K33: The Carbon Cycles

How Carbon Moves Through the Earth / Ocean / Atmosphere System

Fast *vs* Slow Carbon Cycles

- There's a “Fast” cycle, and a “Slow” cycle
- **Fast Carbon Cycle** – rapid interchange between surface ocean, atmosphere, and top layer of soil and biosphere. Time scales of days to ~decade.
- **Slow Carbon Cycles** – involves turnover of the ocean (~millennium), conversion of dissolved ocean CO_2 into carbonates which are ultimately converted to rock, subducted as ocean crust under continental plates (plate tectonics), releasing a portion of CO_2 back into the atmosphere as volcanic CO_2 emissions… Time scales of many thousands to millions of years.

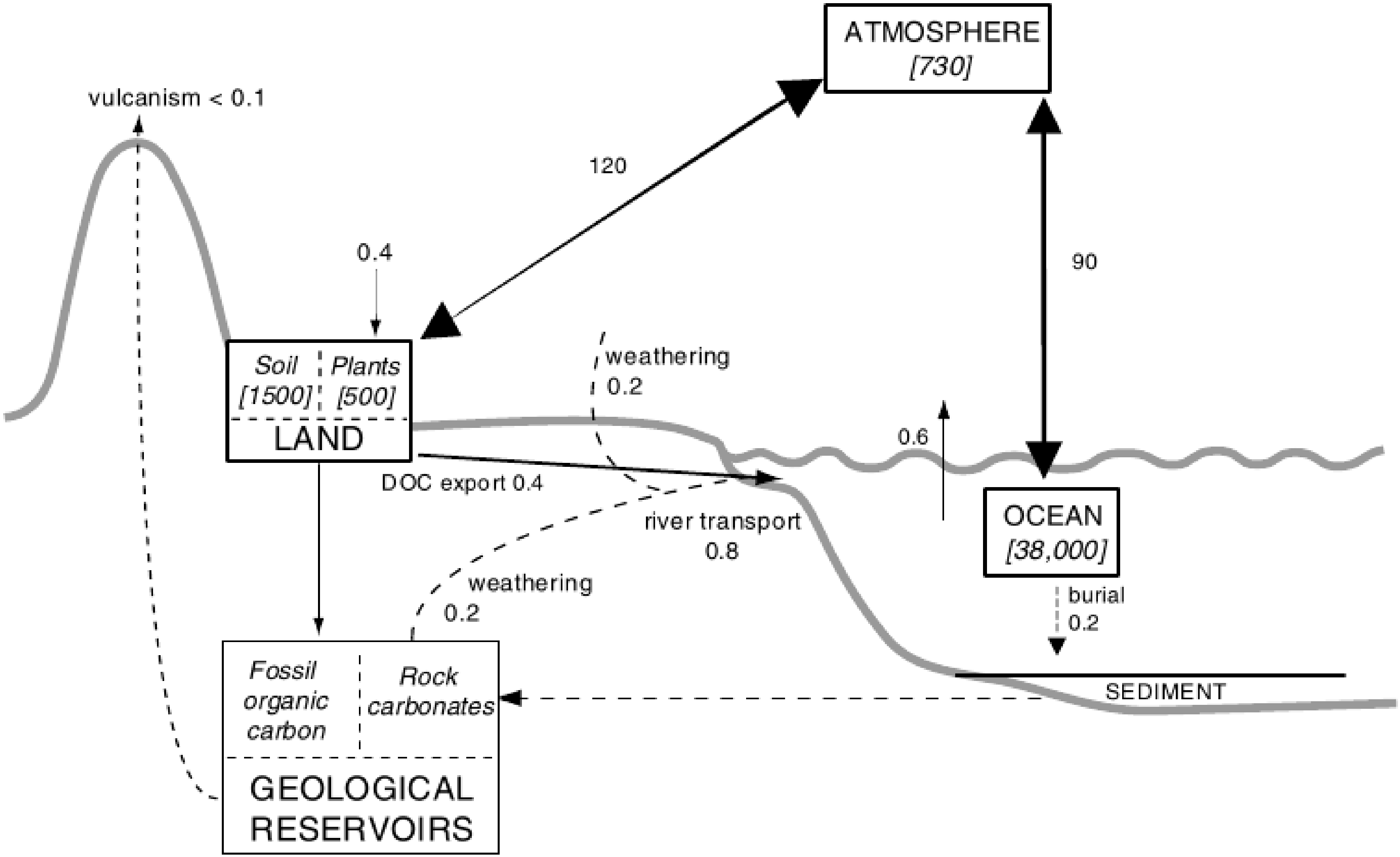
Carbon pools in the major reservoirs on earth.[2]

Pool	Quantity (gigatons)
Atmosphere	720
Oceans (total)	38,400
Total inorganic	*37,400*
Total organic	1,000
Surface layer	670
Deep layer	36,730
Lithosphere	
Sedimentary carbonates	> 60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	2,000
Living biomass	600 - 1,000
Dead biomass	1,200
Aquatic biosphere	1 - 2
Fossil fuels (total)	4,130
Coal	3,510
Oil	230
Gas	140
Other (peat)	250

Important to Remember the Relative Sizes of the Major Carbon Reservoirs, in Gigatons (billions of tons) of carbon (Gt).

- 1. Earth's Crust – ~100 million Gt
- 2. Ocean – 38,000 Gt (only 3% is in biomass)
- 3. Fossil Fuels - ~6,000 Gt
- 4. Land biomass – 2,000 Gt
- 5. Atmosphere – 865 Gt as of year 2016
- So our atmosphere is the SMALLEST reservoir and hence EASIEST to push around!

