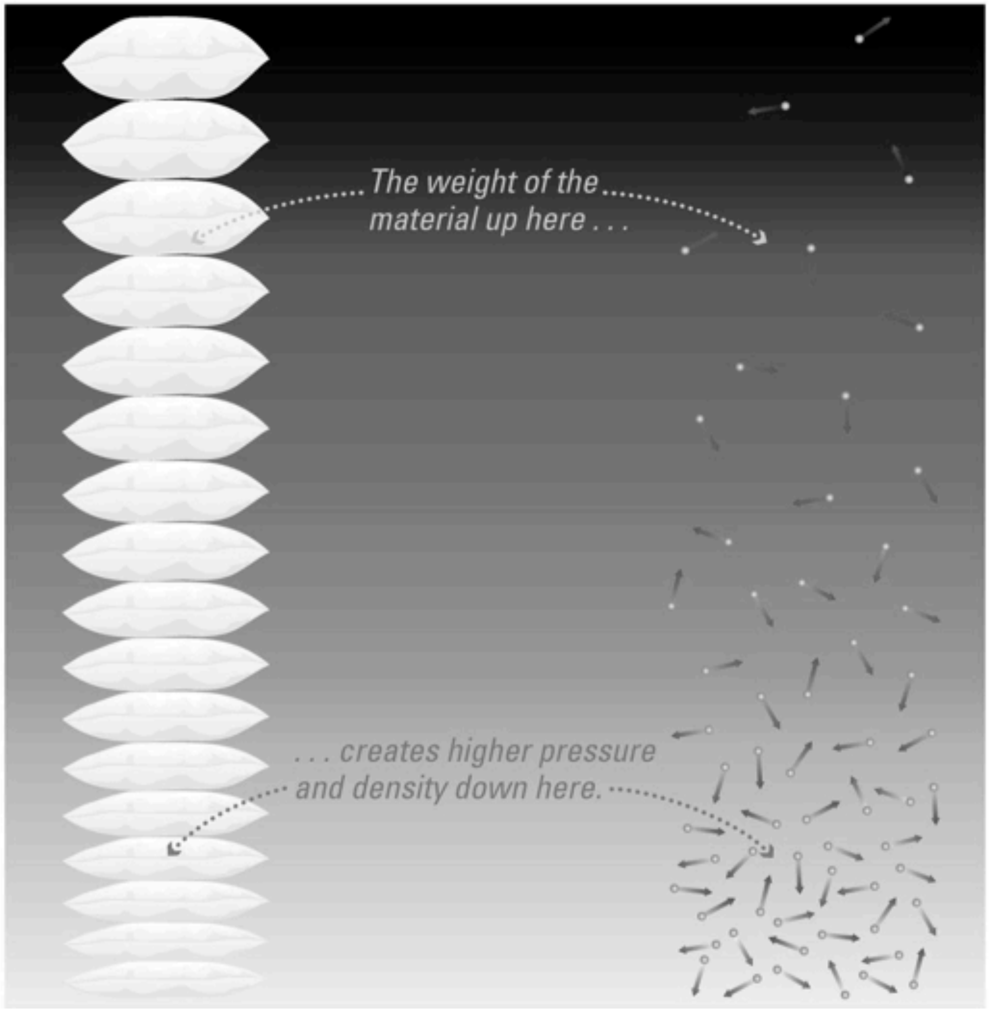
**c** Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

Mathematically: $p = nkT$. Units: energy per unit volume or force per unit area

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

$T$ = temperature (deg Kelvin), $k$ = Boltzmann constant, Units of $kT$ : 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

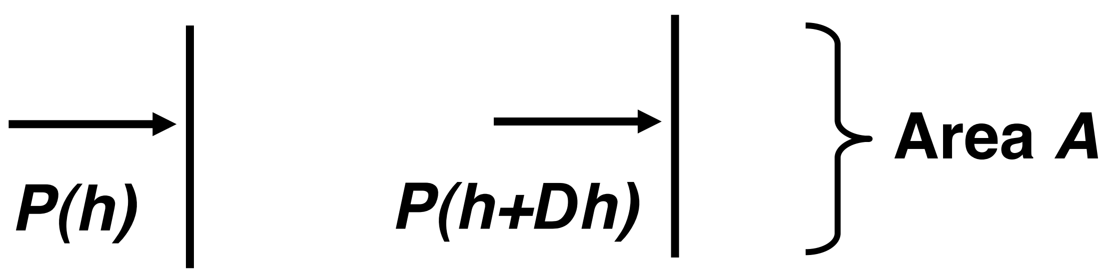
$$\text{Pressure} = \text{Net Force / Area}$$

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

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

$$\Delta P \times A = -\rho g \times A\Delta h$$

$$\frac{\Delta P}{\Delta h} = -\rho g \quad \text{or, in calculus language,} \quad \frac{dP}{dh} = -\rho g$$



# Profile of density with altitude (a calculus-based derivation)

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

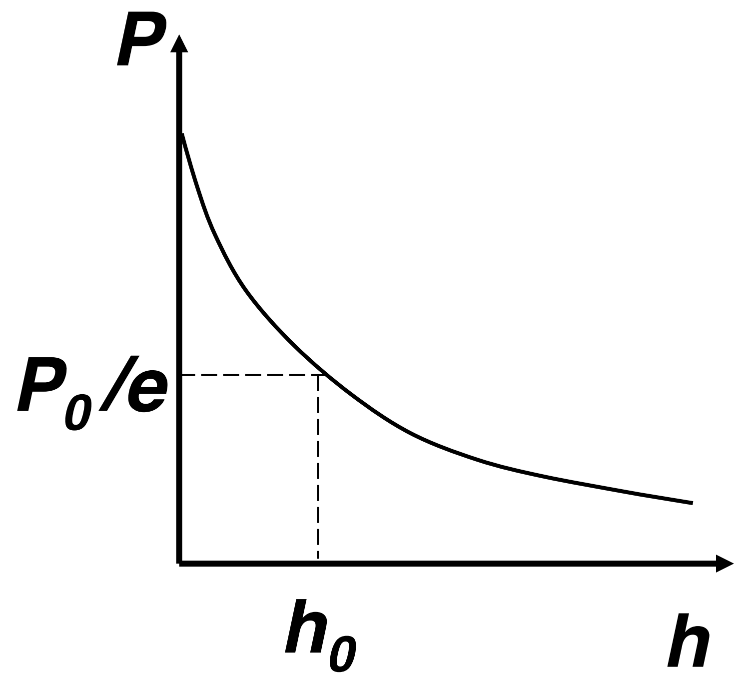
$$\frac{dP}{dh} = \frac{d}{dh}\left(\rho\frac{kT}{m}\right) = -\rho g$$

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: $\rho = \rho_0 e^{-(h/h_0)}$ where $h_0 = \frac{kT}{mg}$




- **Pressure, density fall off exponentially with altitude**
- **Higher temperature *T* larger "scale height" $h_0$**
- **Stronger gravity *g* shorter "scale height" $h_0$**

# *How big is pressure scale height?*

- ***$h_0 = kT / mg$***
  - ***height at which pressure has fallen by 1/e = 0.368***
- **Earth        *$h_0$* = 8 km**
  - **the thin blue line**

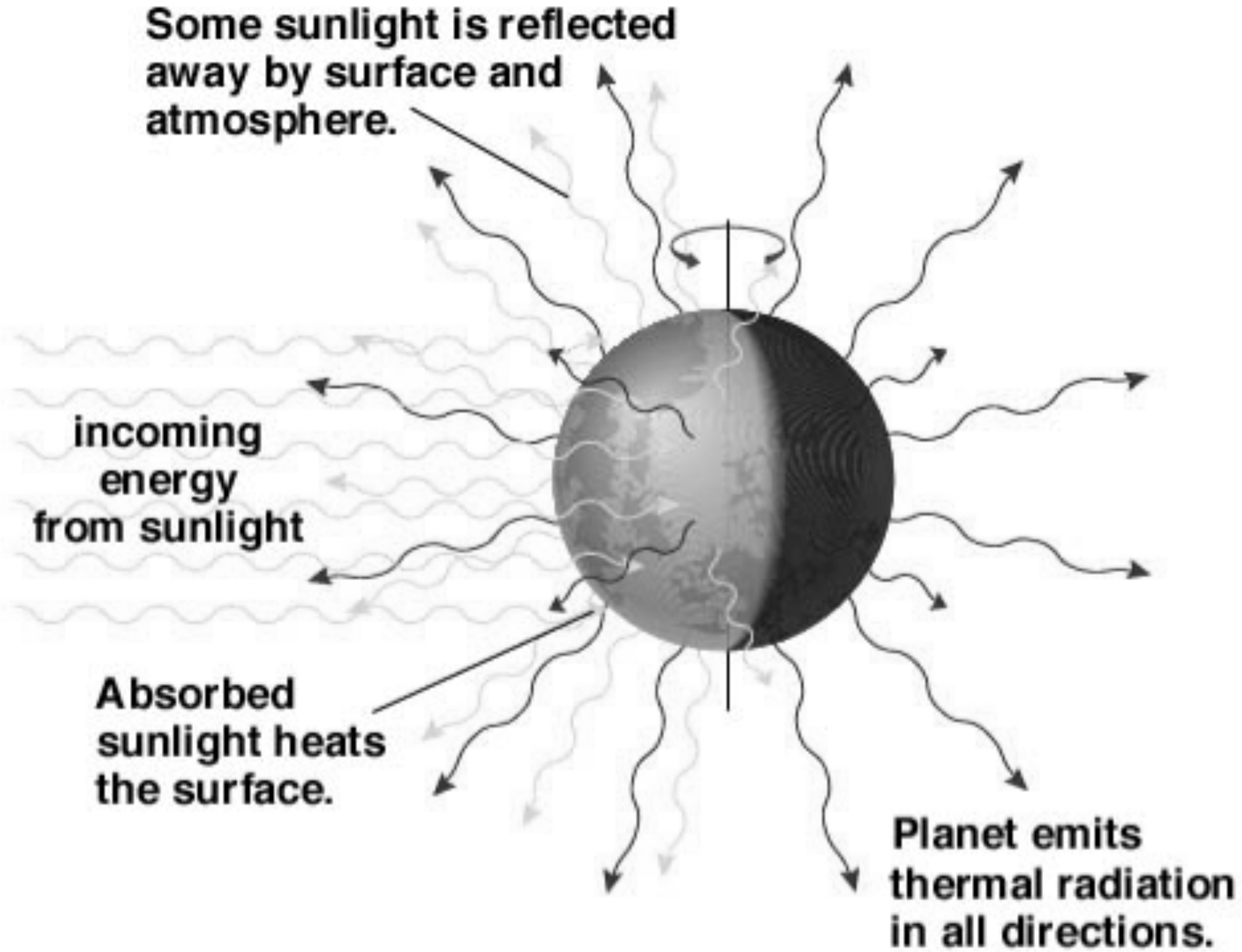
**Hence the "thin blue line"**

- **Venus        *$h_0$* = 15 km**
  - **(*g* a bit lower, T higher)**
- **Mars        *$h_0$* = 16 km**
  - **(both g and T lower)**

# *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)



# Equilibrium temperature: balance solar heating against cooling

Equilibrium or steady state: balance $W/m^2$ = 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

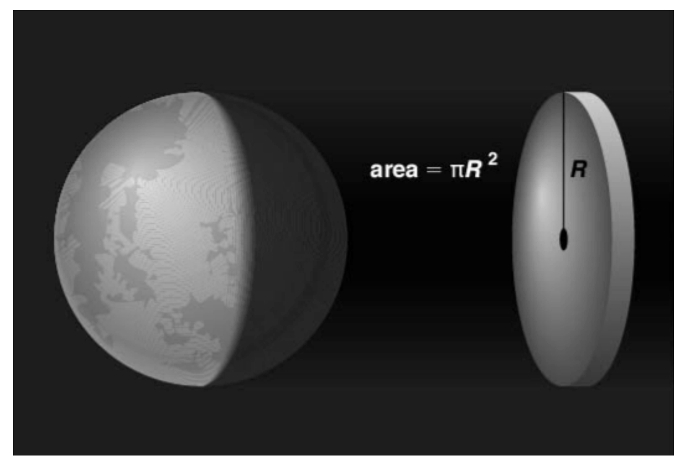
$$1{,}360\ \frac{W}{m^2} \times \left(\frac{1\text{ AU}}{\text{dist. from Sun}}\right)^2 \times \pi\left(R_{planet}\right)^2 \times (1-albedo) = \sigma T^4 \times 4\pi\left(R_{planet}\right)^2$$

Solve for $T$:

$$T = \left[\frac{1{,}360\ W/m^2 \times (1-albedo)}{4\sigma(\text{dist. from Sun/1 AU})^2}\right]^{1/4} = 280K\left[\frac{1-albedo}{(\text{dist. from Sun/1 AU})^2}\right]^{1/4}$$

**"No-greenhouse" temperature**

**albedo = fraction of sunlight that is reflected by a surface**



# “No-greenhouse” temperatures

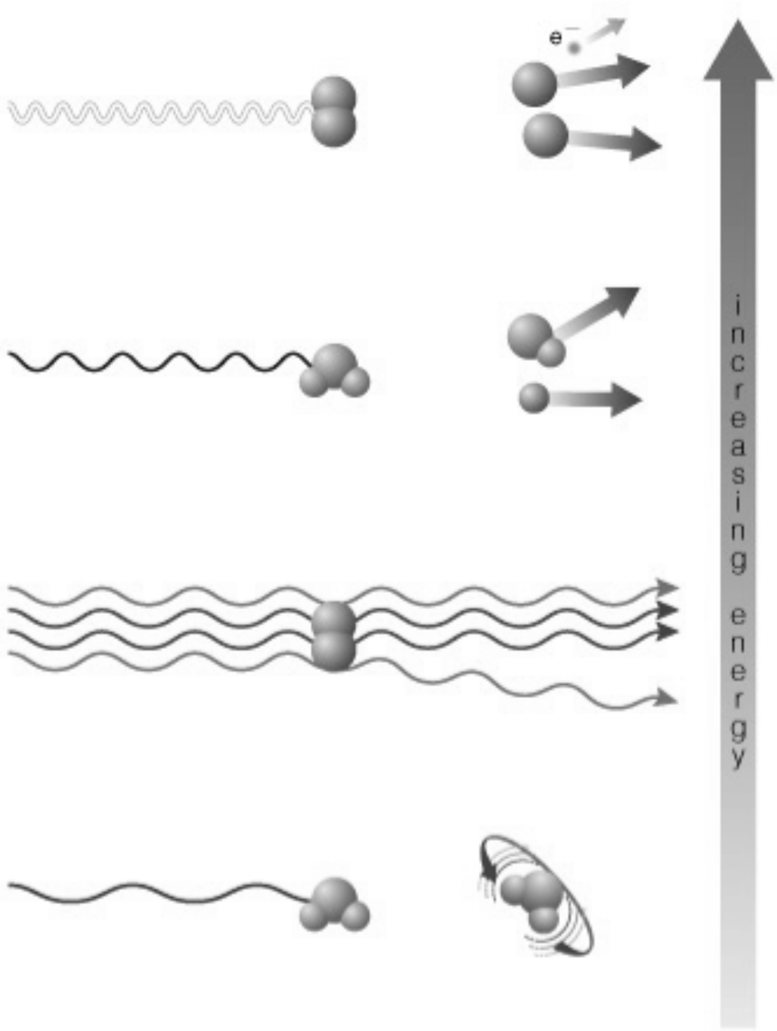
**Table 10.2 The Greenhouse Effect on the Terrestrial Worlds**

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

* 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.

