They are very different

Mercury
- craters
- smooth plains
- cliffs
- no atmosphere

Venus
- Dense atmosphere
- $\text{H}_2\text{SO}_4$ clouds
- Radar can see through
Venus
volcanoes
few craters

Radar view of a twin-peaked volcano

Mars
some craters
volcanoes
riverbeds
thin atmosphere
The nebular theory says the terrestrial planets all formed at about the same time...
It says they formed from similar materials (rock and metal)...

So why have they turned out so differently?

To help figure it out, let’s ask some questions about our own planet Earth
Earth is geologically active…why?
Geological processes affect Earth’s surface…how?
What role does Earth’s atmosphere play?

Why is Earth geologically active?
The answer is inside…

The Structure of Earth’s Interior

- **Core**: Highest density; nickel and iron
- **Mantle**: Moderate density; silicon, oxygen, etc.
- **Crust**: Lowest density; granite, basalt, etc.
- **Lithosphere**: Crust and upper mantle; rigid
The Interiors of Other Terrestrial Planets

- The other terrestrial planets are similar
- They are made of rock and metal, too
- But why did the rock and metal separate?
- Salad dressing will help to explain...

Why do water and salad oil separate?

A. Water molecules repel oil molecules electrically.
B. Water is denser than oil, so oil floats on water.
C. Oil is more slippery than water, so it slides to the surface of the water.
D. Oil molecules are bigger than the spaces between water molecules.
**Differentiation**

- Water is denser than oil, so oil floats on water
- The explanation is similar for why rock and metal separate in Earth:
  - Metal is denser than rock
  - And some rock is denser than other rock
- This process is called “differentiation”
- It requires a *fluid consistency*, a *gravity* field, and a *mixture* of substances of different densities

**Concept Check**

What is necessary for *differentiation* to occur in a planet?

A. It must have metal and rock in it.
B. It must be a mix of materials of different density.
C. Material inside must be able to flow.
D. all of the above
E. a and b
F. b and c
G. a and c
Concept Check

What is necessary for differentiation to occur in a planet?

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F. b and c
G. a and c

Lithosphere

- The least dense stuff rises to the planet’s surface, cools, and becomes rigid
- This is the “lithosphere”
- It “floats” on the warmer, softer rock that lies beneath
- This softer rock underlies geological processes on Earth
- The soft rock has a fluid consistency because of Earth’s internal heat
- Without that heat, geological processes would not occur

Internal Heat Drives Geology

- The internal heat makes the mantle and the outer core molten
- And because they are hotter on the bottom... convection can occur
- Hot material rises, cool material falls
- “convection cells”, shown at right
- Convection is similar to differentiation, but does not need different materials
- It is very slow in the Earth... one turn around a convection cycle in the mantle (pictured) takes ~100 million years on Earth.
- Mantle movement is much slower than the hour hand on a watch
- There are several sources of internal heat...
Sources of Internal Heat

- Initially there were several different sources
  - Kinetic energy of accretion
  - Differentiation
  - Compression
  - Radioactivity

Heating of Interior over Time

- Accretion, differentiation, and compression were important when planets were young
- But no more
- Radioactive decay is the most important source today
- Of course, that heat must escape, because otherwise…

Cooling of Interior

- Convection transports heat as hot material rises and cool material falls
- Conduction transfers heat from hot material to cool material
- Radiation sends energy into space
- Heat loss causes the planet to cool
- How fast it cools depends on how big it is…
Suppose you baked a large potato and a small potato. Which one will cool off faster?
A. The large potato
B. The small potato

Surface Area to Volume Ratio

- How fast something cools depends on its surface-volume ratio
- How much heat something contains depends on its volume
- But heat must be lost through its surface
- So the more surface compared to volume, the faster it will cool

\[
\text{surface area to volume ratio} = \frac{\text{surface of sphere}}{\text{volume of sphere}} = \frac{4\pi r^2}{\frac{4}{3} \pi r^3} = \frac{3}{r}
\]

- Larger objects (bigger \( r \)) have less surface compared to volume
So what will cool off faster?
A. A big terrestrial planet
B. A tiny terrestrial planet

And observation bears this out

Role of Size

- Lithosphere is rigid, therefore cool
- Smaller worlds cool off faster and harden earlier.
- Moon and Mercury are now geologically “dead.”
Planetary magnetic fields are very important

