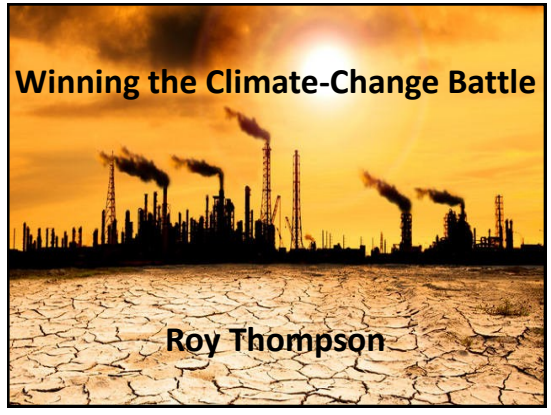
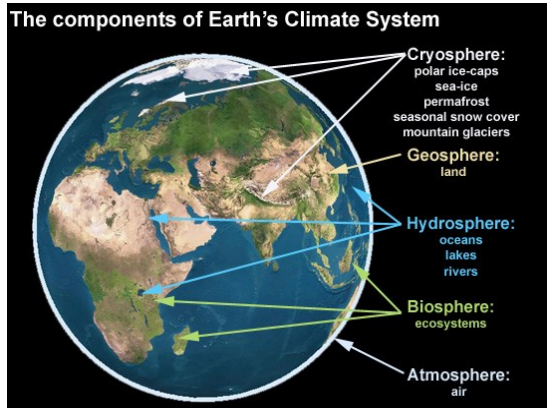


1a. How the climate system works

What is climate?
Average or typical weather for a given area over a relatively long period of time.

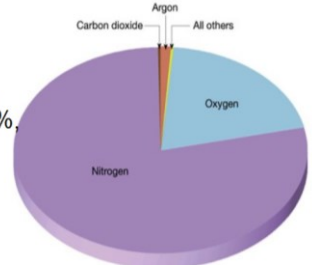
What is weather?
The state of the atmosphere - temperature, precipitation, wind, cloudiness, pressure, and more.

Climate tells you what clothes to buy, but weather tells you what clothes to wear.



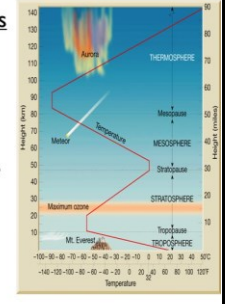
Modern atmosphere

Nitrogen (N2)- 78%,
Oxygen (O2)- 21%,
Carbon Dioxide (CO2) 0.03 %,



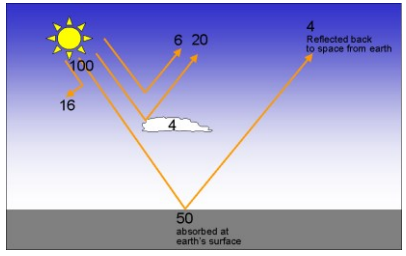
The Structure of the Atmosphere

- The atmosphere thins very quickly as you travel away from Earth's surface
- The atmosphere is divided vertically into 4 layers based on temperature

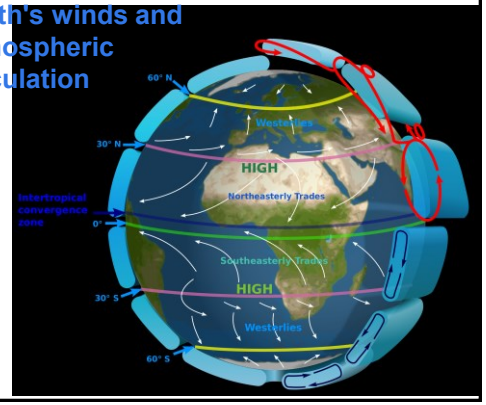


The sun delivers more energy to the earth in just one hour than is currently used worldwide in one year.

On a worldwide, long-term average, air molecules absorb 16% of the incoming energy and reflect 6%. Clouds absorb 4% and reflect 20%. 54% is transmitted through the atmosphere and hits the Earth's surface.

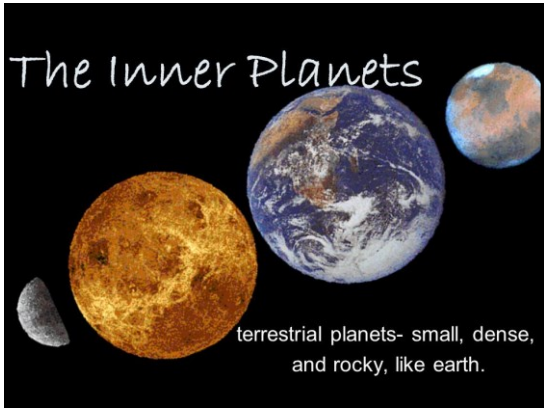


Earth's winds and atmospheric circulation



The energy from the sun also powers our ocean currents and the water cycle, causing clouds and driving hydrological processes.

The Inner Planets



terrestrial planets- small, dense, and rocky, like earth.

Temperature of the inner planets

$S(1-\alpha) = \sigma T^4$

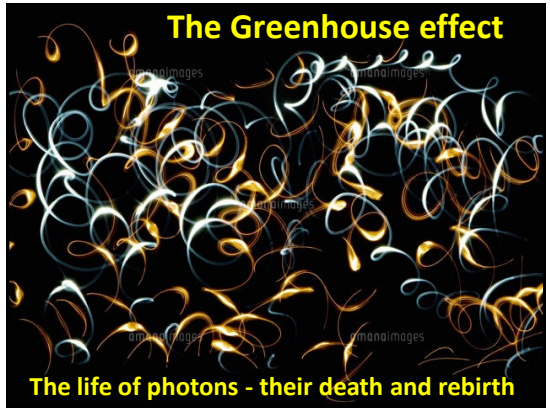
($\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4})

Rearranging: $T = \left\{\frac{S(1-\alpha)}{\sigma}\right\}^{1/4}$

T(°C) = T(K) - 273

	Relative distance	Solar radiation (S) W m^{-2}	Albedo (α)	Net solar radiation S(1- α)	Equilib -rium T (°C)	Actual surface T (°C)	
Mercury	0.39	2250	0.1	2025	162	180	Just about agrees
Venus	0.72	660	0.59	271	-10	453	Disagrees badly
Earth	1	342	0.31	236	-19	15	Disagrees
Mars	1.5	150	0.15	128	-55	-43	Nearly agrees

The Greenhouse effect

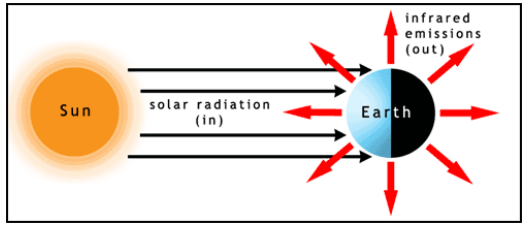


The life of photons - their death and rebirth

We need to think about two types of radiation:-

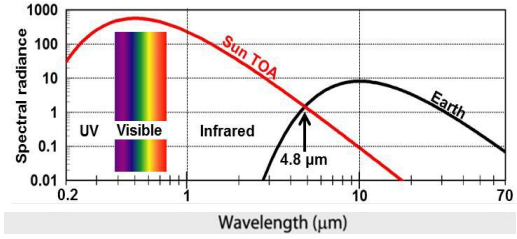
First the energy (light) from the sun

Secondly the infrared energy Earth radiates back into space



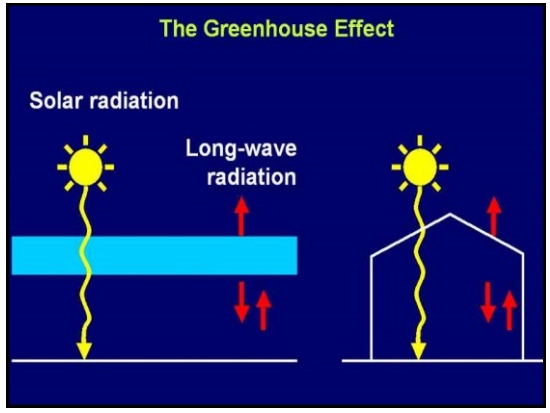
Solar radiation is absorbed by the sunlit side of Earth, and infrared radiation (heat) is emitted from all parts of the planet.

Solar and Terrestrial Radiation



The red line shows the radiation from the Sun received at the top of Earth's atmosphere (assuming a solar temperature of 5770K). The black line shows the radiance emitted by Earth assuming a terrestrial temperature of 288K.

The Greenhouse Effect

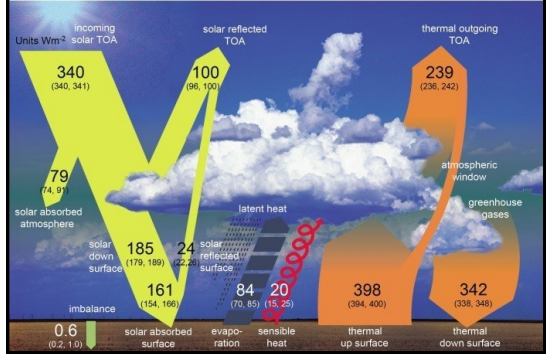


In simple terms "greenhouse gases" act like a blanket or winter clothing.

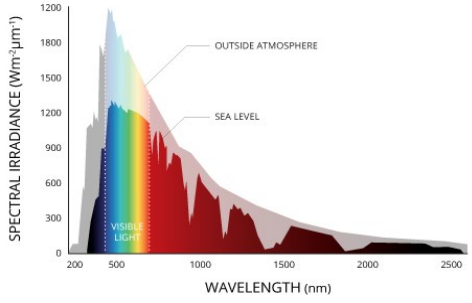
A body that suppresses heat loss cools off less, which is to say "stays warmer."