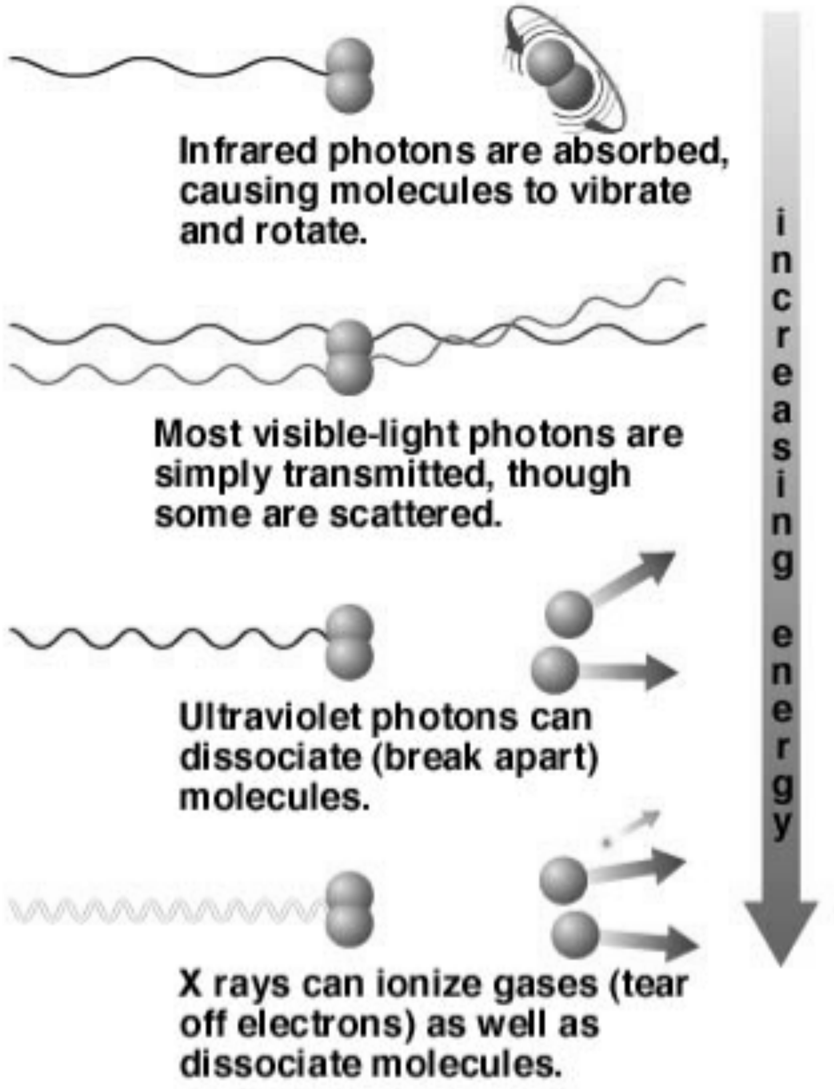
- **Conclusion: for Venus and Earth, at least, something else is going on! (not just radiation into space)**

# ***Light’s Effects on the Atmosphere***

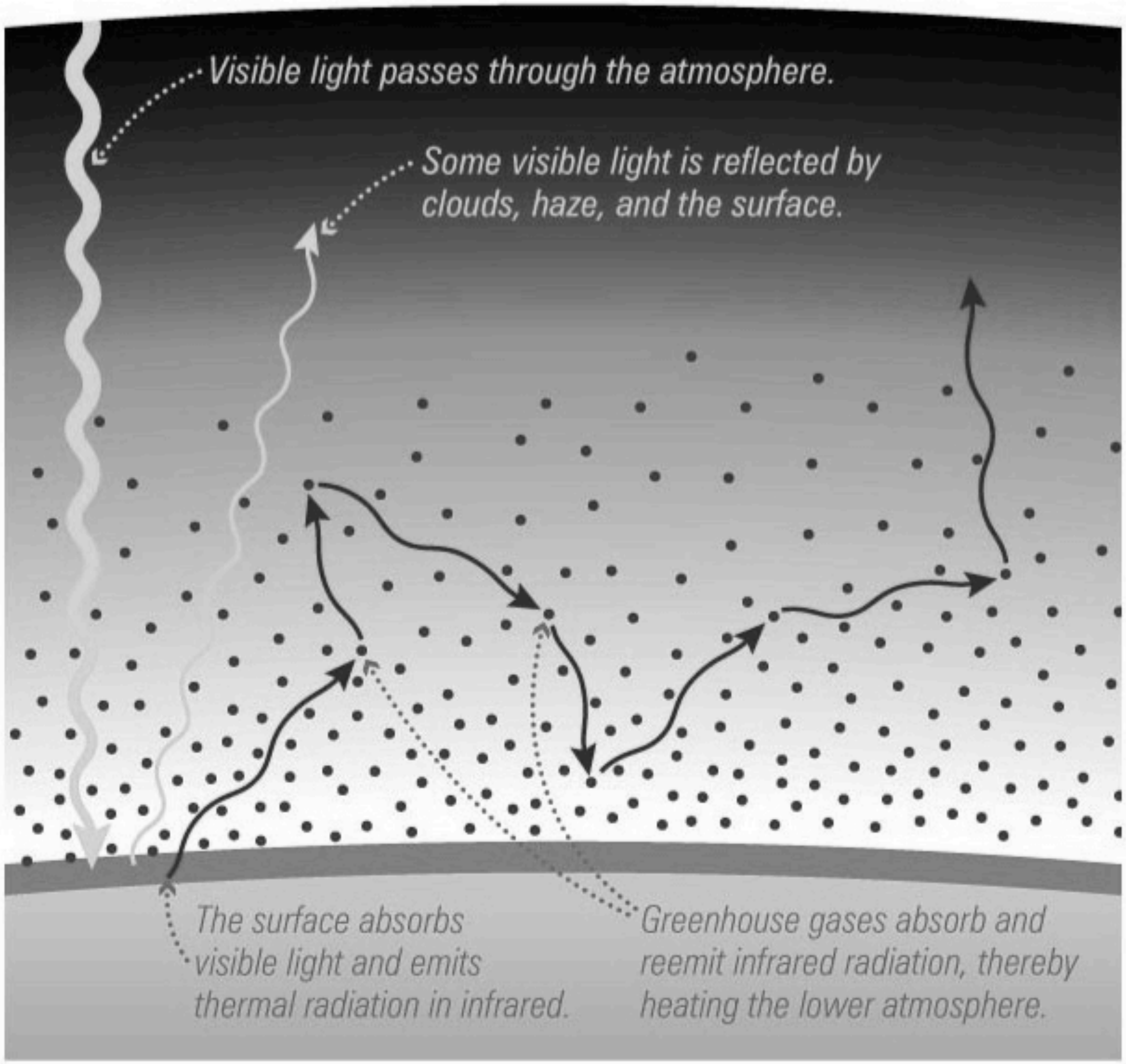



- Ionization: **Removal of an electron**
- Dissociation: **Destruction of a molecule**
- Scattering: **Change in photon’s direction**
- Absorption: **Photon’s energy is absorbed**

# How do different energy photons interact with atmosphere?



# ***How does the greenhouse effect warm a planet?***



# *Greenhouse gases*

- carbon dioxide $CO_2$
- water vapor $H_20$
- methane $CH_4$
- others too ($NO_2$, ....)
- 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

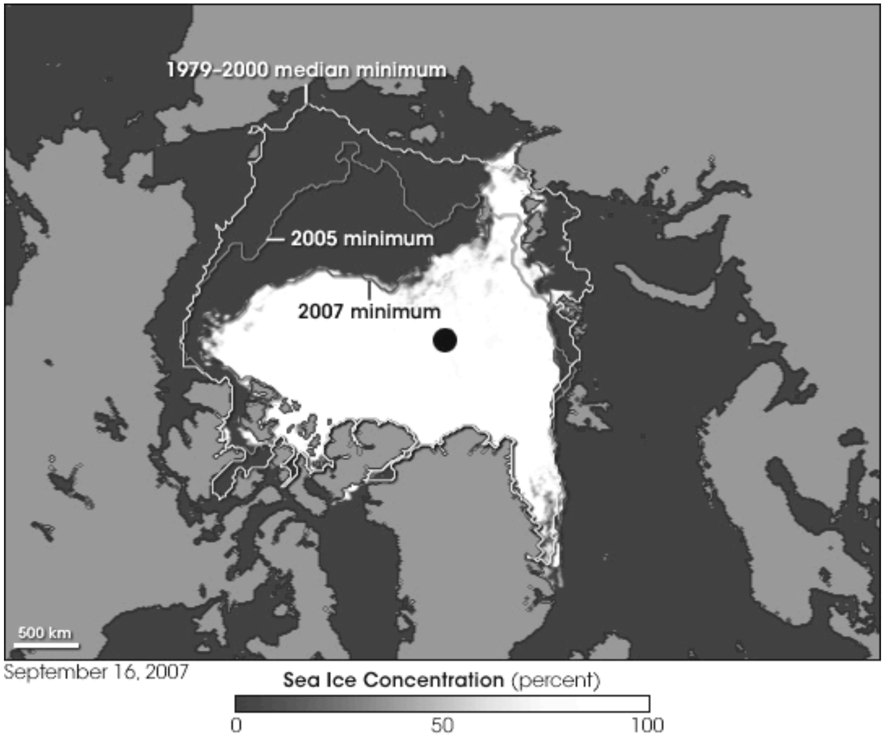
## *Concept Question*

- **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**

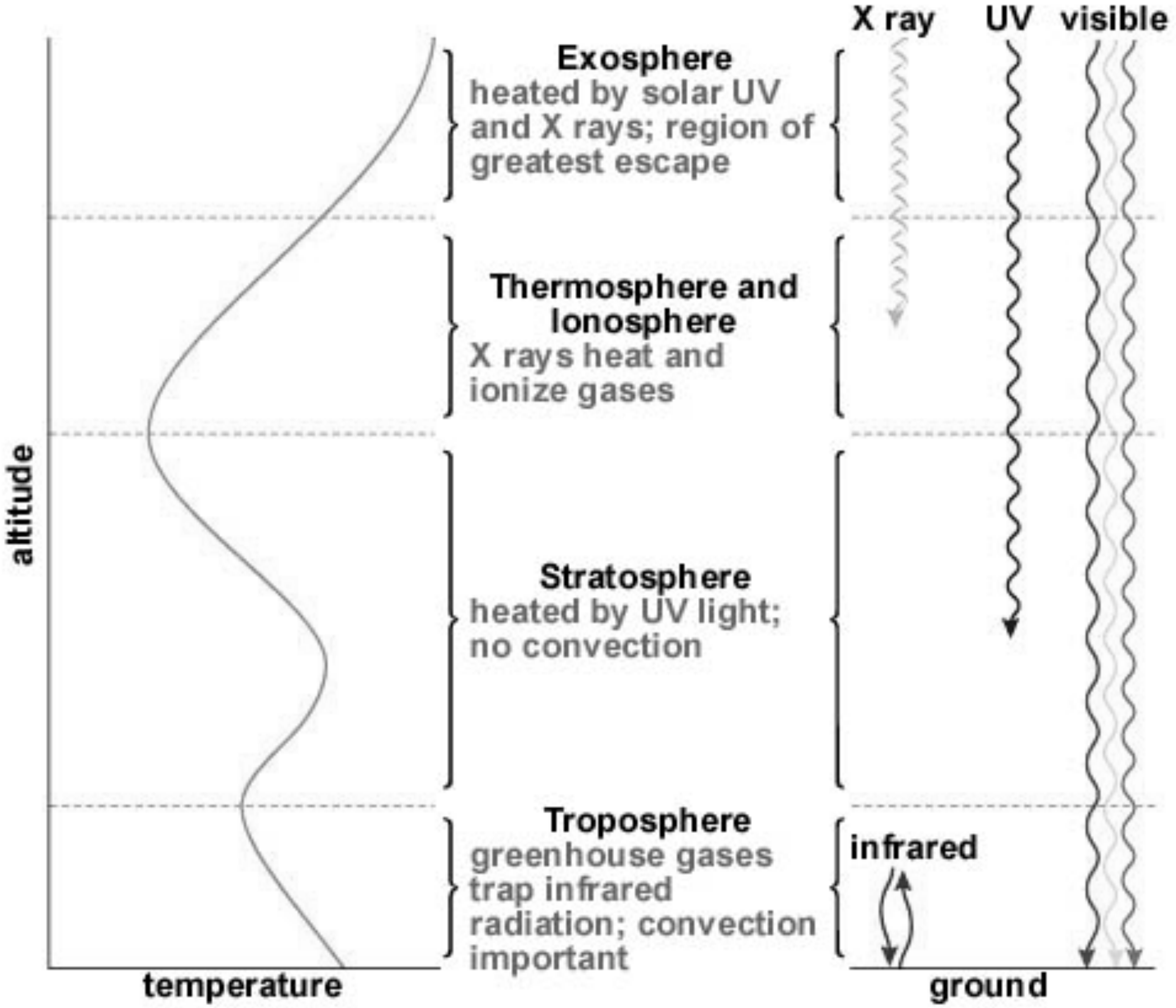
# *Melting sea ice lowers reflectivity, so Earth heats up more*

- This is one of the factors exacerbating global warming.