- Moving charged particles create magnetic fields.
- If a planet’s metal core is hot enough (as Earth’s is) the metal will be molten
- Molten metal is ionized (electrically charged)
- If the core is hotter on the bottom than the top (as Earth’s is) it will convect
  → the electrically charged ions will move...
- If the planet is rotating relatively fast, as Earth is, this will generate a magnetic field
- This is good for us, because Earth’s magnetic field protects us from the solar wind

Earth’s Magnetosphere

The solar wind consists of high-speed charged particles
The magnetosphere diverts most of it around Earth
Otherwise, our atmosphere would be stripped away
Some of the particles do enter near the poles and collide with atmospheric gases
This creates the aurora borealis and aurora australis
Concept Check

If the planet core is cold, do you expect it to have magnetic fields?
A. Yes, refrigerator magnets are cold, and they have magnetic fields.
B. No, planetary magnetic fields are generated by moving charges around, and if the core is cold, nothing is moving.

Our terrestrial planets are thought to look like this inside
But why do we think this? How do we know?
We know what Earth is like from earthquakes…
How do we know what’s inside a planet?

- Earthquakes produce seismic waves
- There are two basic types: P waves and S waves
- P waves *push* matter back and forth.

- S waves shake it *sideways*

---

How do we know what’s inside a planet?

- Measure the seismic waves from an earthquake
- P waves go through Earth’s core
- S waves do not
- S waves need something firm to push back on their sideways motion
- As a result, they don’t travel well through liquid
- Analysis of the overall pattern of seismic waves gives the internal structure

---

How do we know what’s inside a planet?

- Seismology for the Earth (P waves, S waves, etc)
- For other planets and the Moon
  - Seismology
  - Flybys
    - Gravitational field measurements
    - Magnetic field measurements
  - Size and density considerations
• From these methods, the interiors of our terrestrials appear similar
  • But their surfaces are quite different

  • Apparently there are processes at work that cause the differences
  • These processes are called “geological processes”
  • What are they?
  • We know most about Earth, so we’ll start there to find out…

Questions

• Why is Earth geologically active?
• What processes shape Earth’s surface?
What processes shape Earth’s surface?
…and might do the same on the other terrestrial planets…

Geological Processes

• Impact cratering
  — Impacts by asteroids or comets
• Volcanism
  — Eruption of molten rock onto surface
• Tectonics
  — Disruption of a planet’s surface by internal stresses
• Erosion
  — Surface changes made by wind, water, or ice
Impact Cratering

• Most cratering happened soon after the solar system formed
• But it still happens today
• And it affects everything in the solar system
• Craters are about 10 times wider than objects that made them
• Let’s look at some examples

Impact Craters

Meteor Crater (Arizona)
• ~50,000 years old
• ~4,000 feet across
• ~550 feet deep

Tycho (Moon)
• ~108 million years old
• ~50 miles across
• ~3 miles deep

Impact Craters

Round Marsh?
• Timucuan Ecological and Historic Preserve
• ~300 meters across
• Historical evidence for impact in 1565?
Geological Processes

- Impact cratering
  - Impacts by asteroids or comets
- **Volcanism**
  - Eruption of molten rock onto surface
- Tectonics
  - Disruption of a planet's surface by internal stresses
- Erosion
  - Surface changes made by wind, water, or ice

Volcanism

- Volcanism happens when molten rock (magma) finds a path through lithosphere to the surface.
- To have volcanism, you need:
  - a molten interior
  - a thin lithosphere
- So you don’t expect volcanism on small planets

Volcanism

- Molten rock is called lava after it reaches the surface.
- Lava can create surface features, or cover them over
Lava and Volcanoes

- Runny lava makes flat lava plains.
- Slightly thicker lava makes broad shield volcanoes.
- Thickest lava makes steep stratovolcanoes.

