

Average Lifetime of Technological Civilization



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L = ?

- End of Communication Efforts
(Civilization Survives)
(Decades?)
- Civilization **Evolves** away from interest or capability (Post-technological Civilization)
(Centuries - Millenia)

- **Civilization Collapses**
(Reversion to Pre-technological Culture)
Exhaustion of resources
Population explosion
(~ 100 yrs - 1000 yrs)
- **Sudden, Catastrophic End of Civilization or Extinction of our Species**
Nuclear War leads to Nuclear Winter
(10' s - 100' s of years)
Natural Catastrophes ($> 10^5$ yr for most)

Resource Depletion

Metals, Drinkable Water, Arable Land, ...

Energy is most fundamental

Energy is conserved

“Depletion” = conversion to less usable forms
(entropy increases)

World Energy Usage

- 474 exajoules/year (474×10^{18} Joules/year)
 - 15 Terawatts (15×10^{12} Watts)
- Total Available (controversial and uncertain)
 - Fossil fuels 0.4×10^{24} Joules (800 years)
 - Nuclear fission 2.5×10^{24} Joules (5000 yr)
- Potential Renewable (rate of supply)
 - Solar 3.3 x current usage
 - Wind 1.4 x current usage

History of Energy Use in USA

Consumption by Source

Figure 5. Energy Consumption by Source, 1635-2003

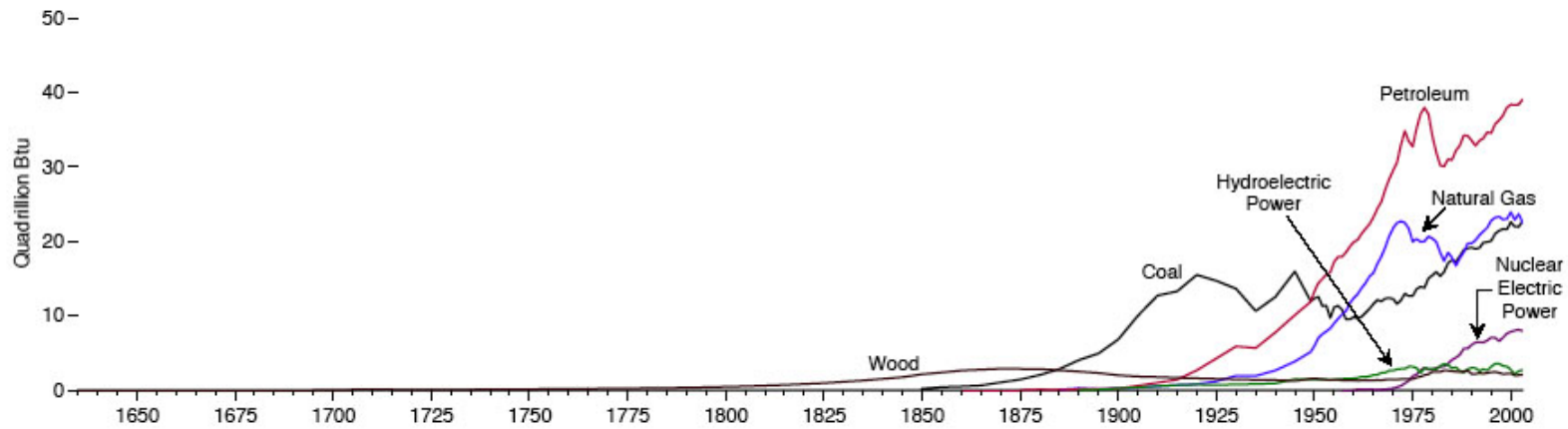
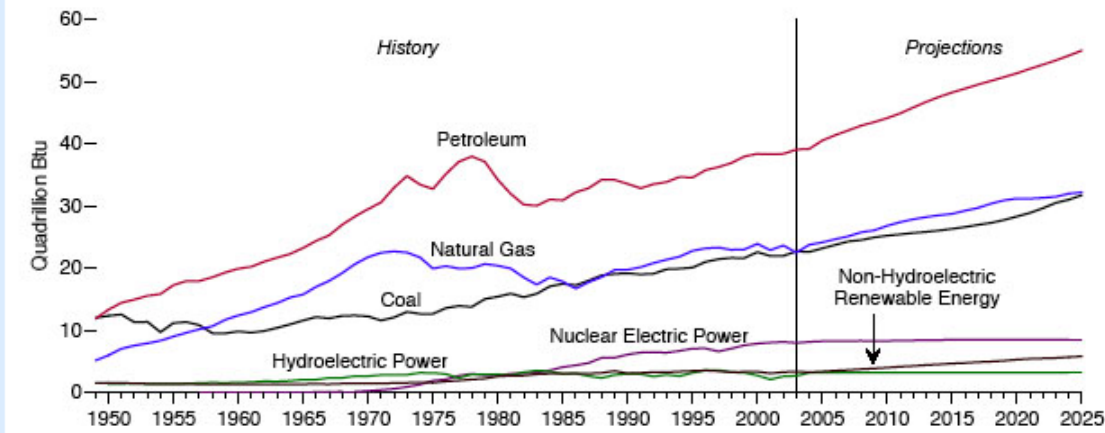


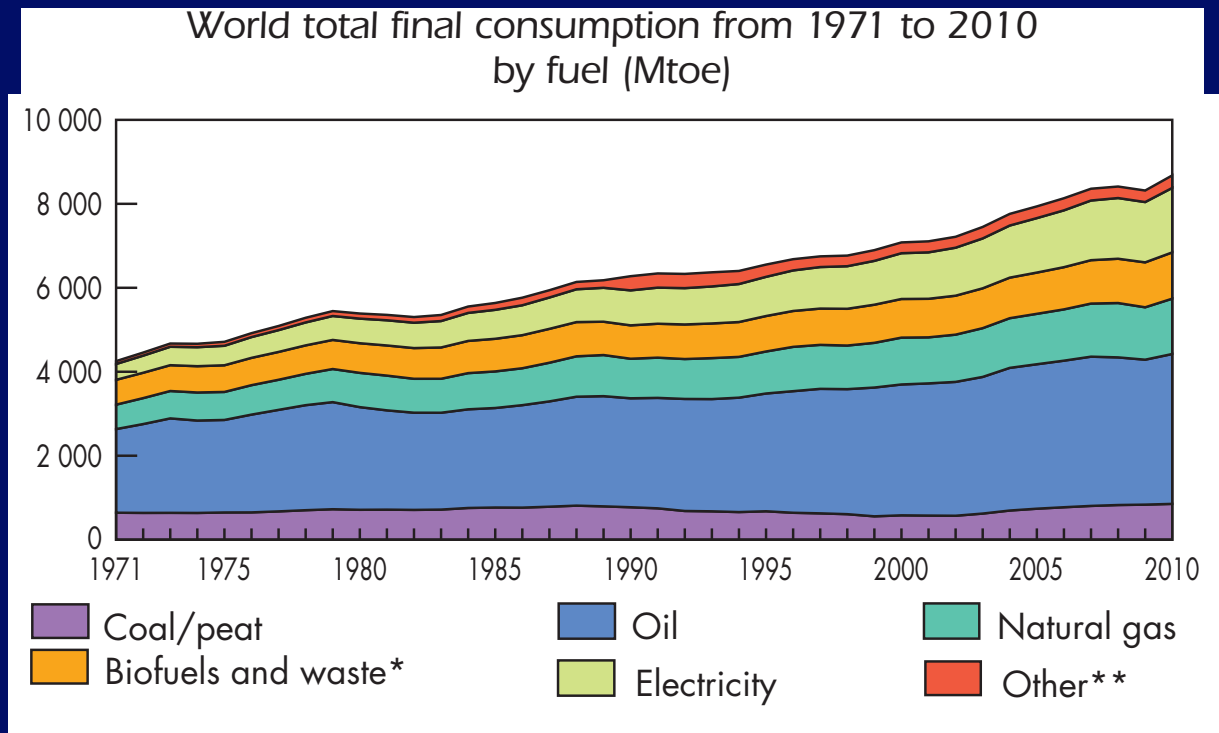
Figure 6. Energy Consumption History and Outlook, 1949-2025



In the long view of American history, wood served as the preeminent form of energy for about half of the Nation's history. Around 1885, coal surpassed wood's usage. Despite its tremendous and rapid expansion, coal was, in turn, overtaken by petroleum in the middle of the 20th century. Natural gas, too, experienced rapid development into the second half of the 20th century, and coal began to expand again. Late in the 20th century still another form of energy, nuclear electric power, was developed and made significant contributions.

While the Nation's energy history is one of large-scale change as new forms of energy were developed, the outlook for the next couple of decades (assuming current laws, regulations, and policies) is for continued growth and reliance on the three major fossil fuels—petroleum, natural gas, and coal—modest expansion in renewable resources, and relatively flat generation from nuclear electric power.

