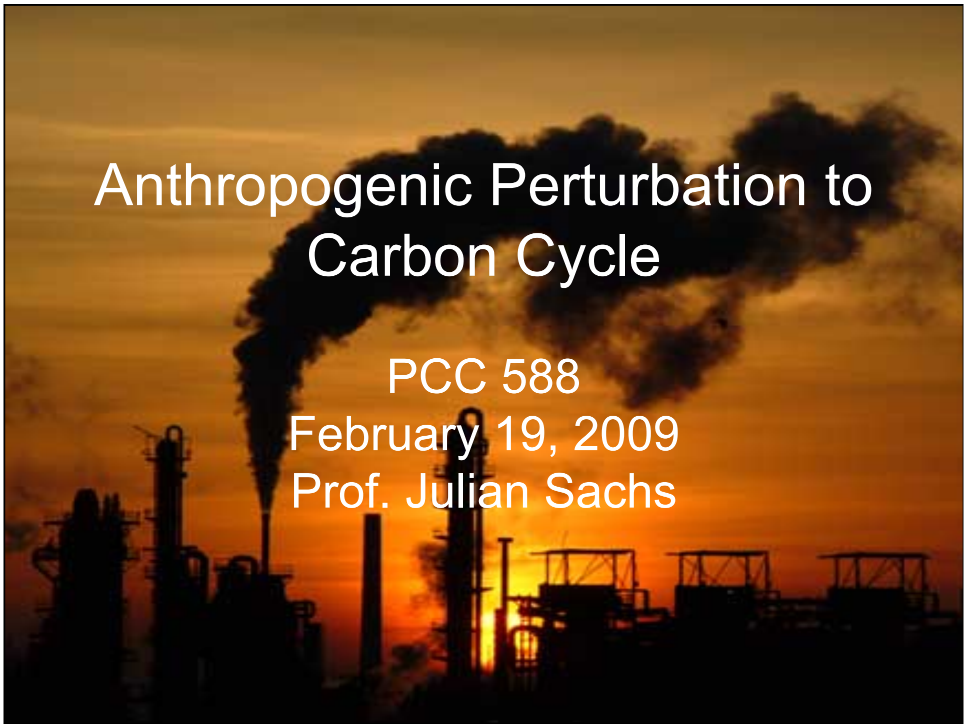
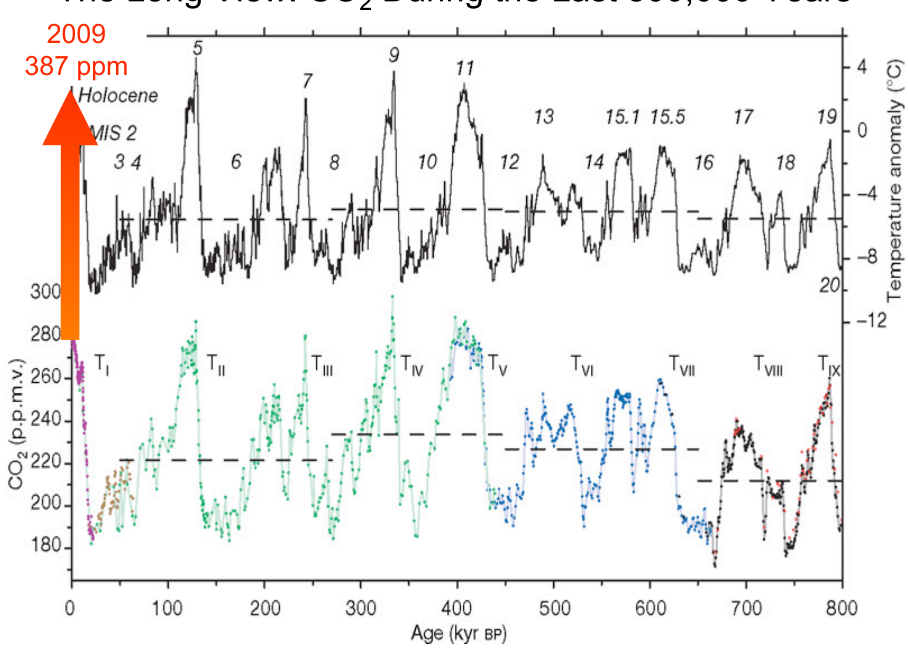


Anthropogenic Perturbation to Carbon Cycle

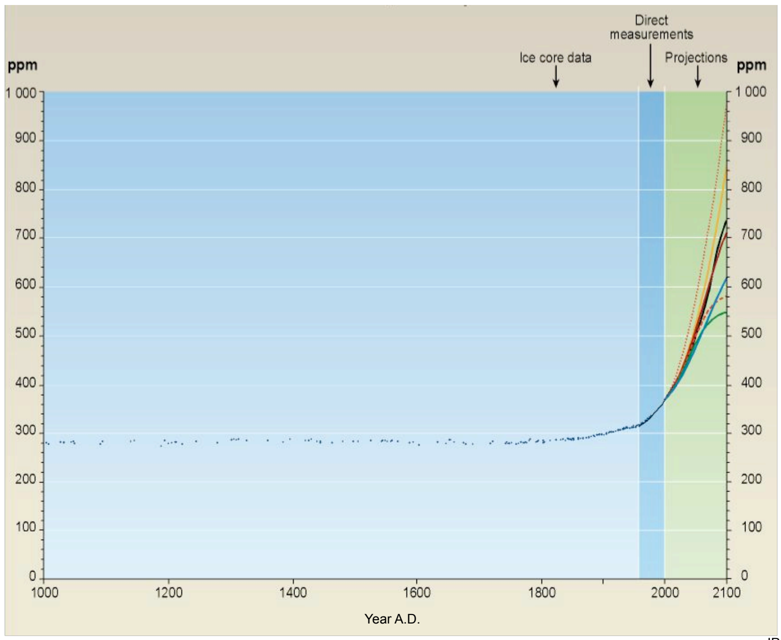
PCC 588
February 19, 2009
Prof. Julian Sachs

The Long View: CO_2 During the Last 800,000 Years



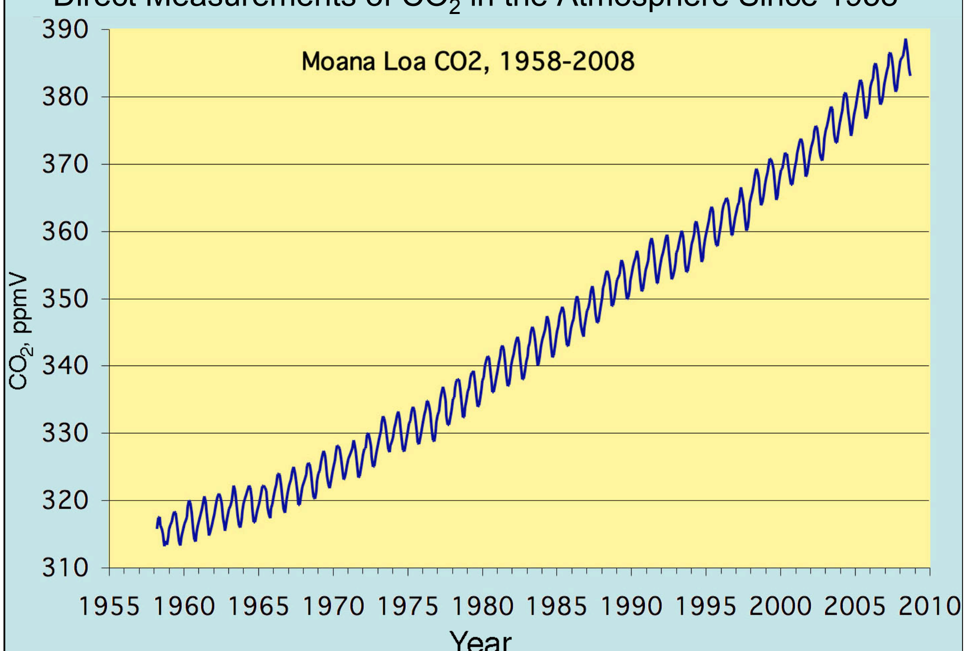
Luthi et al. (2008) *Nature* Vol. 453: 379-382

CO_2 for the last 1000 Years



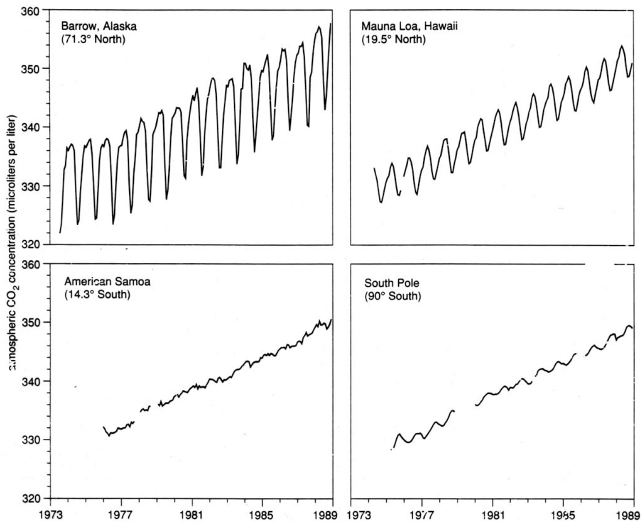
IPCC 2001

Direct Measurements of CO_2 in the Atmosphere Since 1958



Begun by David Keeling of Scripps Inst. Oceanogr.