As the thermal camera testifies:- notice the bright thermal radiation escaping from the children's bare faces versus the darkness of their winter jackets.

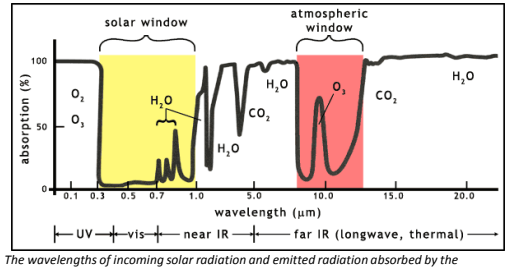
There are enormous transfers of energy into and from the Earth. It receives short wave electromagnetic radiation from the sun and emits long wave radiation to space.



Not all of the solar radiation reaches the Earth's surface, due to reflection and scattering

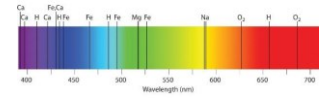


There are 2 so-called atmospheric windows

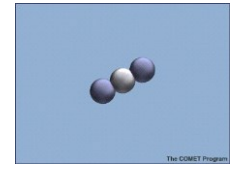


The wavelengths of incoming solar radiation and emitted radiation absorbed by the Earth's atmosphere, showing the solar window and atmospheric (thermal) window. The graph shows the regions of the electromagnetic spectrum that are absorbed by specific molecules. Key: CO_2, carbon dioxide; H_2O, water; IR, infrared light; O_2, oxygen; O_3, ozone; UV, ultraviolet light; vis, visible light.

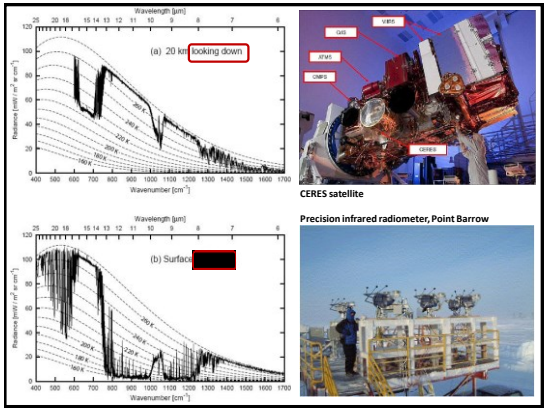
Spectroscopy: The interaction between matter and electromagnetic radiation



ATOMS: Atomic absorptions and emissions (spectral lines) are due to electronic transitions of outer shell electrons as they rise and fall from one electron orbit to another.

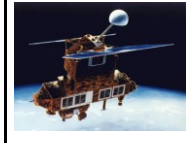


MOLECULES: The combination of atoms into molecules leads to the creation of numerous additional unique energetic states



CERES satellite

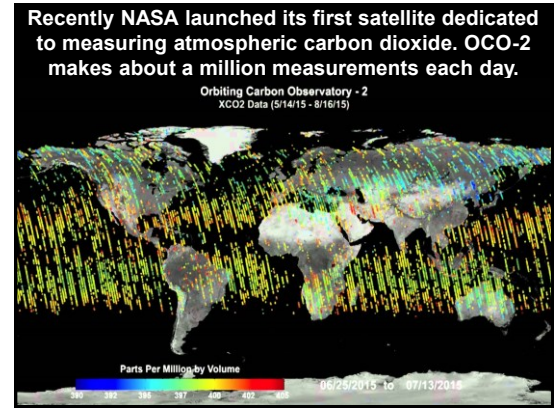
Precision infrared radiometer, Point Barrow



Measuring Earth's Radiation From Space

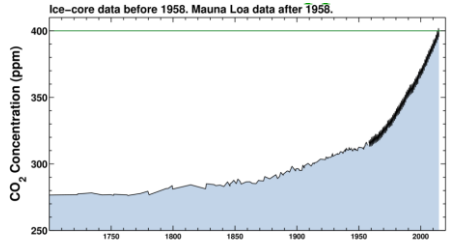
At launch on Oct. 5, 1984 one of the solar arrays on the Earth Radiation Budget Satellite (ERBS) failed to extend. So mission specialist, Astronaut Sally Ride aboard Space Shuttle Challenger, had to shake the satellite with the remote-controlled robotic arm and then finally place the stuck panel into sunlight for the panel to extend.

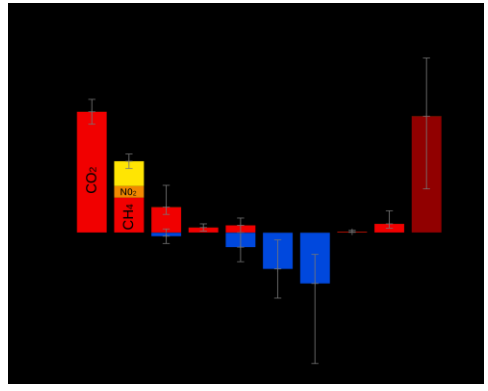
Recently NASA launched its first satellite dedicated to measuring atmospheric carbon dioxide. OCO-2 makes about a million measurements each day.



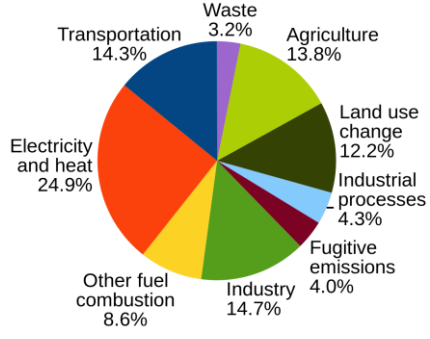
1b. The basic climate-change problem

CO_2 concentration
February 08
406.27 ppm

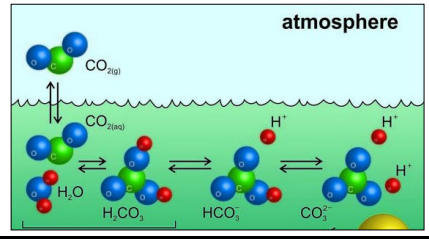


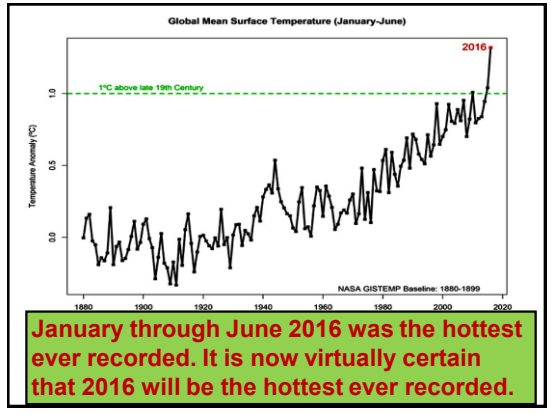


Annual greenhouse gas emissions by sector



In 1957 Revelle and Suess discovered that the chemistry of sea water prevents the oceans from quickly absorbing any excess carbon dioxide.

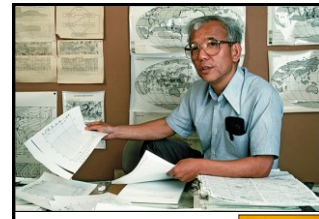




January through June 2016 was the hottest ever recorded. It is now virtually certain that 2016 will be the hottest ever recorded.

Three approaches to pinning down the greenhouse effect

- 1. Physics / chemistry / maths :-
  Computer modelling
- 2. Geology :-
  Palaeoclimate
- 3. Observation & Monitoring :-
  Sea-level / glaciers / plants / isotopes / atmospheric composition / temperature



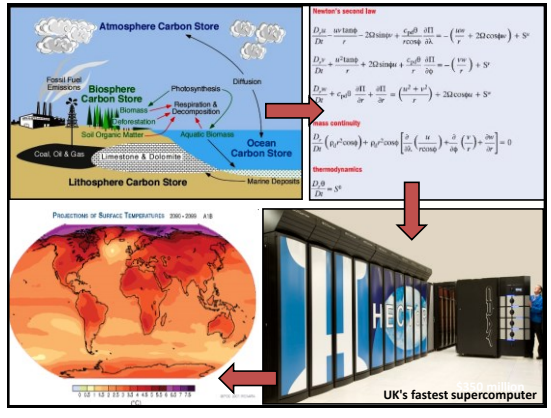
Suki Manabe
"God-father"
of the greenhouse effect

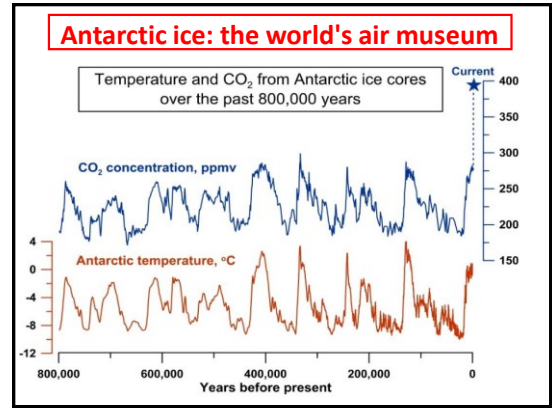
His 1967 paper gave the first modern prediction of how much increased carbon dioxide (due to fossil fuel use) would warm the earth.