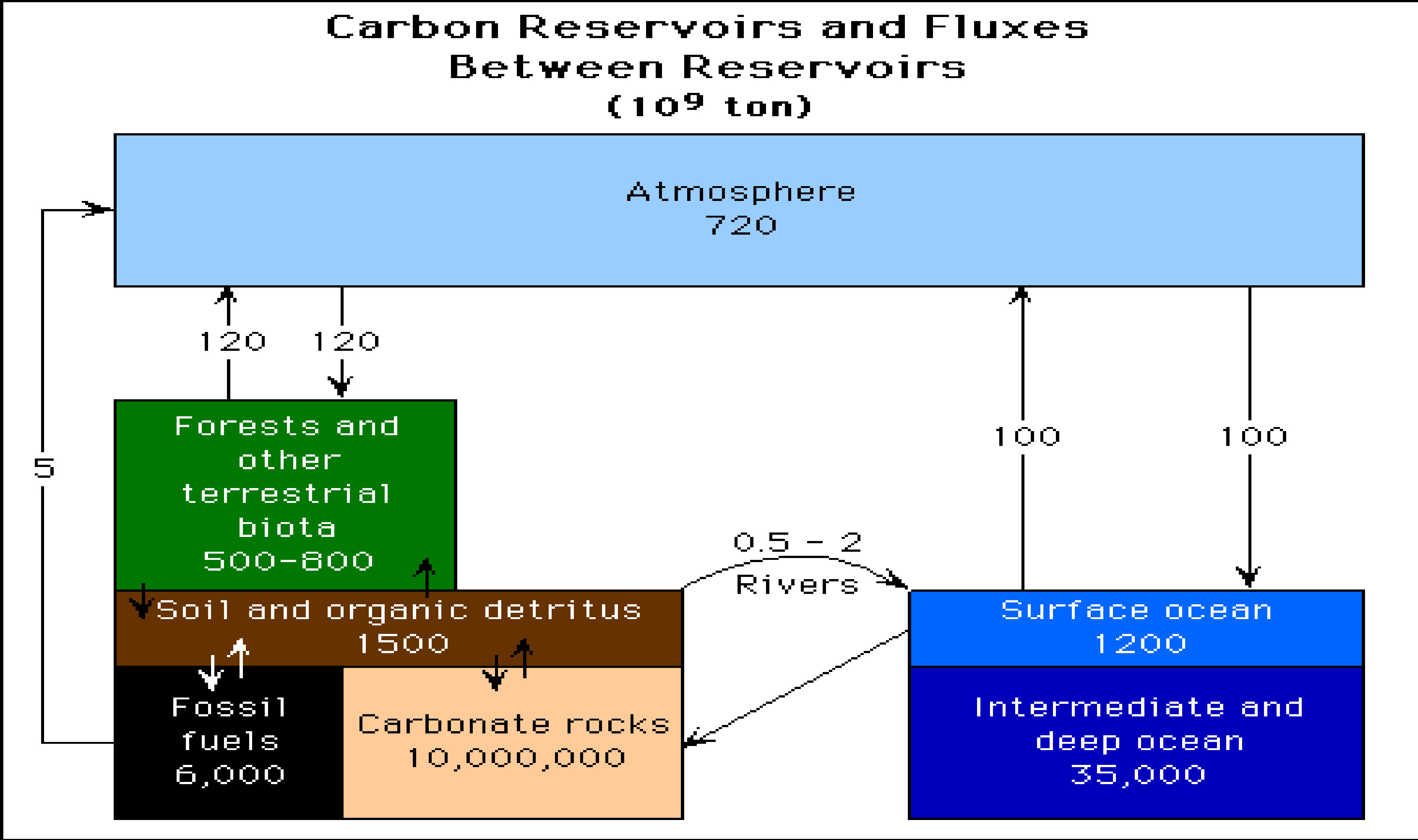
The Main Components of the Carbon Cycles (gigatons/yr)