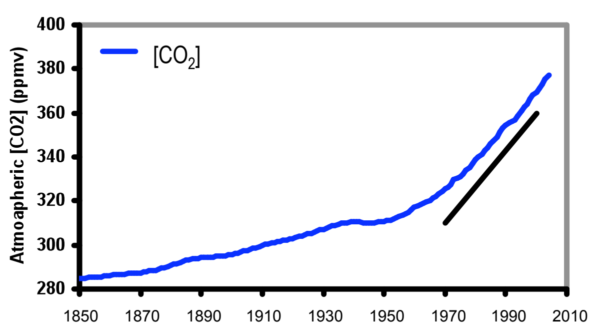
Spatial & Annual Variability of Atmospheric CO_2



- Seasonal cycle of photosynthesis & respiration in Northern Hemisphere—where most land mass occurs--causes high amplitude variation in N vs. S
- Photosynthesis is high relative to respiration in summer vs. winter
- CO_2 minima (maxima) occur during boreal summer (winter)

Atmospheric CO_2 Concentration & Growth Rates

Year 2006
Atmospheric CO_2
concentration:
381 ppm
35% above pre-industrial



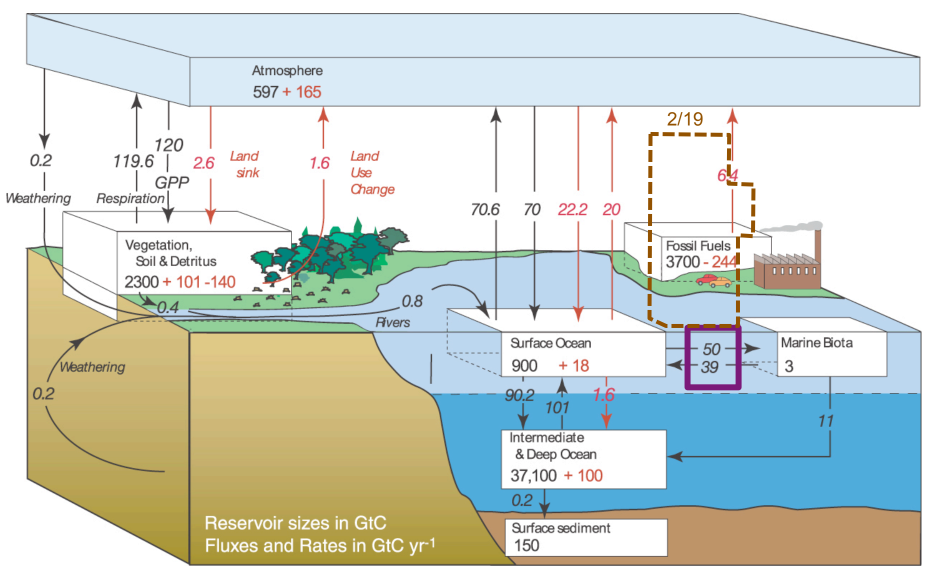
Growth Rates by Decade:
1970 – 1979: 1.3 ppm y^{-1}
1980 – 1989: 1.6 ppm y^{1}
1990 – 1999: 1.5 ppm y^{-1}
2000 - 2006: 1.9 ppm y^{-1}

NOAA 2007; Canadell et al. 2007, PNAS; Canadell et al. (2007) http://www.globalcarbonproject.org/index.htm

Questions to be Addressed

- How did we get to 387 ppm CO_2?
  - Energy use, cement production & deforestation
- Why isn't it even higher?
  - The ocean & land plants have absorbed quite a bit
- Where has the CO_2 we produced that is not in the atmosphere gone?
  - About half in the ocean, half in the terrestrial biosphere (see next lecture)

Anthropogenic Perturbation to Carbon Cycle



Black arrows → natural fluxes Red arrows → anthropogenic fluxes

IPCC 2007, Fig. 7.3

Reservoirs (Pg):	
Atmosphere: CO2 (288 ppm in 1850)	612
(369 ppm in 2000)	784
Oceans: Biota	1-2
DOC	700
Org C in sediments (1 meter)	1,000
DIC	38,000
Terrestrial: Biota	600
Soil Humus (1 meter)	1,500
Fossil Fuels (identified reserves), gas	44
oil	90
coal, oil sand & shale	3440
Fluxes (Pg yr^{-1}):	
Atmosphere-Ocean exchange	90
Gross Primary Production Ocean	100
Land	120
Net Primary Production Ocean	45
Land	60
Net C export from the surface ocean	8-15
Sedimentation of Org. C. in the ocean	0.2
Anthropogenic Changes (Pg or Pg yr^{-1}):	
Cumulative Changes (Pg): (1800-1994)	
Fossil Fuels Burnt & Cement Prod.	244
Atmospheric Increase	165
Storage in the Ocean	118
Inferred Terrestrial Change	-39
Partitioning of Anthropogenic Fluxes (1990s) (Pg yr^{-1})	
Fossil Fuel and Cement Production	6.3 ± 0.4
Atmosphere Accumulation	3.2 ± 0.1
Uptake by Terrestrial Biosphere	-1.4±0.7
Ocean Uptake	-1.7±0.5

Global Carbon Fluxes & Reservoirs – Details

Pg, petagram = 10^{15} g = Gt, gigaton

Emerson & Hedges (2007) Table XI-1

Questions to be Addressed

- How did we get to 387 ppm CO_2?
  - Fossil fuel burning, deforestation, cement production
- Why isn't it even higher?
  - The ocean & land plants have absorbed quite a bit
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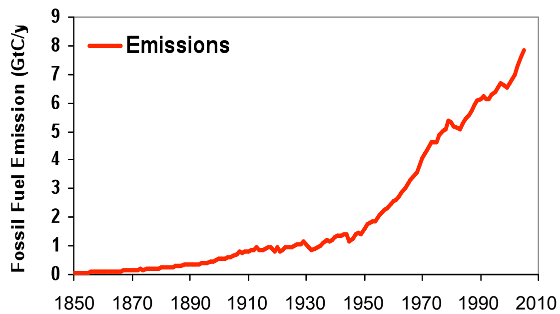
  - About half in the ocean, half in the terrestrial biosphere (see next lecture)

Anthropogenic C Emissions: Fossil Fuel

2006 Fossil Fuel: 8.4 Pg C



Growth Rate:

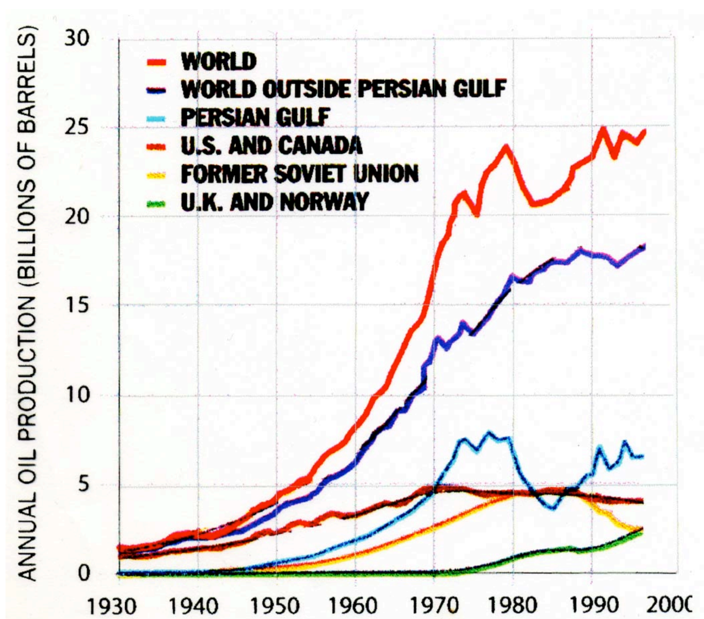
1990 - 1999: 1.3% y^{-1}

2000 - 2006: 3.3% y^{-1}

2006-Total Anthrop. Emissions: 8.4+1.5 = 9.9 Pg

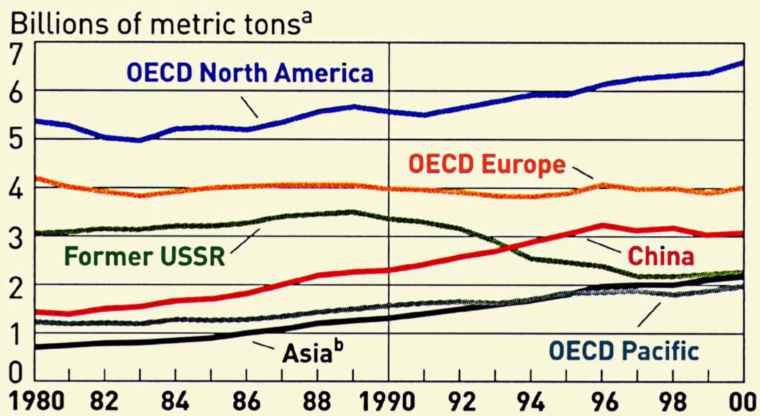
Raupach et al. 2007, PNAS; Canadell et al 2007, PNAS; Canadell et al. (2007) http://www.globalcarbonproject.org/index.htm