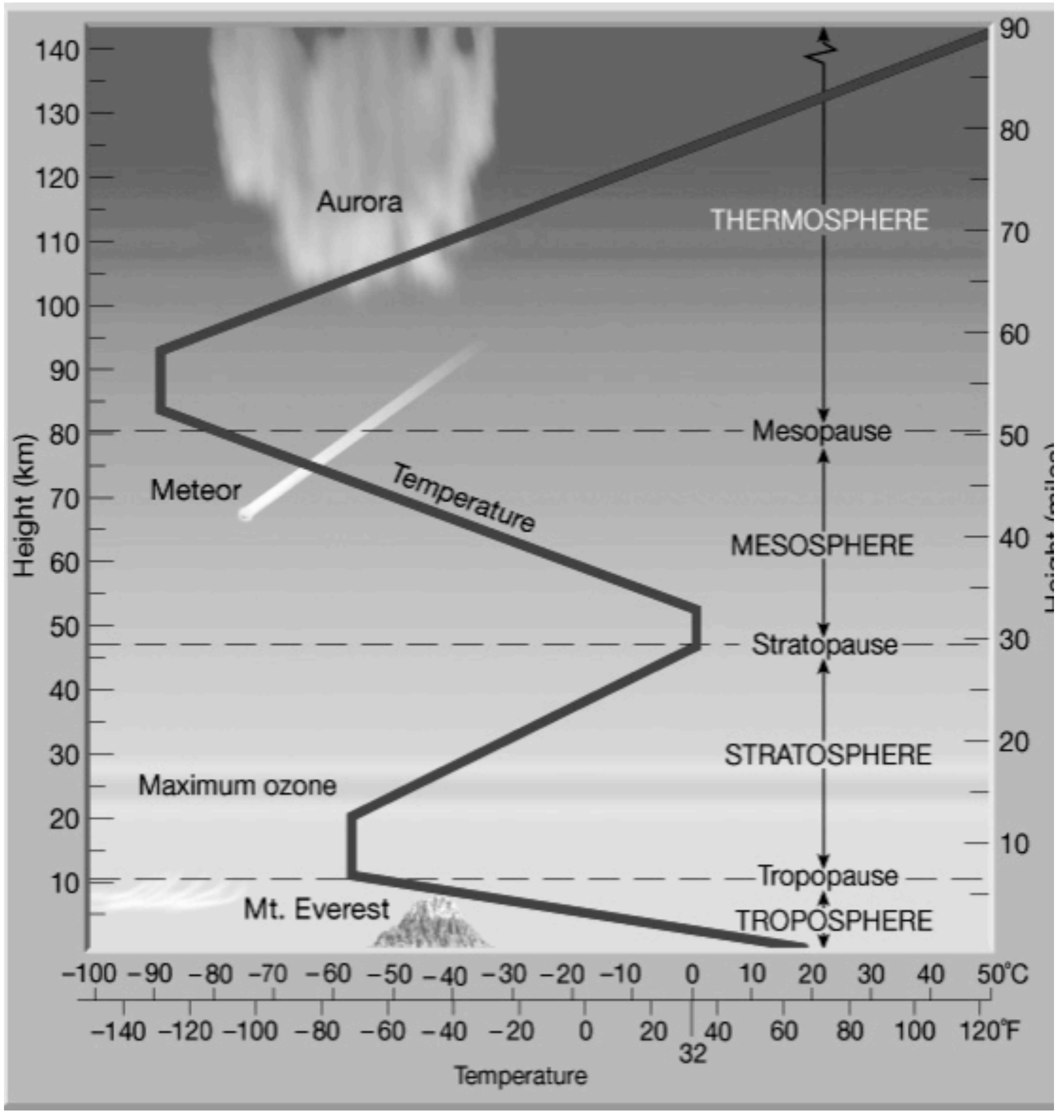
- As more arctic ice melts in summer, arctic ocean absorbs more light, temperature rises



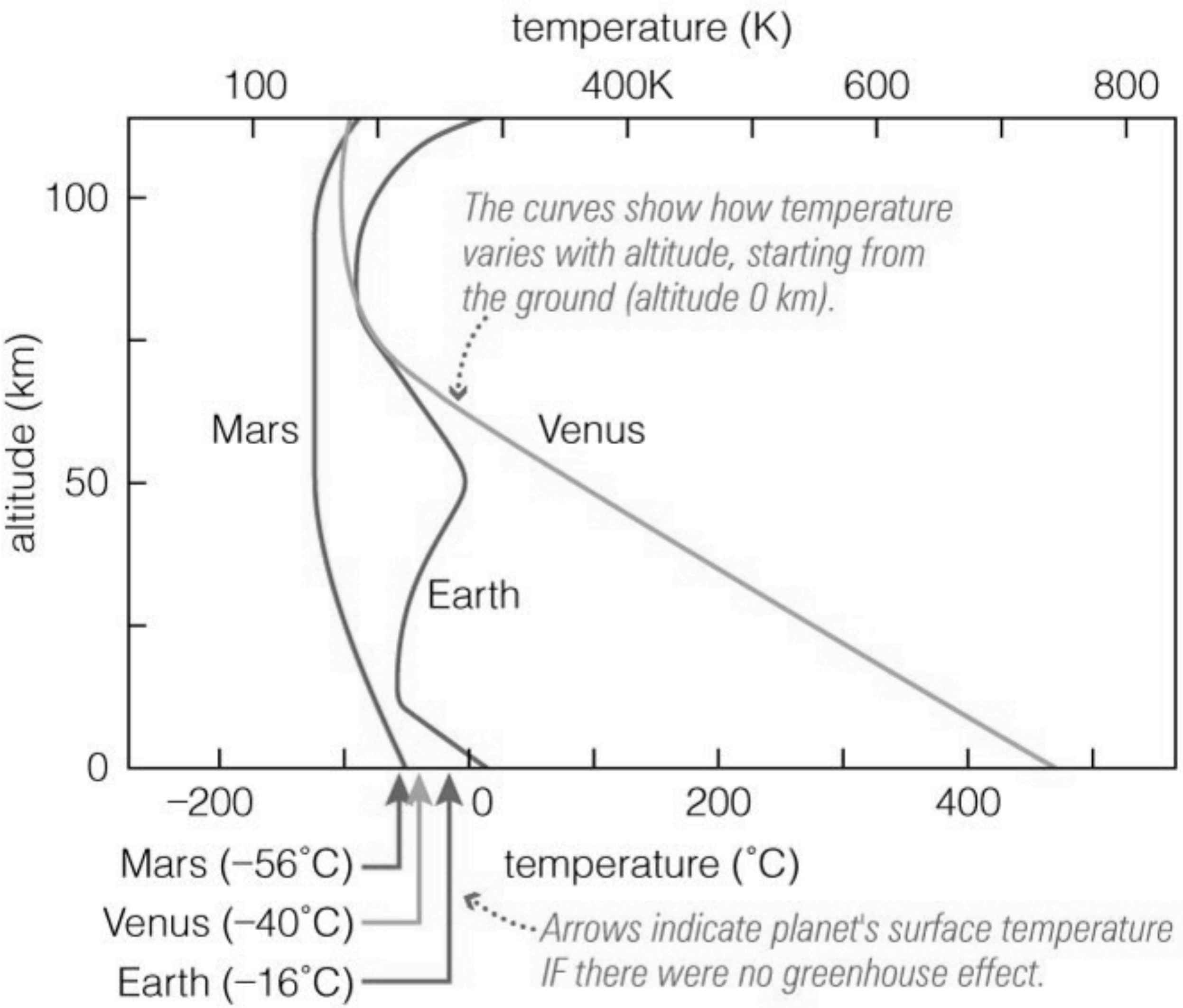
# Generic atmospheric structure



# Temperature structure of Earth's atmosphere



# Compare Earth, Venus, Mars

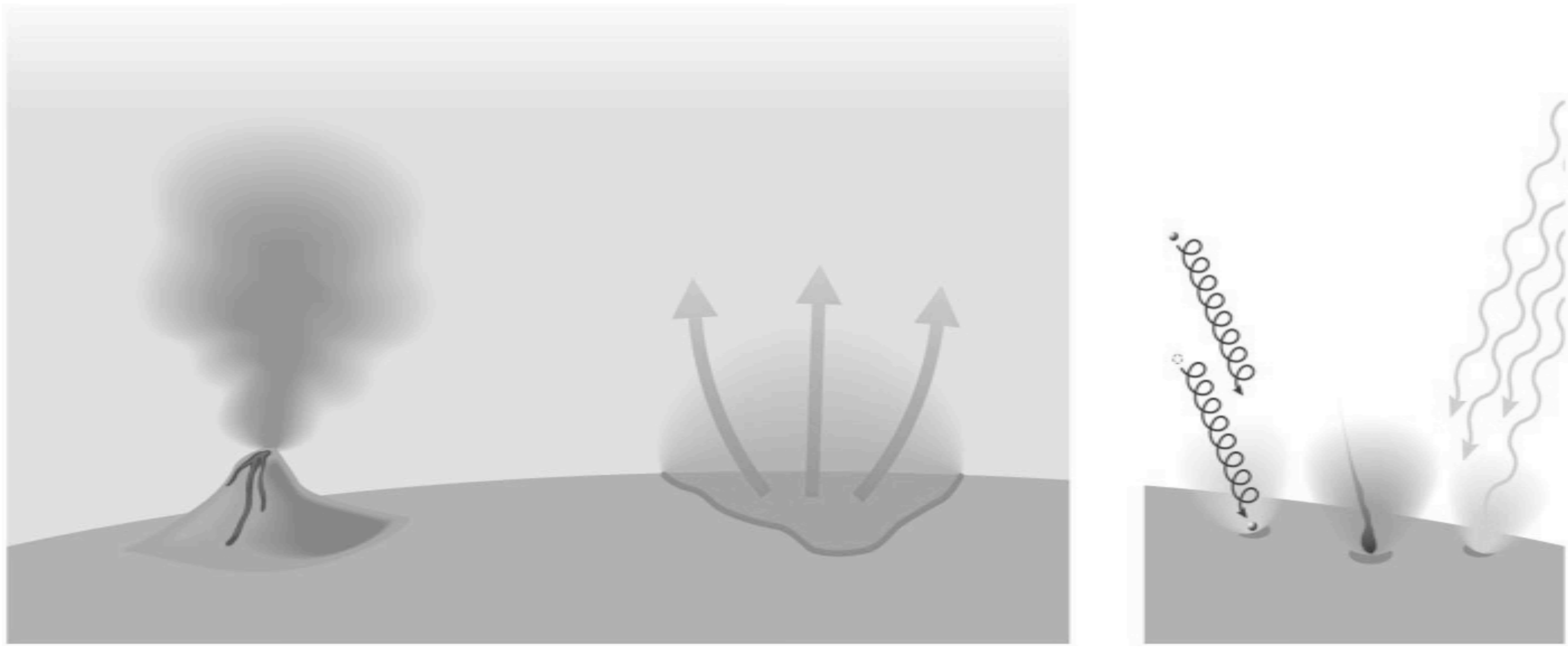


# *History of atmospheres on Venus, Earth, Mars*

- **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*

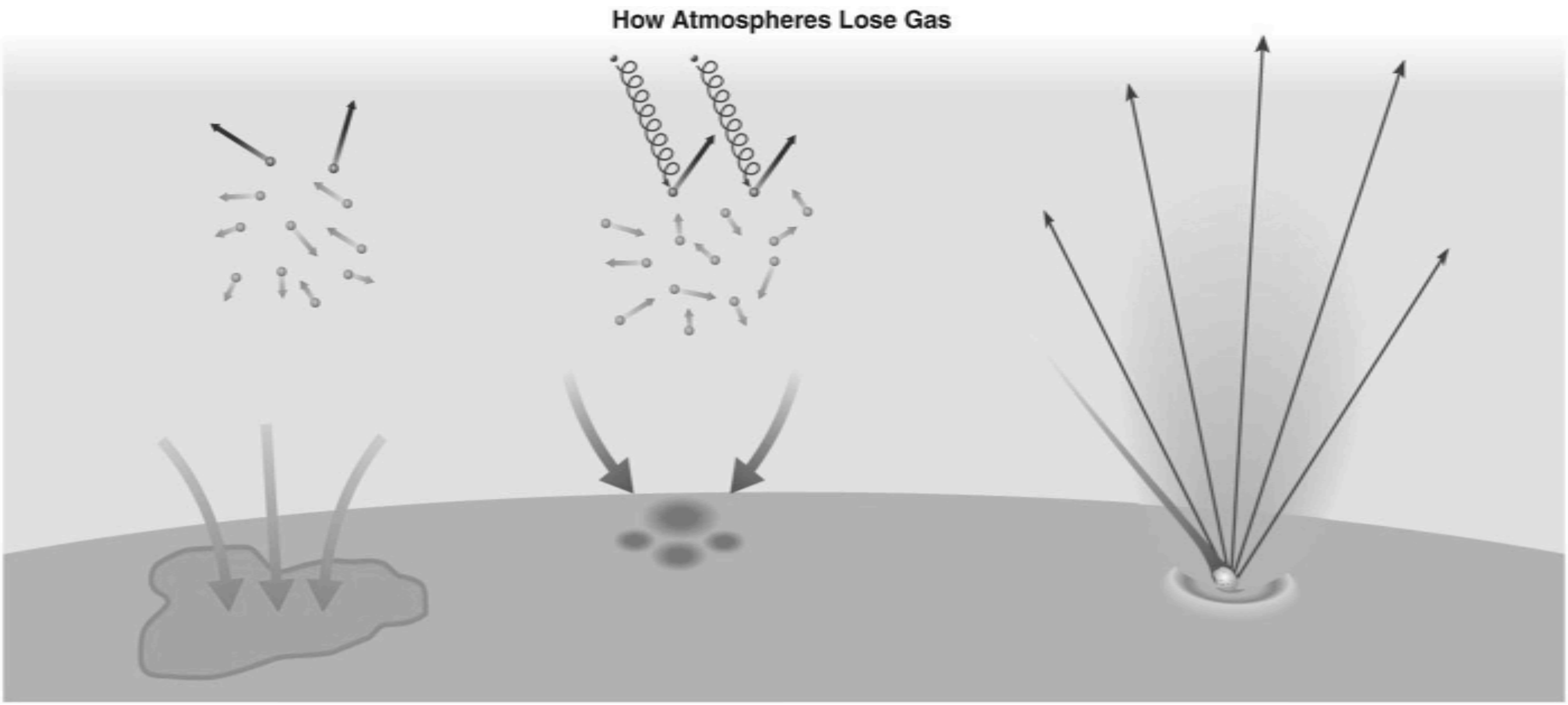
How Atmospheres Gain Gas



| Outgassing from volcanoes | Evaporation of surface liquid; sublimation of surface ice | Impacts of particles and photons eject small amounts |
|---|---|---|