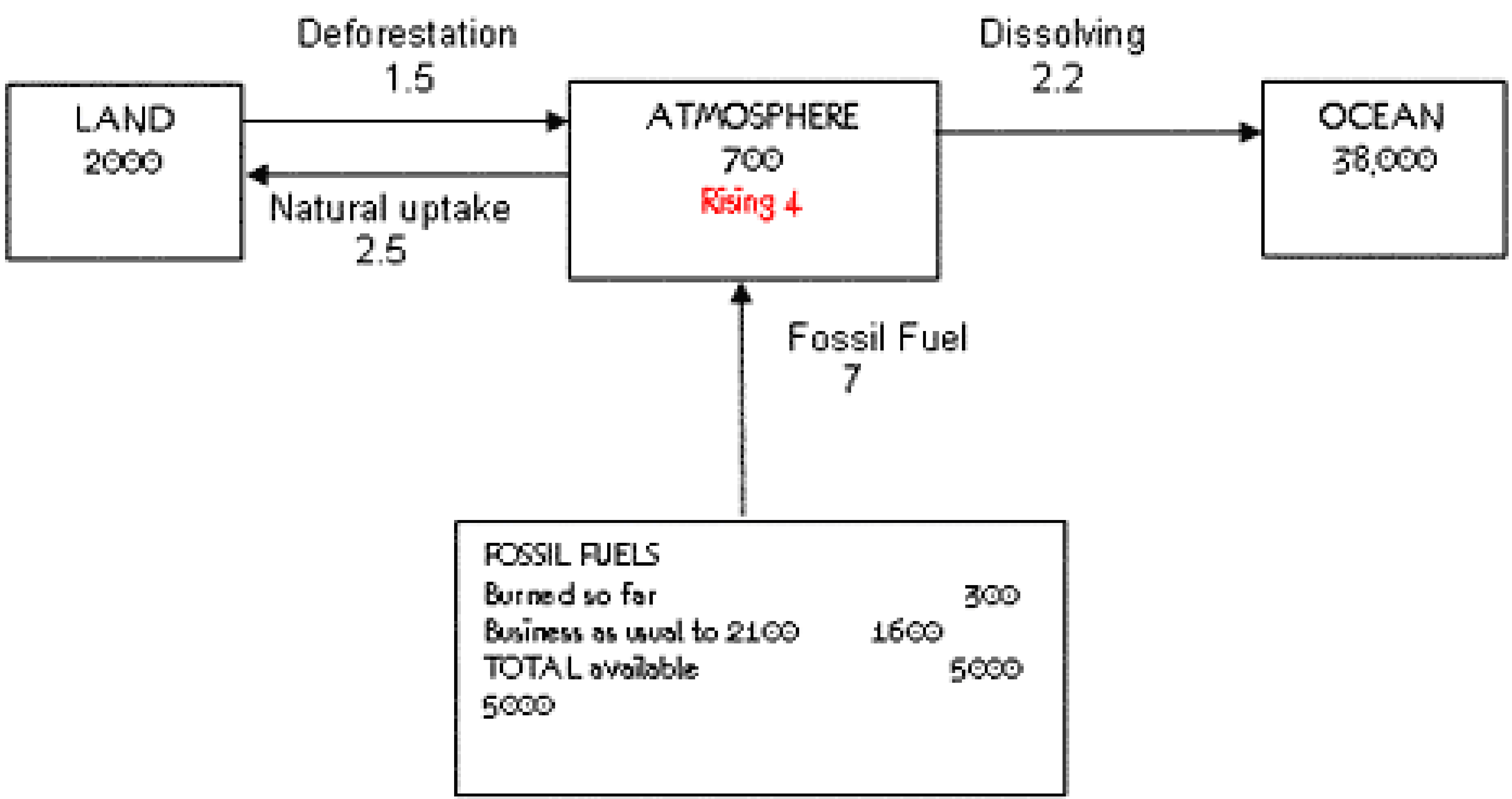
Remember the Slow Drop in Atmospheric CO2 over Geologic Time?

- Only the Slow Carbon cycle ~permanently sequesters carbon, in the form of carbonates subducted into the mantle or otherwise turned to rock
- This is <u>**about ~0.2 gigaton/yr of carbon**</u>.
- For comparison, we are unearthing, burning and depositing into the atmosphere <u>**9 gigatons/yr of carbon**</u> – **45x higher** - overwhelming Earth's ability to take it back .

Caution here: does not show net inflow of atmospheric carbon into land and ocean, and carbonate rocks number is lower than other sources. And, atmosphere today is 865 Gt and rising, not 720



Better: Carbon Reservoirs and Flows (including human-induced) in gigatons of carbon per year (from David Archer). "Land" is bio-carbon, not carbonate rocks). 97% of the ocean carbon is inorganic, 3% is biomass



To Summarize the Slide…

- We add (at the time of the slide's data years ago) 9 billion tons of carbon (mostly as CO2; ~33 billion tons (more like 40 billion in 2018) every year. 57% goes back to land and sea…. That 57% is comprised of:
- About 22% of that gets diffused into the ocean
- About 35% of that gets absorbed on land by plants and soil, and with some amount added by chemical weathering
- Leaving 100-57=43% of our total annual carbon emissions (4 billion tons/yr) which remain long term in the atmosphere, for many thousands of years

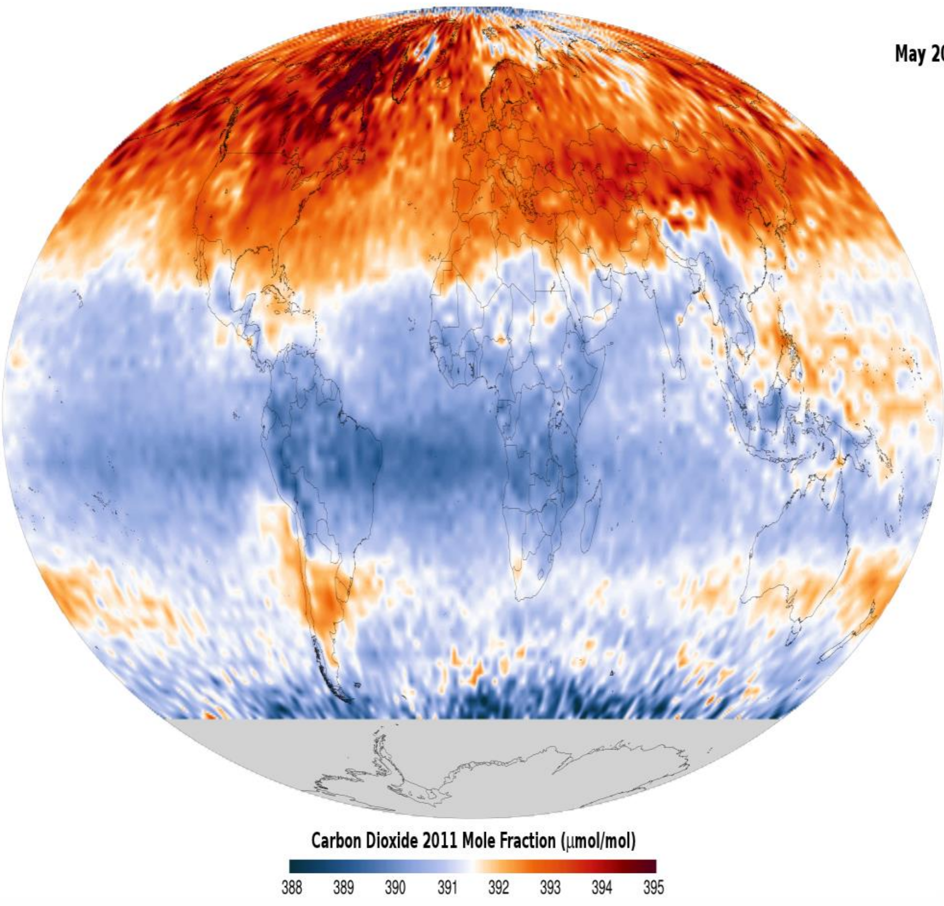
Today we Burn 10+ Gt of Carbon Into the Atmosphere Each Year