Global Oil Production



CO_2 Emissions by Region

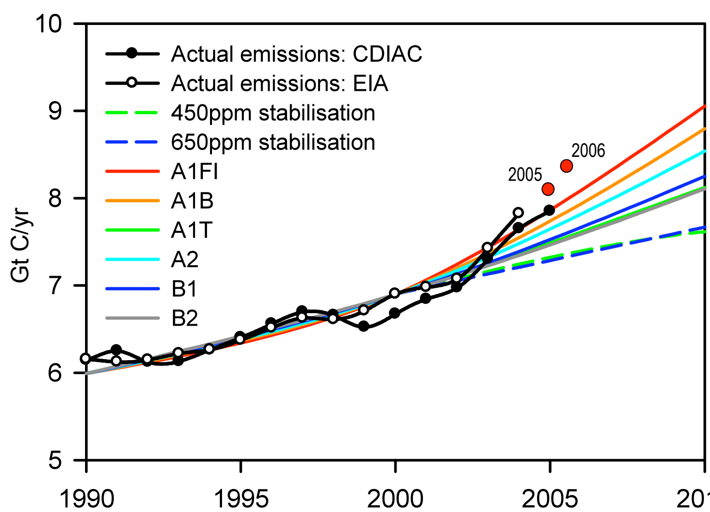
CO_2 emissions from Europe have stabilized, but those from North America have risen sharply



a Emissions from fuel combustion only. **b** Excluding China. **OECD** = Organization for Economic Cooperation & Development
SOURCE: International Energy Agency

source: C&EN Dec. 16, 2002

Trajectory of Global Fossil Fuel Emissions



SRES (2000) growth rates in % y $^{-1}$ for 2000-2010:

A1B: 2.42
A1FI: 2.71
A1T: 1.63
A2: 2.13
B1: 1.79
B2: 1.61

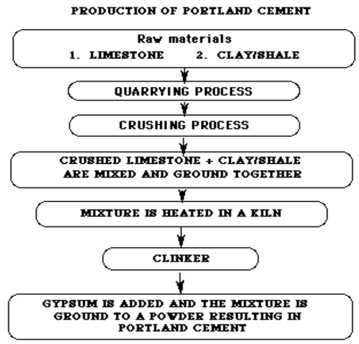
Observed 2000-2006 3.3%

• Current emissions are tracking above the most intense fossil fuel emission scenario established by the IPCC Special Report on Emissions Scenarios-SRES (2000), A1FI (A1 Fossil Fuel intensive)

Raupach et al. 2007, PNAS; Canadell et al. (2007) http://www.globalcarbonproject.org/index.htm

Anthropogenic C Emissions: Cement Production

Concrete components: cement, water, fine aggregate (sand), & coarse aggregate (gravel or crushed stone)



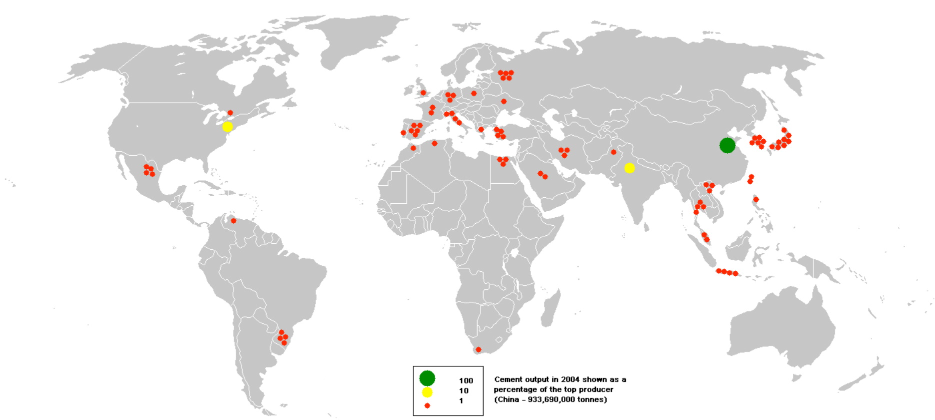
- > 5% of anthropogenic CO_2 emissions come from cement production
- Cement is a fine gray powder that constitutes 7-15% by weight of concrete's total mass
- Vast amounts of coal burned to heat kilns > 1,500°C
- 60% of CO_2 emitted during cement production is due to calcination:

$$CaCO_3 = CaO + CO_2;\ 848°C$$

- Concrete is the 2nd most used product on the planet, after water; almost half is produced in China

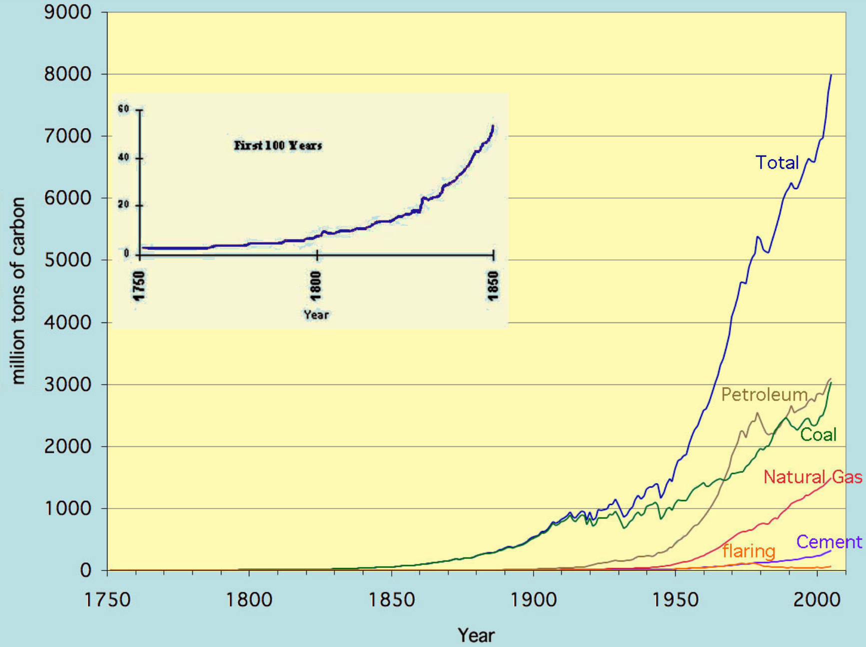
http://www.concretethinker.com/Content/ImageLib/pcano55361.jpg; http://matse1.mse.uiuc.edu/concrete/prin.html; http://www.guardian.co.uk/environment/2007/oct/12/climatechange

Global Cement Output in 2004 as a Percentage of Top Producer (China)

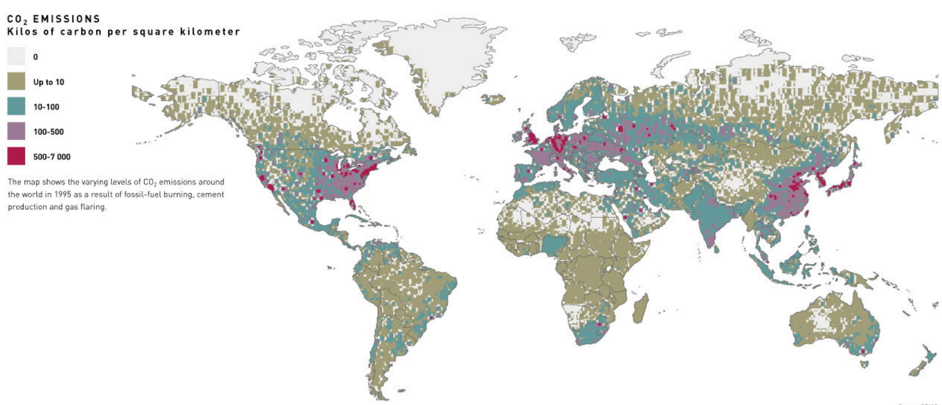


http://upload.wikimedia.org/wikipedia/en/b/bf/2004cement_(hydraulic).PNG

Anthropogenic CO_2 emissions through 2005



Global CO_2 Emissions by Area in 1995



- Includes fossil fuel burning, cement production & gas flaring

Anthropogenic C Emissions: Land Use Change

Tropical deforestation

13 Million hectares each year

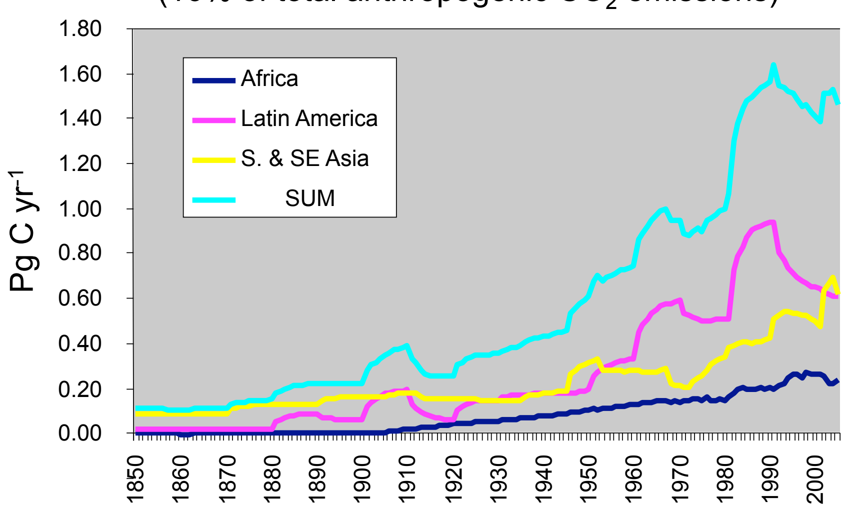
	2000-2005
Tropical Americas	0.6 Pg C y^{-1}
Tropical Asia	0.6 Pg C y^{-1}
Tropical Africa	0.3 Pg C y^{-1}
	1.5 Pg C y^{-1}

Borneo, Courtesy: Viktor Boehm; FAO-Global Resources Assessment 2005; Canadell et al. 2007, PNAS