# Kilauea volcano outgassing

# Losses of Atmospheric Gases

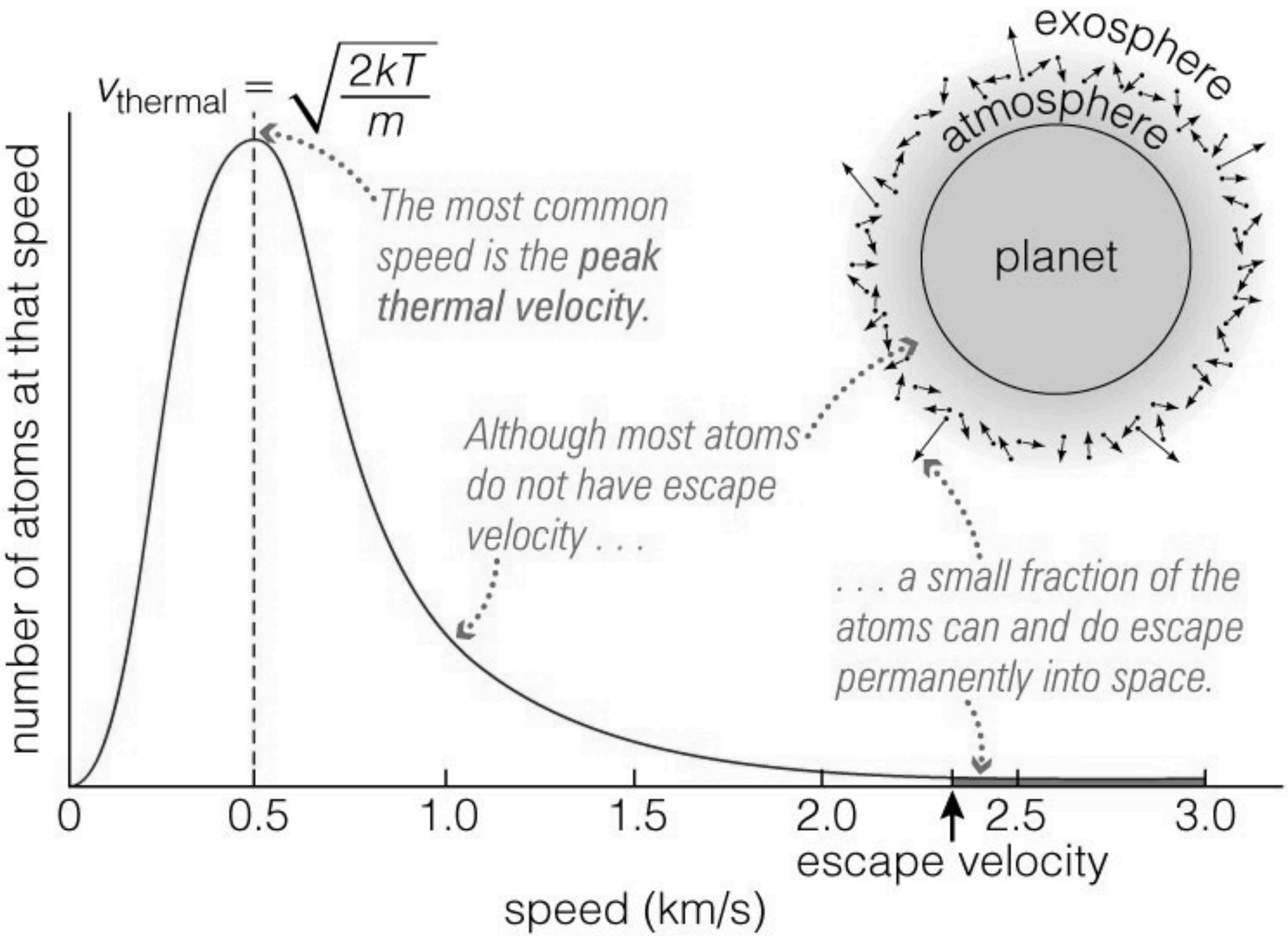



Condensation onto surface

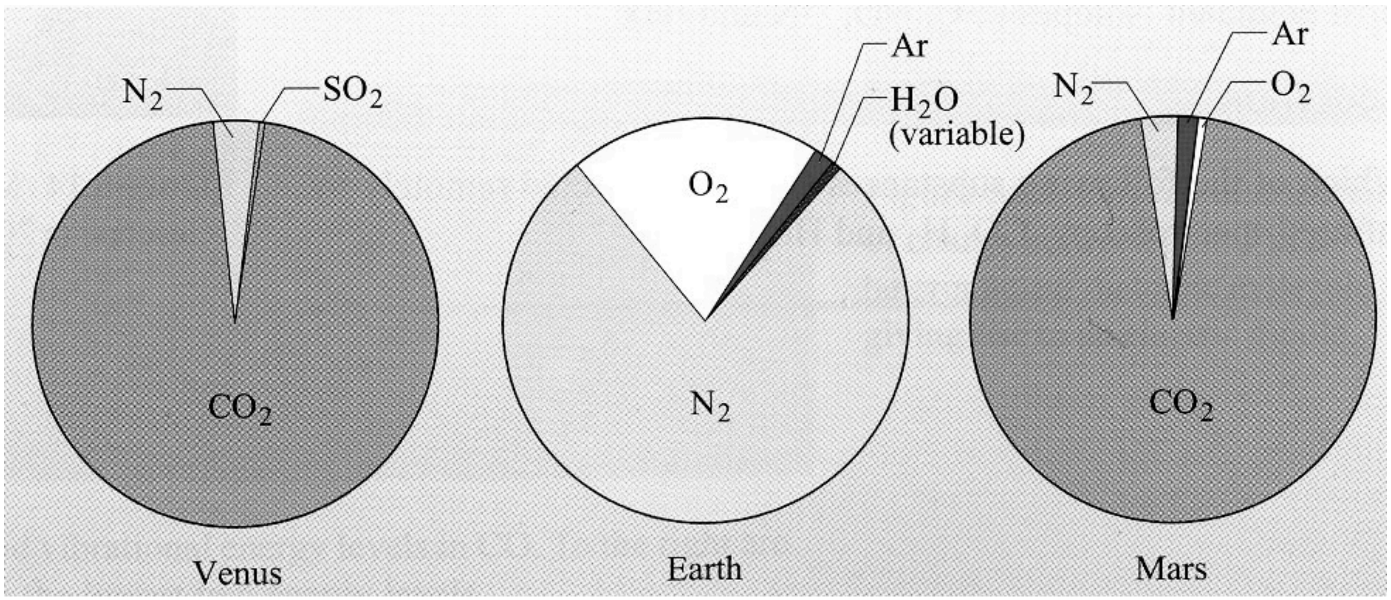
Chemical reactions with surface

Large impacts blast gas into space

# Thermal Escape of atmospheric gases



# 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

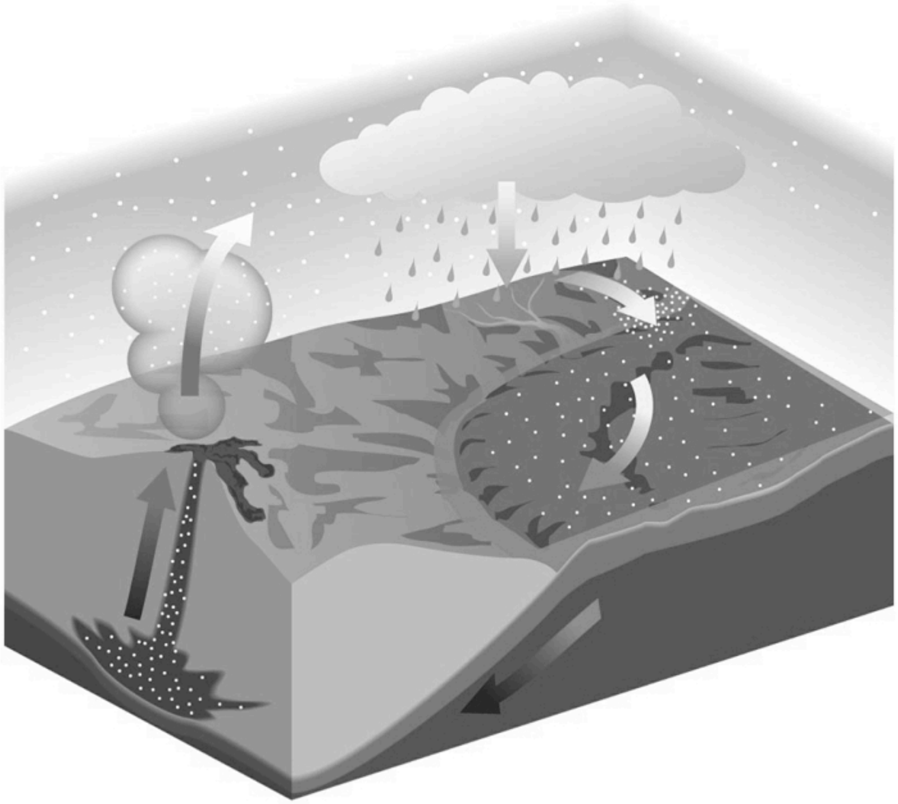
- Gases similar to those from modern volcanoes ($H_2O$, $CO_2$, $SO_2$, $CO$, $S_2$, $Cl_2$, $N_2$, $H_2$) and $NH_3$ (ammonia) and $CH_4$ (methane)
- No free oxygen ($O_2$ not found in volcanic gases)
- Ocean Formation - As Earth cooled, $H_2O$ produced by outgassing could exist as liquid
- $CO_2$ could 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: $CO_2 + H_2O$ + 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

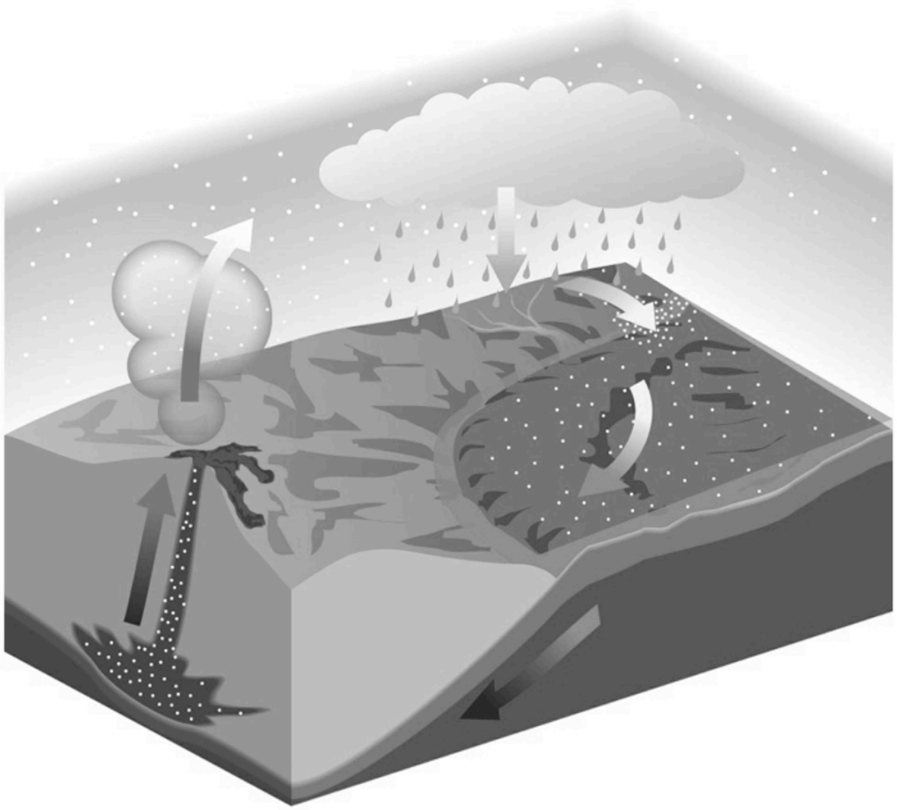
# *Why does Earth's climate stay relatively stable?*