Total Energy Usage



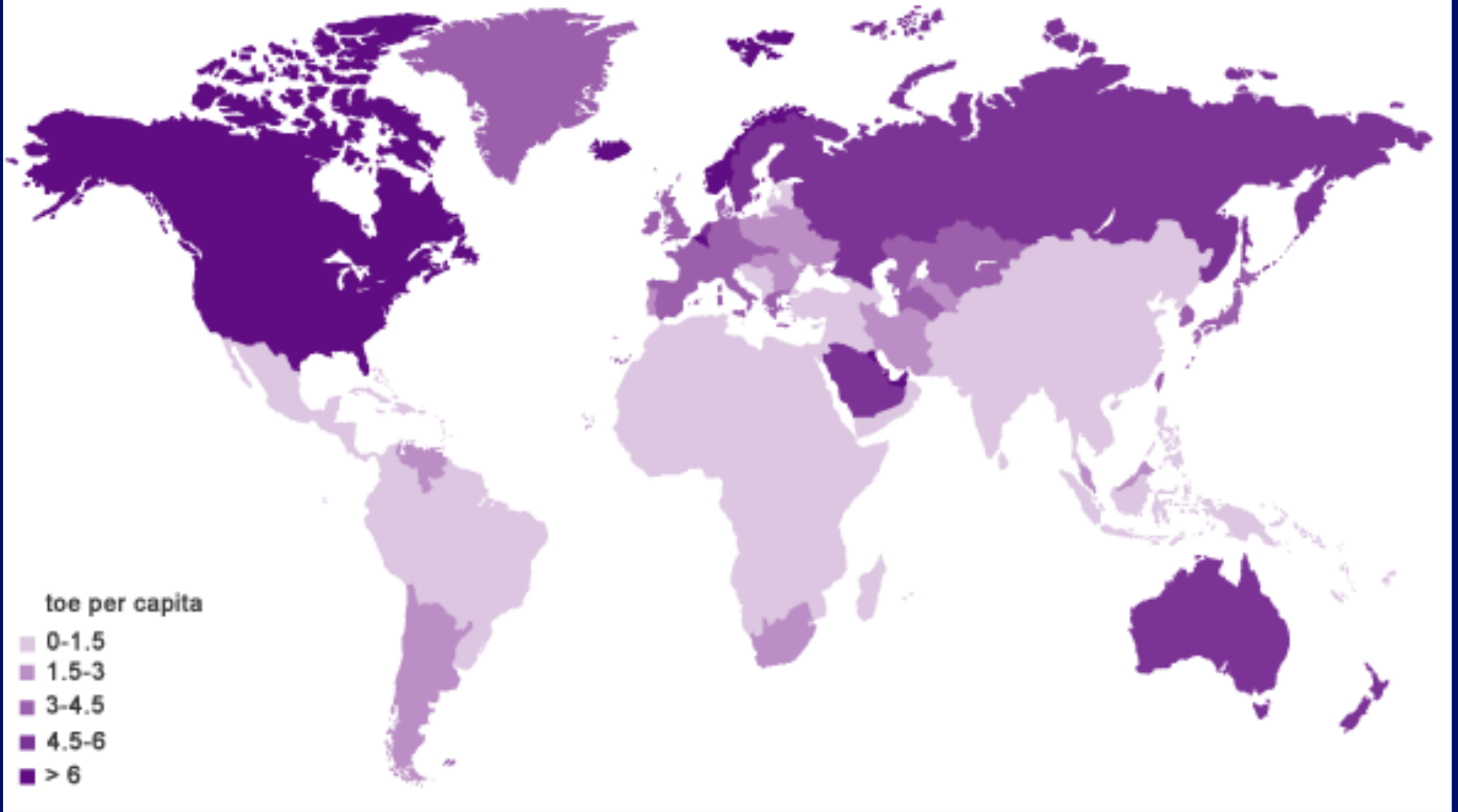
International Energy Agency

1 Mtoe = energy from burning 1 Million metric tonnes of oil

1 toe = 42×10^9 Joules

Energy Consumption per capita

Primary energy consumption per capita
Tonnes oil equivalent



International Energy Agency

Side Effects

- General Pollution of Air, Water, Land
 - Makes resources less usable
 - Air pollution, respiratory problems
 - Undrinkable water
 - Desertification of farm-lands
- Ozone Layer Destruction
 - ⇒ UV reaches surface
 - Skin Cancer, Cataracts, ...
 - Crop Damage

Caused by CFC's (refrigeration, styrofoam,...)
other chemicals

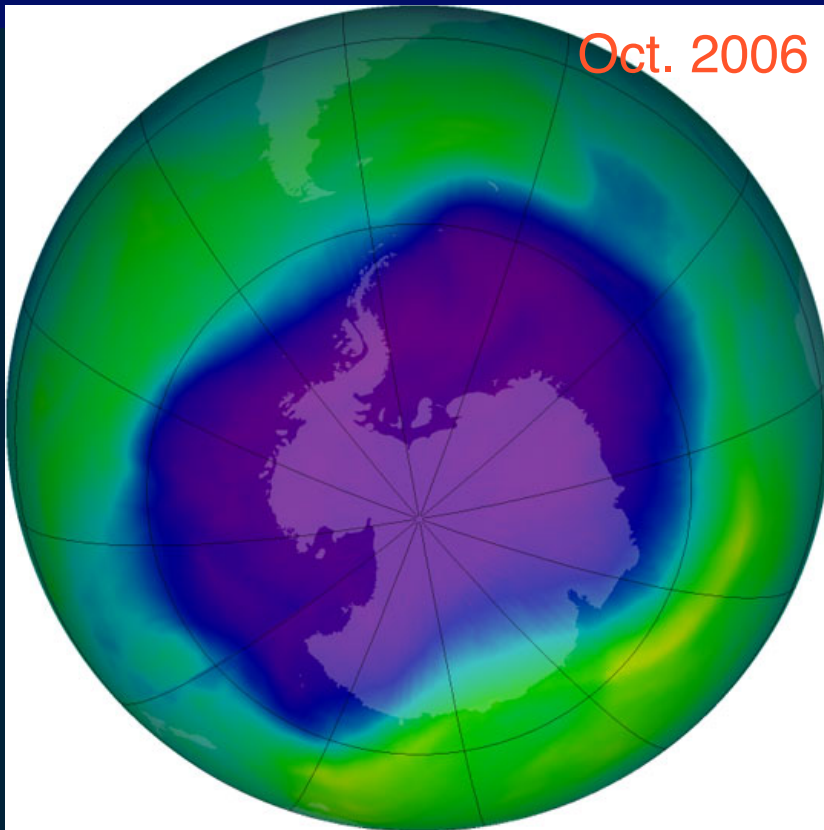
Stratosphere is very sensitive and
poorly understood

Catalytic reactions: One CFC molecule
leads to the destruction of **many** ozone
molecules



Growth of ozone hole

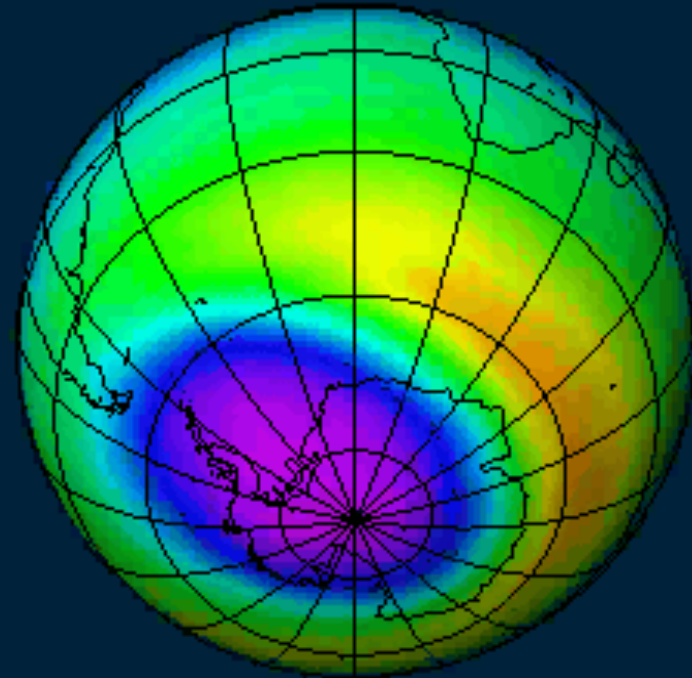
Oct. 2006



Total Ozone (Dobson Units)

110 220 330 440 550

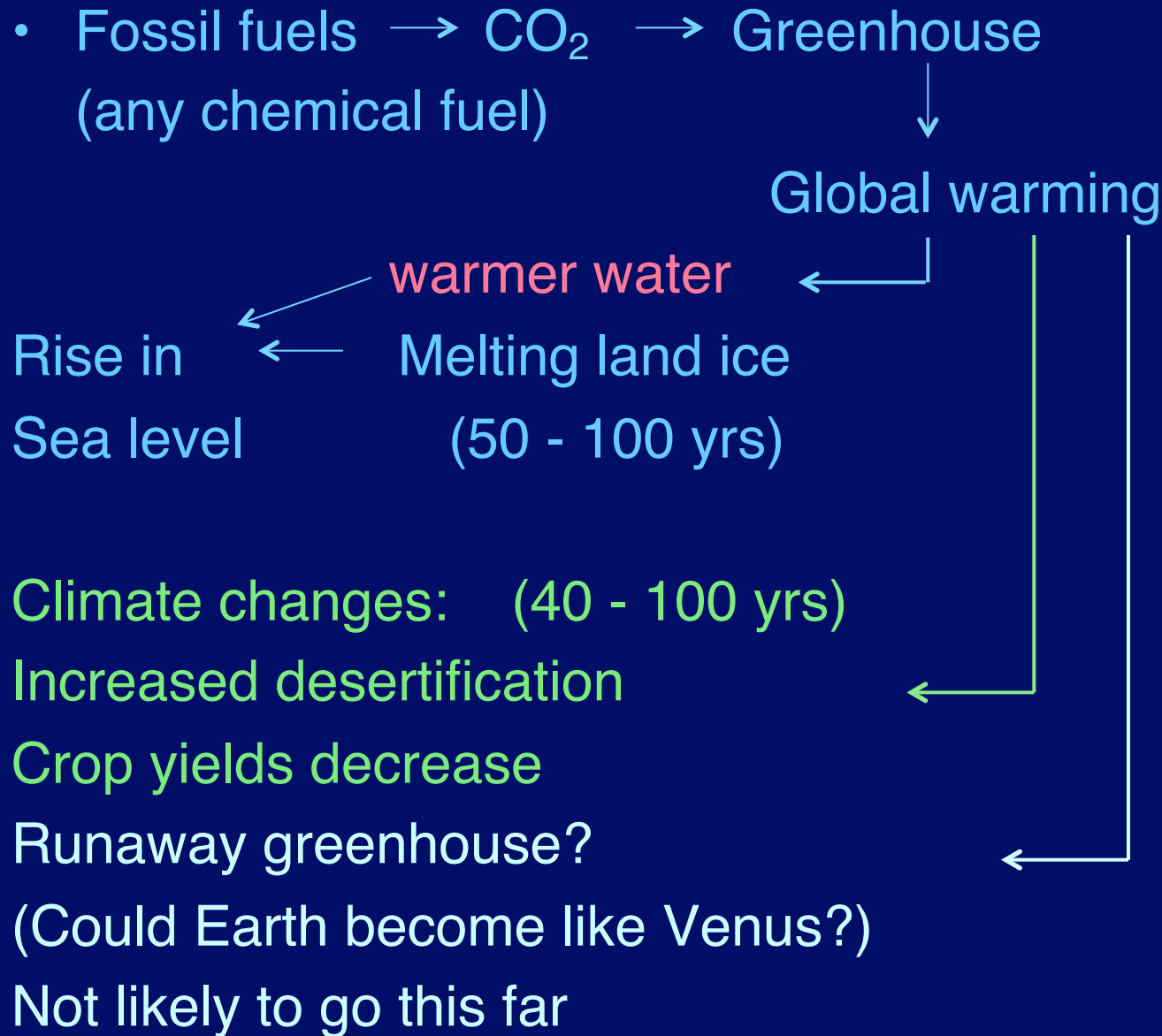
TOMS Ozone (DU): Oct 1991



100 140 180 220 260 300 340 380 420 460 500

100 140 180 220 260 300 340 380 420 460 500

Side Effects (cont.)