Carbon Emissions from Tropical Deforestation

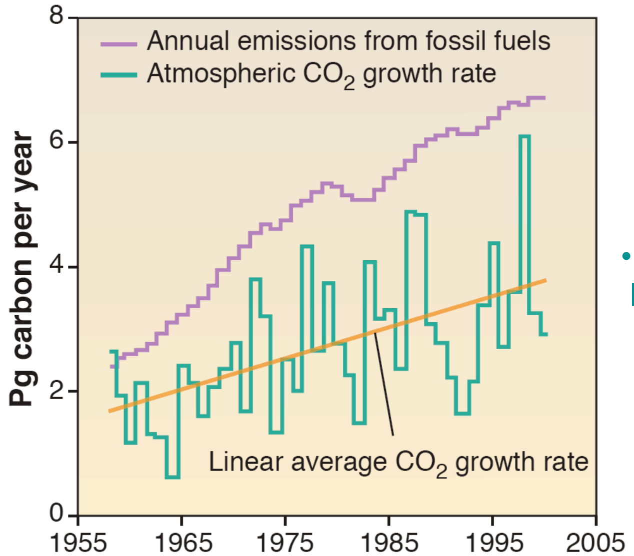
2000-2006: 1.5 PgC/yr

(16% of total anthropogenic CO_2 emissions)



Houghton, unpublished

Atmospheric CO_2 growth rate

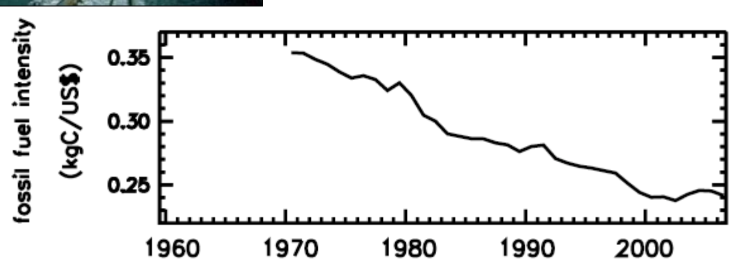


• Includes land use changes

Quay (2002) CLIMATE CHANGE: Enhanced: Ups and Downs of CO_2 Uptake. *Science Vol.* 298(5602): 234.

Carbon Intensity of the Global Economy

• Kg Carbon Emitted to Produce 1 $ of Wealth

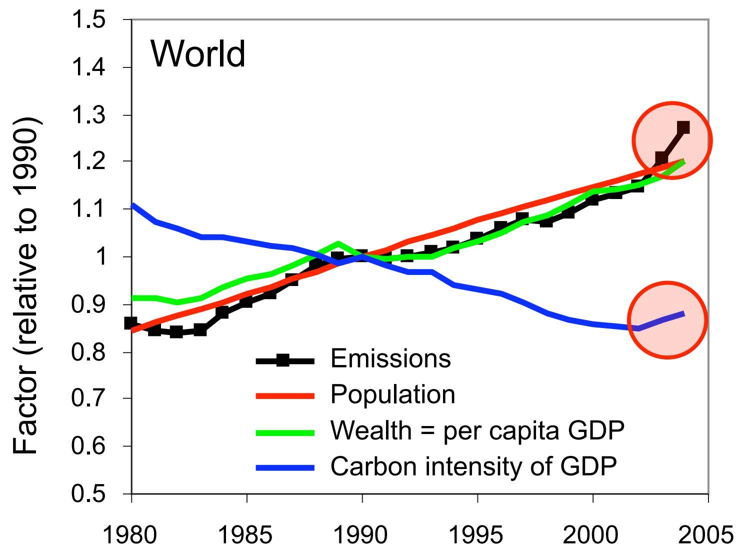


• 1970-2000: Declined from 0.35-0.24, a decrease (improvement) of 1.3%/yr

• 2000-2006: Trend reversed & C intensity increased (deteriorated) at 0.3%/yr

Canadell et.al (2007) *PNAS* Vol. 104:18866-18870

Drivers of Anthropogenic Emissions

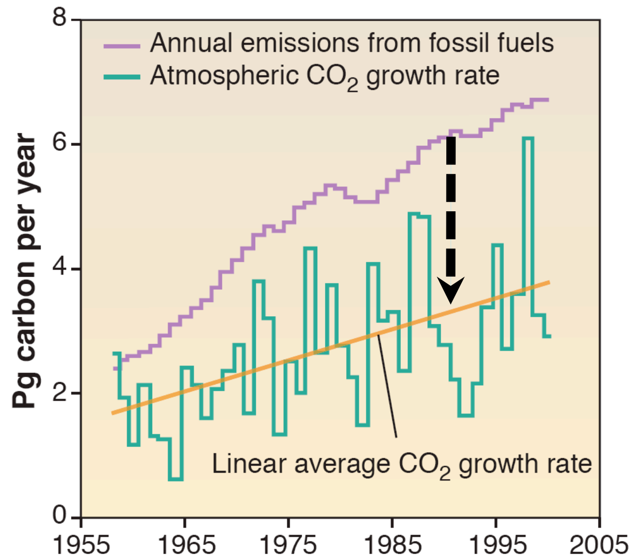


Raupach et al 2007, PNAS

Questions to be Addressed

- How did we get to 387 ppm CO_2?
  - Energy use, cement production & deforestation
- Why isn't it even higher?
  - The ocean & land plants have absorbed quite a bit
- Where has the CO_2 we produced that is not in the atmosphere gone?
  - About half in the ocean, half in the terrestrial biosphere (see next lecture)

Why Isn't All the Fossil Fuel CO_2 in the Atmosphere?



- Includes land use changes

Quay (2002) CLIMATE CHANGE: Enhanced: Ups and Downs of CO_2 Uptake. *Science Vol.* 298(5602): 234.

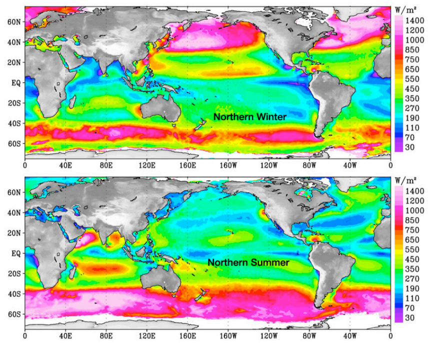
Some is in the Ocean

(we'll discuss this today)

Some is in the Terrestrial Biosphere

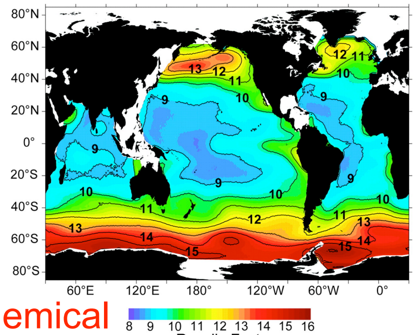
(Lyatt will discuss on Tues 2/24)

Rapidly Increasing Atmospheric CO_2 Causes Disequilibrium with Surface Ocean & Subsequent Uptake of CO_2



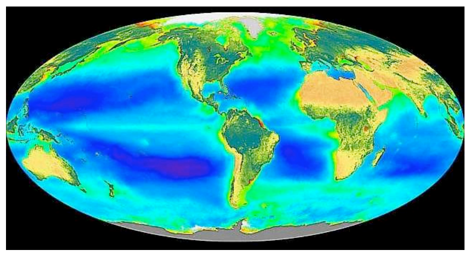
Physical

Quikscat surface wind power density



Chemical

Carbonate buffer

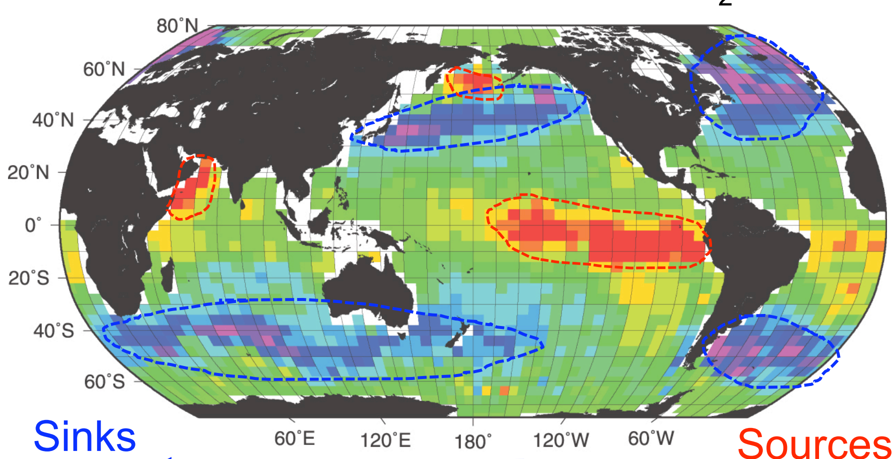


Biological

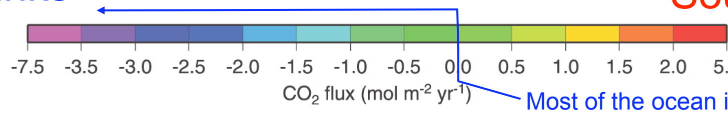
SeaWifs ocean color

Sabine et al. (2004) *Science* Vol. 305: 367-3
http://www.nasa.gov/images/content/257995main_quikscat-wind-browse.jpg
http://oceancolor.gsfc.nasa.gov/SeaWiFS/TEACHERS/sanctuary_7.html

Modern Air-Sea Fluxes of CO_2



Sinks **Sources**

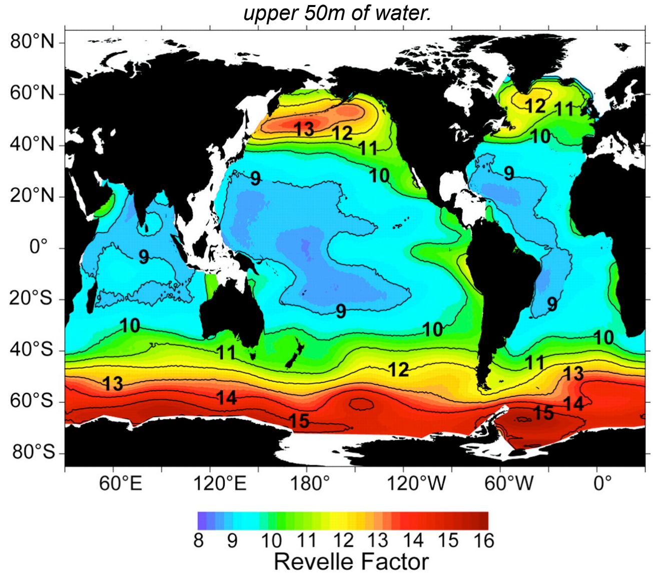


- *Sinks exceed sources as a result of the high & growing atmospheric pCO_2 burden*

IPCC 2007 Fig. 7.8

CO_2 is Stored in Ocean as DIC

1994 distribution of the Revelle factor averaged over upper 50m of water.