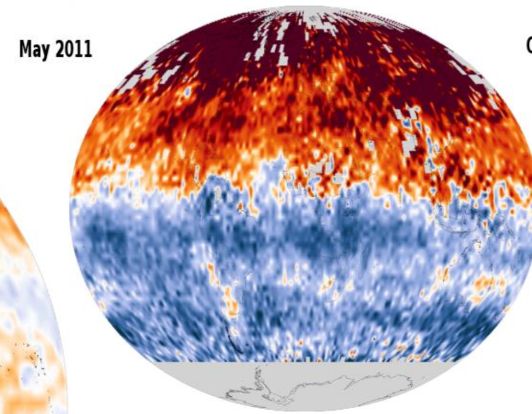
- This produces 40 billion tons of CO_2 each year. Note the vast fossil carbon deposits – 10,000 gigatons.
- Enough to burn for a thousand years, at current emission rates.
- If we try and burn all of these, we and the vast majority of other life on Earth are truly doomed. The Republican love for coal and fossil fuels is deadly to the future of this planet.

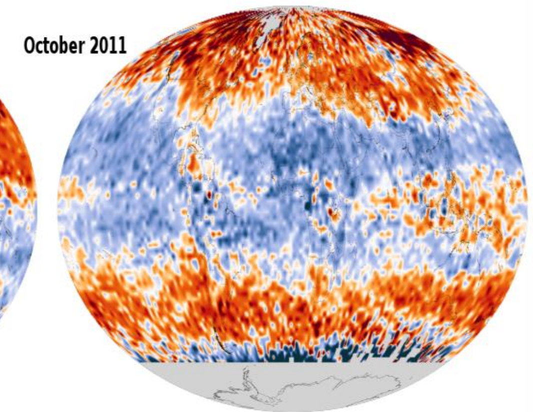
Mixing of Atmospheric Gases

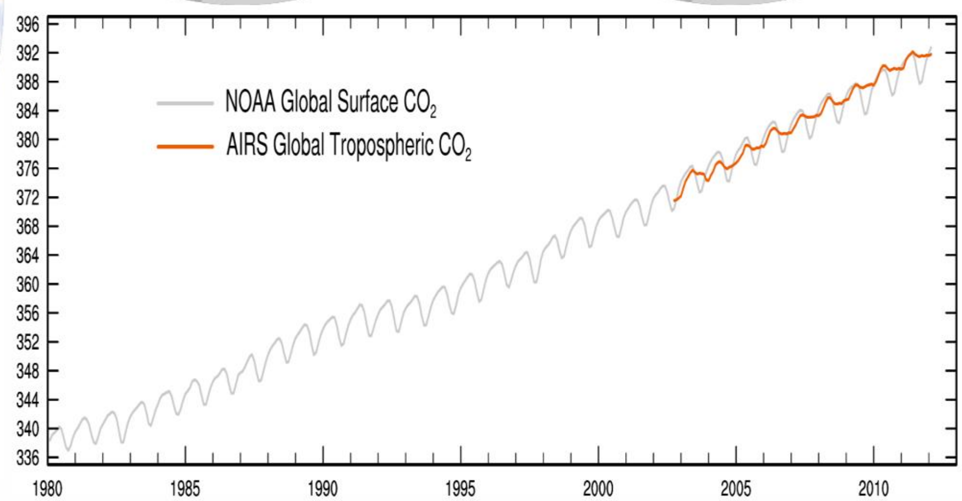
- Our atmosphere is **“well mixed”** – meaning the concentration of each molecule evens out across the globe rapidly, certainly compared to the times scales of climate change
- CO2 mixes within a few weeks across the northern hemisphere, and across the southern hemisphere
- Mixing between the hemispheres is not as efficient due to diverging winds at the equator. Still, it takes only a year for “well mixed” to apply between the hemispheres

Atmospheric CO2 Concentration Distribution. Well-mixed (*i.e.* note how narrow is the scale (388-395ppm in 2011. Now over 410 ppm in 2017), but the clear source is human population – focused across the densely populated mid-northern latitudes and surface wind downstream areas. Note: surface CO2 seasonal cycle more pronounced (due to plants) than tropospheric average