GLOBAL MEAN SEA LEVEL

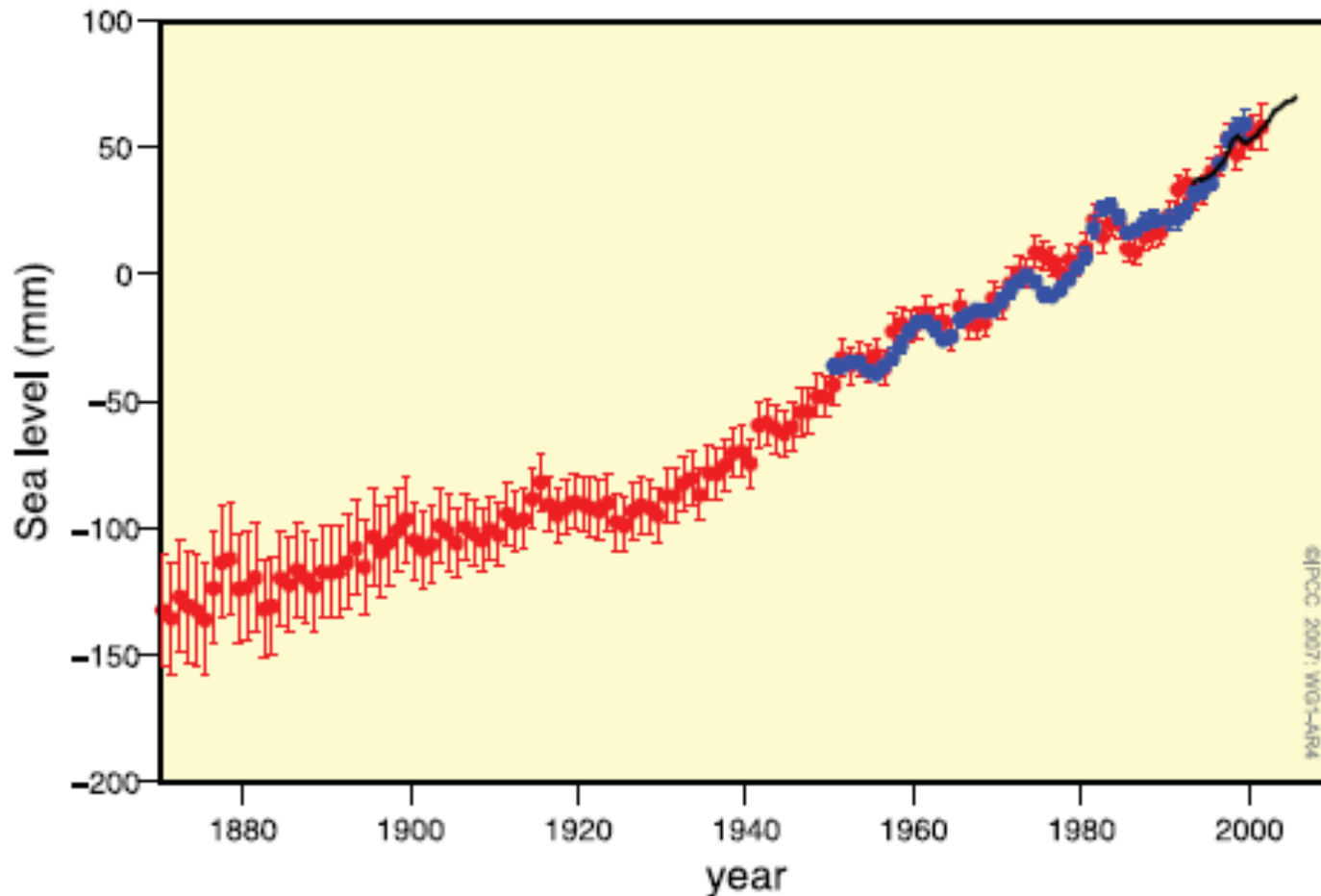
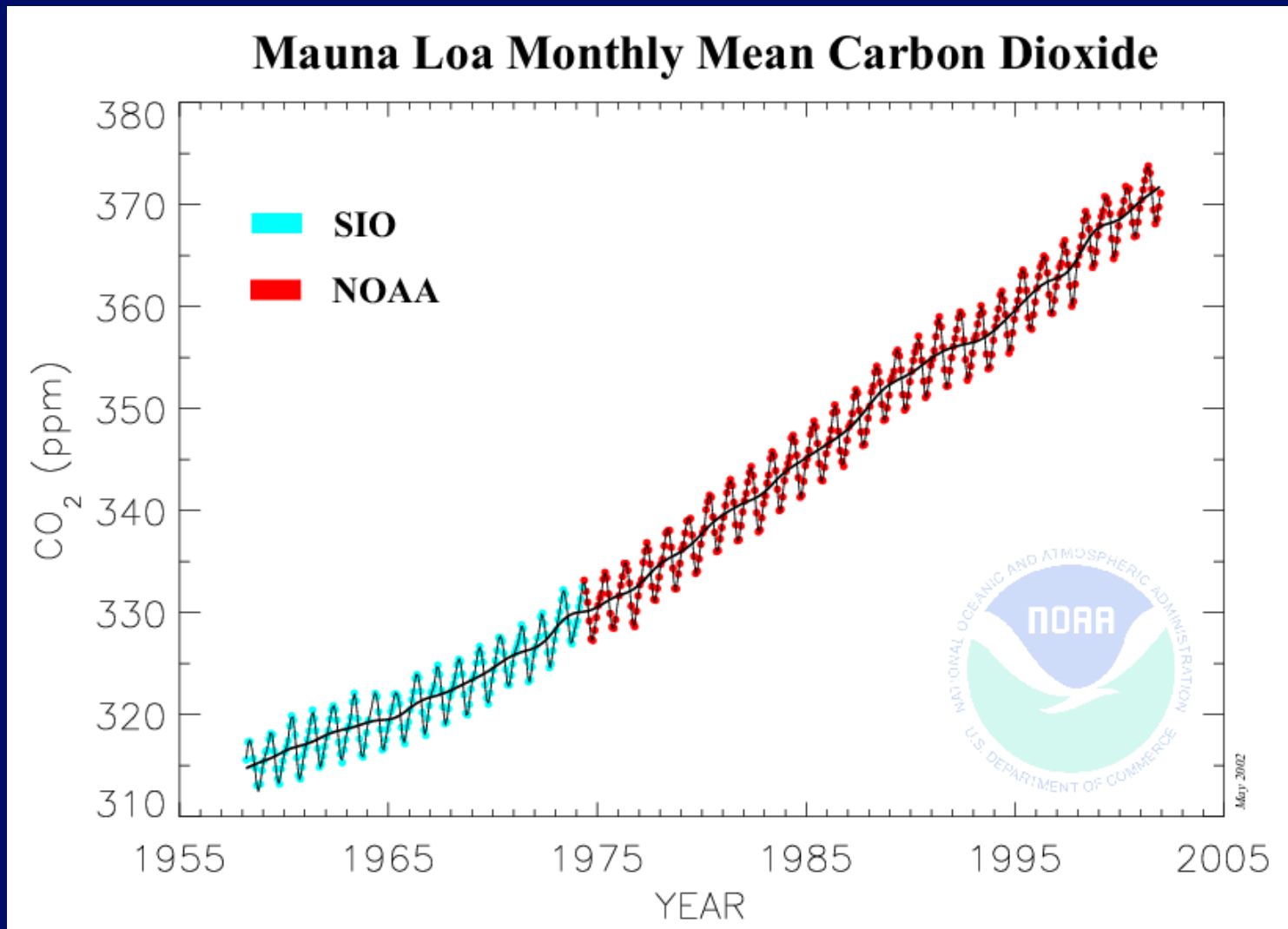