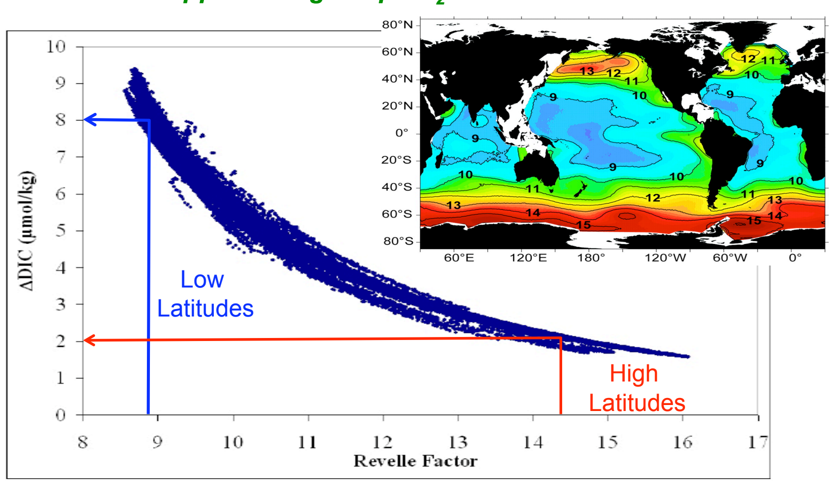
- According to the Revelle Factor, a 10% increase in pCO_2 causes a 1% increase in DIC
- The 100 ppmV increase in atm. CO_2 since ~1850, representing a 34% increase ([390-290]/ 290=0.34), therefore increased surface ocean DIC by 3.4%, or (0.034*2000 µmol/kg) 68 µmol/kg
- Concurrently RF has decreased by 1 unit globally

Sabine et al. (2004) *Science* Vol. 305: 367-371

Lower RF = Greater buffering capacity

Lower Latitudes Absorb CO_2 are More Efficiently

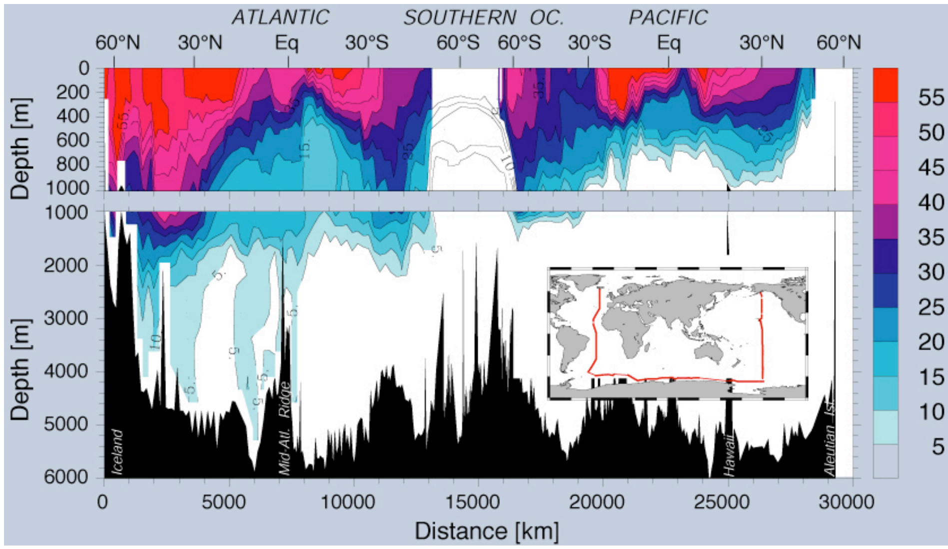
- *ΔDIC for* ***a 10 ppm change in*** pCO_2 *as a function of Revelle Factor*

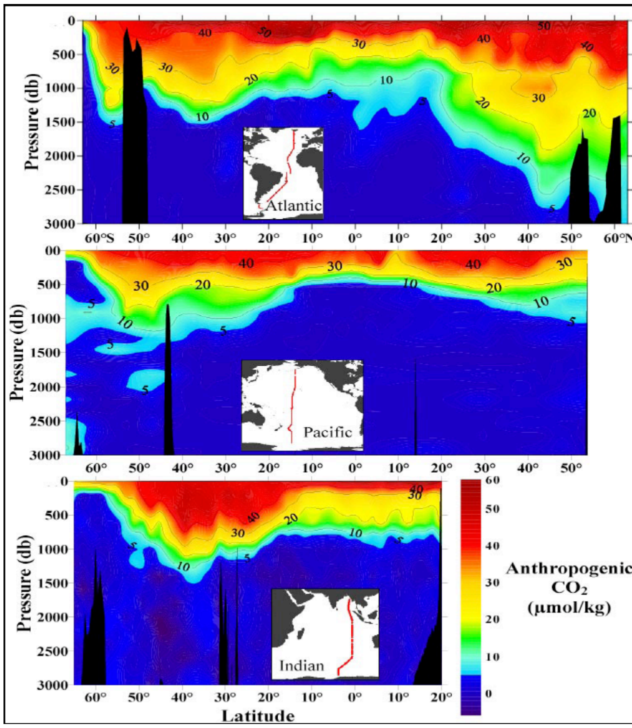


- More intuitively: a 2 µmol/kg increase in DIC causes the same increase in pCO2 in high latitude surface waters as an 8 µmol/kg increase in DIC in low latitude surface waters

Adapted from Chris Sabine, NOAA PMEL

Anthropogenic CO_2 in the World Ocean (μmol/kg)



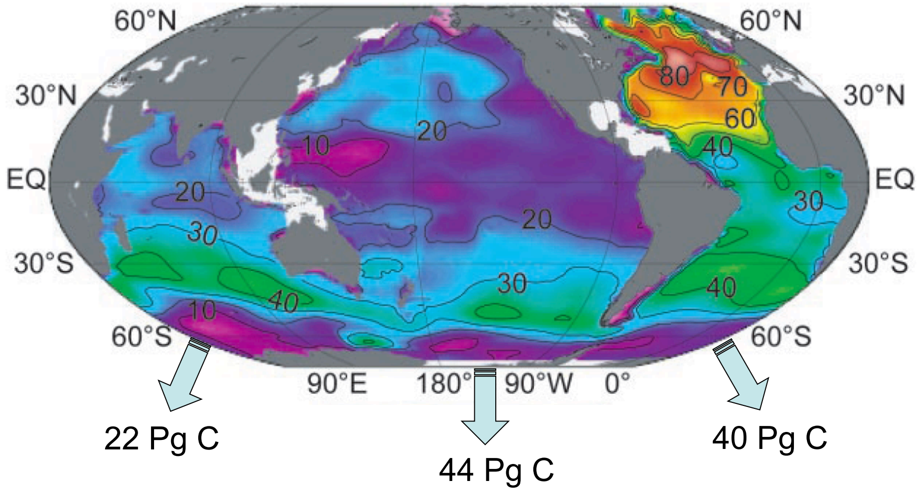


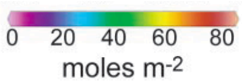
Owing to Slow Ocean Mixing, 50% of Anthropogenic CO_2 in the Ocean (~15% of Total Anthro. CO_2) is in Upper 400 m (as of 1994)