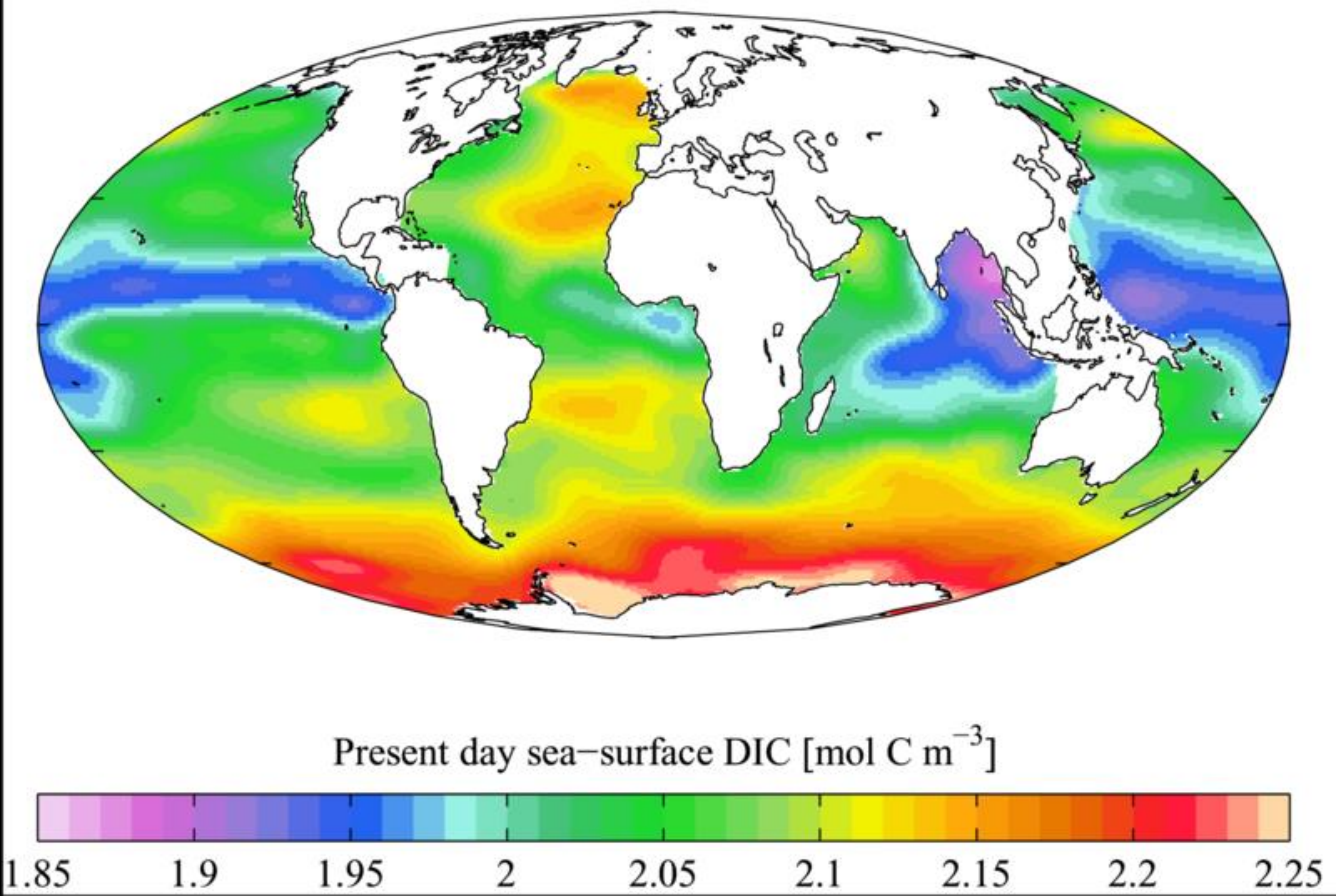








Higher Temperature Ocean Can Hold <u>Less</u> Dissolved CO2



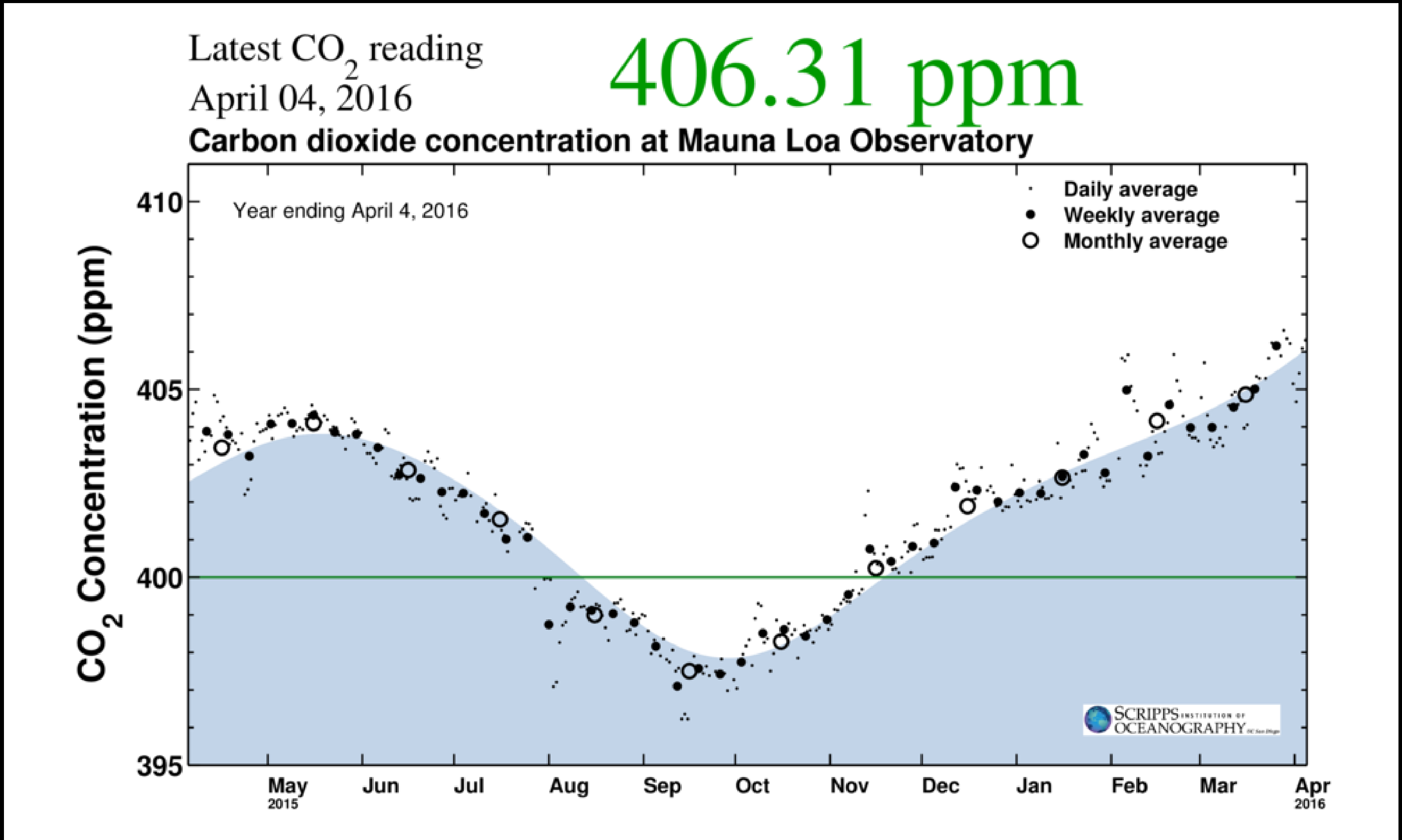
Carbon Exchange with Biosphere

- Carbon is exchanged with varying speed with the terrestrial biosphere. It is absorbed in the form of carbon dioxide by plants and converted into organic compounds.
- Carbon is also released from the biosphere into the atmosphere in the course of biological processes…
- **CO2 comes from Aerobic respiration** of organic carbon into carbon dioxide and
- **CH4 (methane) comes from anaerobic respiration** (*i.e.* without oxygen present)
- After respiration, both carbon dioxide and methane are typically emitted into the atmosphere.

Organic carbon is also released into the atmosphere during burning

- One species – Humans – mine large quantities of sequestered fossil carbon and burn it, releasing it into the atmosphere as CO2.
- Humans also have eliminated many large land mammal species to make way for domesticated cattle, which release large amounts of carbon in the form of methane into the atmosphere, a powerful greenhouse gas.
- Deforestation is a major contributor of carbon from the biosphere into the atmosphere as wood decays and soil sequestration is damaged.

The seasonal Cycle of Atmospheric CO2: dominated by northern hemisphere where most land is. Plants decompose and release CO2 to the atmosphere until Siberia and the highly seasonal northern latitudes of North America emerge from cold and spring gets going. Peak is lagged a bit as well, to May. Now in 2017, 410ppm