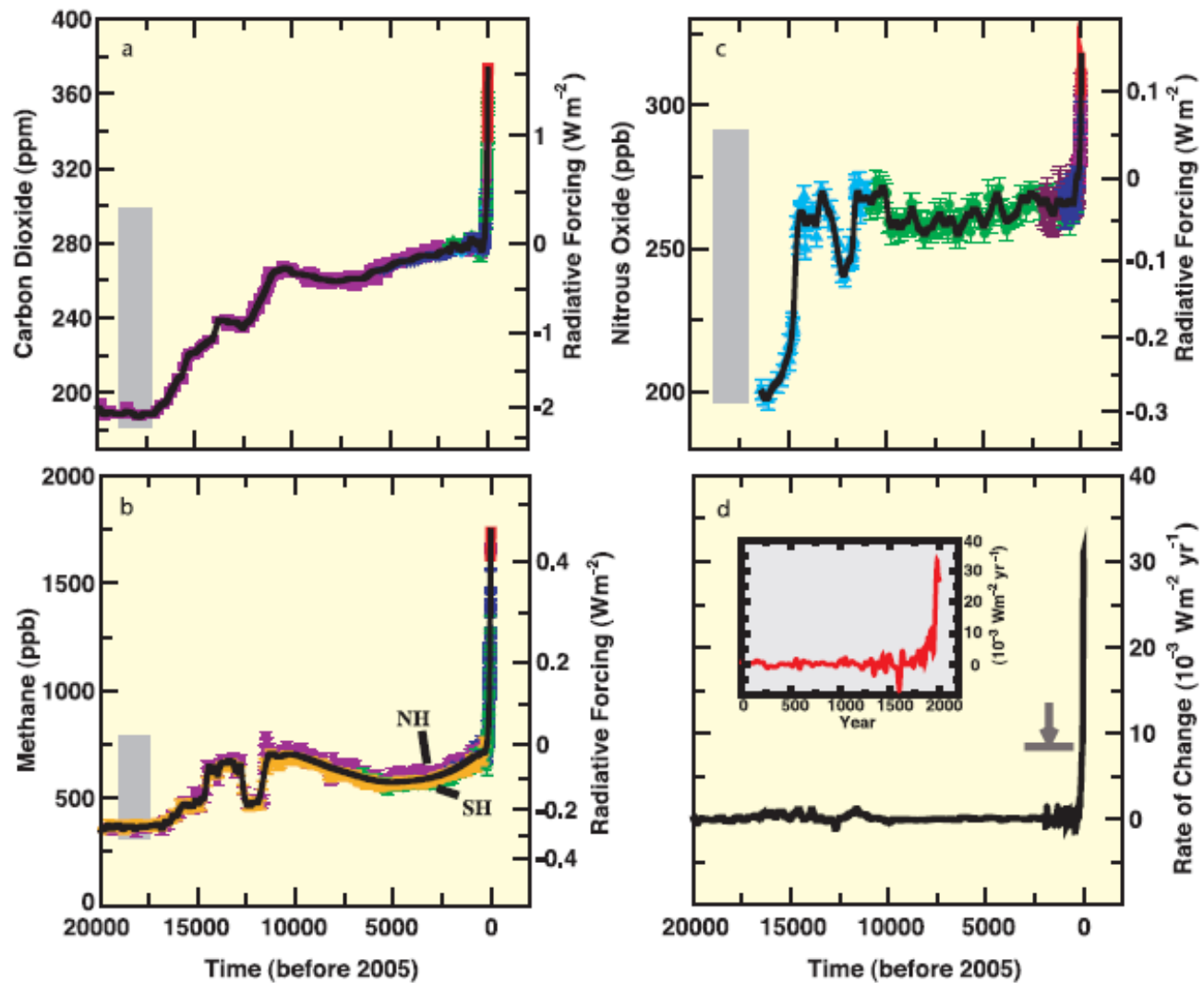
Figure TS.18. Annual averages of the global mean sea level based on reconstructed sea level fields since 1870 (red), tide gauge measurements since 1950 (blue) and satellite altimetry since 1992 (black). Units are in mm relative to the average for 1961 to 1990. Error bars are 90% confidence intervals. {Figure 5.13}