- Average penetration depth ~1000 m

Sabine et al. (2004) *Science* Vol. 305: 367-371

Column Inventory of Anthropogenic CO_2 that Accumulated in the Ocean 1800-1994

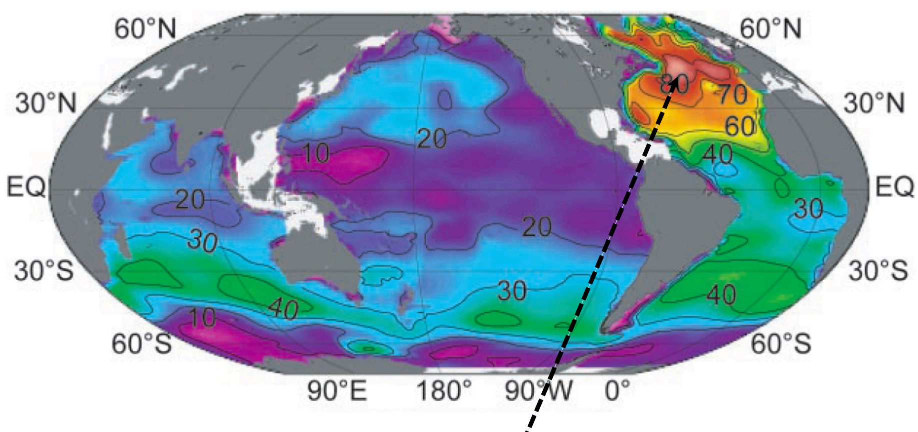




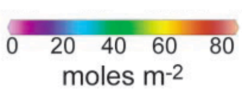
• Mapped Inventory = 106 ± 17 Pg C

Adapted from Sabine et al. (2004) *Science* Vol. 305: 367-371

N. Atlantic is an Important Sink for Anthropogenic CO_2



• 25% of column CO_2 inventory with just 15% of mapped area



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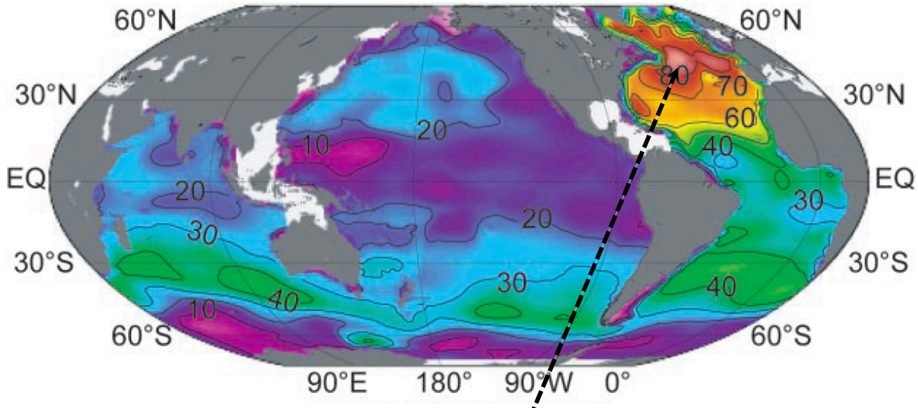

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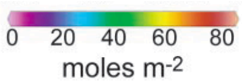

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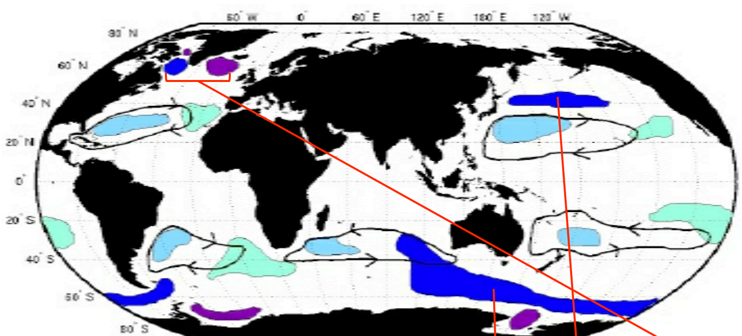
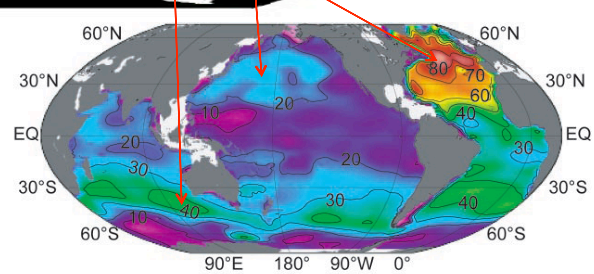
Adapted from Sabine et al. (2004) *Science* Vol. 305: 367-371

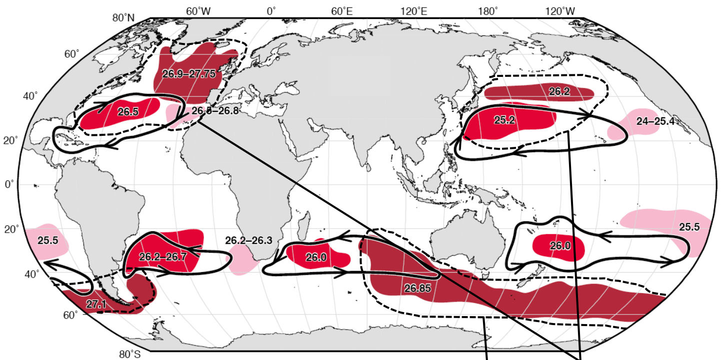
Highest Inventories Occur Where Subsurface (Mode) Waters Form





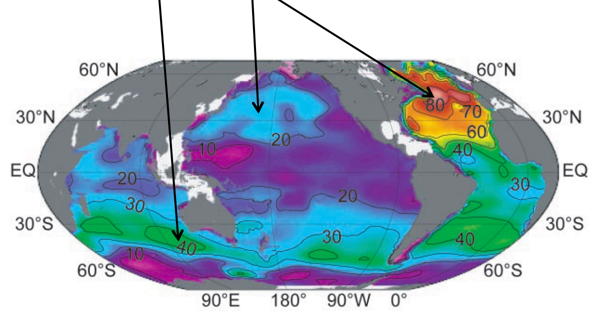
- Convection transports surface water and its anthropogenic CO_2 into ocean interior

Talley (2000)



Highest Inventories Occur Where Subsurface (‘Mode’) Waters Form

• Convection transports surface water & its anthropogenic CO_2 into ocean interior



Hanawa & Talley (2001) Mode Waters. In *Ocean Circulation and Climate*, Academic Press, 373-386

Questions to be Addressed

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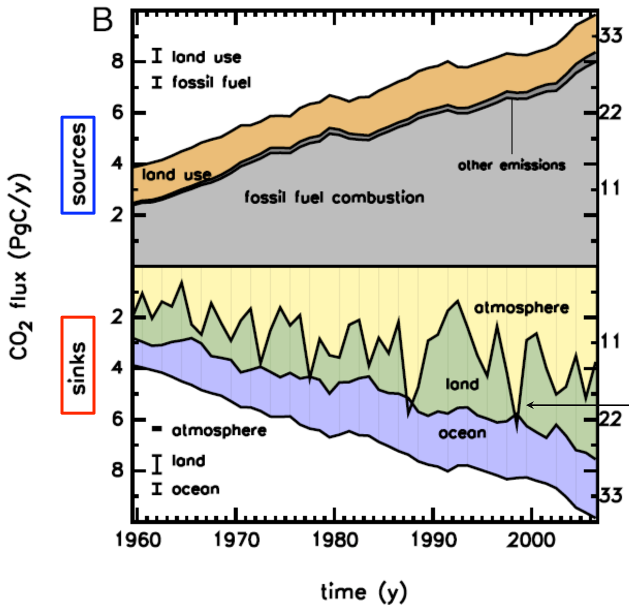
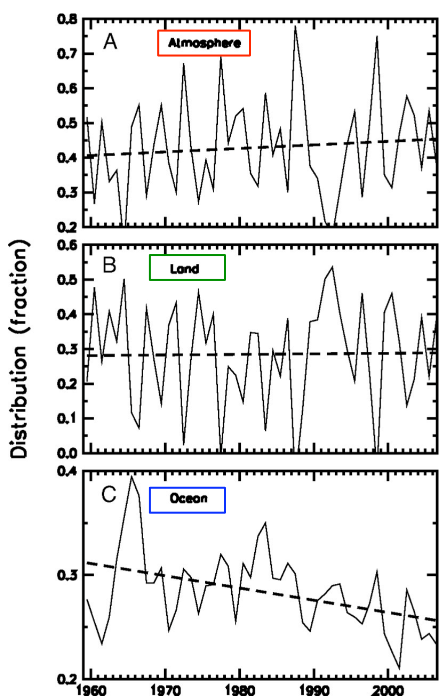
- Why isn’t it even higher?
  - The ocean & land plants have absorbed quite a bit
- Where has the CO_2 we produced that is not in the atmosphere gone?
  - About half in the ocean, half in the terrestrial biosphere (see next lecture)

Sources & Sinks of Anthropogenic CO_2 1959-1960



- Other CO_2 emissions are primarily from cement production
- Land CO_2 sink variability results predominantly from natural climate variability, such as ENSO

Canadell et.al (2007) *PNAS* Vol. 104:18866-18870



Fraction of Total Emissions

(= Fossil Fuel + Cement +

Land Use Change) that Remains in:

Atmosphere

Land Biosphere

Ocean

Canadell et.al (2007) *PNAS* Vol. 104:18866-18870

Summary of Global C Budget 1959-2006

Global carbon budget	Mean 1959–2006	1970–1999	1990–1999	2000–2006	Proportional trend, % y^{-1} 1959–2006
Economy, kgC/U.S. dollars					
Carbon intensity	0.29*	0.30	0.26	0.24	−1.18†
Sources, PgC y^{-1}					
Fossil Fuel (F_{Foss})	5.3	5.6	6.5	7.6	2.12
Land Use Change (F_{LUC})	1.5	1.5	1.6	1.5	0.21
Total (F_{Foss} + F_{LUC})	6.7	7.0	8.0	9.1	1.71
Sinks, PgC y^{-1}					
Atmosphere	2.9	3.1	3.2	4.1	1.89
Ocean	1.9	2.0	2.2	2.2	1.25
Land	1.9	2.0	2.7	2.8	1.87
Distribution of annual emissions					
Atmosphere‡	0.43	0.44	0.39	0.45	0.25 ± 0.21§
Ocean	0.28	0.28	0.27	0.24	−0.42
Land	0.29	0.28	0.34	0.30	0.06

- 43% of CO_2 emissions 1959-2006 remain in the atmosphere
- 28% have been taken up by the ocean
- 29% have been taken up by the terrestrial biosphere