Volcanoes are major contributors to the atmosphere
- This is because they release gases from planetary interiors
- This is called “outgassing”
- It’s where most of the atmosphere comes from
- There are a couple of other sources as well…

Ways to add gas to an atmosphere

- Gas must be taken out of the atmosphere as well…
Ways to take gas out of an atmosphere

- Thermal escape, bombardment, and atmospheric cratering lead to permanent loss
- Condensation is completely reversible
- Chemical removal is potentially reversible

Geological Processes

- Impact cratering
  - Impacts by asteroids or comets
- Volcanism
  - Eruption of molten rock onto surface
- Tectonics
  - Disruption of a planet’s surface by internal stresses
- Erosion
  - Surface changes made by wind, water, or ice

Tectonics

- Convection of the mantle creates stresses in the crust called tectonic forces.
Convection of the mantle creates stresses in the crust called tectonic forces. Compression forces make mountain ranges. Where the crust is compressed mountain ranges can form. Where it’s stretched, valleys can form. There’s a special kind of tectonics on Earth…Plate tectonics

Earth’s continents move around on separate plates of crust. This is important for life here on Earth. We’ll get to that later.
Geological Processes

- Impact cratering
  - Impacts by asteroids or comets
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Erosion

- Erosion is term covering all processes that break down or transport rock.
- Most are weather-driven
- Processes that cause erosion include
  - Glaciers
  - Rivers
  - Wind

Erosion by Ice

- Glaciers carved the Yosemite Valley.
Erosion by Water

• The Colorado River continues to carve the Grand Canyon.

Erosion by Wind

• Wind wears away rock and builds up sand dunes.

Erosional Debris

• New features can be created by depositing debris from erosion.
• Extensive erosion happens on Earth because of our atmosphere.
• But erosion can happen even without an atmosphere…
Erosion without an Atmosphere

- This is a footprint made by Apollo 11 astronaut Buzz Aldrin on the Moon
- It is in the “lunar regolith”
- Billions of years of micrometeorite impacts have pulverized the lunar surface
- And in time, they will erase this footprint

Summary of Geological Processes

- Impact cratering
  - Impacts by asteroids or comets
- Volcanism
  - Eruption of molten rock onto surface
- Tectonics
  - Disruption of a planet’s surface by internal stresses
- Erosion
  - Surface changes made by wind, water, or ice

Questions

- Why is Earth geologically active?
- What processes shape Earth’s surface?
- How does Earth’s atmosphere affect the planet?
Effects of Atmosphere on Earth

- There are a variety of effects caused by the atmosphere
- Erosion is one
- Radiation protection
- Sky color
- Greenhouse effect

Radiation Protection

- Sunlight contains X-rays and ultraviolet light
- But Earth’s atmosphere prevents them from reaching the ground
- X-rays are absorbed very high in the atmosphere
- Ultraviolet light is absorbed by ozone (O₃)
- This is fortunate for surface-dwelling organisms, like us
- Both X-rays and UV are harmful to biological organisms
- But it is unfortunate for ground-based X-ray and UV telescopes

- In fact, our atmosphere absorbs most wavelengths of light
- Only visible light and some radio-wavelength light get all the way to sea level
- All wavelengths of visible light get through, so the sky should be white, right?
- But it is not white, it’s blue
- Let’s do a survey to see if you know why…
Why is the sky blue?
A. The sky reflects light from the oceans.
B. Oxygen atoms are blue.
C. Nitrogen atoms are blue.
D. Air molecules scatter blue light more than red light.
E. Air molecules absorb red light.

Why the sky is blue
- The atmosphere scatters blue light from the Sun off to the side
- It comes to you from all directions
- So the sky is blue
- Sunsets (and sunrises) are red
- Why?
- When the Sun is low, the light travels through more air to get to you
  - By the time it gets to you blue light has been scattered out

Why is the sky blue?
A. The sky reflects light from the oceans.
B. Oxygen atoms are blue.
C. Nitrogen atoms are blue.
D. Air molecules scatter blue light more than red light.
E. Air molecules absorb red light.
• Most visible light does reach the ground
• When it does, it heats it up
• And that is essential for the “greenhouse effect”

The greenhouse effect requires “greenhouse gases”
• Greenhouse gases are gases that absorb infrared light

In the animation, sunlight is warming the surface of a planet with no atmosphere
• The warm surface emits thermal radiation in the infrared (which we experience as heat)
• With no greenhouse gases, the infrared heat escapes into space
• The surface of the planet reaches some equilibrium temperature
• But with greenhouse gases...
• Infrared light doesn’t escape as quickly
• And the equilibrium temperature is higher
• Typical greenhouse gases have molecules with more than two atoms (CO₂, H₂O, CH₄)
• Non-greenhouse gases have molecules with one or two atoms (O₂, N₂)

Is the Greenhouse Effect Bad?
• The answer is...
  ...it depends
• On Earth, if it weren’t for the greenhouse effect, liquid water would not exist...
  ...and neither would we
• So that’s good
• But the greenhouse effect can be very bad, as exemplified by Venus
• We’ll come back to that later...
• But first, we’re going to consider what has happened on the other terrestrial planets in our solar system
Was there ever geological activity on the Moon or Mercury?

