CARBON RESERVOIRS

100,000,000 Gt

LITHOSPHERE

OCEANS 38,000 Gt

TERRESTRIAL BIOSPHERE & SOIL 2,400 Gt

ATMOSPHERE 830 Gt

1 Gt = X 6 MILLION

CARBON IN THE TERRESTRIAL BIOSPHERE

CO₂ IN ATMOSPHERE

ATMOSPHERE HOLDS 830 Gt CARBON
NET ANNUAL INCREASE ~4 Gt

BURNING FOSSIL FUELS, LARGE SCALE DEFORESTATION & CEMENT MANUFACTURE RELEASES CO₂ INTO THE ATMOSPHERE

PHOTOSYNTHESIS

6H₂O + 6CO₂ ⇌ C₆H₁₂O₆ + 6O₂

RESPIRATION

RESPIRATION BY PLANTS, ANIMALS & SOIL MICROBES USES THE ENERGY STORED IN CARBOHYDRATES & RELEASES CO₂ BACK INTO THE ATMOSPHERE

SOIL HOLDS 1500 - 2400 Gt ORGANIC CARBON

CARBON CARRIED BY RIVERS TO OCEAN

VEGETATION HOLDS 450-650 Gt CARBON

SOIL MICROBES DECOMPOSE DEAD ORGANISMS AND WASTE PRODUCTS

AUTOTROPHS EXTRACT CO₂ FROM THE ATMOSPHERE DURING PHOTOSYNTHESIS & CONVERT IT INTO ORGANIC MATTER

$\text{CO}_2$ in the ocean reacts with $\text{H}_2\text{O}$ to form $\text{H}_2\text{CO}_3$, which dissolves $\text{CaCO}_3$. The more $\text{CO}_2$ in the water, the more $\text{CaCO}_3$ dissolves.

$\text{CO}_2$ held in water increases with decreasing temperature.

Increasing $\text{CO}_2$ in water.

Decreasing $\text{CO}_2$ in water.

Organisms build $\text{CaCO}_3$ shells.

Above CCD, $\text{CaCO}_3$ accumulates.

Below CCD, $\text{CaCO}_3$ dissolves.

Marine snow.

$\text{CaCO}_3$ solubility increases with depth due to increasing pressure & decreasing temperature. Decomposition of sinking organic matter causes $\text{CO}_2$ concentration to increase with depth.

$\text{CO}_2 = \text{carbon dioxide}$

$\text{H}_2\text{CO}_3 = \text{carbonic acid}$

$\text{CaCO}_3 = \text{calcium carbonate}$
WHY IS VENUS SO HOT?

Earth and Venus are similar sized planets and whilst Venus is closer to the Sun, its thick cloud cover reflects most of the sunlight that hits it. Venus's atmosphere however is 96.5% Carbon Dioxide (CO₂) and it is much denser than Earth's. This amount of CO₂ creates a strong greenhouse effect, raising Venus's surface temperature to around 462 °C, hotter than any other planet in the solar system.
CARBON & THE GREENHOUSE EFFECT

SOLAR RADIATION (LIGHT) 340 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

* The Earth intercepts solar radiation as a 2D disc but radiates infrared radiation in all directions as a 3D sphere

Data: NASA Earth Observatory

GREENHOUSE GASES (GHGs)

\(\text{CO}_2, \text{CH}_4, \text{NO}_x, \text{H}_2\text{O}\)

*GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs
-18°C WITHOUT GHGs

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 W\(\text{m}^{-2}\)

SOLAR RADIATION ABSORBED BY ATMOSPHERE

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

INFRARED RADIATION (HEAT)*

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 W\(\text{m}^{-2}\)
CARBON & CLIMATE CHANGE

INCREASING CO₂ CONCENTRATION IN THE ATMOSPHERE ENHANCES THE GREENHOUSE EFFECT AND HAS A POSITIVE FEEDBACK ON GLOBAL WARMING. THIS HAS SEVERAL SIGNIFICANT AND POTENTIALLY IRREVERSIBLE KNOCK-ON EFFECTS...

OCEAN pH

↓ 0.1 pH in surface water (since 1880)
equivalent to 26% increase in concentration of H⁺ ions

More difficult for marine organisms like molluscs, corals, coccolithophores & foraminifera to build calcium carbonate shells.

GLOBAL SEA LEVEL

↑ 3 mm/year (since 1993)

ARCTIC SEA ICE

↓ 12.8% / decade
(relative to 1981-2010 average)

ANTARCTIC ICE MASS

↓ 127±39 Gt / year
(since 2002)

GREENLAND ICE MASS

↓ 286±21 Gt / year
(since 2002)

GLOBAL TEMPERATURE ANOMALY

CO₂ concentration in atmosphere:
Parts per million (ppm)

INCREASING CONCENTRATIONS OF CO₂ LARGELY DUE TO BURNING FOSSIL FUELS, CEMENT MANUFACTURE & LARGE-SCALE DEFORESTATION

Highest level of CO₂ in past 400,000 years

YEAR

GLOBE TEMPERATURE ANOMALY

TEMPERATURE ANOMALY / °C

YEAR

INCREASED TEMPERATURE FROM MAN-MADE ACTIVITIES

INCREASED TEMPERATURE FROM MAN-MADE ACTIVITIES

Data from NASA Goddard Institute for Space Studies

(1) NOAA/ESRL Physical Sciences Laboratory, Global Monitoring Division. Data source: http://www.esrl.noaa.gov/gmd/grad/co2/ and Dr. Ralph Keeling, Scripps Institution of Oceanography (scifaps05.ucsd.edu)

(2) Global Temperature Anomaly data used in this presentation. These data are obtained from the NOAA Climate Data Center, available at http://www.esrl.noaa.gov/gmd/grad/ma2/.