2.4 °C rise for 2xCO_2

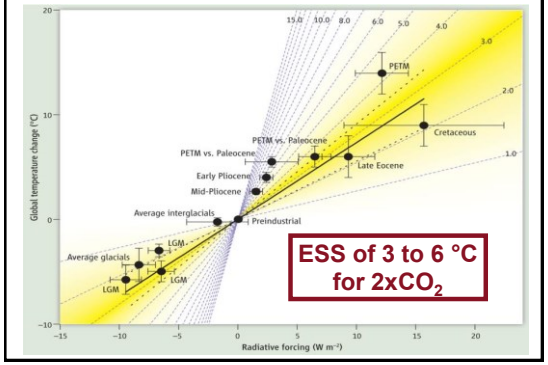
In 1967 you could pick up a 1.3 MHz CPU with half a megabyte of RAM and 100 megabyte hard drive for a mere US$1.6 million.

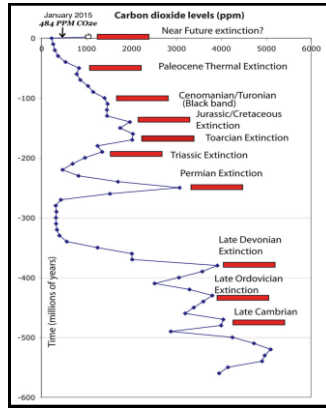
Oh, and you want a printer too...?





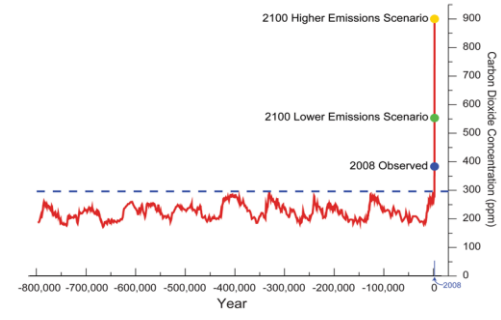
Climate Sensitivity Estimated From Earth's Climate History



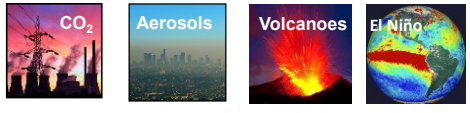


Carbon dioxide levels and mass extinction events

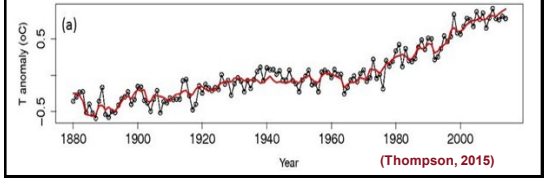
Big changes ahead!



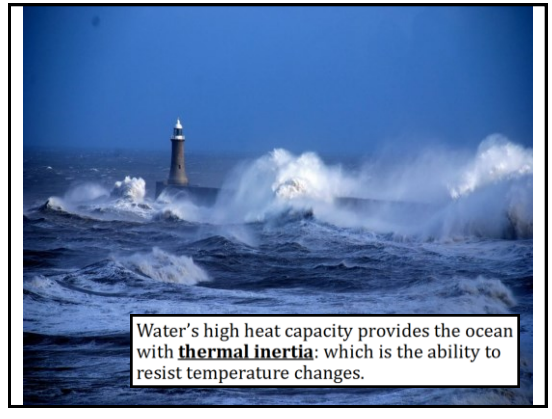
An empirically based energy balance forecast



Temperature ~ Greenhouse gases + aerosols + ENSO + Volc

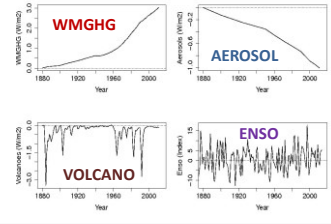


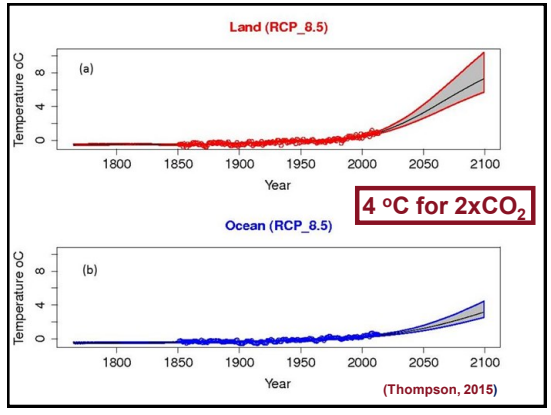
(Thompson, 2015)

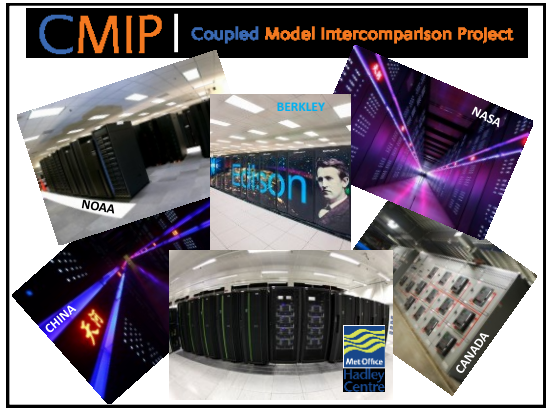


Heat balance in terms of a time-series analysis

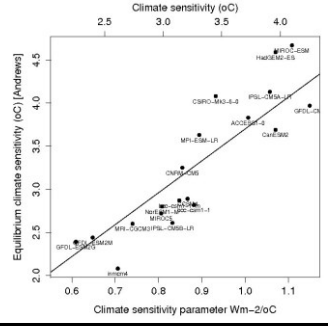
Multiple regression: $y_i = \beta_0 + \sum_{j=1}^{p} \beta_j x_{ij} + e_i,$





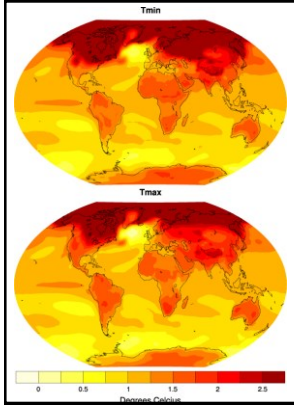


Using CMIP5 (the most ambitious coordinated multi-model climate change experiment ever attempted) to check sensitivity as found using the empirical approach.



SUMMARY OF EMPIRICAL APPROACH

- WMGHG, Aerosols, Volcanoes and ENSO are all found to be significant forcings.
- Because individual forcings are highly correlated, the effect of aerosols needs to be carefully disentangled.
- Once aerosols are taken into account estimates of climate sensitivity are high, +4 °C (with 95% confidence intervals of 3.0 to 6.3 °C)
- Business-as-usual economics yields a 7.9 °C rise, over land, by 2100.
- Typical cities (Riga/Minneapolis/Windhoek) will experience 500-year heatwaves, in most years, by 2100 on a BaU trajectory.
- The Paris Accord is hopeless, the 1.5 °C guardrail will be easily breached before 2030.



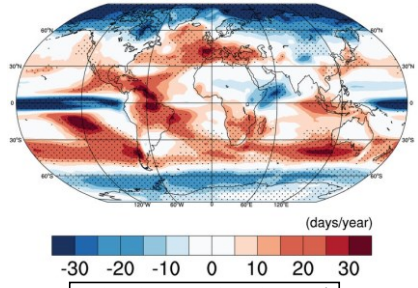
State-of-art modelling of future temperature change.

Note the amplified warming projections for the high latitudes and altitudes of the northern hemisphere.

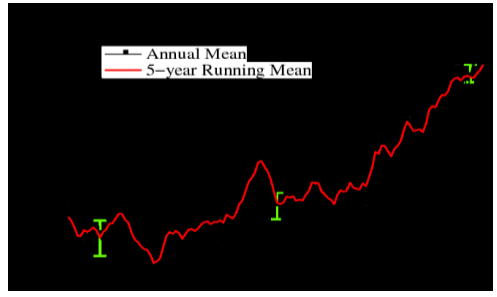
Based on CMIP5 models.

State-of-art modelling of precipitation change.

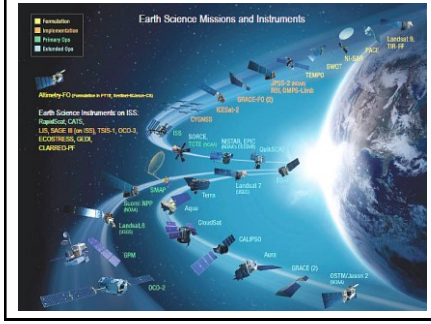
28 CMIP5 multi-model ensemble average mean change in frequency of dry days (days/year) by 2060–2089, relative to the historical period 1960–1989, using the RCP8.5 forcing scenario.



2a. Global signals of a changing climate and environmental impact

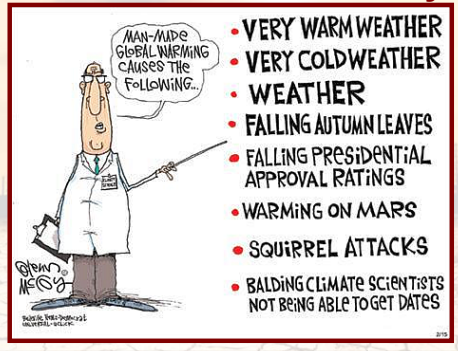


NASA's current satellite fleet includes 20 Earth-observing missions



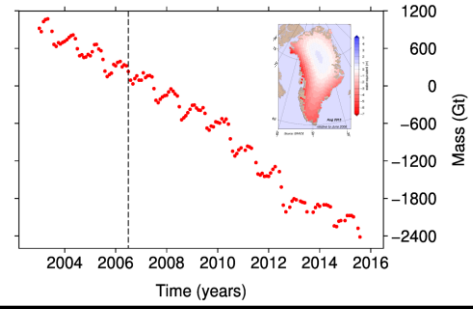
Since the 1957 launch of Sputnik thrust mankind into the space age, the U.S. and other space-faring nations have placed thousands of artificial satellites into a variety of Earth-centered orbits.