Canadell et.al (2007) *PNAS* Vol. 104:18866-18870

2000-2006 Anthropogenic Carbon Emission Sinks

45% of all CO_2 emissions accumulated in the atmosphere

Atmosphere

The Airborne Fraction

The fraction of the annual anthropogenic emissions that remains in the atmosphere

55% were removed by natural sinks

Ocean removes 24%

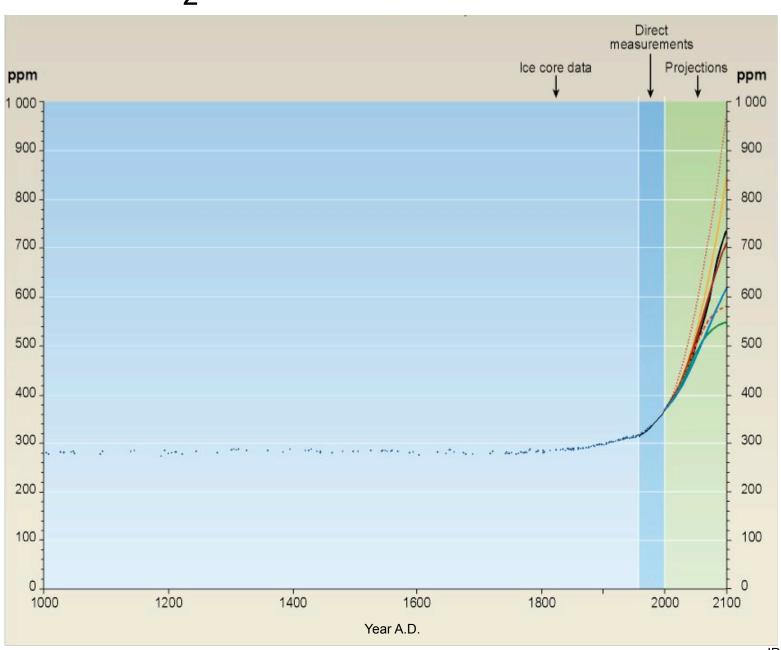
Land removes 30%

Canadell et al. 2007, PNAS; Canadell et al. (2007) http://www.globalcarbonproject.org/index.htm

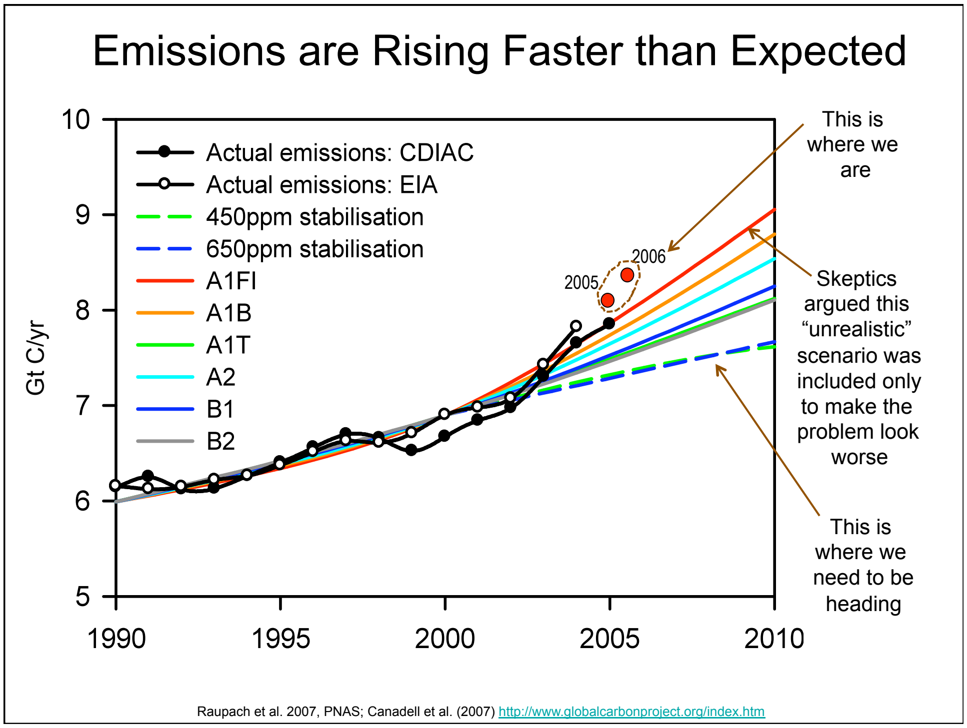
The Future

- Higher Atmospheric CO_2
- Warmer Global Mean Temperature
- More Acidic Ocean
- Rising Sea Level

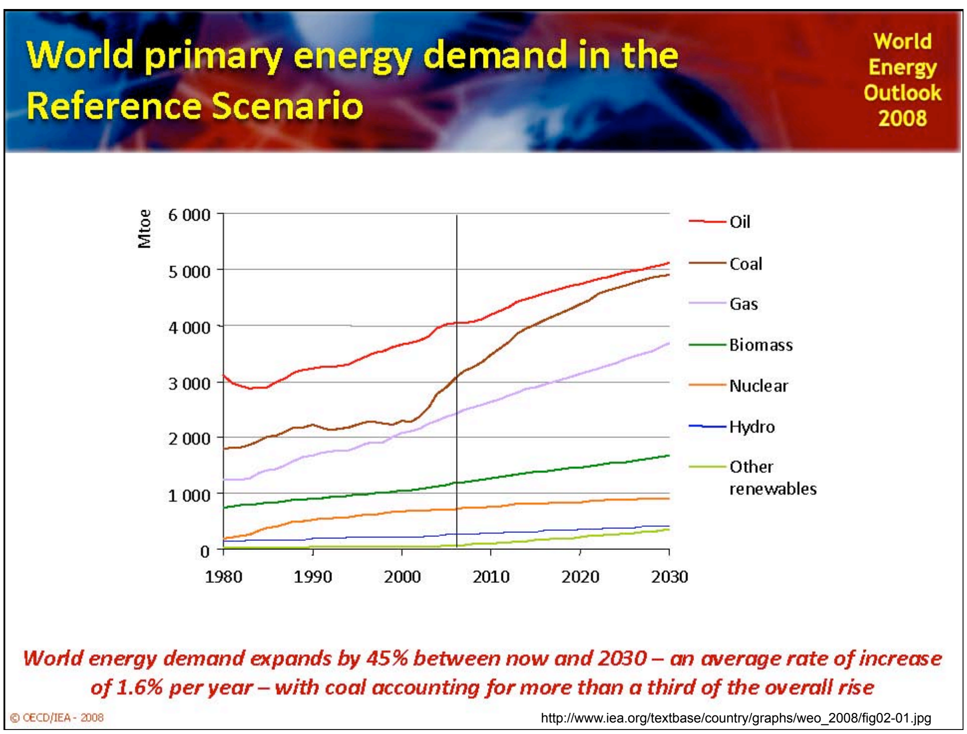
CO_2 for the last 1000 Years



IPCC 2001

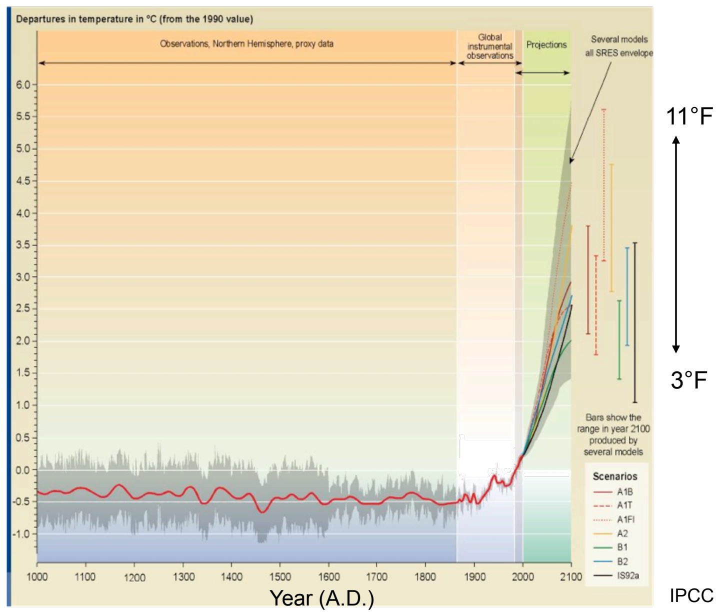


Emissions are Rising Faster than Expected
Gt C/yr
10
9
8
7
6
5
1990
1995
2000
2005
2010
Actual emissions: CDIAC
Actual emissions: EIA
450ppm stabilisation
650ppm stabilisation
A1FI
A1B
A1T
A2
B1
B2
2005
2006
This is where we are
Skeptics argued this "unrealistic" scenario was included only to make the problem look worse
This is where we need to be heading
Raupach et al. 2007, PNAS; Canadell et al. (2007) http://www.globalcarbonproject.org/index.htm