Carbon Dioxide Increase



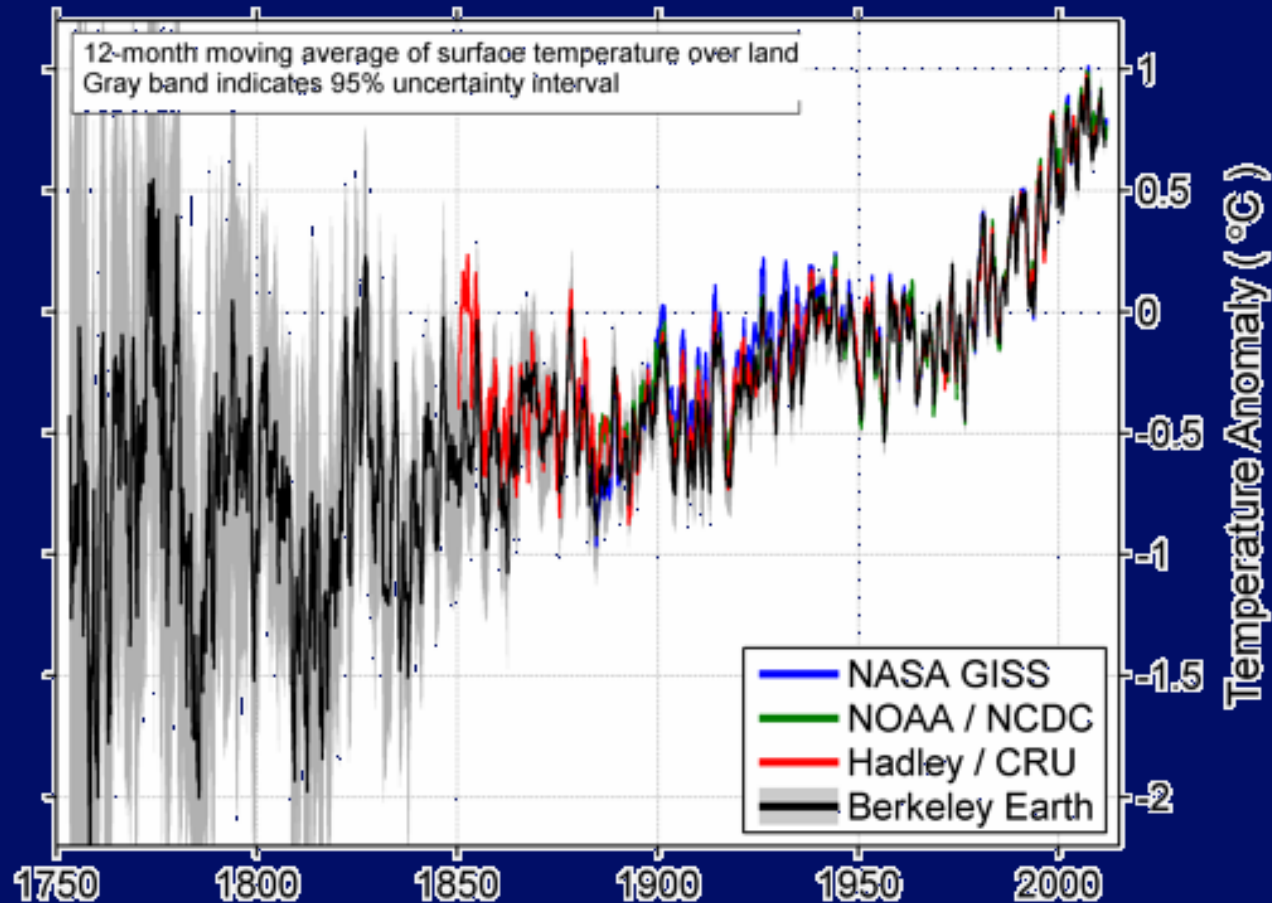
Over a Longer Period

CHANGES IN GREENHOUSE GASES FROM ICE CORE AND MODERN DATA



The Temperature is Warming

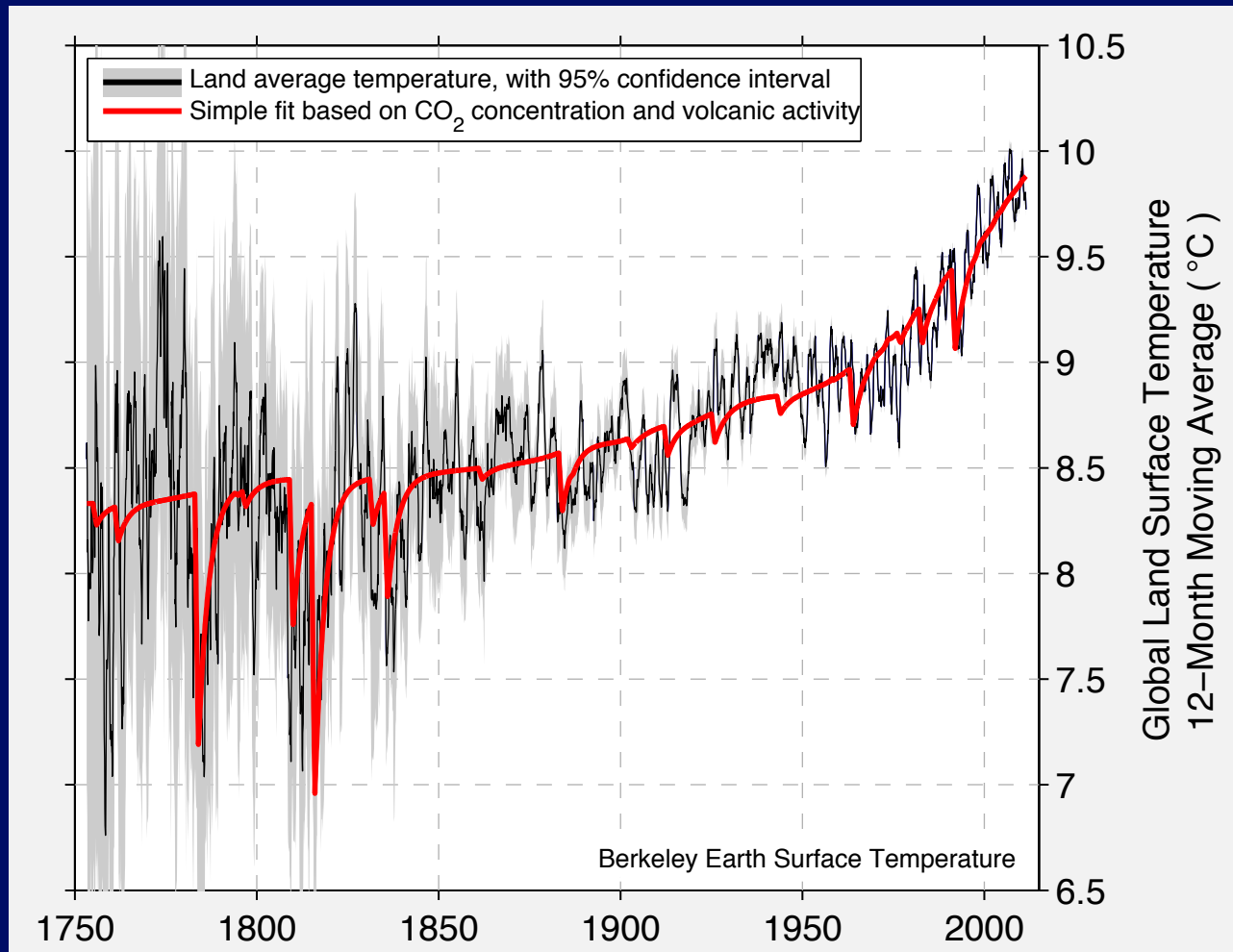
Annual Land-Surface Average Temperature



berkeleyearth.org

From R. Muller, a climate change skeptic until 2012

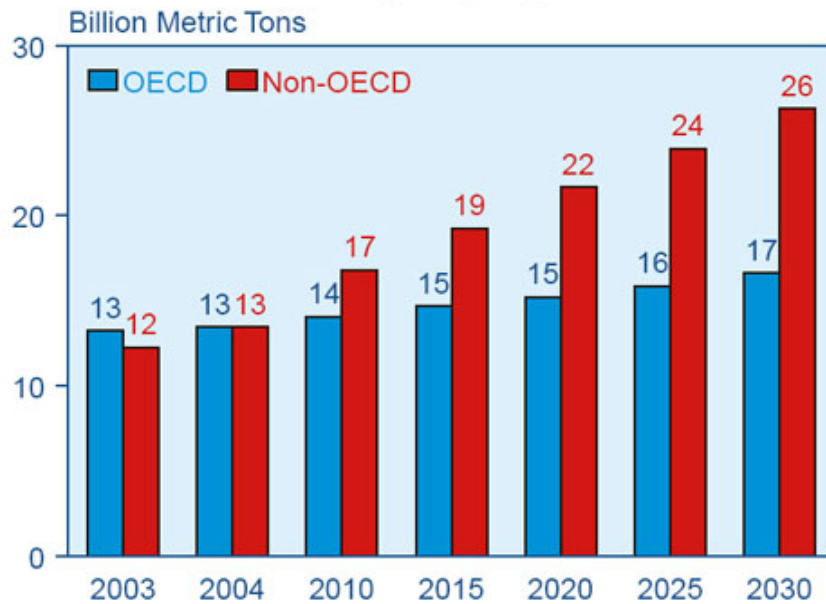
Increased CO₂ and Volcanoes Explain the Data



Muller found no effects from changing solar output.

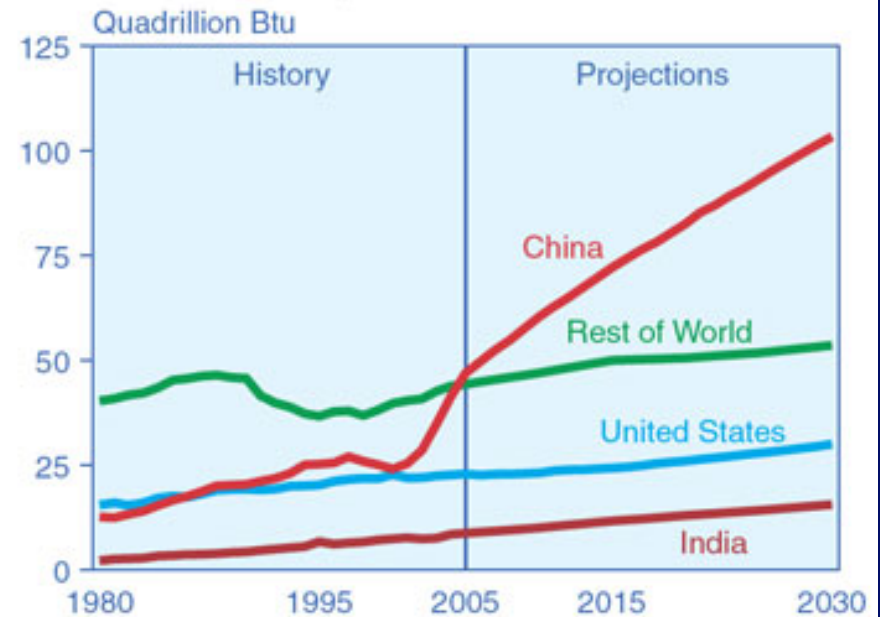
Production of CO₂

Figure 77. World Energy-Related Carbon Dioxide Emissions by Region, 2003-2030



Sources: **2003 and 2004:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, *System for the Analysis of Global Energy Markets* (2007).

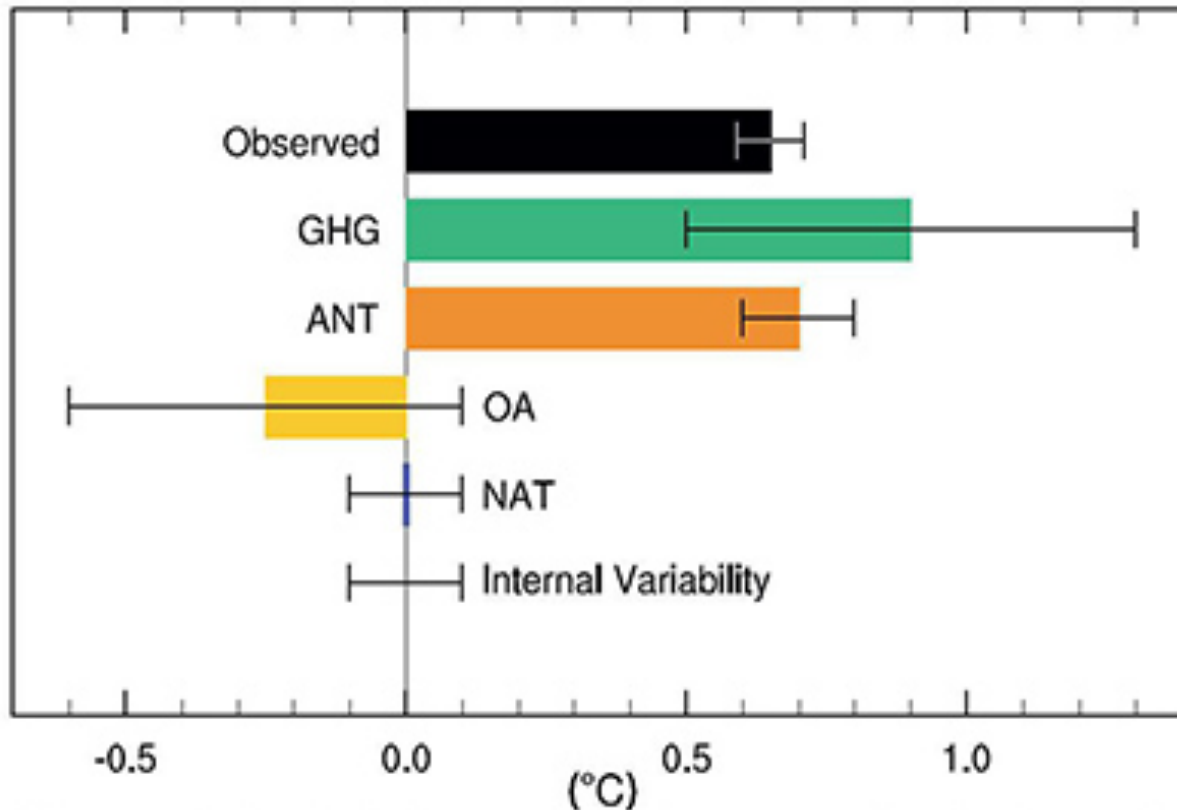
Figure 13. Coal Consumption in Selected World Regions, 1980-2030



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2005* (June-October 2007), web site www.eia.doe.gov/iea. **Projections:** EIA, *World Energy Projections Plus* (2008).

OECD: Europe, US, Canada, Australia, Japan, Mexico
Not Russia, India, China

Global Temperature Change 1951 to 2010 Balance Sheet



This reconciliation of what has caused the warming we are observing is from the 2013 IPCC from 1951 to 2010. Black (Observed) is the global temperature record, Green (GHG) is greenhouse gas warming, ANT (anthropogenic) is the combined forcings both from greenhouse gas warming and global cooling pollutants and mechanisms which are dominated by coal pollution in the form of optical aerosols and their interactions with clouds, OA is optical aerosols alone, NAT (natural forcings) includes solar irradiance changes from sunspot cycles and fluctuations in solar output, as well as volcanoes, and Internal Variability is things like El Nino, La Nina (ENSO), the Pacific Decadal Oscillation (PDO) and Atlantic Meridional Overturning (AMO).

From: Figure 10.5, IPCC 2013, Chapter 10, Detection and Attribution of Climate Change, page 884.

From 2013 IPCC Report

Observed = 1950-2010
GHG = Greenhouse gases (heat)
OA = Optical Aerosols (cool)
ANT = Net caused by humans
NAT = natural forcings (sunspots, ...)
Internal = El Nino, etc.

Climate Change Reports

- Report of Intergovernmental Panel on Climate Change released March 2014
- <https://www.ipcc.ch/report/ar5/wg1/>
- Concerns about melting permafrost releasing methane, more warming, feedback
- Rising sea levels
- Food shortages

Population Explosion

(The revenge of Malthus?)

Agriculture - Population Growth - Disease

Population Growth leads to more rapid depletion of resources

More pollution

More conflict?

Two “events” (transitions)

10,000 yrs ago

Agriculture

250 yrs ago

Disease lessened

(demographic transition)

Time	Total Pop.	Growth Rate (per thousand per year)
Before Agriculture	$\sim 8 \times 10^6$ (??)	0.015
~ 8000 BCE - 1 CE	$\sim 3 \times 10^8$	0.36
1 CE - 1750 CE	$\sim 8 \times 10^8$	0.56
1750-1800	$\sim 1 \times 10^9$	4.4
⋮		
1950 - 1975	4×10^9	17.1
2000	6×10^9	~ 12
2012	7×10^9	

Population Mathematics

Rate of increase \propto Number \times (Birth – Death)
leads to exponential growth if (Birth – Death) constant

$$\text{Pop (t)} = \text{Pop (Now)} 2^{(t/t_d)}$$

t_d = doubling time \simeq 65 years currently

So doubles in 65 yrs

Quadruples (2^2) in 130 yrs, ...

1170 yr (18 t_d) Pop = 1.8×10^{15}

~ fills land area

2990 yr (46 t_d) Mass $> M_{(\text{earth})}$!

14,625 yr (225 t_d) Mass expands at c !!