The Carbon Dioxide Cycle



1. **Atmospheric $CO_2$ 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?*

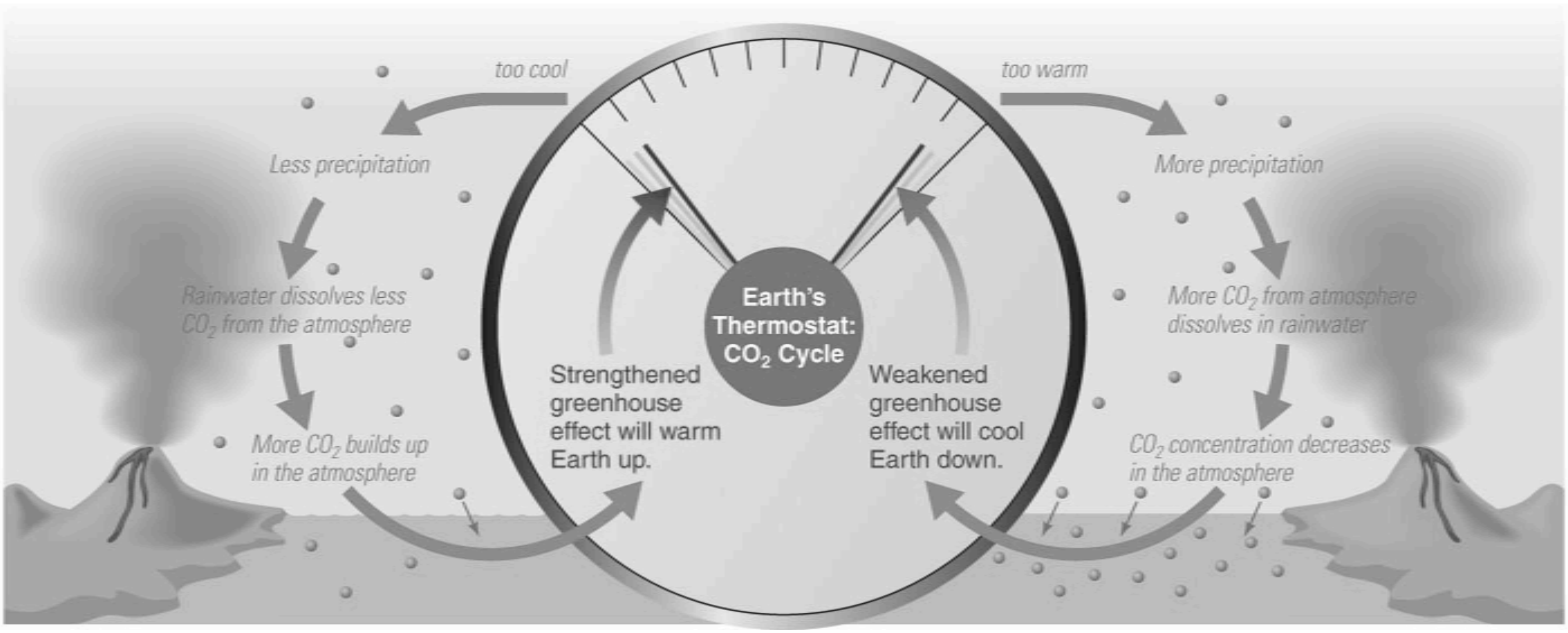


4. Subduction carries carbonate rocks down into mantle

5. Rocks melt in mantle and outgas $CO_2$ back into atmosphere through volcanoes

6. Note that Plate Tectonics is essential component of this cycle

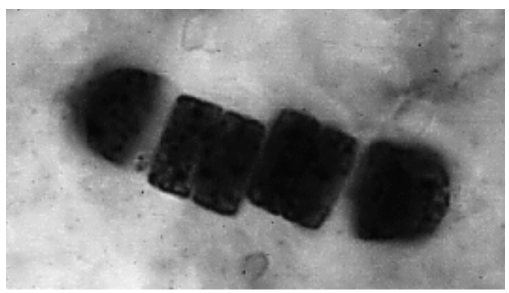
# Earth's Thermostat

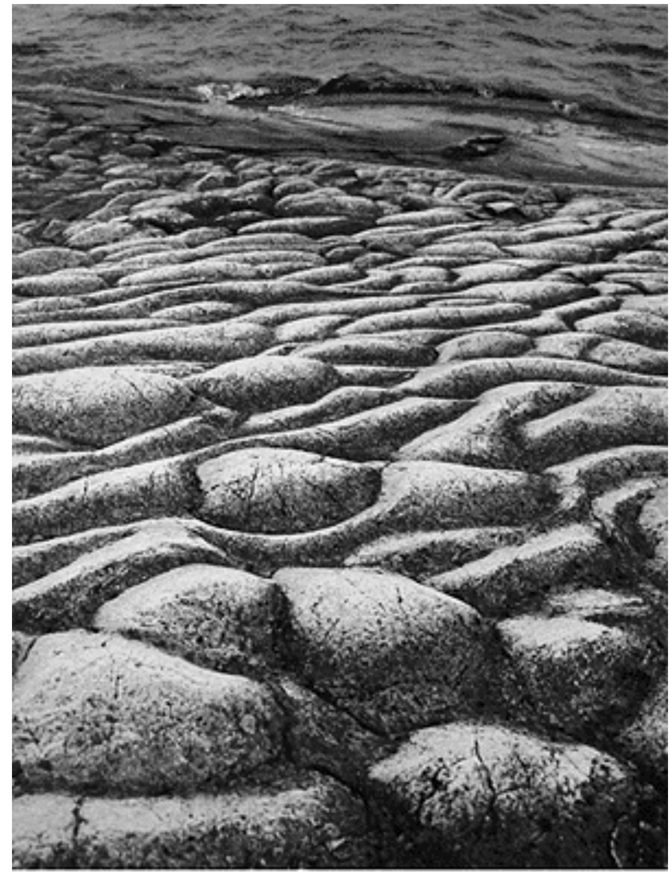



- **Cooling allows $CO_2$ to build up in atmosphere**
- **Heating causes rain to reduce $CO_2$ in atmosphere**

# *Cyanobacteria and stromatolites made early oxygen for atmosphere*

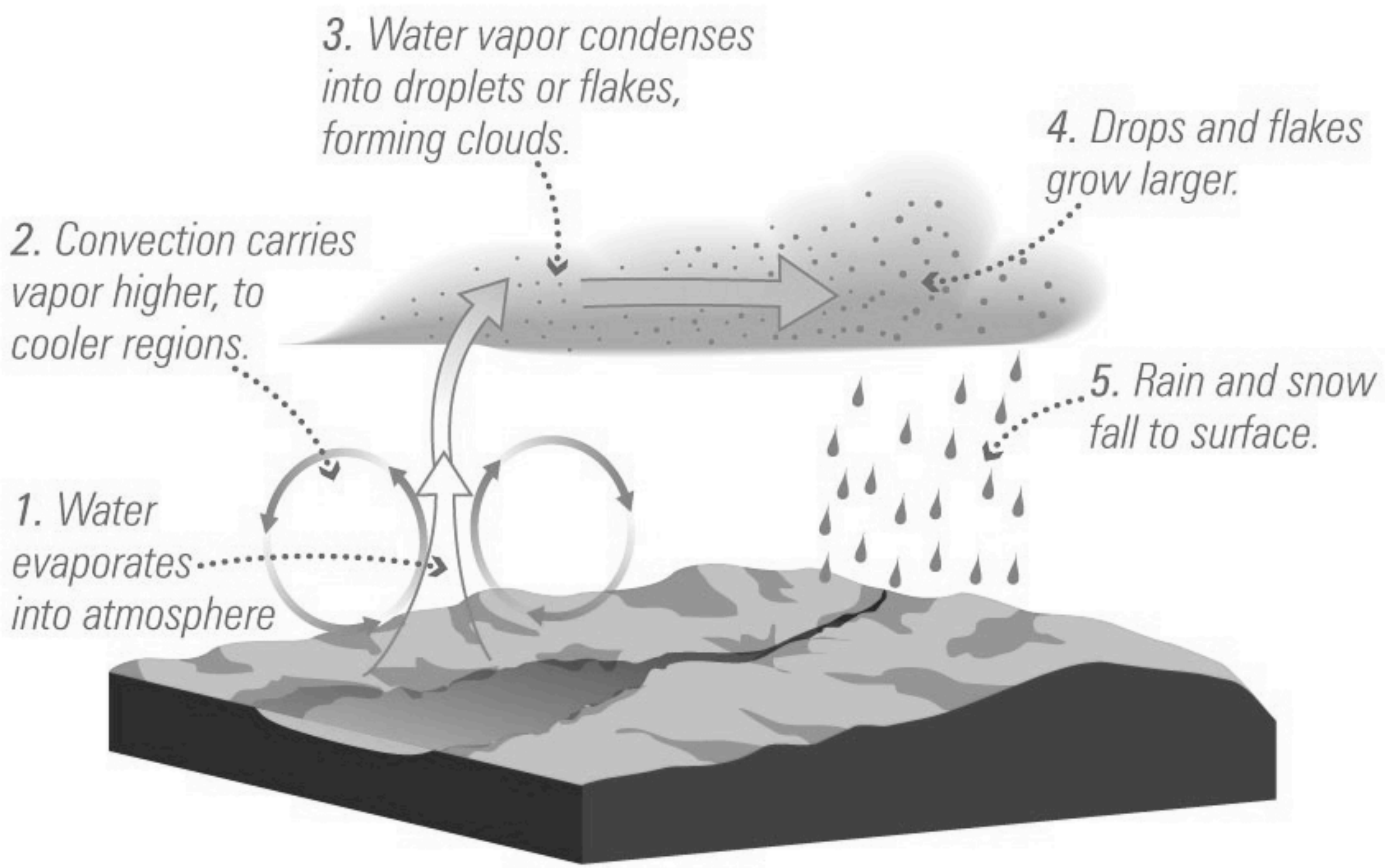
- **The first photosynthesis**
  - **Consumes $CO_2$, release $O_2$**





**Cyanobacteria: colonies are called stromatolites**

# Earth: hydrological cycle



# *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**

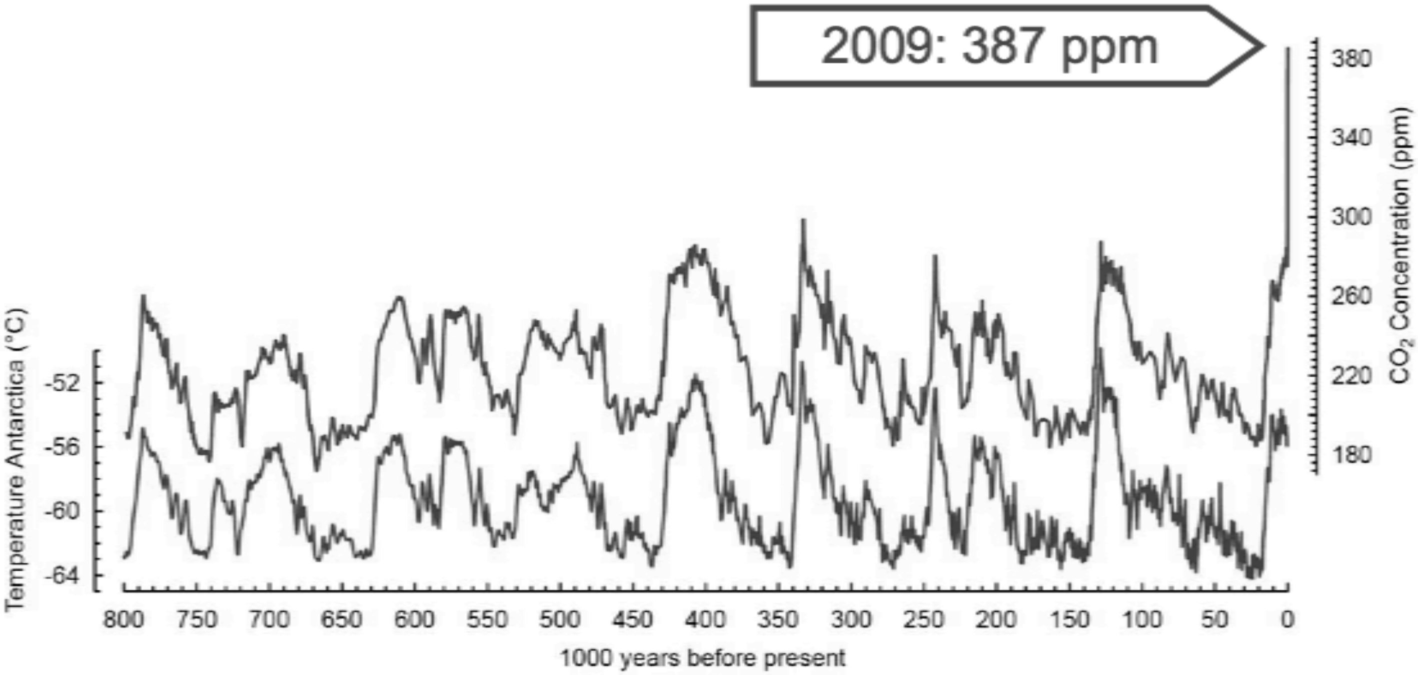
# Changes in Reflectivity

- 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

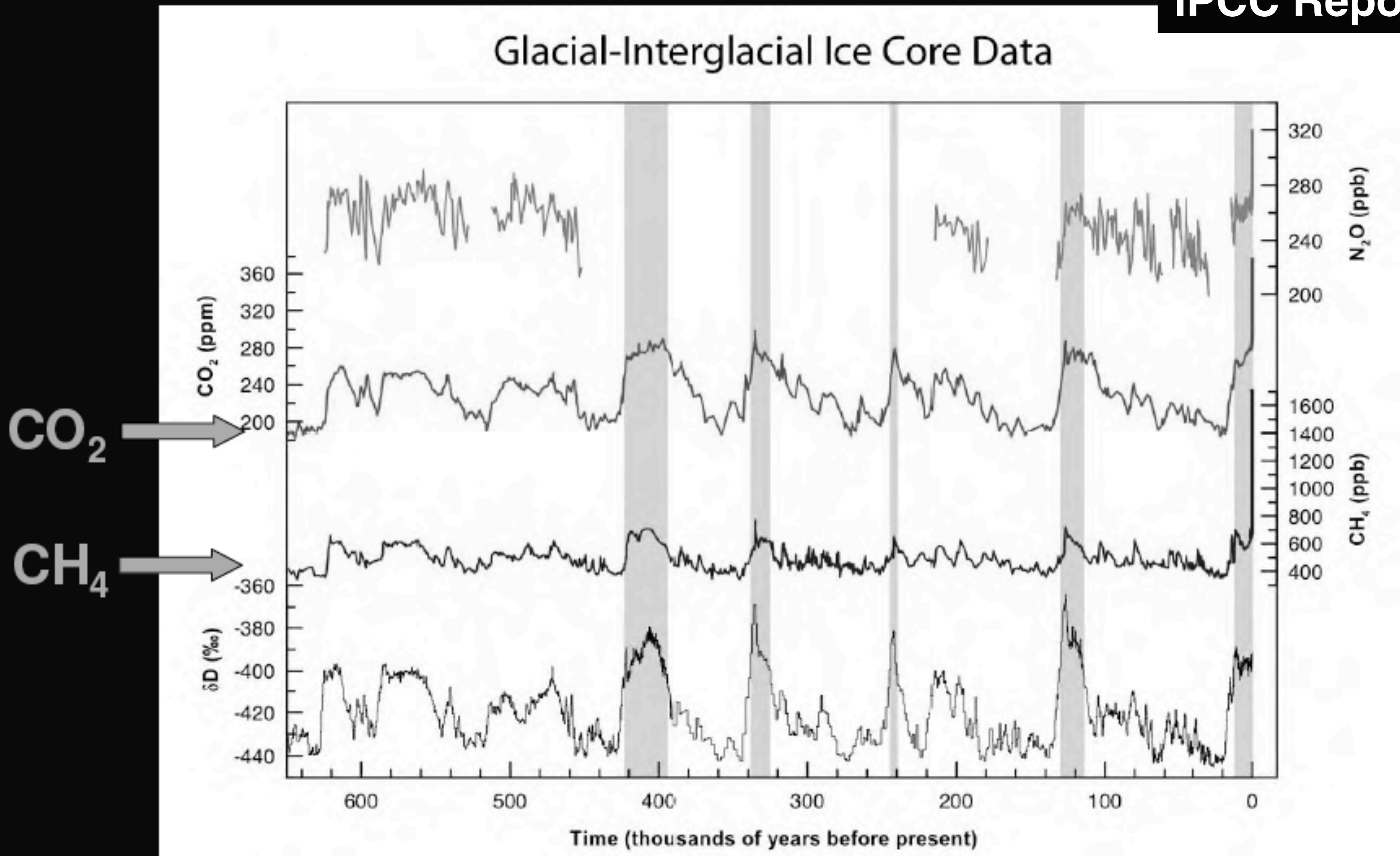



- Global temperatures have tracked $CO_2$ concentration for last 500,000 years
- Antarctic air bubbles indicate current $CO_2$ concentration is highest in at least 500,000 years