Effects observable today

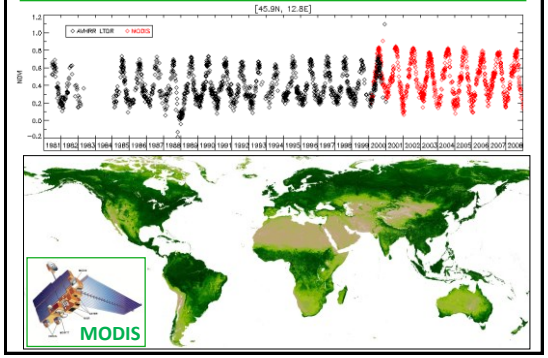


Latest GRACE satellite results

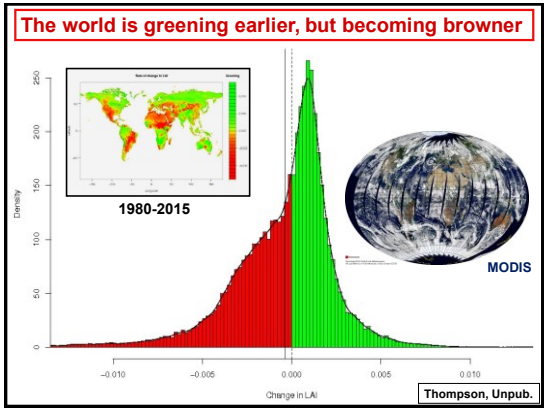
GRACE reveals that most ice loss in Greenland has been from near the ice sheet margins, while the ice sheet interior has experienced a slight mass gain owing to increased snowfall.



Vegetation as observed from space



The world is greening earlier, but becoming browner



Continent-wide response of mountain vegetation to climate change (2001-8)

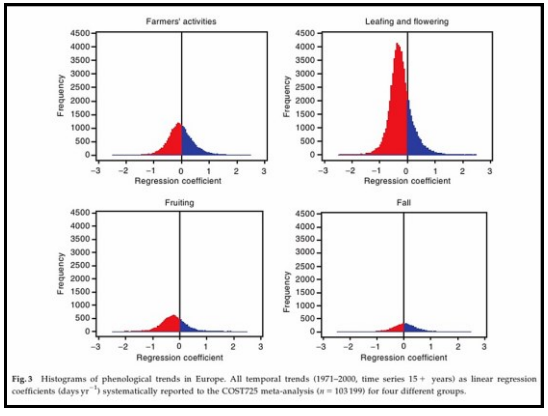
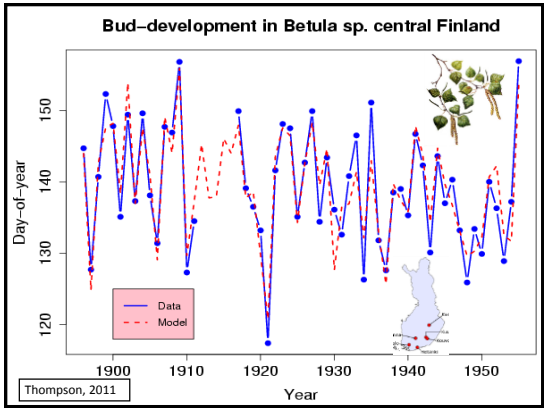


Fig. 3 Histograms of phenological trends in Europe. All temporal trends (1971–2000, time series 15 + years) as linear regression coefficients (days yr^{-1}) systematically reported to the COST725 meta-analysis ($n = 103\,199$) for four different groups.

Bud–development in Betula sp. central Finland

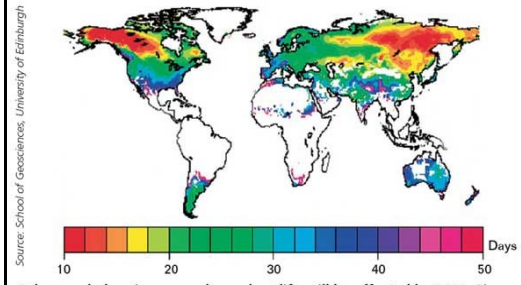


Managing Daylength in Commercial Greenhouse and Nursery Production

High-pressure sodium lamps with oscillating reflectors cast moving beams of light to crops below in order to increase yield, inhibit dormancy, or accelerate flowering

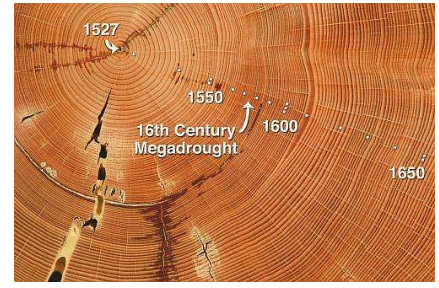
Recent developments in LED technology create new opportunities for lighting of greenhouse crops.

Desynchronisation

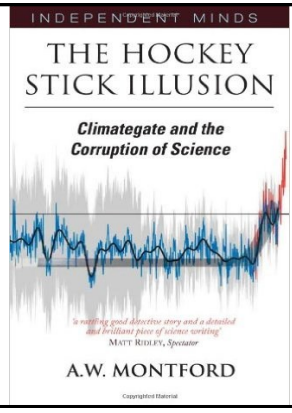


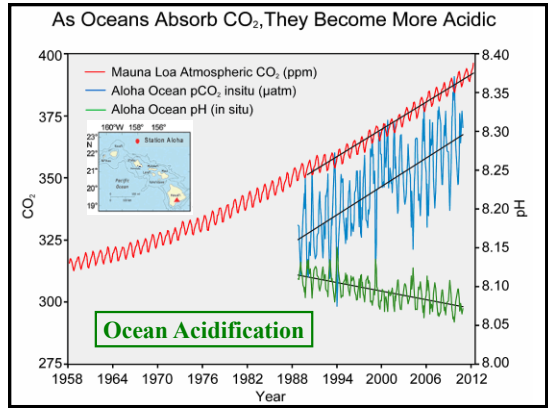
Colour-coded regions are where plant life will be affected by 2080. Figures reveal the number of days by which plants will flower earlier than expected

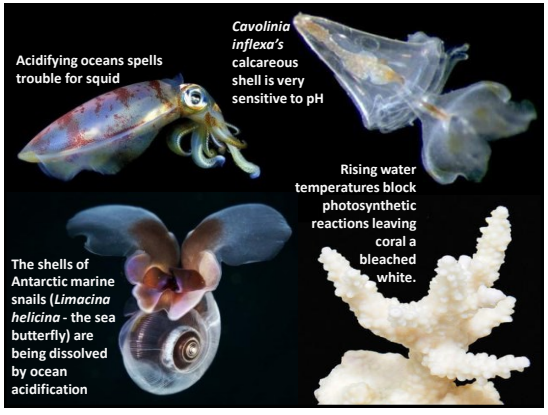
Tree rings and climate

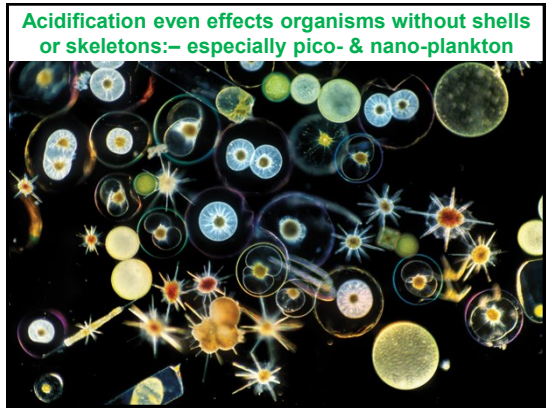


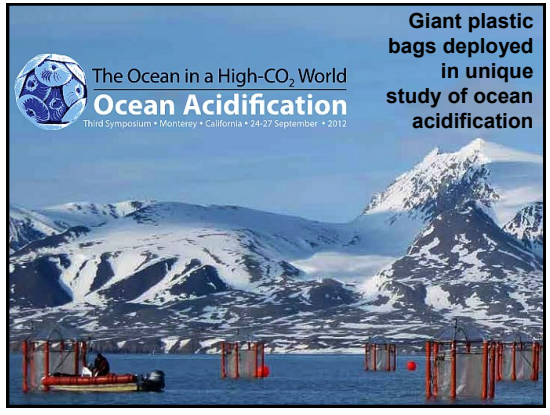
Douglas-fir sample from the Southwest USA has annual tree rings dating back to 1527. The narrowing of the rings that formed from the 1560s through the 1590s indicates that the tree grew little during the 16th century megadrought.