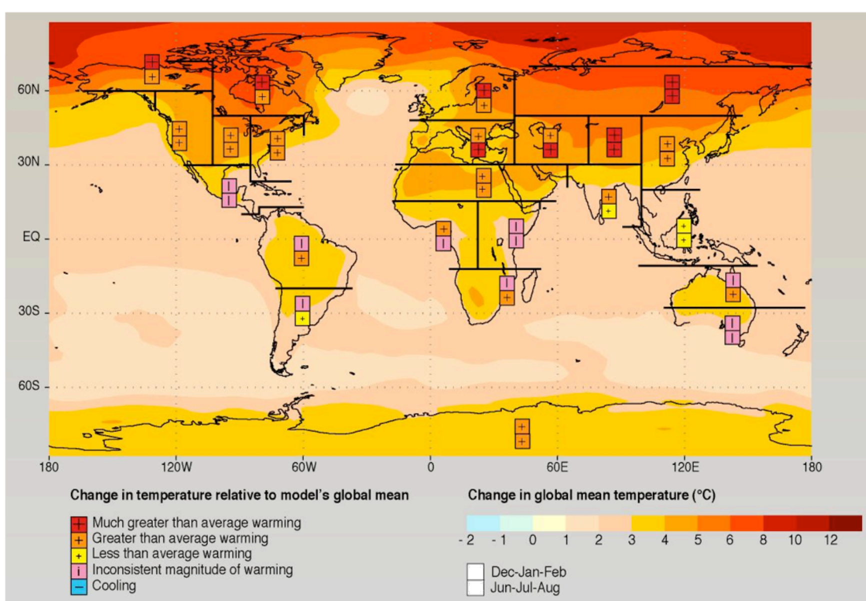
World primary energy demand in the Reference Scenario
World Energy Outlook 2008
Mtoe
6 000
5 000
4 000
3 000
2 000
1 000
0
1980
1990
2000
2010
2020
2030
Oil
Coal
Gas
Biomass
Nuclear
Hydro
Other renewables
World energy demand expands by 45% between now and 2030 – an average rate of increase of 1.6% per year – with coal accounting for more than a third of the overall rise
© OECD/IEA - 2008
http://www.iea.org/textbase/country/graphs/weo_2008/fig02-01.jpg

Global Temperature: 1000-2100 A.D.



IPCC 2001

Expected Warming in 2100 A.D.



IPCC 2001

Ocean Acidification

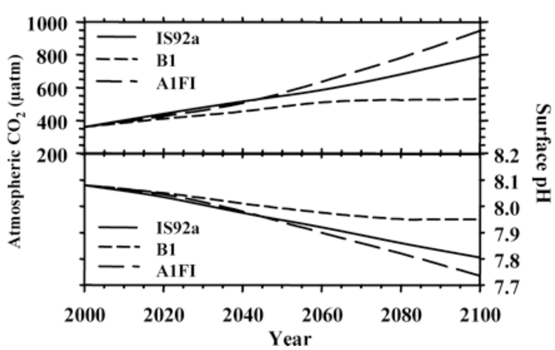
$$CO_2 + H_2O = H_2CO_3$$

Carbon Dioxide + Water = Carbonic Acid*

$$H_2CO_3 + CaCO_3 = Ca^{2+} + CO_3^{2-} + H_2O$$

Carbonic Acid + Calcium Carbonate = Dissolved Shells

Ocean Acidification



- Rising CO_2 levels this century…

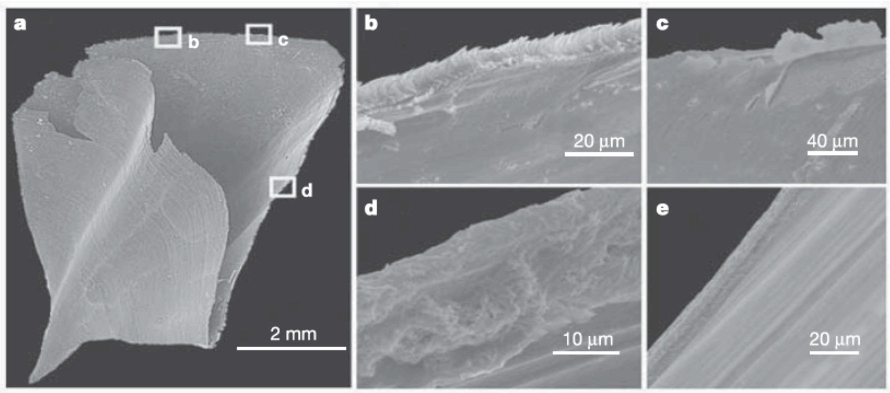
…will acidify the surface ocean…

…making it difficult for calcifying organisms (corals, plankton, mollusks) to grow.

Fabry et al. (2008) *ICES Journal of Marine Science* Vol. 65(3):414-432.

Effects of Ocean Acidifcation on Pelagic Ecosystems

• Pacific Ocean pteropod (*C. pyramidata*, c) rapidly dissolves in water undersaturated with respect to aragonite (b-d). Unexposed shell in (e).



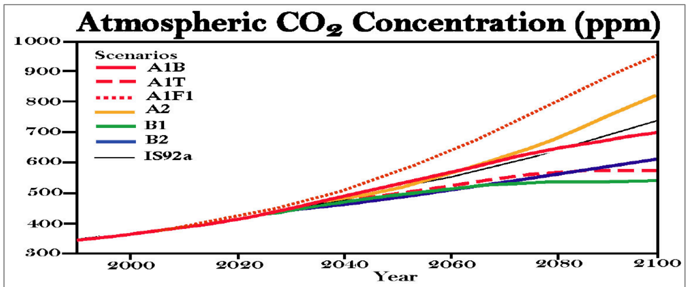
Orr et al. (2005) *Nature* Vol. 437: 681-686.

Effects of Ocean Acidification on Coral Reefs

2006 A.D. … in 10 years … in 30 years

http://www.noaanews.noaa.gov/stories2007/images/co2coral2.jpg

Ocean Acidification



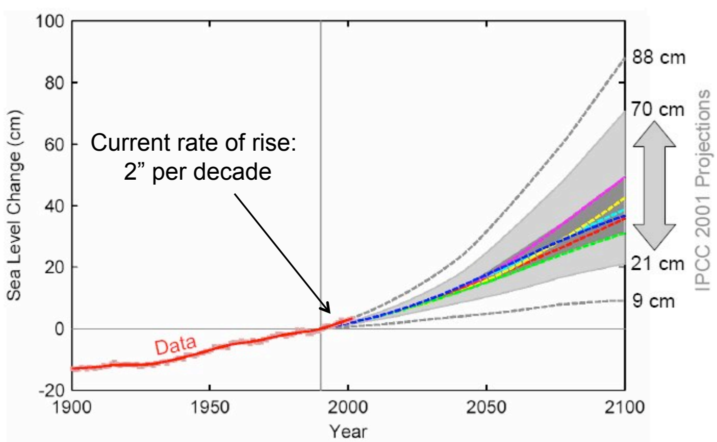
	Glacial	Pre-industrial	Present	$2XCO_2$	$3XCO_2$	
$CO_2(g)$ Gas Exchange	180 (56)	280 (0)	380 (36)	560 (100)	840 (200)	Atmosphere / Surface ocean
$CO_2(aq) + H_2O \leftrightarrow H_2CO_3$ Carbonic acid	7 (29)	9 (0)	13 (44)	18 (100)	25 (178)	
$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ Bicarbonate	1666 (4)	1739 (0)	1827 (5)	1925 (11)	2004 (15)	
$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$ Carbonate	279 (20)	222 (0)	186 (-16)	146 (-34)	115 (-48)	
$H^+ x10^{-9}$ Hydrogen Ion Concentration	4.79 (45)	6.92 (0)	8.91 (29)	12.3 (78)	17.4 (151)	
Ω Ca Omega Calcite	6.63 (20)	5.32 (0)	4.46 (-16)	3.52 (-34)	2.77 (-48)	
Ω Ar Omega Aragonite	4.26 (19)	3.44 (0)	2.9 (-16)	2.29 (-33)	1.81 (-47)	
	1952 (1)	1970 (0)	2026 (2.8)	2090 (6.1)	2144 (8.8)	DIC
	8.32	8.16	8.05	7.91	7.76	pH

- Average rate of surface water DIC increase in 2000 A.D. ~1.2 μmol/kg/yr

Modified from Feely et al., (2001)

Sea Level Rise Through 2100 A.D.

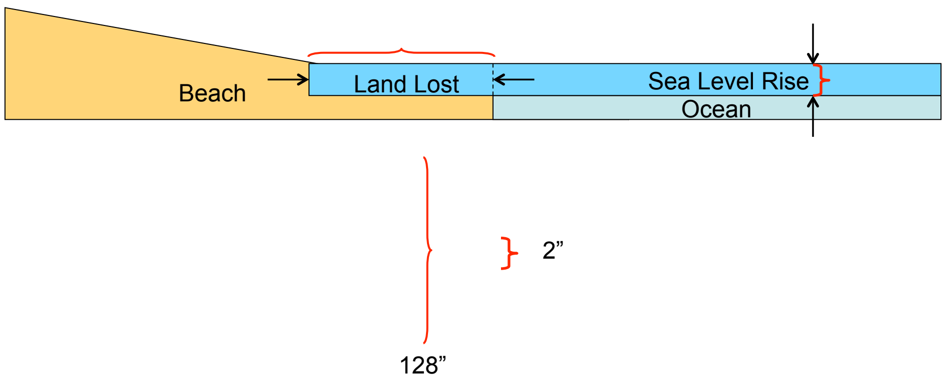
- 10-30 inch rise in sea level this century will likely inundate substantial parts of the RMI



- Average slope of shore ~ 1%

IPCC 2001

Exaggerated Loss of Land from Rising Sea



• A 2” sea level rise results in a 128” (10.5’) loss of land in this example with a beach slope of 1:64 or 1.6%

Summary

- How did we get to 387 ppm CO_2?
  - Energy use, cement production & deforestation
- Why isn’t it even higher?
  - The ocean & land plants have absorbed quite a bit
- Where has the CO_2 we produced that is not in the atmosphere gone?
  - About 50% each in the ocean & terrestrial biosphere
- In the Future we can expect:
  - Higher Atmospheric CO_2
  - Warmer Global Mean Temperature
  - More Acidic Ocean
  - Rising Sea Level