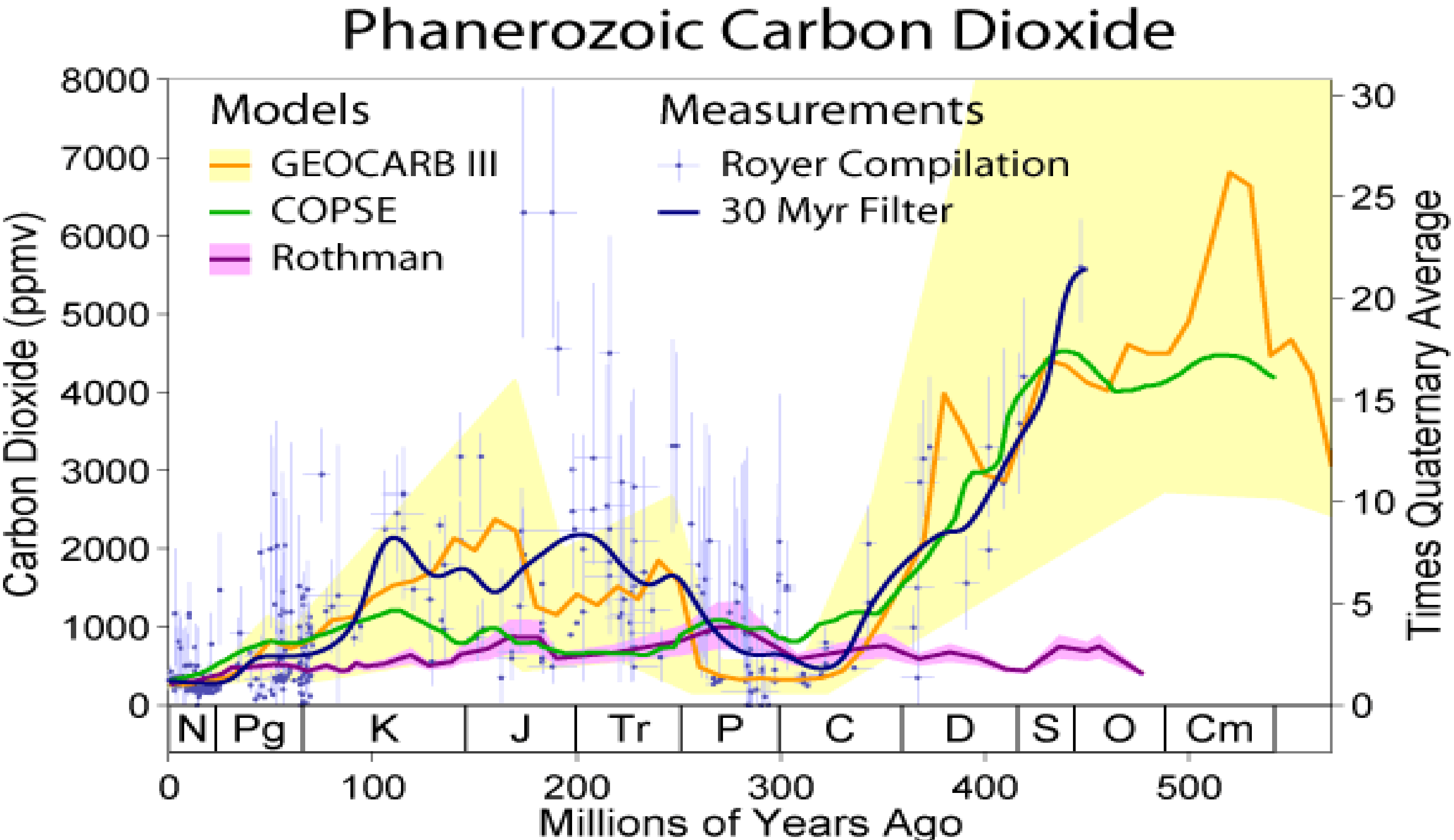
Carbon Exchange with the Ocean

- The oceans contain around 38,000 billion tons (gigatons) of carbon, mostly in the form of bicarbonate ion (over 90%), with most of the remainder being carbonate (CO3)
- That's about 1,000 years worth of our current CO2 emissions, for comparison
- At the surface of the oceans towards the poles, seawater becomes cooler and more carbonic acid is formed as CO2 becomes more water soluble. This is coupled to the ocean's **thermohaline circulation** which transports denser surface water into the ocean's deeper layers around the globe

Ocean “breathes” CO_2, depending on environment

- Cold ocean can hold more CO_2, so where there is upwelling of deep cold to warm surface, the CO_2 leaves the ocean and enters the atmosphere; this is nearer the equator.
- Near the poles, cooler water absorbs CO_2 and it sinks to the bottom, not to emerge for a thousand years or so
- But the poles are warming now much faster than the equator, and so ocean absorption of CO_2 is declining.
- We’re also now killing the corals which help turn the dissolved CO_2 into carbonate where is may be (or used to be) stable

Slow Cycle – Mostly this is a subtractive process – CO2 is pulled out of the atmosphere, to ocean and formation of CaCO3, much of which is pressed geologically into limestone, both organic and inorganic processes. Some is returned via volcanoes.



CO2 and Chemical Weathering of Rocks: Silicates and Limestones

- Carbonic acid is formed when CO2 is dissolved in water (e.g. rain). Consumption of carbonic acid will induce more CO2 to be taken out of the atmosphere to restore balance.
- Carbonic acid will dissolve silicate rocks, consuming the carbonic acid and thus removing CO2 from the atmosphere
- This is a (slow) negative feedback, as higher temperatures are expected to produce more CO2-enriched rain and more weathering.
- How strong is this? Not well determined by the data, but it is a very slow process and dwarfed by the flows in our current rapid climate change…