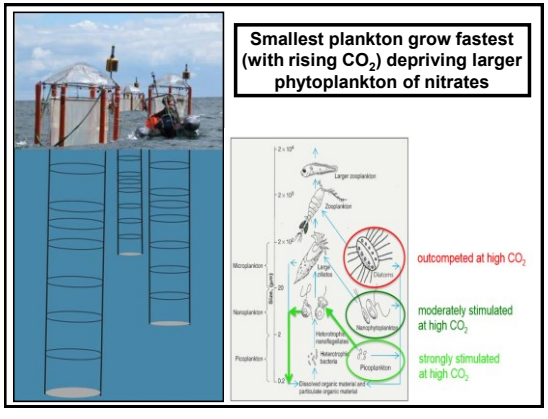


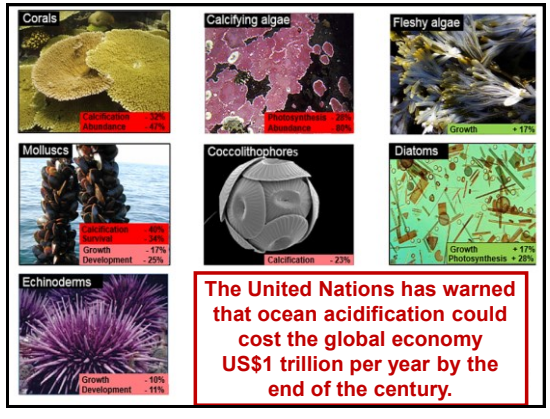


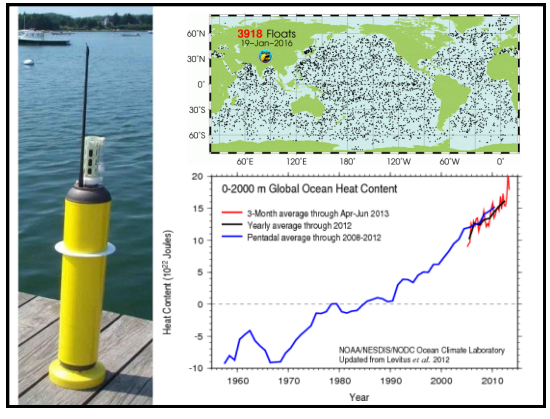

Acidifying oceans spells trouble for squid
Cavolinia inflexa's calcareous shell is very sensitive to pH
Rising water temperatures block photosynthetic reactions leaving coral a bleached white.
The shells of Antarctic marine snails (*Limacina helicina* - the sea butterfly) are being dissolved by ocean acidification

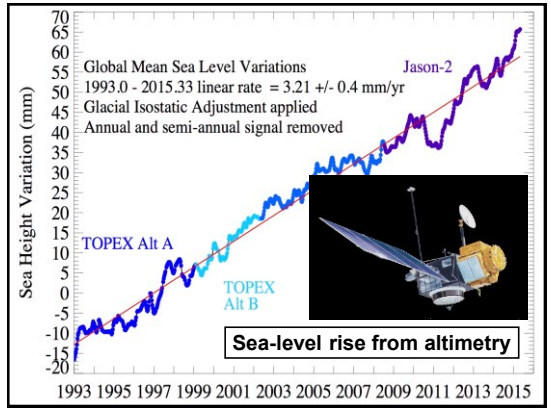

Acidification even effects organisms without shells or skeletons:– especially pico- & nano-plankton

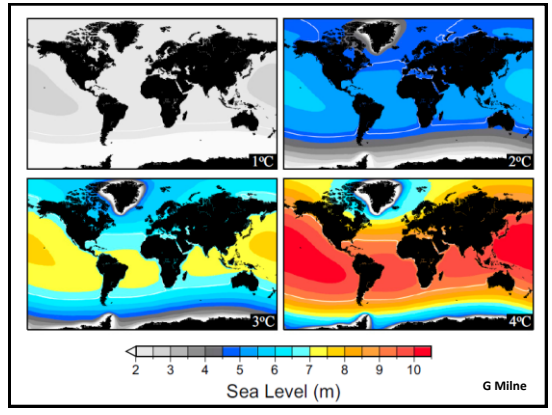

The Ocean in a High-CO_2 World
Ocean Acidification
Third Symposium • Monterey • California • 24-27 September • 2012
Giant plastic bags deployed in unique study of ocean acidification

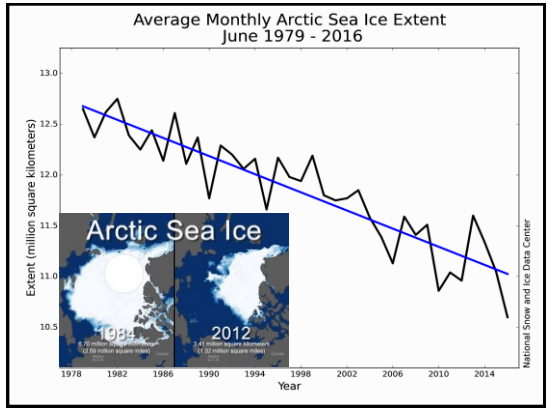

Smallest plankton grow fastest (with rising CO_2) depriving larger phytoplankton of nitrates
outcompeted at high CO_2
moderately stimulated at high CO_2
strongly stimulated at high CO_2

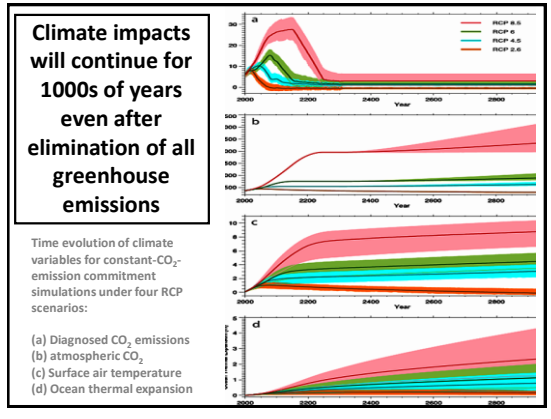

Corals
Calcification -17%
Abundance -47%
Calcifying algae
Photosynthesis -25%
Abundance -80%
Fleshy algae
Growth +17%
Molluscs
Calcification -40%
Survival -34%
Growth -17%
Development -25%
Coccolithophores
Calcification -23%
Diatoms
Growth +17%
Photosynthesis +28%
Echinoderms
Growth -10%
Development -11%
The United Nations has warned that ocean acidification could cost the global economy US$1 trillion per year by the end of the century.


3918 Floats
19-Jan-2016
0-2000 m Global Ocean Heat Content
3-Month average through Apr-Jun 2013
Yearly average through 2012
Pentadal average through 2008-2012
Heat Content (10^{22} Joules)
Year
NOAA/NESDIS/NODC Ocean Climate Laboratory
Updated from Levitus *et al.* 2012



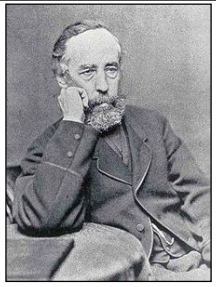






The history of climate change

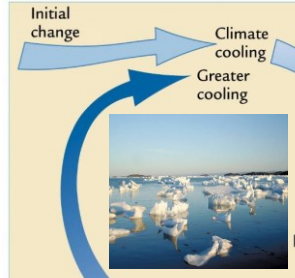
- 1860s - 1890s – the basic science is established
- 1900s - 1960s – doubts and indifference
- 1960s - 2010s – a slow reawakening
- The future – winning the climate battle



James Croll - visionary 19th-century Scottish scientist (1821 – 1890)

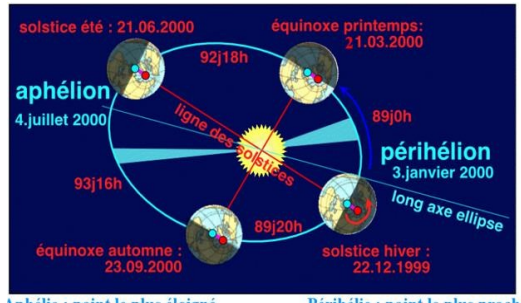
When James was three years old, the family croft was cleared by the landowner, Lord Willoughby, and displaced to an area of bog-land a mile to the west at Wolfhill.

Probable birthplace, Little Whitefield, Tuesday 2nd of January 1821



1. Croll pioneered the idea of positive feedback effects in climate studies.

2. Correctly interpreted the influence of eccentricity on the duration of the seasons, and hence on climate



Aphélie : point le plus éloigné 329 W/m2

Périhélie : point le plus proche 351 W/m2

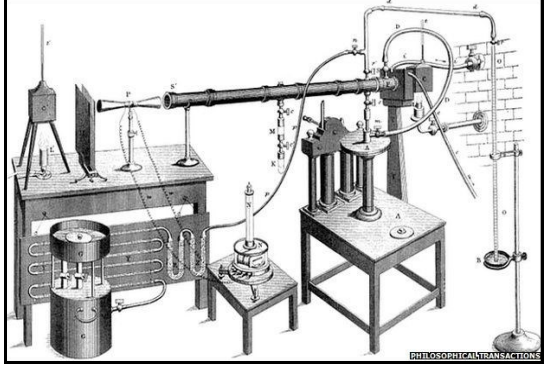
Greenhouse pioneers

FOURIER, 1766-1830

TYNDALL, 1820-1893

ARRHENIUS, 1859-1927

Tyndall's 1872 setup for measuring the heat absorption of gases



Anders Jonas Ångström (1814 – 1874) Swedish physicist, studied the light coming from the sun. His pioneering contributions to science were sufficient to have a tiny unit of length named after him, the angstrom, which is one ten-billionth of a metre.

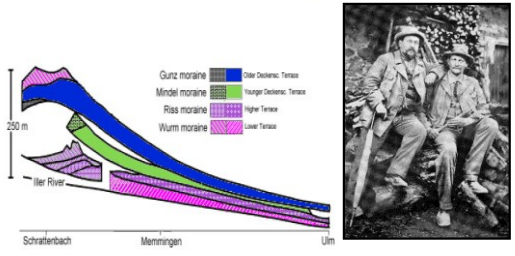
Knut Ångström (1857–1910), eminent Professor of Physics, studied the absorption of solar radiation by water-vapour, carbon dioxide and ozone.