Moon

- The Moon was volcanically active 3 billion years ago
- Lava flooded lunar craters, creating lunar maria
- But the Moon is now as good as geologically dead

Cratering of Mercury

- Mercury has a mixture of heavily cratered and smooth regions like the Moon
- And like the Moon, the smooth regions are likely ancient lava flows, also from around 3 Gya
Cratering of Mercury

- The Caloris basin is the largest impact crater on Mercury.
- Region opposite the Caloris Basin shows signs of disruption from seismic energy of impact.

Tectonics on Mercury

- Long cliffs suggest that Mercury shrank early in its history as the core cooled.

Why does it make sense that a cooler core would be smaller?
Tectonics on Mercury

- Long cliffs suggest that Mercury shrank early in its history as the core cooled...because the cooler core was smaller...
- As the core cooled and shrank, it dragged the surface down with it, and cracked it

Mars: A Victim of Planetary Freeze-drying

- What geological features are there?
- How do they suggest that water once flowed on Mars?
- Why did Mars change?

The surface of Mars:
Geological activity and past (and maybe present) liquid water
• Mars has plenty of evidence of past geological activity

• There are volcanoes active as recently as 180 million years ago...

• There is evidence of past tectonic activity...
There is evidence of erosion...

For example, there are ancient riverbeds:
- This riverbed is older than the uneroded impact crater on it.

Other craters do show evidence of erosion.
- Close-up of eroded crater, showing terraces
- Terraces could be from sediment deposition

In fact, low-lying regions may once have had oceans.

- Mars rovers have found strong evidence that abundant liquid water existed on Mars in the distant past.
For example, they have found mineral deposits, such as these "blueberries", that can only have formed in liquid water.

Today, most water lies frozen underground (blue regions) or in the polar ice caps (water + CO₂).

Some scientists believe accumulated snowpack melts carve gullies even today. But simulations suggest that many recently formed gullies were probably from landslides.
This one, reported 3/2014, is thought to be "likely driven by seasonal carbon dioxide frost", not liquid water.

• But some atmospheric water apparently does exist
• Analysis of data from the Phoenix lander shows that it still snows on Mars
• And droplets condensed on the legs of Phoenix are believed to be salty water
• But Mars seems to be much drier now than it used to be
• So if it was warmer and wetter in the past, why isn't it now?

Climate Change on Mars

• Mars has not had widespread surface water for 3 billion years
• But it did before that
• There must have been a substantial greenhouse effect at that time
• Which means it must have had a thicker atmosphere
• So what happened?
• Here's what we think...
Climate Change on Mars

- The young Mars probably had a molten core and a significant magnetic field
- Its volcanism probably gave it an atmosphere at least as dense as ours
- The magnetic field would have protected its atmosphere
- And the atmosphere would have provided warmth and water
- But as Mars cooled, its magnetic field decreased...
- And today it has almost no magnetic field

Climate Change on Mars

- With no magnetic field to protect it...
- the Martian atmosphere was gradually stripped away by the solar wind...
- leaving it in its present state
- With hardly any atmosphere (<1% of Earth’s), it became cold and dry

Venus

- Is Venus geologically active?
- Why is Venus so hot?
Is Venus geologically active?

Cratering on Venus
- Impact craters, but fewer than Moon, Mercury, Mars

Volcanoes on Venus
- Many volcanoes, including both shield volcanoes and stratovolcanoes
Tectonics on Venus

- Fractured and contorted surface indicates tectonic stresses

Erosion on Venus

- Photos of rocks taken by lander show little evidence of erosion
- Understandable given the sluggish surface atmosphere
- This is a result of its very slow rotation

Does Venus have plate tectonics?

- Most of Earth’s major geological features can be attributed to plate tectonics, which gradually remakes Earth’s surface.
- As a “sister planet”, Venus might be expected to have plate tectonics as well.
- But this does not seem to be the case...
- From crater counts, however, its entire surface seems to have been “repaved” ~750 Mya.
- What exactly happened to do the repaving—and why—is not known.
- We do have a handle on why it’s so hot, though.
Why is Venus so hot?