Atmospheric CO_2 absorbed in rain, creates carbonic acid, dissolving metal ions (like calcium=Ca), carrying to the ocean, where the Ca combines with dissolved CO_2 to make calcium carbonate rocks (limestone). Only 20% of limestones made this way. 80% are made by sea life taking up carbonate to make sea-shells

Chemical Weathering of Limestone Consumes Atmospheric CO2 and turns it into bicarbonate

- 10% of Earth's Land is covered with limestone, mostly organic in origin
- $H_2O + CO_2 + CaCO_3$ --> $Ca^{+2} + 2HCO_3^-$
  water + carbon dioxide + calcite dissolve into calcium ion and bicarbonate ion.
- The chemical reaction:
    - **CO2 + H2O => H2CO3**
  - **carbon dioxide + water => carbonic acid**
    - **H2CO3 + CaCO3 => Ca(HCO3)2**
  - **carbonic acid + calcium carbonate => calcium bicarbonate**
- Acidic waters (from pollution or natural) dissolve limestone allowing for additional water to gain entrance. Can cause sinkholes and karst features as well as dissolution of statutes and grave stones.

Limestone Statue weathers under acid rain

An Intriguing Theory – Observed CO_2 loss from the Atmosphere in last 50 million years – Mostly Caused by Accelerated by Rise of the Himalayas?

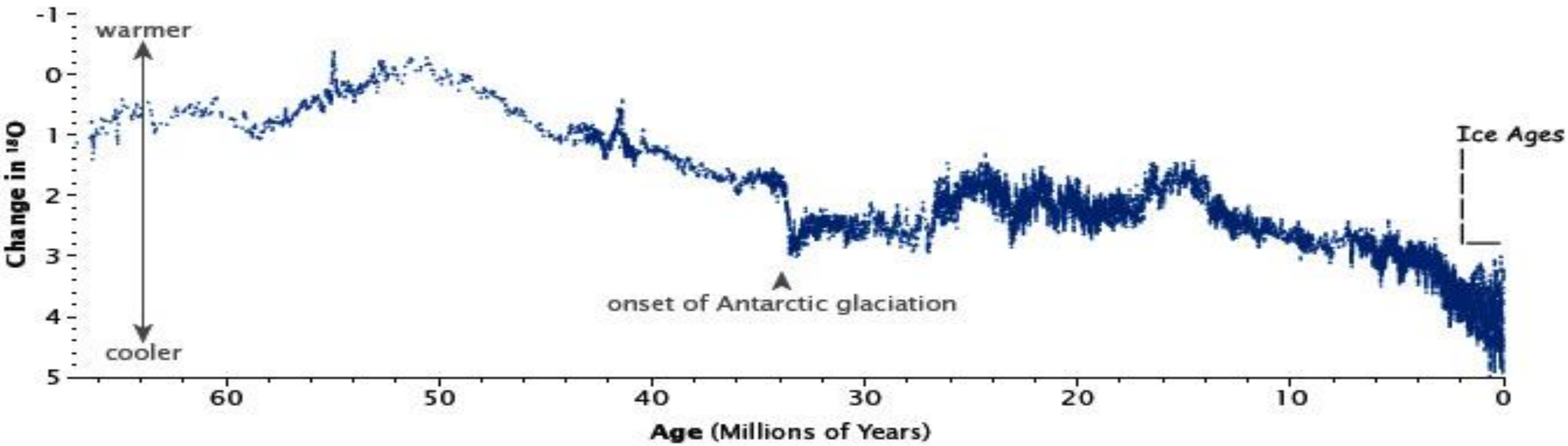
- The tectonic collision of India with Eurasia created (and continues to create) the Himalaya Mountains
- High elevation, monsoon winds and then rain create relatively rapid erosion and chemical weathering.
- Observations infer that large uplifts of mountain ranges globally result in higher chemical erosion rates, thus lowering the volume of CO_2 in the atmosphere as well as causing global cooling (Raymo, *et.al.* 1992) This occurs because in regions of higher elevation there are higher rates of mechanical erosion (i.e. gravity, fluvial processes) and there is constant exposure and availability of materials available for chemical weathering. The following is a simplified equation describing the consumption of CO_2 during chemical weathering of silicates:

$$-CaSiO_3 + CO_2 \leftrightarrow CaCO_3 + SiO_2$$

From this equation, it is inferred that carbon dioxide is consumed during chemical weathering

- …and thus lower concentrations of the gas will be present in the atmosphere as long as chemical weathering rates are high enough.
- **Bottom Line:** Chemical weathering of silicate rocks takes CO_2 out of the atmosphere, over geologic time scales. But more recent work says CO_2 removal rates by this mechanism are much less, and that the dominant carbon sink effect of the Himalaya is erosional removal of biologic carbon and burial at sea (France-Lanord *et.al.* 1997). **O18/O16 temperature proxy shows cooling climate (consistent with dropping greenhouse CO_2 concentrations) during this time period…**

Past 50 Myrs; Rise of the Himalaya: Collision of India into Eurasia. Removes atmospheric CO2 *via* chemical weathering and biological erosion and burial at sea



On very long time scales (millions to tens of millions of years), the movement of tectonic plates and changes in the rate at which carbon seeps from the Earth's interior may change the temperature on the thermostat. Earth has undergone such a change over the last 50 million years, from the extremely warm climates of the Cretaceous (roughly 145 to 65 million years ago) to the glacial climates of the Pleistocene (roughly 1.8 million to 11,500 years ago). [See Divisions of Geologic Time—Major Chronostratigraphic and Geochronologic Units for more information about geological eras.]

The uplift of the Himalaya, beginning 50 million years ago, reset Earth's thermostat by providing a large source of fresh rock to pull more carbon into the slow carbon cycle through chemical weathering. The resulting drop in temperatures and the formation of ice sheets changed the ratio between heavy and light oxygen in the deep ocean, as shown in this graph. (Graph based on data from Zachos at al., 2001.)

So only now are CO_2 levels and temperatures low enough, in the past few million years, that the weak Milankovich cycle climate forcings (see PaleoClimate Powerpoint) have been able to take us into and out of Ice Ages

However…

- Chemical weathering of the Himalaya are expected to be able to remove **<u>all</u>** of the CO_2 from the atmosphere (Raymo *et.al.)* , and it has not.
- Various negative and positive feedback mechanisms have been proposed to try and explain why CO_2 remains in the atmosphere today, but data poorly constrains all of this
- **This problem may go away if France-Lanord *et al.* 1997 are correct in their subsequent work showing silicate weathering is much less than Raymo *et al.* thought.**
- So, the take-away for now is – the "Slow Carbon Cycle" still contains some significant uncertainties in the rates of weathering and on which types of rocks, the rates of organic matter burial and while we can see that CO_2 has in general been decreasing, over ~hundred million year time scales, the exact rates are still being worked out.
- **These uncertainties are not relevant for understanding current climate change, however** – rate changes for chemical weathering and carbon burial are all extremely slow on the human time scale. A thousand years is the blink of an eye geologically, while it is essentially "forever" on human time scales, especially recently.

K33: Key Points – Carbon Cycles

- **Fast cycle:** CO_2 between atmosphere, ocean, top meter of soil; time scale of years
- **Slow cycle:** atmospheric CO_2->carbonate via sea life, burial, subduction, volcanic emission. Time scale: tens to thousands of centuries
- **Relative size of carbon reservoirs: carbonate rocks is vast, ocean is large, fossil fuel is moderate, atmosphere is tiny**
- Direct forcing of our carbon into atmosphere will only be taken out slowly by ocean and biosphere
- Volcanic return of CO_2 to atmosphere is tiny. 1% compared to fossil fuel burning CO_2 production happening today
- Photosynthetic removal of atmospheric CO_2 in Carboniferous Period to create fossil carbon led to deep drop in CO_2 levels. We're now reversing that very rapidly
- **The Ocean absorbs about ¼ of the CO_2 which we emit into the atmosphere each year.**
- Slow cycle is not a true cycle – net removal of CO_2 over cosmic and geologic time scales. Modern CO_2 only 300 parts per million (well, 400 now during industrialization period)
- CO_2 also removed by chemical weathering of silicate rocks, rise of Himalaya may have accelerated CO_2 atmospheric removal during the past 50 million years, leading to recent Ice Ages (past 3 million years).
- Chemical weathering of limestone also consumes atmospheric CO_2, rate decreases with increasing temperature.
- Slow carbon cycle uncertainties are not relevant for understanding current climate change, which is happening on times scales of decades, not millions of years