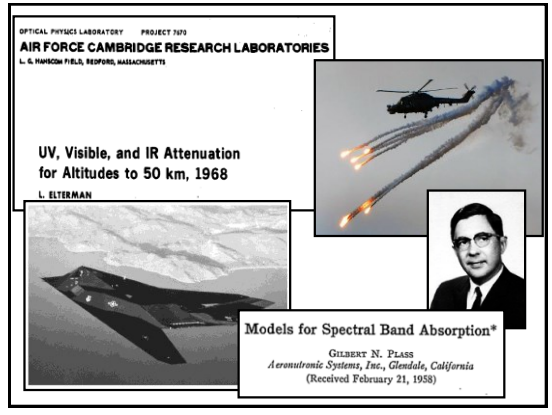
The remarkable Ångström dynasty from Uppsala

The Swedish meteorologist Anders Ångström (1888 – 1981) not to be confused with his more famous grandfather.

1909 A.Penck and E.Bruckner - Alpine Glacial Chronology

Glacials named for tributaries of the Danube River in Germany.
Based on Relative levels of river terraces separated by weathering and soils.





The Deep Sea Drilling Project (DSDP) operated from 1968 to 1983, and continues today as IODP.

The history of climate change

- **James Croll** – a Scottish scientist ahead of his time. His understanding of positive climate feedbacks (1864) ushered in the modern age of climate change.
- **The greenhouse effect** and the dangers of fossil-fuel burning were fully understood by Tyndall, Arrhenius and Ekholm (1897).
- **Doubts and indifference** characterised the 1900s – 1960s.
- **Keeling's CO_2 curve** (1957) followed by Revelle's elucidation of ocean buffering & Manabe's pioneering modelling of how the Earth's atmosphere behaves (1963) reignited an awareness of the dangers of fossil-fuel burning.
- **Palaeoclimate** deep-sea (1970s), ice-core (1980s) & extinction event (1990s) records confirm and extend the 2-4.5ºC climate sensitivity of computer models.
- **Today:** CO_2 exceeds 400 ppm; with a fundamental change to ocean chemistry. Land temperatures have increased by 1.5 ºC over the past 250 yr. Sea-level has risen 10-20 cm in 100 yr, and is accelerating rapidly. Spring is starting earlier, but plant and animal behaviour is desynchronising and the Earth is becoming browner.

Five types of climate change denial argument

1 **Conspiracy theories** (Vast conspiracy by scientists to deceive in order to win funding and/or status.)

2 **There is no consensus** (But only between fake-experts and non-specialists.)

3 **Impossible expectations** (e.g., requiring 100% proof; climate models are uncertain; IPCC reports are flawed, incomplete or fuzzy science.)

4 **Misrepresentations & logical fallacies** (e.g., scientists can't even predict the weather; climate has changed in the past.)

5 **Cherry-picking** (Ignoring all other evidence, e.g., global warming stopped in 1998.)

Main sceptical arguments of climate-economics

1 **Rate of technological advance** (e.g., RCP8.5 is too conservative and not representative of business-as-usual.)

2 **Damage costs** (e.g., CO_2 &T make plants grow better; uncertainties over impacts on society.)

3 **Mitigation costs** (e.g., renewables are already too expensive; we can never know the full costs with a reasonable level of precision.)

4 **Other priorities** (There are more pressing concerns, e.g., child mortality, AIDS, malaria, TB, malnutrition, clean water, E-Government.)

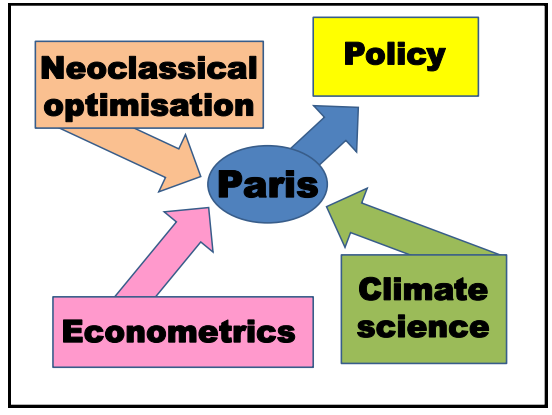
5 **Low risk of tipping points** (Nature is robust, mankind is resilient; Malthus was wrong.)

Main Skeptic Arguments

1 Climate's changed before
2 It's the sun
3 It's not bad (+ive impacts far outweigh any –ives)
4 There is no consensus
5 It's cooling (warming has now stopped)
6 Models are unreliable
7 Temp record is unreliable
8 Animals and plants can adapt
9 It hasn't warmed since 1998
10 Antarctica is gaining ice
11 CO2 lags temperature
12 Ice age predicted in the 70s
13 Climate sensitivity is low
14 We're heading into an ice age
15 Ocean acidification isn't serious
16 Hockey stick is broken
17 Climategate CRU emails suggest conspiracy
18 Hurricanes aren't linked to global warming
19 Al Gore got it wrong
20 Glaciers are growing
21 It's cosmic rays
22 1934 - hottest year on record
23 It's cold today!
24 Sea level rise is exaggerated
25 It's Urban Heat Island effect
26 Medieval Warm Period was warmer
27 Mars is warming
28 Arctic ice-melt is a natural cycle
29 Increasing CO2 has little to no effect
30 Oceans are cooling
31 Human CO2 is a tiny % of CO2 emissions

John Cook, founder of the blog Skeptical Science Wins Award for communication that motivates action to reduce the impacts of climate change.

The Paris Climate Agreement – grounds for optimism, or for scepticism and grim foreboding?



"…pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels…"
Article 2.1(a)

1. Seminal turning point
2. Meaningful progress
3. Phenomenally expensive
4. Unfeasible
5. Legal cynicism

Web-based reports of reactions to the Paris Agreement

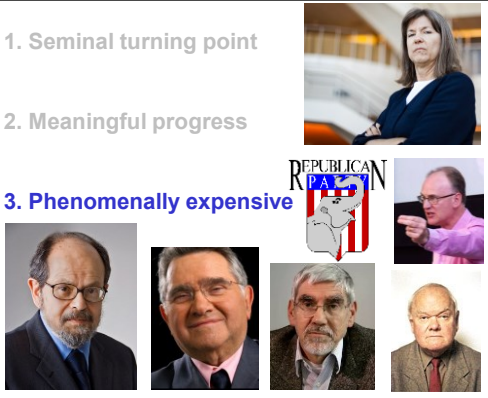
1. Seminal turning point

2. Meaningful progress

1. Seminal turning point

2. Meaningful progress

3. Phenomenally expensive



1. Seminal turning point

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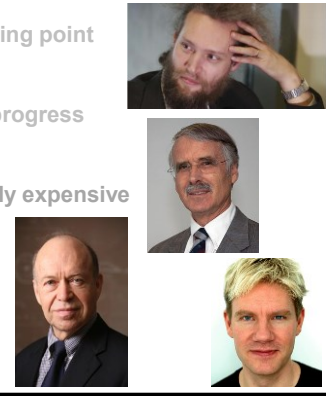

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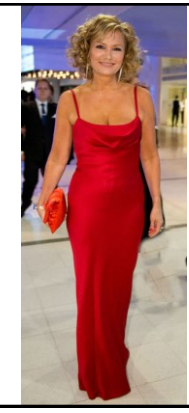
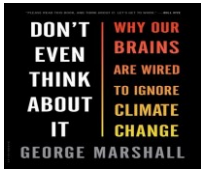
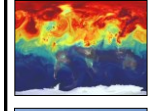




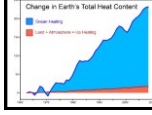
- Marshall argues that our evolutionary origins shapes the way we see the world and how we respond to threats.
- Climate change challenges and reverses some deeply held assumptions. The way of life we previously associated with comfort, wellbeing and material progress is now seen as dangerous.
- We are best prepared and inordinately skilled at identifying and anticipating threats from other humans, but not from ourselves.
- We are wired to be alert to dangers that are concrete, immediate and certain. But climate change is gradual, hard to observe and indefinite. Addressing it requires making palpable sacrifices now in order to prevent unclear costs in the distant future.
- Climate-change deniers are not normally short on scientific literacy. Deniers are generally better versed in the science than accepters. Climate change being a very complex science with profound uncertainties is exceptionally open to biased interpretations.
- In the end, Marshall is neither fatalistic nor idealistic about our chances of survival. Yes, we're wired to ignore climate change, but we're also wired to do something about it. Human history provides many examples of social movements that have overcome apparently impossible obstacles.

"The economics problem from hell"



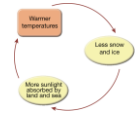
1. Multi-national problem

2. Irreversibilities

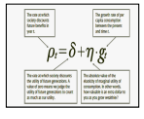


3. Long time-scale

4. Low-probability catastrophic outcomes



5. Large uncertainties



6. Externalities

Global Change's Terrifying Maths

Three simple numbers that add up to a global catastrophe…

The First Number: 2°C

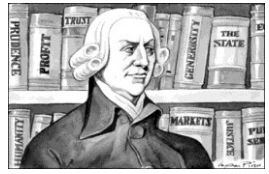
A 2°C target is often used in International negotiations as a guide line for avoiding dangerous climate change.

The Second Number: 900 Gigatons

Humans can pour roughly 900 Gt of carbon dioxide into the atmosphere and still have some hope of staying below two degrees.

The Third Number: >11,000 Gigatons

This number – the scariest of all – describes the amount of carbon contained in coal, oil, gas & hydrofracking resources. In short, the fossil-fuel mankind can burn is over 10 times higher than the 900 Gt 'limit'.