Current population growth is NOT sustainable

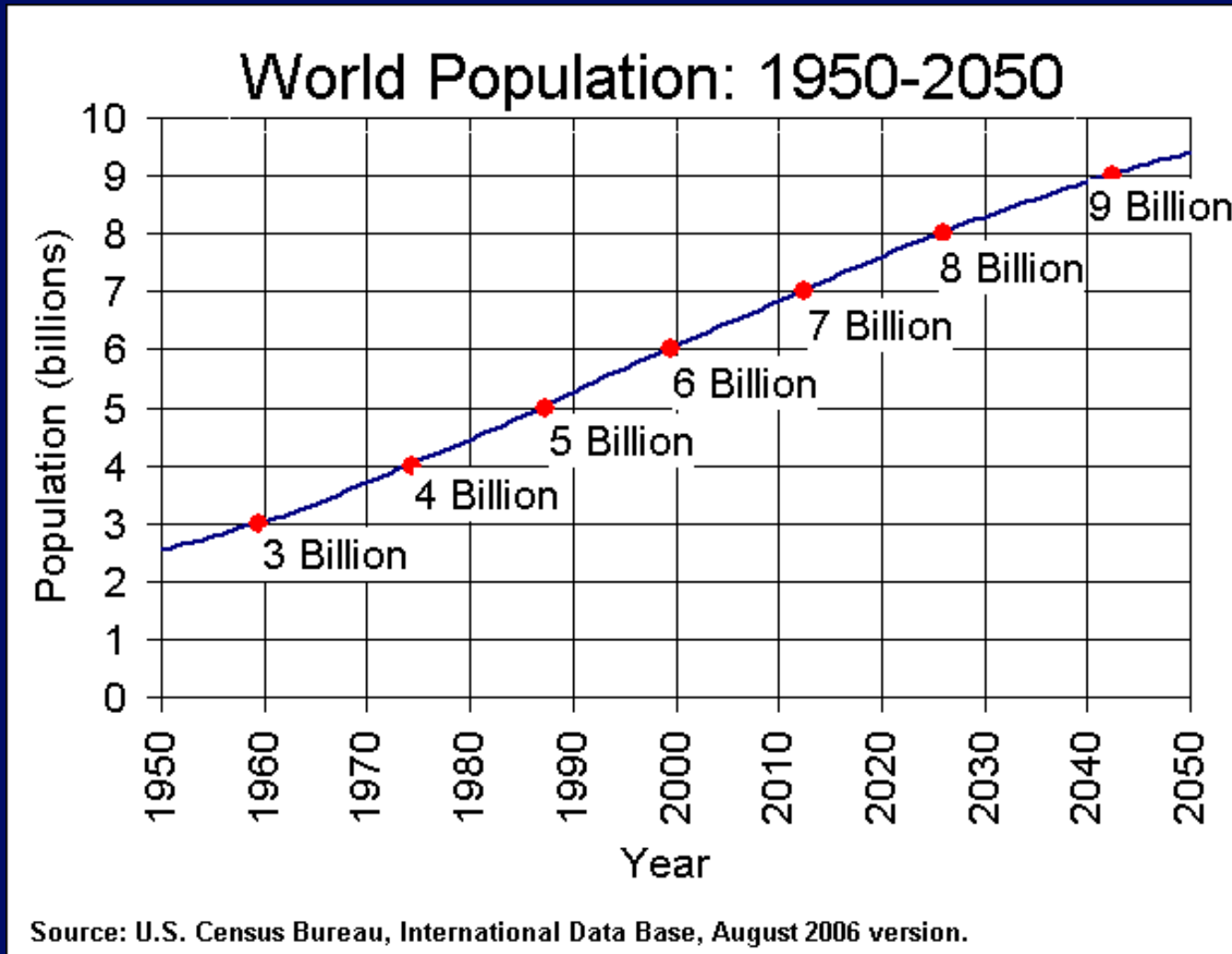
World Vital Events Per Time Unit: 2009

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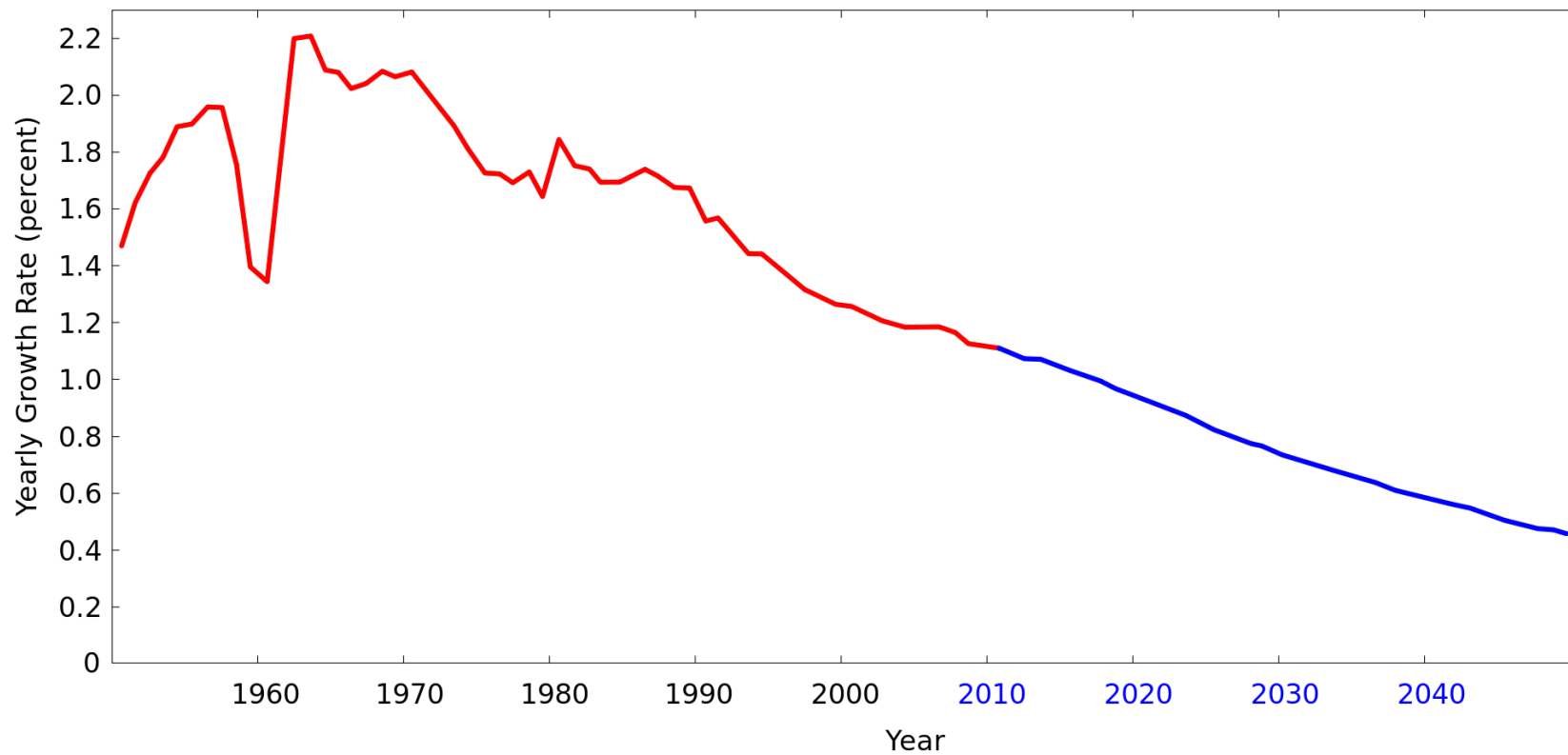
- (Figures may not add to totals due to rounding)
- -----
- Natural
- Time unit Births Deaths increase
- -----
- Year 135,474,672 55,664,164 79,810,508
- Month 11,289,556 4,638,680 6,650,876
- Day 371,163 152,505 218,659
- Hour 15,465 6,354 9,111
- Minute 258 106 152
- Second 4.3 1.8 2.5