It's the greenhouse effect

- Venus’s atmosphere is what really distinguishes it from Earth
- It is 95% carbon dioxide
- It is very thick, with a surface pressure 90 times that of Earth
- Its clouds, which contain droplets of sulfuric acid, are very reflective
- This means that most of the energy from sunlight is not absorbed
- But the temperature is hellishly hot, ~470°C (880°F) all over the planet
- This is due to the greenhouse effect from the carbon dioxide
- But how did the greenhouse effect on Venus become so much stronger than on its sister planet Earth?

Atmosphere of Venus

- Why has Venus turned out this way?
- As Earth’s “sister planet”, Venus should have about the same amount of CO₂ and water as Earth
- On Earth, most of the CO₂ is in rocks, and the water is in oceans
- On Venus, most of the CO₂ is in the atmosphere, and there is very little water
- They are very different now, but it’s possible that Venus was once more like Earth...
Runaway Greenhouse Effect

If Earth moved to Venus's orbit:

Average temperature ~15°C → ~64°C

More evaporation, stronger greenhouse effect
Runaway Greenhouse Effect

Average temperature: ~15°C → ~64°C

This cycle would continue...

Leading to a "runaway greenhouse effect"...
Runaway Greenhouse Effect

If Earth moved to Venus’s orbit:

More evaporation, stronger greenhouse effect

Average temperature ~15°C → ~64°C

This cycle would continue... leading to a “runaway greenhouse effect”... turning Earth into a young Venus.

Higher temperatures, more evaporation

Runaway greenhouse effect

Runaway Greenhouse Effect

If Earth moved to Venus’s orbit:

More evaporation, stronger greenhouse effect

Eventually, the heat would bake CO₂ out of the rocks...

Further increasing the greenhouse effect

The runaway greenhouse effect could also explain why Venus has little water.

Once the water was in the atmosphere, solar UV split it

One piece of evidence for this is an elevated \(\text{H}_2\text{O}/\text{H}\) ratio...

So Venus appears to be a victim of location

What have we learned?

- Is Venus geologically active?
  - Its surface shows evidence of major volcanism and tectonics during the last billion years.
  - There is no evidence for erosion or plate tectonics.
- Why is Venus so hot?
  - The runaway greenhouse effect made Venus too hot for liquid oceans.
  - All carbon dioxide remains in the atmosphere, leading to a huge greenhouse effect.

Runaway greenhouse effect

Average temperature
7.5 Earth as a Living Planet

- What unique features on Earth are important for life as we know it?
- Is human activity changing our planet?
- What makes a planet habitable?

What unique features of Earth are important for life as we know it?

- Surface liquid water
- Atmospheric oxygen
  - These are obvious
- Less obvious are:
  - Plate tectonics
  - Climate stability

Earth's distance from the Sun and moderate greenhouse effect make liquid water possible.
What unique features of Earth are important for life as we know it?
1. Surface liquid water
2. Atmospheric oxygen
3. Plate tectonics
4. Climate stability

Photosynthesis (plant life) is required to make high concentrations of O₂, which produces the protective layer of O₃.

Plate tectonics are an important step in the carbon dioxide cycle. (Interestingly, plate tectonics itself may require liquid water)

And the CO₂ cycle is important for climate stability.
Plate Tectonics

- Earth's crust is broken into plates
- These plates move on the underlying mantle convection
- This is "plate tectonics"
- And it leads to collisions between plates

Seafloor Recycling

- Where the plates collide, "subduction" happens
- The denser plate slides beneath the less dense one into the mantle
- Subduction causes earthquakes and volcanoes
- And since seafloor is denser than continental crust, it enables the "carbon cycle"

Carbon Dioxide Cycle

- Atmospheric CO₂ dissolves in rainwater and in the ocean.
- Rain erodes minerals that flow into the ocean.
- Minerals combine with carbon to make rocks on ocean floor.
- Key fact: Minerals combine with carbon faster at higher temperatures
Carbon Dioxide Cycle

- Subduction carries carbonate rocks down into the mantle.
- Rock melts in mantle and outgasses CO$_2$ back into atmosphere through volcanoes.
- **Key fact: Volcanic outgassing happens at a fairly constant rate**