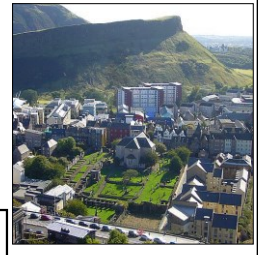


Adam Smith's insight

"The market is the most creative and dynamic economic engine known to man."

Adam Smith's Invisible Hand Theory

The theory of the Invisible Hand states that if each consumer is allowed to choose freely what to buy and each producer is allowed to choose freely what to sell and how to produce it, the market will settle on a product distribution and prices that are beneficial to all the individual members of a community, and hence to the community as a whole.



The problem: Smith's invisible hand sets prices incorrectly when a by-product of economic activity (eg CO_2) damages innocent bystanders.

Canongate Kirkyard

Discounting - a major econometrics headache

A bird in the hand …

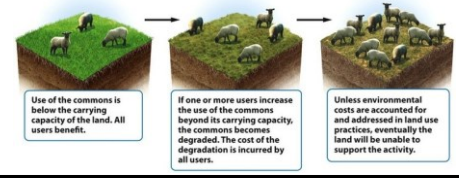
How should we value a sustainable future?

History of climate change within the sustainable development discourse

1968	Tragedy of the commons	(Hardin)
1972	Limits to growth	(Meadows et al)
1979	Gaia theory	(Lovelock)
1989	Blueprint for a green economy	(Pearce)
Today	Market based, utilitarian approaches (with a focus on energy efficiency & international political agreements)	

Tragedy of the commons 1968

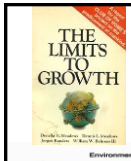
Garrett Hardin addressed the conflict between the short-term interests of individuals and the long-term welfare of society.



Use of the commons is below the carrying capacity of the land. All users benefit.

If one or more users increase the use of the commons beyond its carrying capacity, the commons becomes degraded. The cost of the degradation is incurred by all users.

Unless environmental costs are accounted for and addressed in land use practices, eventually the land will be unable to support the activity.



THE CLUB OF ROME

1972

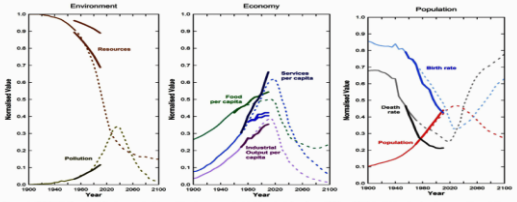
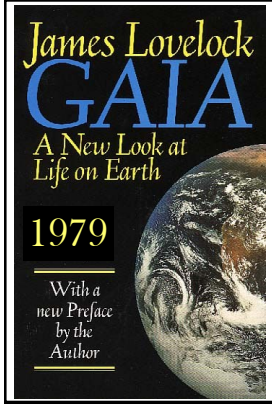
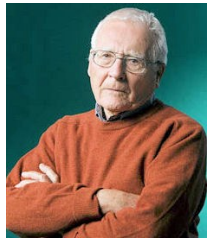


Figure 1. *LTG* BAU (Standard Run) scenario (dotted lines) compared with historical data from 1970 to 2010 (solid lines)—for demographic variables: population, crude birth rate, crude death rate; for economic output variables: industrial output per capita, food per capita, services per capita (upper curve: electricity p.c.; lower curves: literacy rates for adults, and youths [lowest data curve]); for environmental variables: global persistent pollution, fraction of non-renewable resources remaining (upper curve uses an upper limit of 150,000 EJ for ultimate energy resources; lower curve uses a lower limit of 60,000 EJ (Turner 2008)).

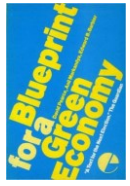




"The climate and the chemical properties of the Earth throughout its history seem always to have been optimal for life. For this to have happened by chance is … unlikely"

The Green Economy

1989



David Pearce

- **Getting the prices right:** In order to integrate the environment into economic decisions, the environment needs to be assigned economic values.
- **Environmental services:** Even though it is not possible to put an exact value on the environment, it is necessary try to show that environmental services are not free.
- **Sustainability & resilience:** More attention should be given to planning for the inheritance of future generations. They should inherit a stock of wealth (man-made & environmental) that is no less than we have today.
- **Market-based reform:** In the absence of a price, there is no mechanism to restrict consumption and to curb environmental damage. Hence there is a need to internalize environmental and climatic externalities.

Today: Three approaches

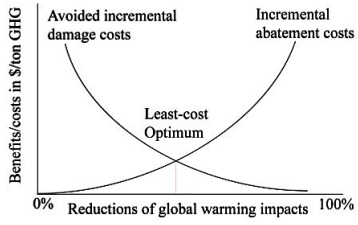
1. Command & control

2. Cap & trade

3.Carbon tax

Cost-benefit analysis

Cost-benefit analysis: the standard approach



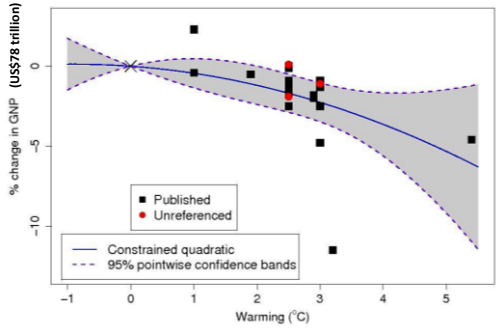
GLOBAL WARMING AND THE EFFECTS ON PEOPLE

Heat deaths Karachi 2015

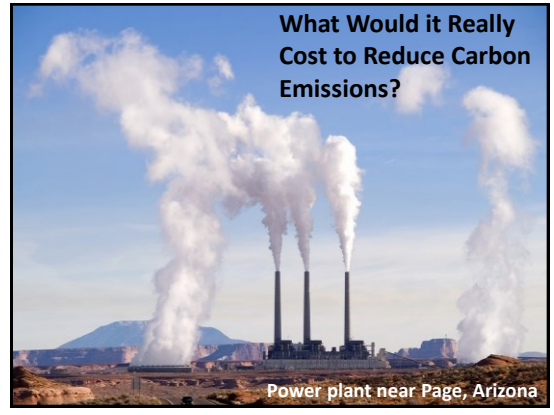
Malaria
Dengue fever
West Nile virus

Social unrest 2015

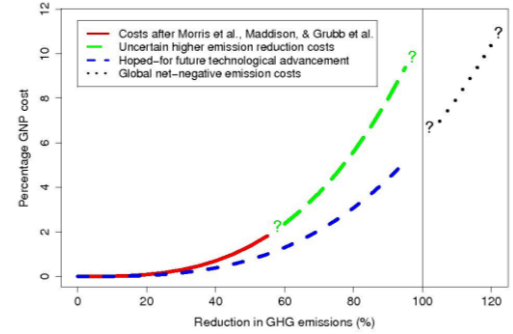
Damage function

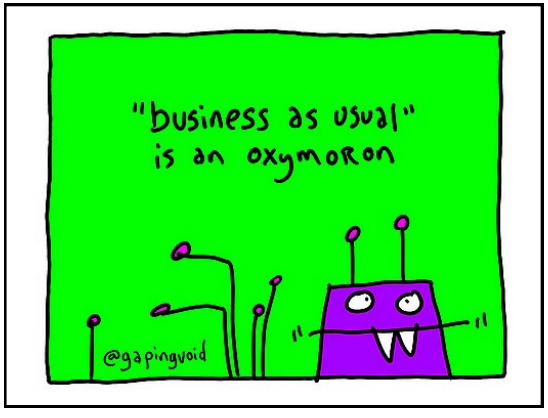


What Would it Really Cost to Reduce Carbon Emissions?



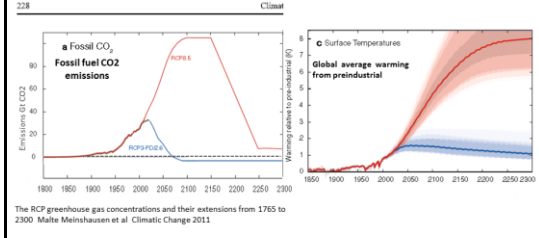
Costs of global emissions reduction





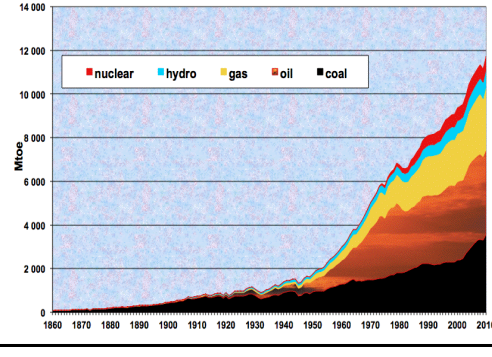
RCP scenarios best and worst case scenario

Projected 'best-estimate' global-mean surface temperature increases (using inter alia a climate sensitivity of 3°C) range from 1.5°C by 2100 for the lowest of the four RCPs, called both RCP3-PD and RCP2.6, to 4.5°C for the highest one, RCP8.5, relative to pre-industrial levels.