(5) NOAA/ESRL Physical Sciences Laboratory, Global Monitoring Division. Data source: http://www.esrl.noaa.gov/gmd/grad/co2/ and Dr. Ralph Keeling, Scripps Institution of Oceanography (scifaps05.ucsd.edu)

(6) Global Temperature Anomaly data used in this presentation. These data are obtained from the NOAA Climate Data Center, available at http://www.esrl.noaa.gov/gmd/grad/ma2/.


(9) Global Temperature Anomaly data used in this presentation. These data are obtained from the NOAA Climate Data Center, available at http://www.esrl.noaa.gov/gmd/grad/ma2/.


(12) Global Temperature Anomaly data used in this presentation. These data are obtained from the NOAA Climate Data Center, available at http://www.esrl.noaa.gov/gmd/grad/ma2/.


**GRAPHITE FORMATION**

2. Contact Metamorphism with Coal Seam
3. Igneous Rocks Associated with Metamorphosed Graphite-Bearing Sedimentary Rocks

**STRUCTURE**
- Layer of fused benzene rings
- Covalent bond
- Van der Waals bond
- Carbon atom

**PROPERTIES**
- High Melting Point
- Conductor of heat & electricity
- Lubricant
- Opaque
- Soft

**USES**
- Pencils
- Anode in lithium ion batteries
- Lubricant
- Refractory applications e.g., crucible
- Graphene sheets
DIAMOND FORMATION

1. DIAMOND WINDOW - ZONE UNDER STABLE CONTINENTAL INTERIORS. MAJORITY OF MACROSCOPIC DIAMONDS FORM HERE & CAN BE TRANSPORTED TO THE SURFACE IN DEEP SOURCE VOLCANIC ERUPTIONS

2. ULTRA HIGH PRESSURE METAMORPHISM OF CARBONATE SEDIMENTS

3. METEORITE IMPACT (NANO DIAMONDS)

STRUCTURE

- COVALENT BOND
- CARBON ATOM

PROPERTIES

- HIGH MELTING POINT
- HIGHEST THERMAL CONDUCTIVITY OF ANY NATURAL MATERIAL
- TRANSPARENT
- HARDEST NATURAL MATERIAL

USES

- DIAMOND WINDOWS IN LASERS & X-RAYS
- JEWELLERY
- ANVILS IN HIGH PRESSURE EXPERIMENTS
- SAWs
- DRILL BITS

*high tech applications of diamond use synthetic rather than natural diamond
LIMESTONE FORMATION

1. Accumulation of $\text{CaCO}_3$ from algae, coral, shells & faecal matter in warm shallow seas.
2. Accumulation of $\text{CaCO}_3$ in deeper water (<4500m) from calcifying plankton.
3. Precipitation of $\text{CaCO}_3$ in saturated waters e.g. in lagoons & hot springs.
4. Evaporation of water leaves behind $\text{CaCO}_3$ deposits.

CHALK

- Limestone formed predominantly from nanoplankton called coccolithophores.
- Chalk deposited in the late Cretaceous period (~89-85 Ma) forms the famous White Cliffs of Dover & the Needles on the Isle of Wight.
- The UK chalk acts as an aquifer - a permeable rock that holds ground water.

MODERN MARINE LIMESTONE FORMING ENVIRONMENTS
CARBON

C

ATOMIC NUMBER 6

- 6 ELECTRONS
+ 6 PROTONS
6 NEUTRONS

6 ELECTRONS
6 PROTONS
6 NEUTRONS

4 VALENCE ELECTRONS ABLE TO FORM COVALENT BONDS WITH OTHER ATOMS

CARBON CAN FORM OVER 10 MILLION COMPOUNDS

4th MOST ABUNDANT ELEMENT IN THE UNIVERSE

15th MOST ABUNDANT ELEMENT ON EARTH

NATURAL ALLOTROPES (PHYSICAL FORMS):
GRAPHITE, DIAMOND & AMORPHOUS CARBON

ISOTOPES

C\textsuperscript{12} 99.9%
C\textsuperscript{13} 1.1%
C\textsuperscript{14} TRACE

STABLE
STABLE
RADIOACTIVE HALF LIFE 5730 YEARS

CARBON DIOXIDE
BICARBONATE
METHANE
ETHANOL
BUTANE
NUCLEOBASES (THYMINE)
BENZENE RING
CARBONATE

\rightarrow DNA

AMINO ACID
\rightarrow PROTEINS

RADICARBON DATING

LIVING ORGANISMS EXCHANGE CARBON WITH THE ATMOSPHERE/OCEAN AND INCORPORATE IT INTO THEIR TISSUES. DURING LIFE, ORGANISMS HAVE THE SAME PROPORTION OF C\textsuperscript{12} AS THE ATMOSPHERE (1 ppt). WHEN ORGANISMS DIE THEY NO LONGER EXCHANGE CARBON SO THE RADIOACTIVE C\textsuperscript{14} IN THEIR TISSUES STARTS TO DECAY. WITH TIME, THE RATIO OF C\textsuperscript{12}:C\textsuperscript{14} DECREASES AT A KNOWN RATE. THIS CAN BE USED TO DETERMINE HOW LONG AN ORGANISM HAS BEEN DEAD FOR, RELIABLY UP TO ~50,000 YEARS.