<http://www.census.gov/popclock/>

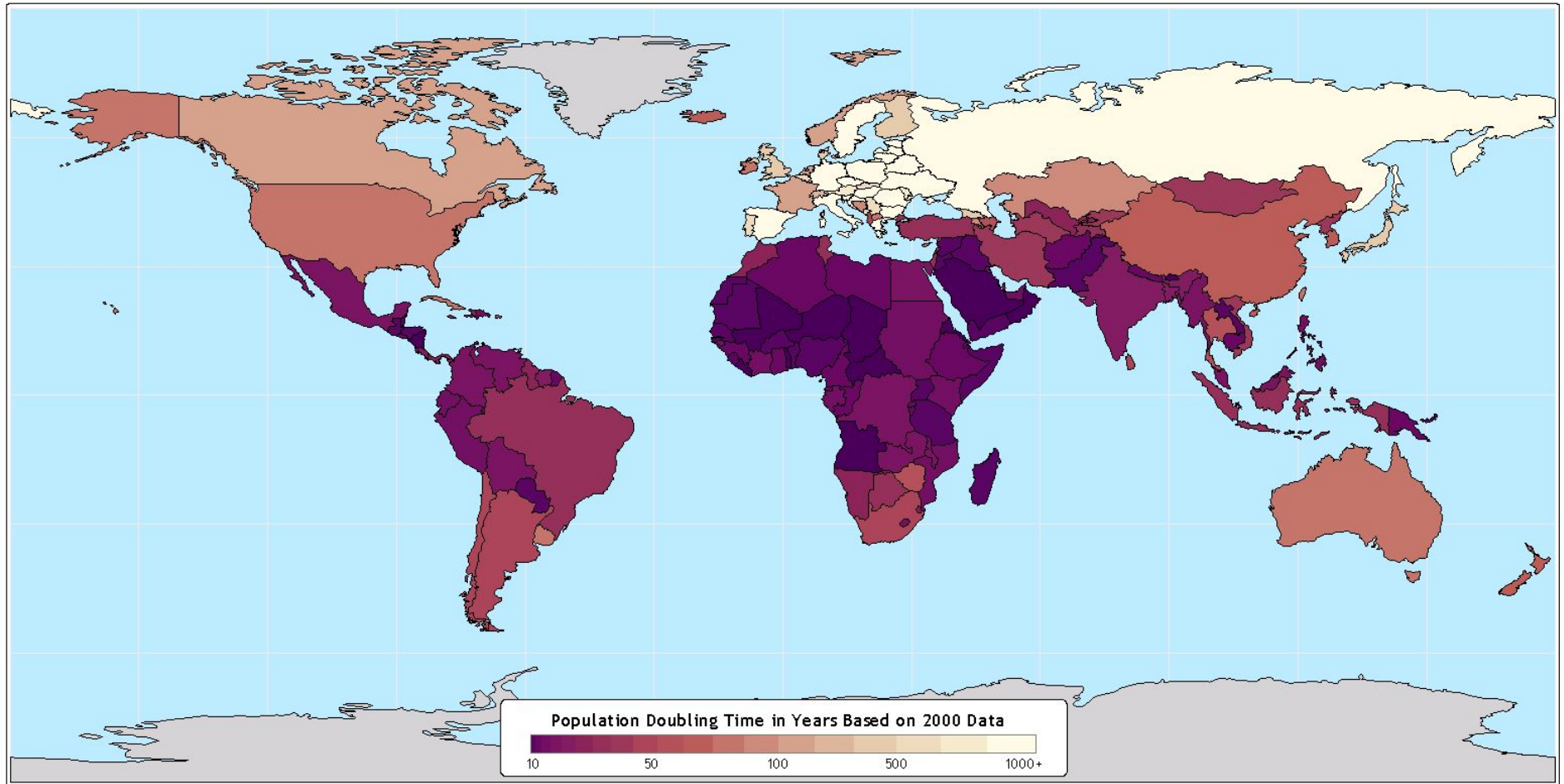
Projected World Population Growth



Changes in Population



Population Doubling Time



Data taken from: Population Reference Bureau (2000)

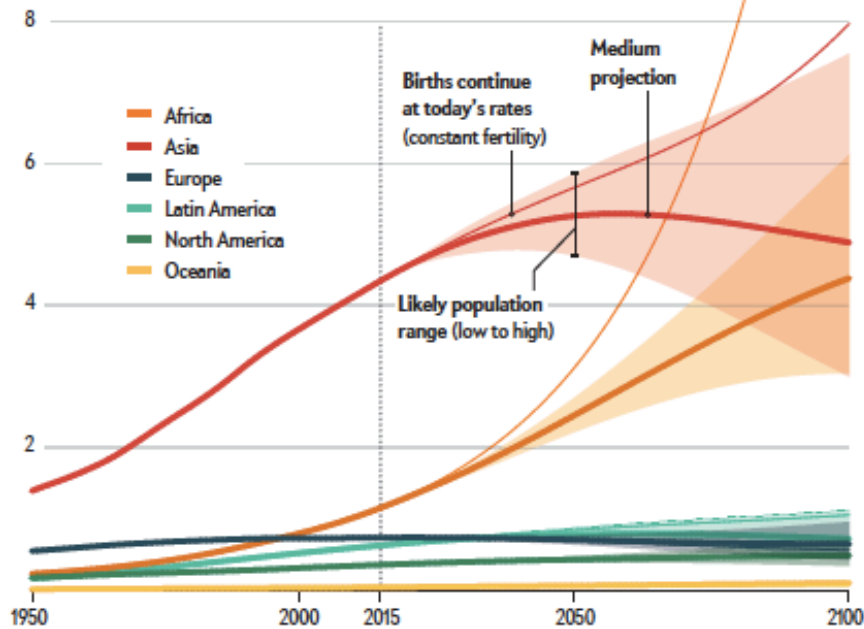
Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

Africa Drives Global Population Growth

Total Population
16 billion

Africa's population is expanding so much faster than expected that the United Nations has revised sharply its medium projection for world population, up from 9.1 billion to the current prediction of 11.2 billion by 2100. Almost all the unanticipated increase comes from Africa (orange), now forecast to reach three billion to 6.1 billion people by then. Although the midrange estimate for Asia (thick red line) at that time would still be larger—about 4.9 billion, compared with Africa's 4.4 billion—Asia's total would be decreasing, and Africa's would still be increasing.

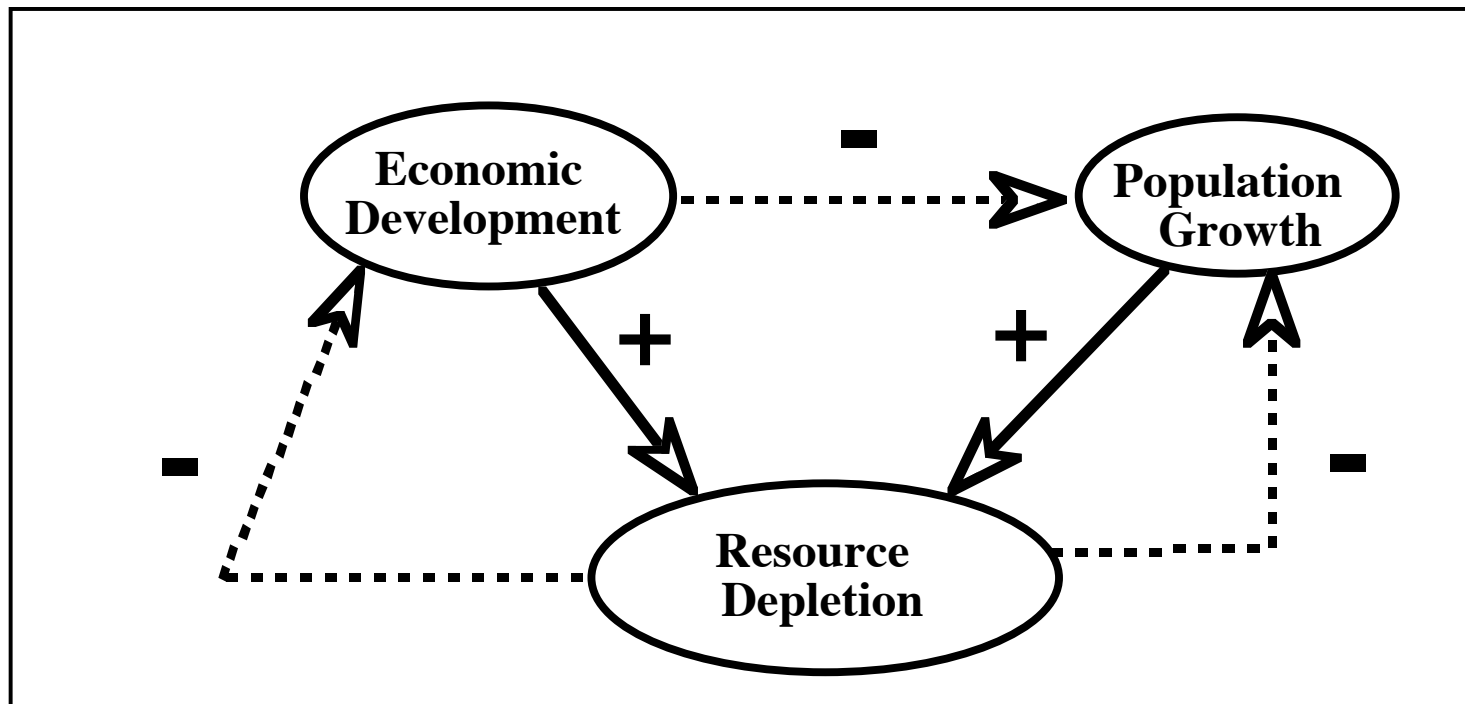
If Africa's birth rate stays at its current level (thin orange line), 15.8 billion people would inhabit the continent by 2100—more than twice the world's population today. Demographers do not expect that to happen, but the projection shows how powerfully fertility drives growth.



Current population growth dominated by Asia, but expected to level out by mid-century.

Unless current trends change, Africa will be the main driver of population growth.

Scientific American Feb. 2016



Effects of economic development:
Does negative effect on population growth
Beat positive effect on resource depletion?

Can we get to sustainable economy before
We exhaust resources?

The Example of China

- From 1990 to 2004, 400 million Chinese citizens escaped poverty (~1/3 of population)
- Population grew by about 120 million
- Growth rate about 1% per year
- Rate projected to decrease to 0.2% by 2025
- Population will be about 1.5 billion

Nuclear War

Total arsenal world-wide






Peaked at ~ 10,000 megatons

One ton is energy equivalent to “ton of TNT”




Global effects of all-out war

- Depletion of ozone
- Radioactive fallout
- Dust and smoke in atmosphere would block sunlight and lead to cooling of the Earth
“Nuclear Winter”

The World's Nuclear Arsenals

Country	Suspected Strategic Nuclear Weapons	Suspected Non-Strategic Nuclear Weapons	Suspected Total Nuclear Weapons
 China	250	120	400
 France	350	0	350
 India	60	?	60+
 Israel	100-200	?	200+
 Pakistan	24-48	?	24-48

The World's Nuclear Arsenals (~2013)

Country	Suspected Strategic Nuclear Weapons	Suspected Non-Strategic Nuclear Weapons	Suspected Total Nuclear Weapons
 Russia	~ 1499	~ 3022	~ 4500
 United Kingdom	160	65	225
 United States	1722	3391	5113

Nuclear Warheads being Deactivated

- US-Russia Agreement to deactivate warheads (START Agreement 1994)
 - Agreed to reduce to 6000 warheads each
 - Expired Dec 2009
- Moscow Agreement (2002)
 - Decrease to 1700 – 2200 by 2012
- New Start
 - signed April 2010, into effect Feb. 2011
 - Reduces deployed nuclear weapons to 1550 per side

Natural Catastrophes

Collisions

Stars? Negligible Chance

Molecular Clouds? $t \sim 10^8$ yr

Likely, but the effects are unclear

Less dense clouds? More common but effects are probably less

Asteroids and other debris

(comets, meteoroids, ...)