# *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/**

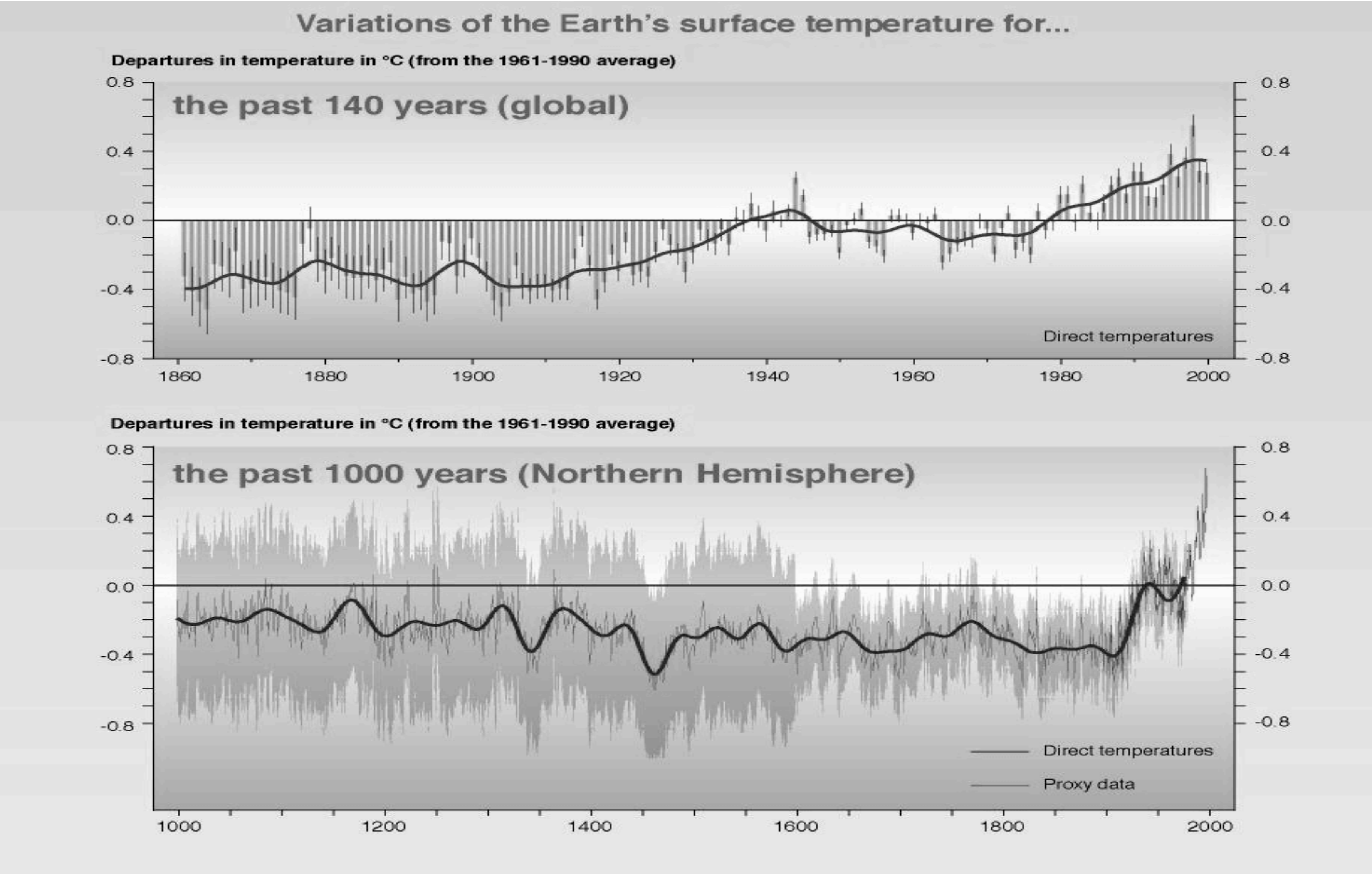
IPCC Report 2007




The atmospheric concentration of $CO_2$ and $CH_4$ in 2005 exceeds by far the natural range of the last 650,000 years

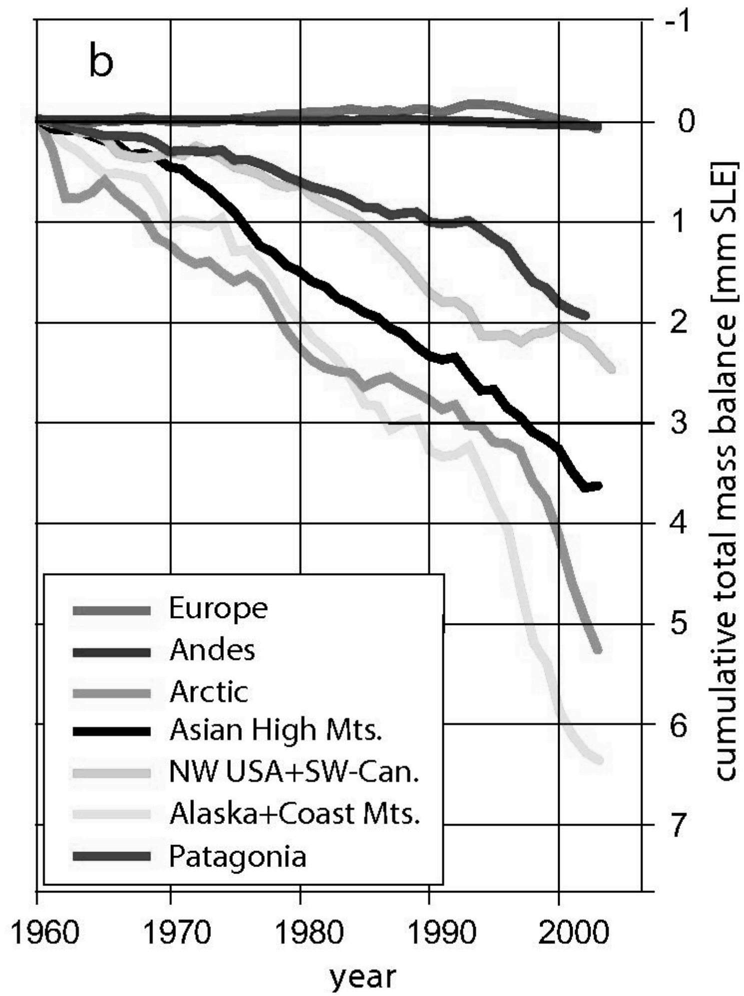
# Global mean surface temperatures have increased