The CO$_2$ cycle acts like a thermostat for Earth's climate:
- Outgassing is ~constant
- Higher temperatures increase removal of CO$_2$ from atmosphere, reducing greenhouse effect
- Lower temperatures slow down removal, increasing greenhouse effect
- So the temperature stays relatively constant

Features Making Earth a "Habitable" Place

- Plate tectonics...creates climate stability
- Climate stability...allows liquid water to persist
- Long-term liquid water...permits life as we know it to develop
- Atmospheric oxygen...
  - Life itself generates it
  - Required by some forms of life, including us
  - Protects all forms of surface life from harmful UV radiation
- These features made it possible for complex life like humans to evolve
- But we humans, more than any other life form, can alter Earth
Is human activity changing our planet?

![Graph showing temperature changes over time](image)

Some Effects of Human Activity

- Humans build things...
  - Cities, roads, railroads, dams...
- Humans make things...
  - Sometimes these things can be harmful
  - Example: CFCs and the ozone layer
- By doing what they do, humans can make other species extinct
  - And that can disrupt ecospheres
- Human use of fossil fuels produces greenhouse gases
  - And that can cause global warming and climate change

Global Warming

- Since the '50s, Earth's average temperature went up nearly 1°C
- The concentration of CO₂ is rising rapidly
- Unchecked rises in greenhouse gases will lead to global warming
- And if that goes far enough, things will be different
- Evidence?
Global temperatures have been determined back 420,000 years. Oxygen isotope ratios in ancient ice reveal the temperature. Atmospheric CO₂ concentrations were determined for the same time span. These come from air bubbles trapped in the ice. The temperatures track the CO₂ concentrations. These CO₂ concentrations can be compared to direct measurements in today's air...

The zoomed graph shows measurements made on Mauna Loa in Hawaii. Most of the CO₂ increase above previous peaks has happened in last 50 years. And the temperature is increasing as well...

This shows temperature "departures" from 1961-1990 average since 1000 BCE. It also shows the "margin of error" (95% confidence interval) in those temperatures. Why is this happening? Computer models can be used to assess.
Modeling of Climate Change

- Complex computer models of climate can be run and compared to observations.
- The models fit observations best when human production of greenhouse gases is included.
- So the recent temperature increase is consistent with human production of greenhouse gases being the cause.
- But reducing greenhouse gas production is expensive and politically controversial.
- So it is likely to continue for the foreseeable future.
- Global warming won’t lead to the end of life on Earth.
- But it will change living conditions.

One of the effects of global warming is sea level rise.

This shows a map of Florida as it is now:

And as it would be if sea level rises were 1 meter.
Modeling of Climate Change

• One of the effects of global warming is sea level rise.
• And as it would be if sea level rises were:

  2 meters

http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/mapping_slr/

Modeling of Climate Change

• One of the effects of global warming is sea level rise.
• And as it would be if sea level rises were:

  3 meters

http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/mapping_slr/

Modeling of Climate Change

• One of the effects of global warming is sea level rise.
• And as it would be if sea level rises were:

  4 meters

http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/mapping_slr/
Modeling of Climate Change

• One of the effects of global warming is sea level rise
• And as it would be if sea level rises were
  5 meters

http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/mapping_slr/

Modeling of Climate Change

• One of the effects of global warming is sea level rise
• The most recent analysis by the IPCC is that the rise is "likely" to be ≤1 meter

http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/mapping_slr/

Modeling of Climate Change

• One of the effects of global warming is sea level rise
• The most recent analysis by the IPCC is that the rise is "likely" to be ≤1 meter
• But that rise may be uneven
• And it might rise higher
• And there will be other effects of global warming

But Earth will still be habitable, even for humans
• It will just be a very different place to inhabit
• Which brings up the question: What is a "habitable planet"?
What makes a planet habitable?
(for life as we know it)

- Plate tectonics to create climate stability
- Climate stability to allow liquid water for long periods of time
- Liquid water for life (as we know it) to form
- Life to produce atmospheric oxygen so that life like us can exist

What makes a planet habitable?

- For liquid water to exist, the planet must be located at an optimal distance from the star: not too close, not too far, but just right

What makes a planet habitable?

- This optimal distance – the “habitable zone” – is different for different stars
What makes a planet habitable?

- To produce and retain an atmosphere, it must be large enough
- And for long-term climate stability, plate tectonics is probably necessary