Meteor over Siberia February 15, 2013



Shallow angle entry, air burst, shock wave
1700 people injured, mostly by broken windows

Effect of Meteorite/Asteroid Impact

- $E_{\text{kin}} = \frac{1}{2} M v^2$
- Two examples: 2013 Meteorite and larger one

	2013 Siberian	Larger one
Size	~20 m	¼ km
Speed	19 km/s	30 km/s
E_{kin} (TNT equiv)	500 kilotons	7200 Megatons

- Hiroshima bomb was 13-18 kilotons
- 7200 Megatons would be like all-out nuclear war at height of cold war

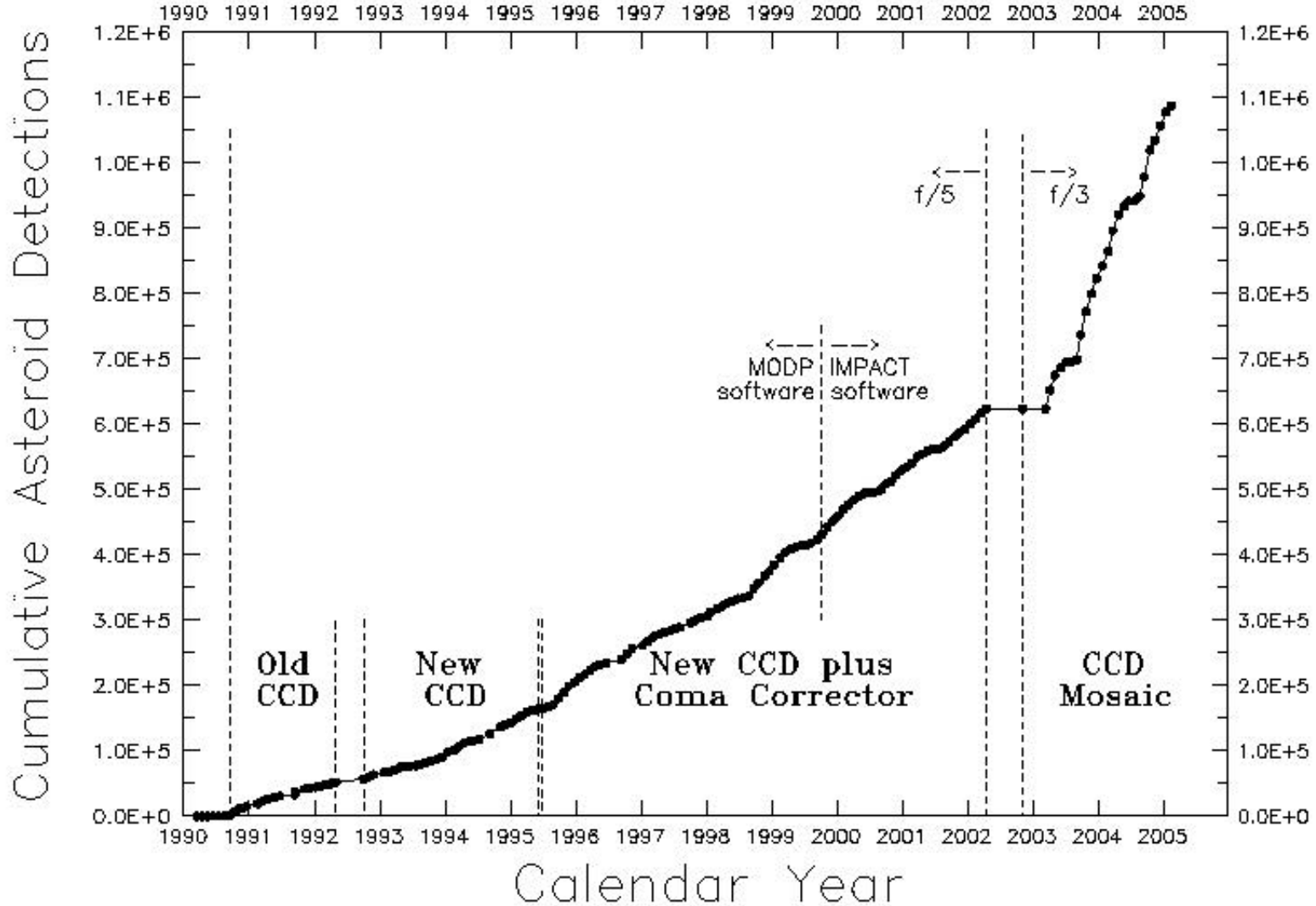
How Often?

- Depends on size (many small, few large)
 - 2013 Siberian $t \sim 100$ yr
 - 1908 Siberian $t \sim 1000$ yr
 - (1 km or larger) $t \sim 10^5$ yr - 10^6 yr
 - Major Extinctions $t \sim 30 \times 10^6$ yr
 - Mass Extinctions $t \sim 100 \times 10^6$ yr ?
- These are statistical: no guarantees...

Spacewatch Detections

Asteroid Detections by Spacewatch 0.9-m

2005 Feb 22 J. Montani/LPL



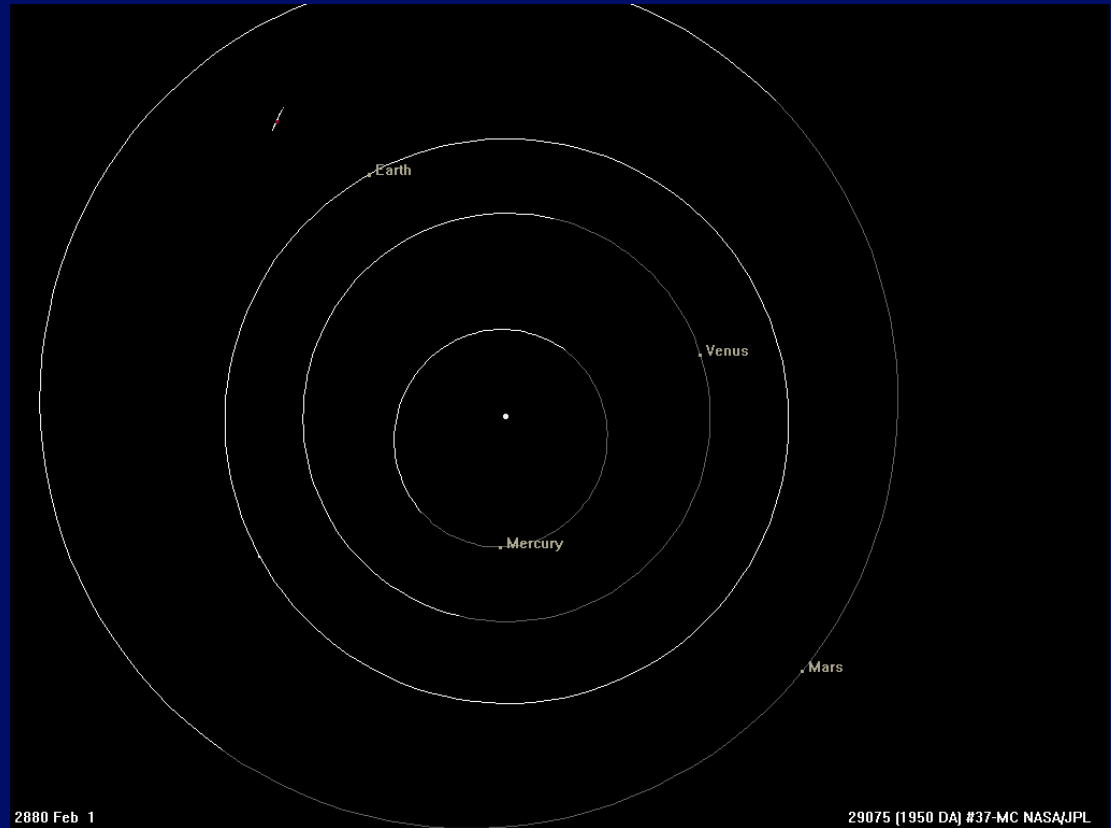
Most Dangerous Known Asteroid

1950 DA

Radar used to map orbit

~ 1 km in diameter

Close approach in
Yr 2880



Probability of collision ~ 0.33%

$V \sim 14 \text{ km s}^{-1}$ $E \sim 10^5 \text{ Megatons}$

Exact orbit depends on small effects - tugs from Earth, Mars, light absorption + radiation, ...

Another “Interesting” Asteroid

- Apophis (2004 MN4)
- $d = 0.25$ km, would release 400 Megatons
- 1/45000 chance of collision in 2036
- <http://neo.jpl.nasa.gov/risk/>
- Has data base of Near Earth Objects
- Search for smaller ones?
 - B612 Foundation (Ed Lu)
 - Privately funded space telescope

Solar variations

$\sim 10^5$ yr

1. Short term - cyclic variations in L, orbit of Earth -----> ice ages, climate change

$\sim 1-2 \times 10^9$ yr

2. Sun increases in L
on main sequence -----> loss of oceans
 $UV + H_2O = 2H + O$ H lost to space

$\sim 5 \times 10^9$ yr

3. Off main sequence leads to Red Giant
atmosphere evaporates

Could advanced civilization delay loss of oceans?

(Decrease greenhouse, add dust)

Move to Mars? Mars will be in HZ by end of Sun's main sequence lifetime.

Red giants lose mass in winds: Earth's orbit moves out to 1.15 AU by 7.6×10^9 yr; but HZ is now 50-80 AU!

Sun's atmosphere engulfs Earth and it spirals in.

Other stars?

Nearby star leads to Supernova

If within 30 ly, ozone is destroyed

$\sim 2 \times 10^9$ yr

Extreme supernova, gamma ray burst

If within ~ 6000 ly, would affect ozone,

Atmospheric chemistry

Ultimate Limits

If Universe Closed, recollapses

$\sim 10^{12}$

Big Crunch
(unlikely)



Very unlikely because evidence now indicates that expansion is accelerating (dark energy)

But, since we don't understand dark energy, it could reverse.

If open, expands forever

About 5×10^9 years, Andromeda collides with MW

10^{11} local galaxies collapse into a supergalaxy, if acceleration continues, all other galaxies have disappeared

$10^{12} - 10^{14}$ all stars die

10^{17} planetary systems disrupted

$10^{18} - 10^{20}$ galaxies “evaporate”

$10^{33} - 10^{34}$ protons decay?

10^{100} Black holes evaporate

What to choose for L?

- For number of civilizations now,
 $L \leq 5 \times 10^9$ yrs -
[age of galaxy – time to evolve]

Important to choose L consistent with what you think is the most likely way civilizations end.

Darkness

I had a dream, which was not all a dream.
The bright sun was extinguish' d, and the stars
Did wander darkling in the eternal space,
Rayless, and pathless, and the icy earth
Swung blind and blackening in the moonless air;

- Lord Byron, 1816