IPCC Report 2007

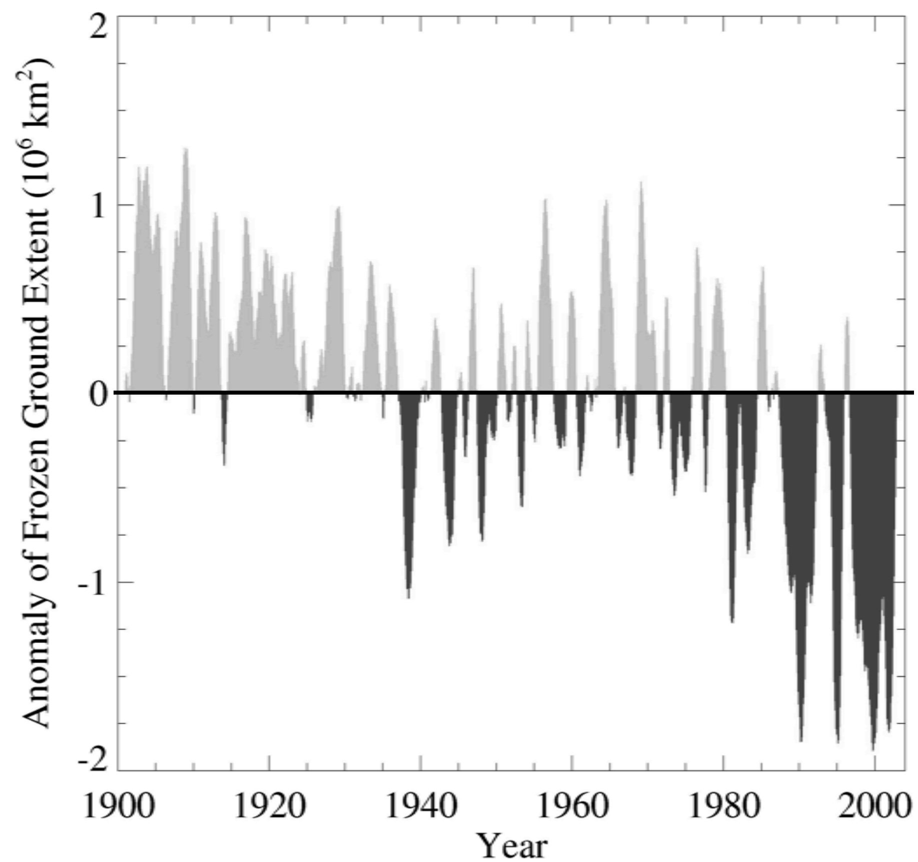


IPCC Report 2007

# *Glaciers and frozen ground are receding*

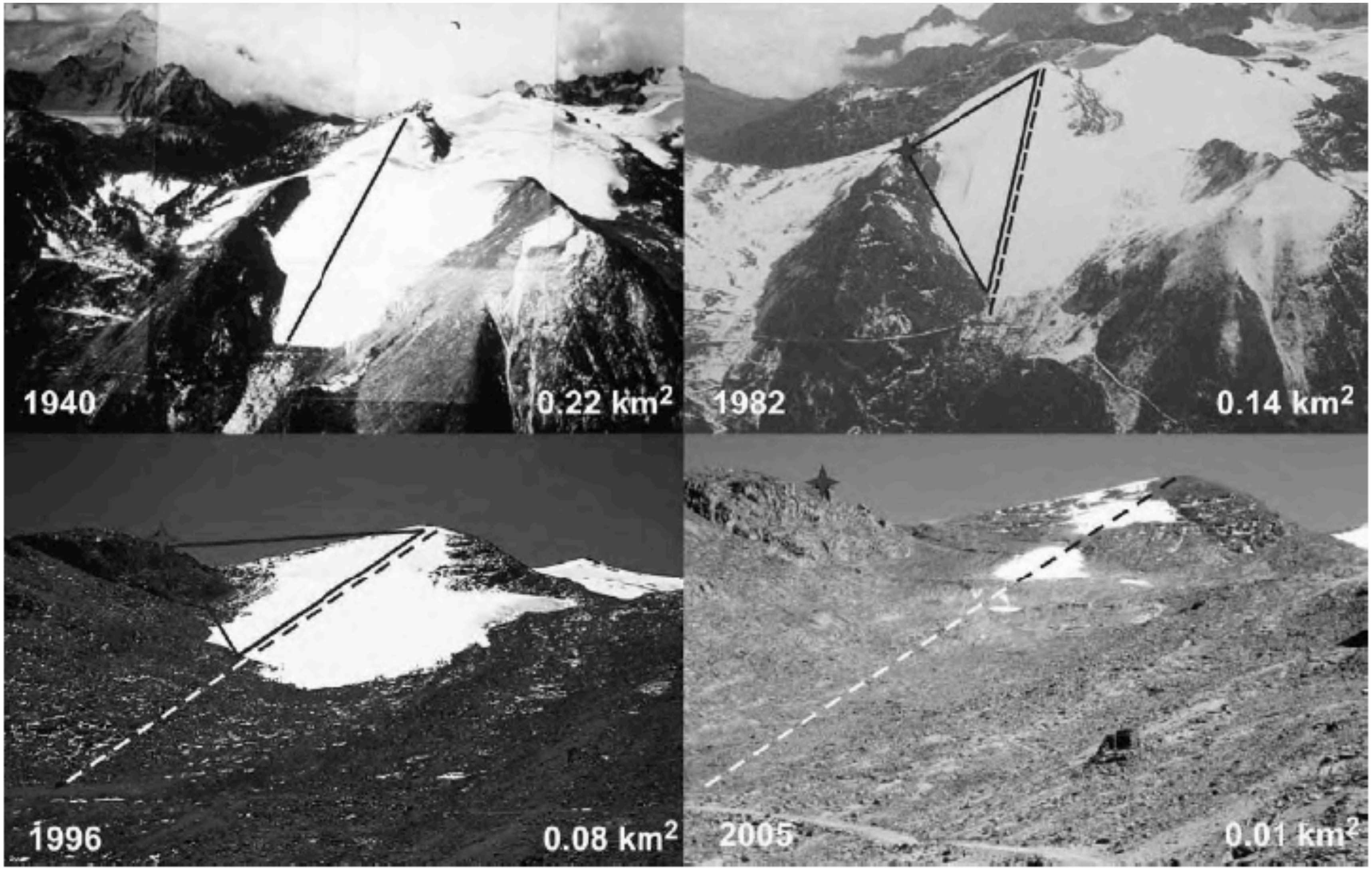



**Increased Glacier retreat since the early 1990s**



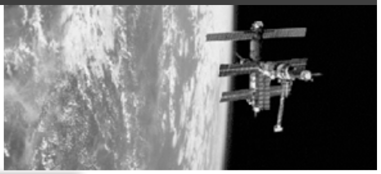

**Area of seasonally frozen ground in NH has decreased by 7% from 1901 to 2002**

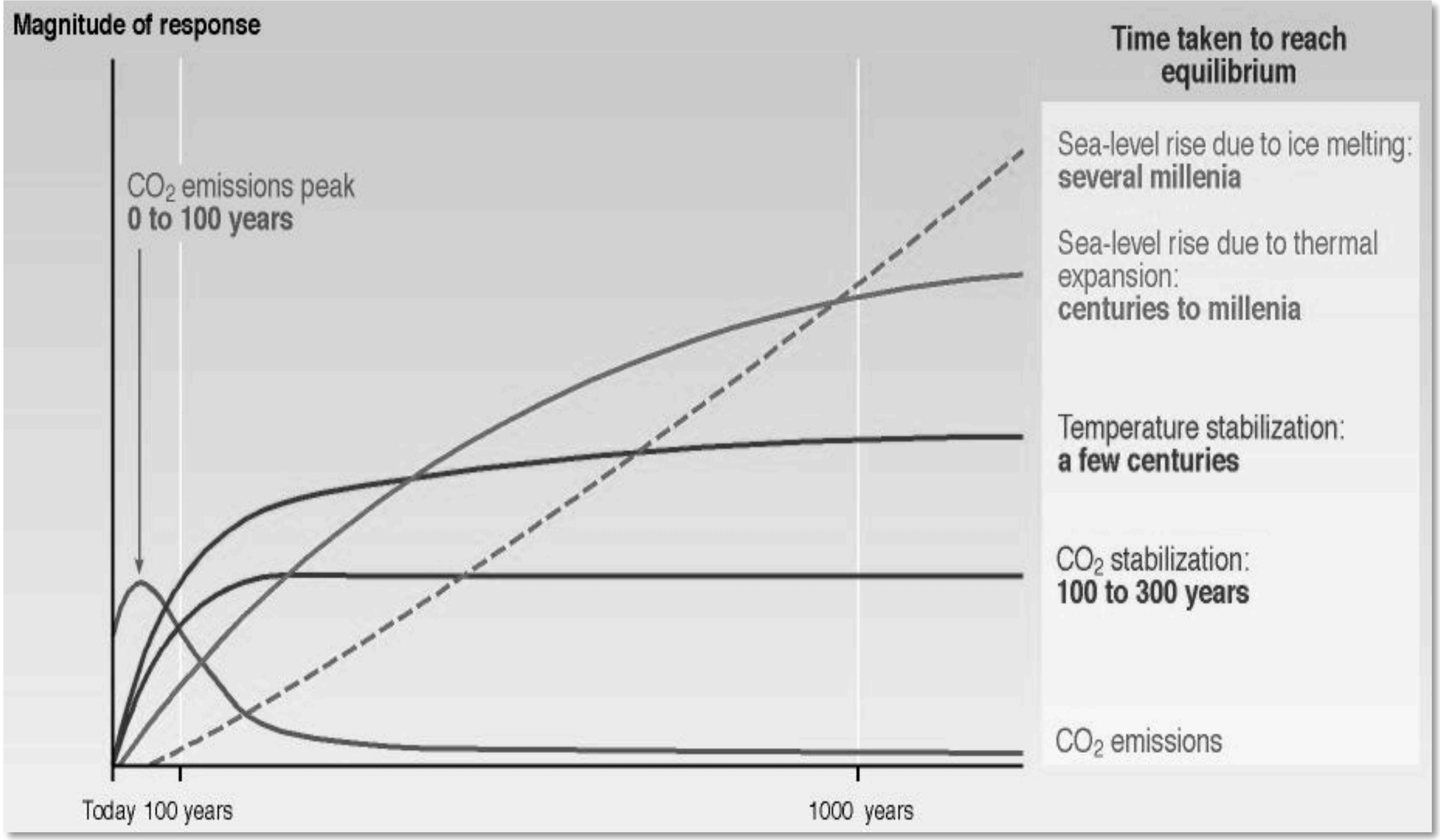
# The Chacaltaya Glacier and Ski Lift, Bolivia



# Global temperature will keep rising even after $CO_2$ emissions are reduced

IPCC Report 2007






**Once $CO_2$ gets into atmosphere, it stays there for hundreds of years!**

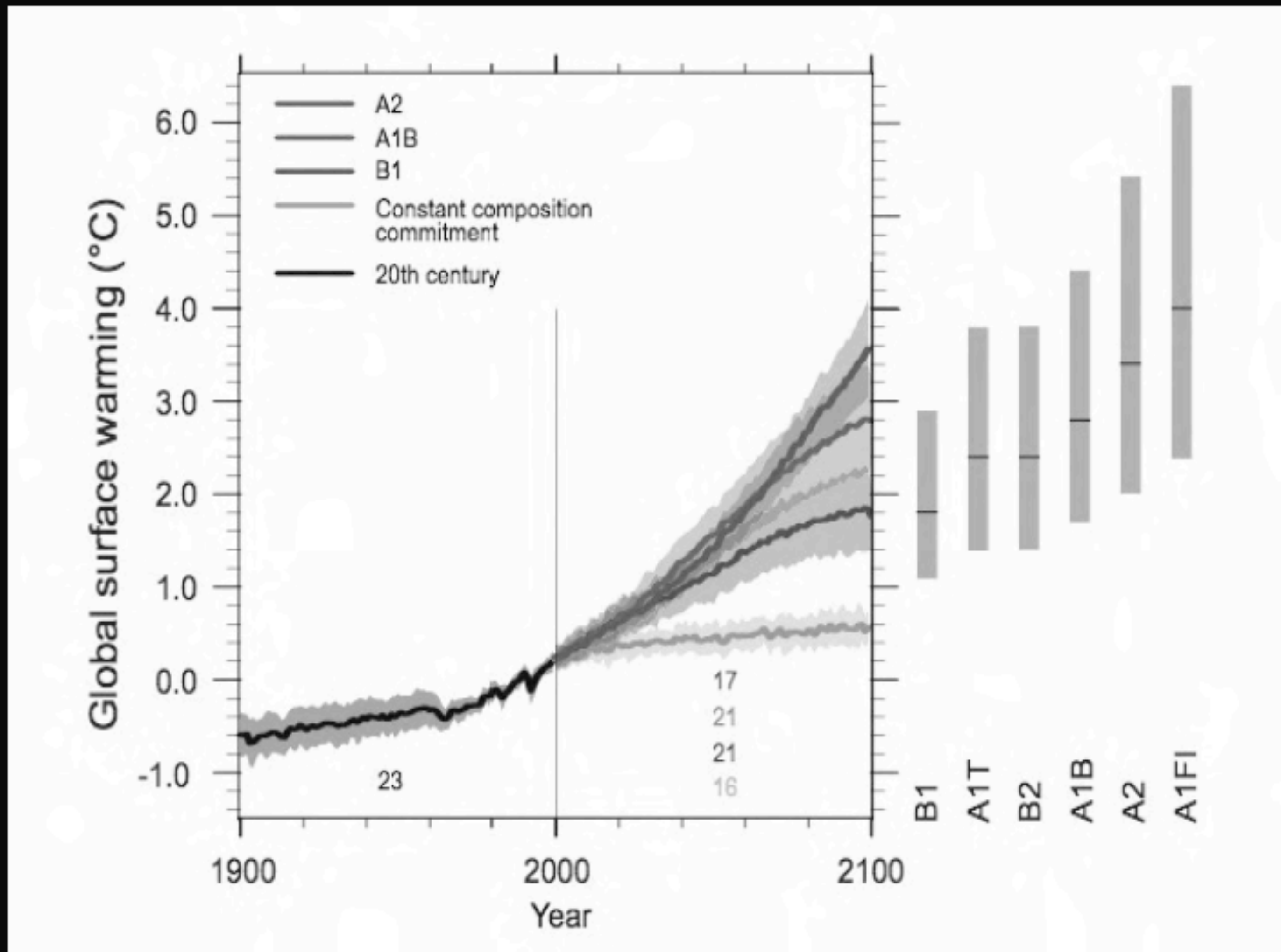
IPCC Report 2007

# Projections of Future Changes in Climate

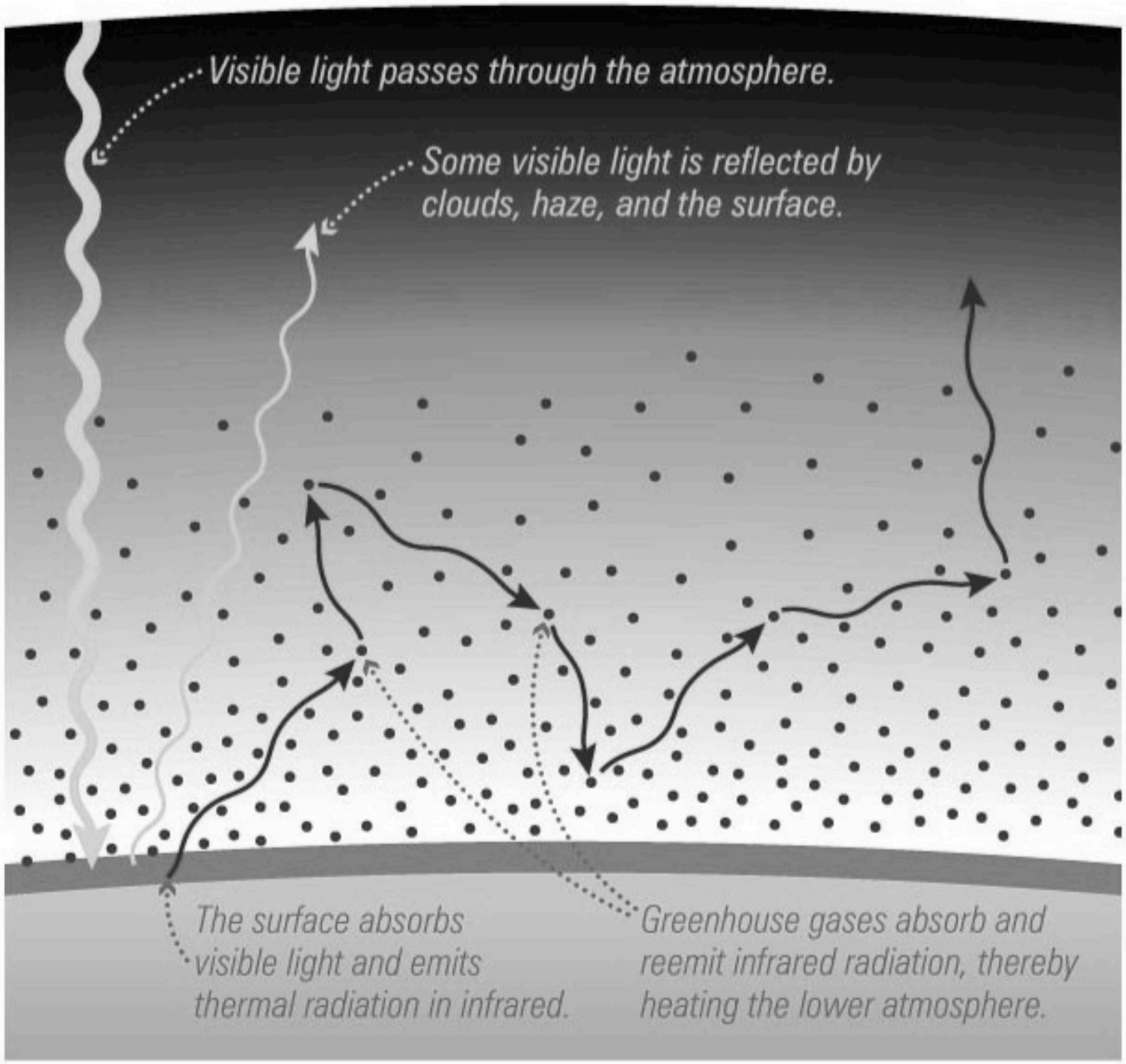
Best estimate for low scenario (B1) is 1.8℃ (*likely* range is 1.1℃ to 2.9℃),

and

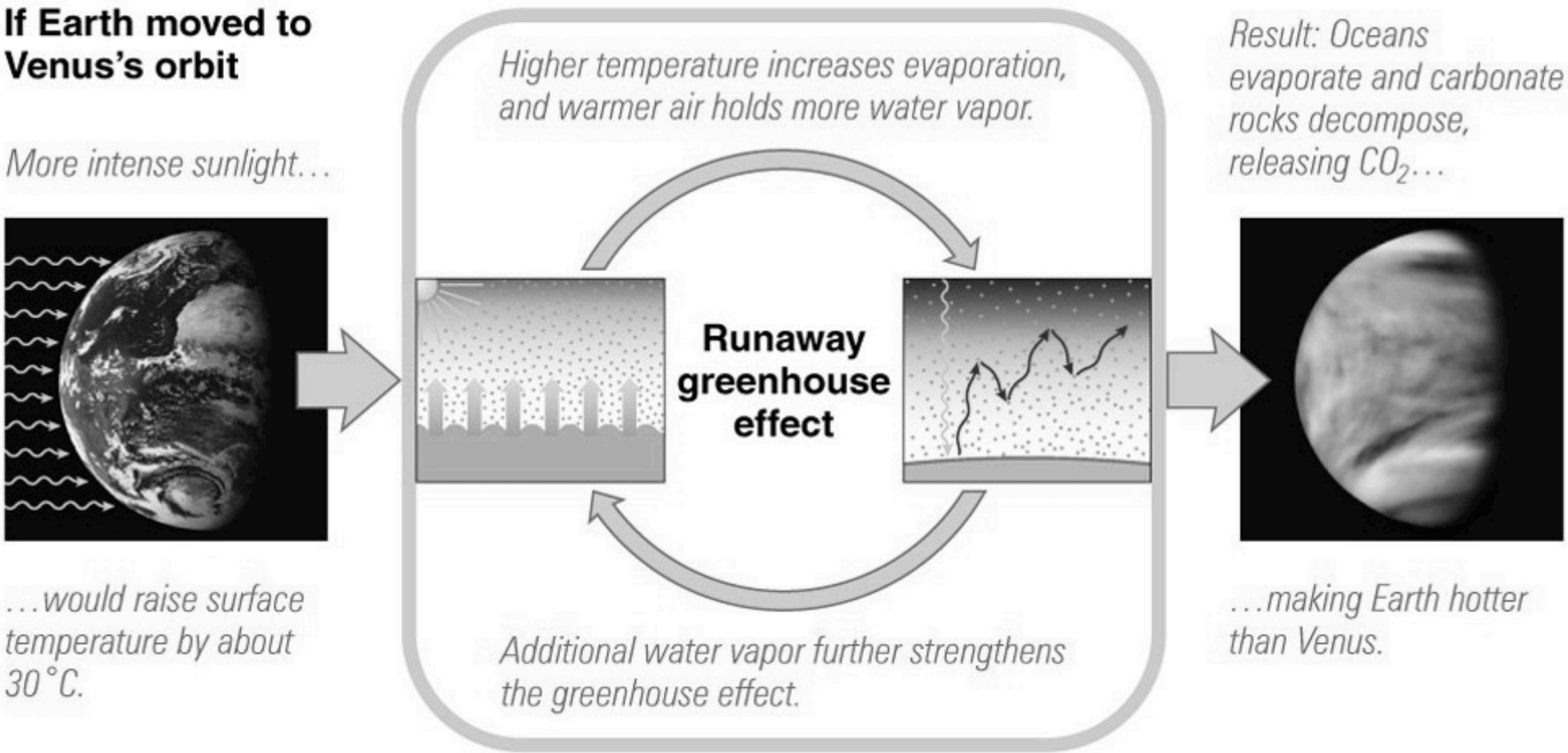
for high scenario (A1FI) is 4.0℃ (*likely* range is 2.4℃ to 6.4℃).



# The greenhouse effect: What about Venus and Mars?

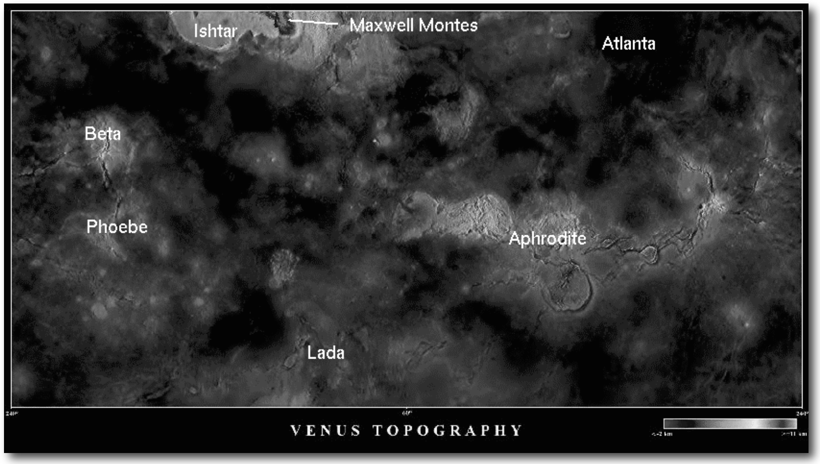


# Venus Climate

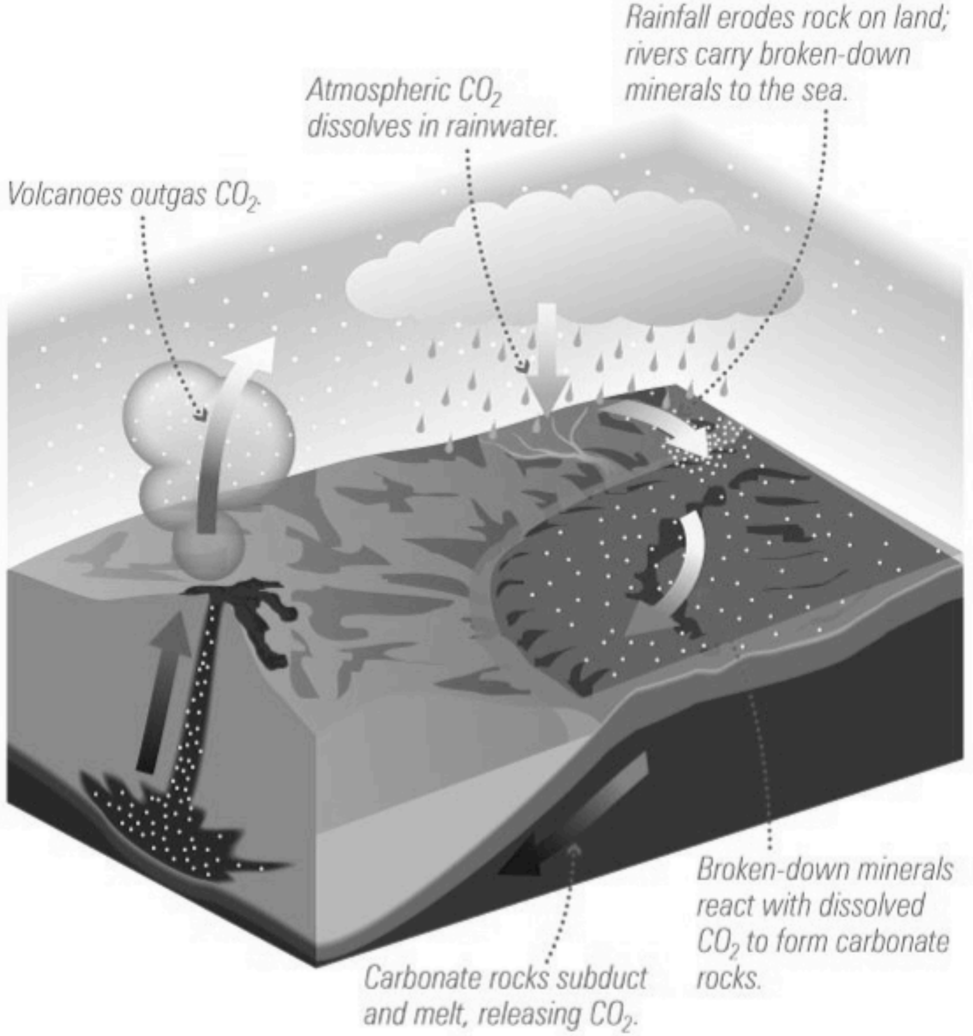


# Venus tectonics

- **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



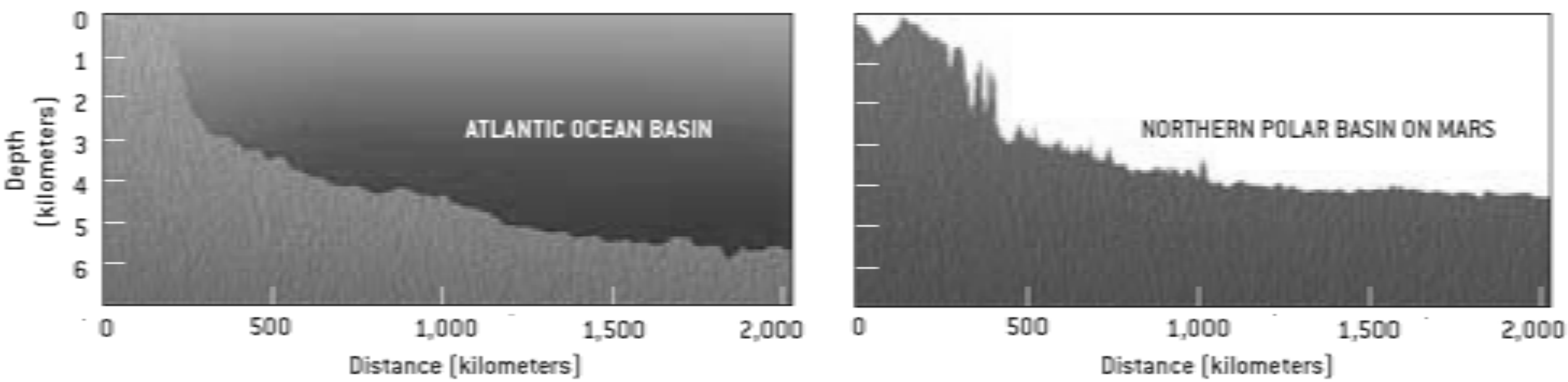

**Earth's carbon-silicate cycle**

# 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?

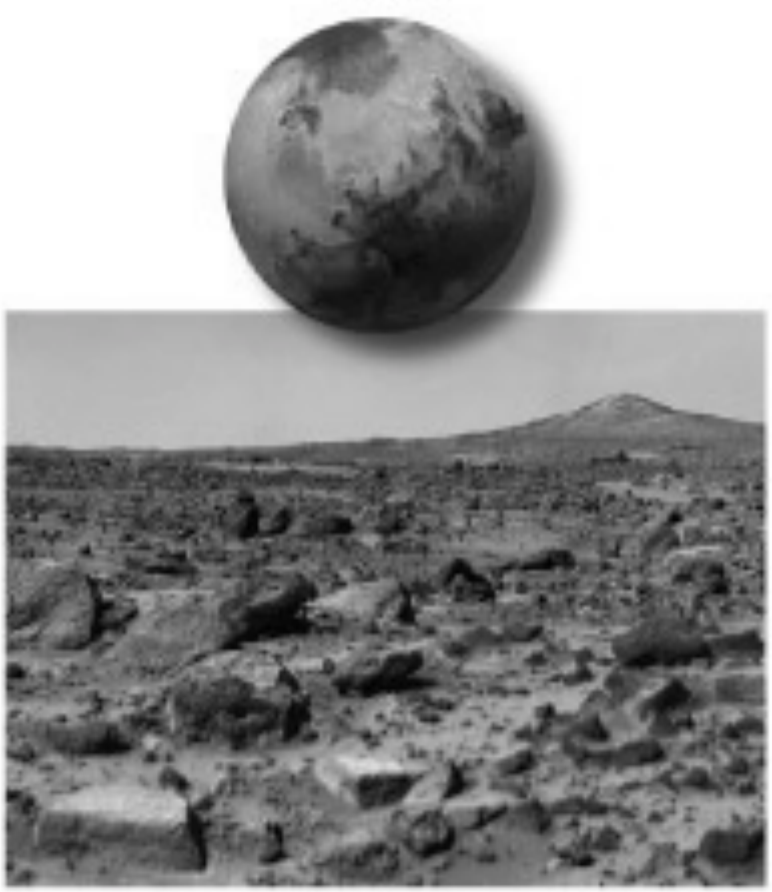
# *There was once liquid water on Mars*

- **Geomorphological evidence (*lots* of it)**
  - **River and flood channels, alluvial fans, slumps, canyons, ...**
- **One more piece of evidence: shape of ocean basins**



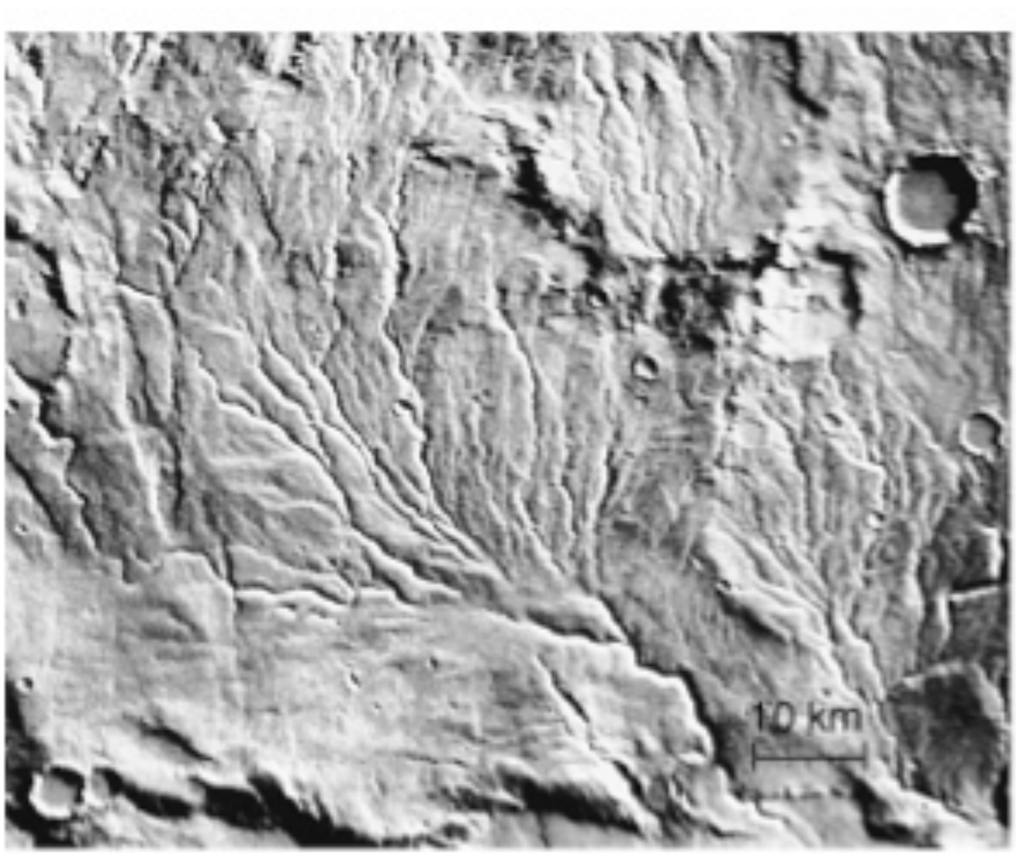

TOPOGRAPHIC MAPPING of Mars has recently revealed remarkable similarities to the ocean basins on Earth. For example, the western Atlantic near Rio de Janeiro (*left*) presents a similar profile to that of the northern polar basin on Mars (*right*).

# *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 $CO_2$ and $H_2O$ vapor into atmosphere, greenhouse effect increased temperature above 0 C (freezing) so liquid water could exist.
- Two competing effects determined amount of $CO_2$ in atmosphere: volcanoes adding $CO_2$, and rocks absorbing $CO_2$.  Result: moderate level of $CO_2$ .
- 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, $CO_2$ 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