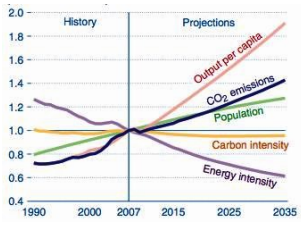


The RCP greenhouse gas concentrations and their extensions from 1765 to 2300 Malte Meinshausen et al Climatic Change 2011

Rise in global energy production



Kaya identity and global CO_2 emissions

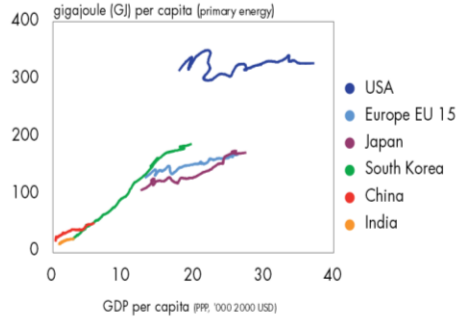


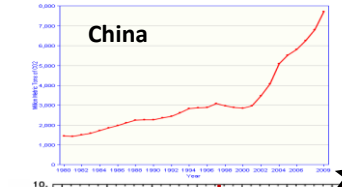
Yoichi Kaya
Japanese energy economist

$$CO2\ emissions = People \times \frac{GDP}{Person} \times \frac{Energy}{GDP} \times \frac{CO2}{Energy}$$

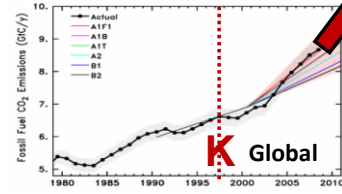
Climbing the energy ladder

Data shown 1970-2005



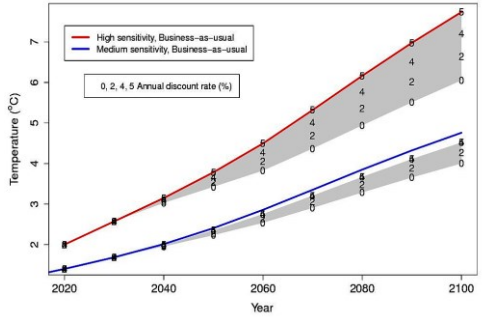


Where are we now?



Despite Kyoto, global CO_2 emissions are rising even faster than business-as-usual projections.

Optimisation of the economic/energy-balance analysis



Disentangling the Nordhaus/Stern controversy

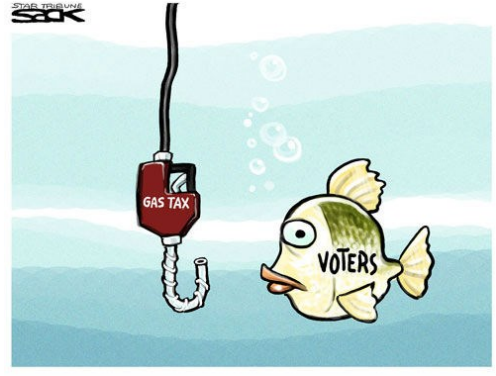
Lord Stern:

Claims the benefits of strong, early action outweigh the costs.
Prefers cap and trade.
Champions a low discount rate

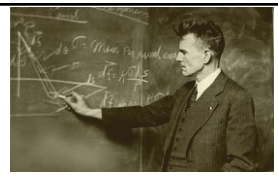
Carbon Tax, or Cap & Trade?

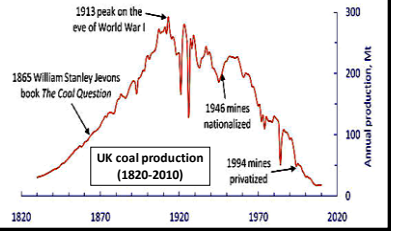
Nordhaus:

Strongly favours a carbon tax (initially around $10/ton), and has criticised the Stern Review for its use of a low discount rate.

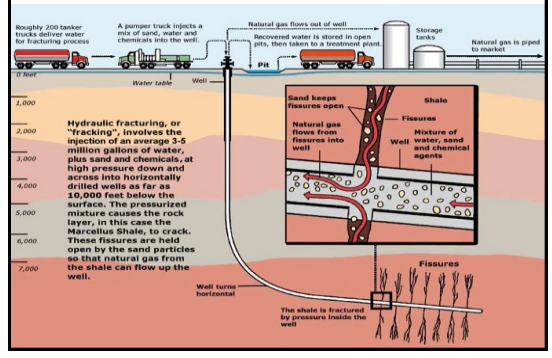


3b. Fracking?
Renewables?
Nuclear?
Peak Oil?
Peak Coal?





What is fracking?



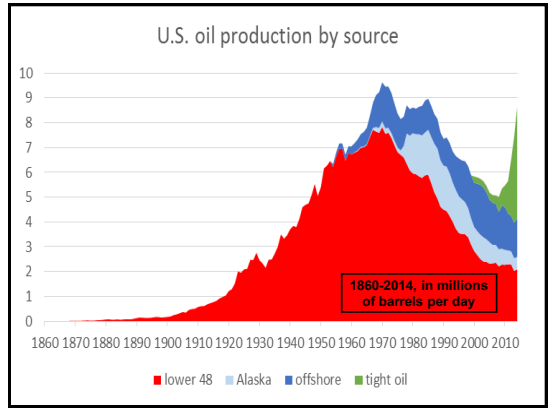
George P. Mitchell, the father of fracking

Billionaire Texas oilman, developer and philanthropist

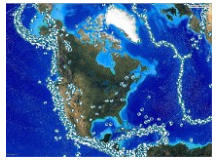
Fracking operations near a farm over the Marcellus shale formation in Pennsylvania

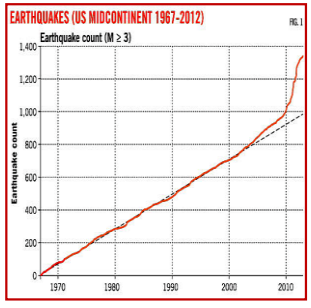
Horizontal drilling:
a key process – laterals can extend over 10,000 feet.

Hydrofracturing:
1 to 5 million gallons of water, mixed with sand and chemicals, are required for fracking each well.



Human induced earthquakes

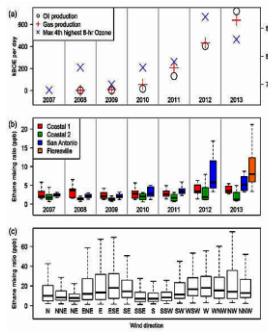


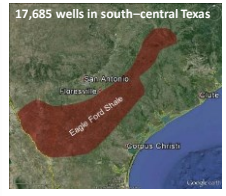


Fracking pit for contaminated (carcinogenic) wastewater

Is the Shale Boom Causing Ozone Pollution?

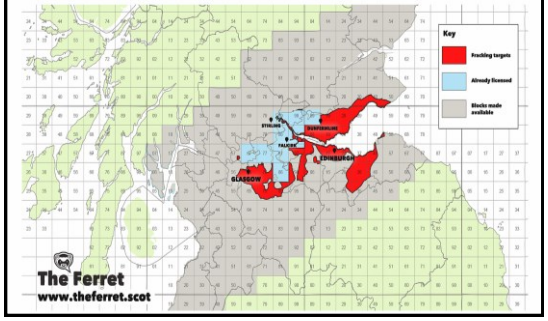
Schade and Roest 21 April 2015

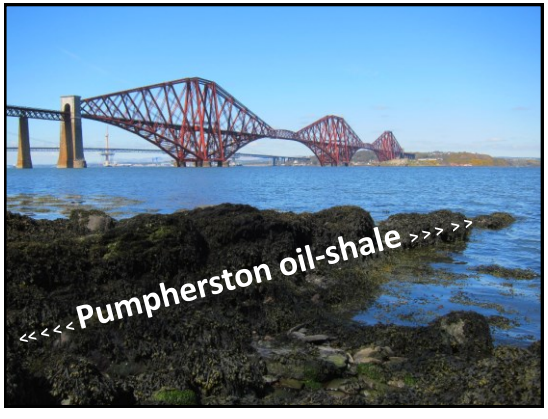




Gas flaring & crescent-shaped scatter of night light

Where do companies want to frack in Scotland?





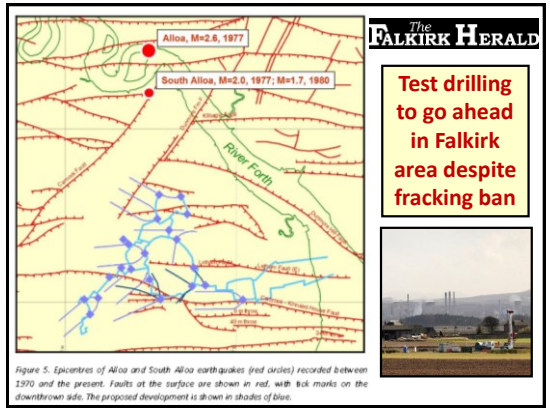


Figure 5. Epicentres of Alloa and South Alloa earthquakes (red circles) recorded between 1970 and the present. Faults at the surface are shown in red, with tick marks on the downthrown side. The proposed development is shown in shades of blue.

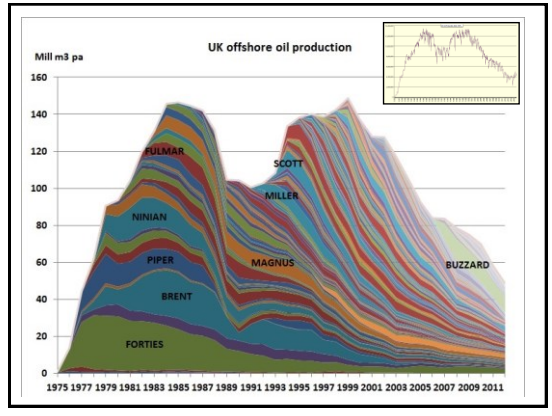
The Falkirk Herald

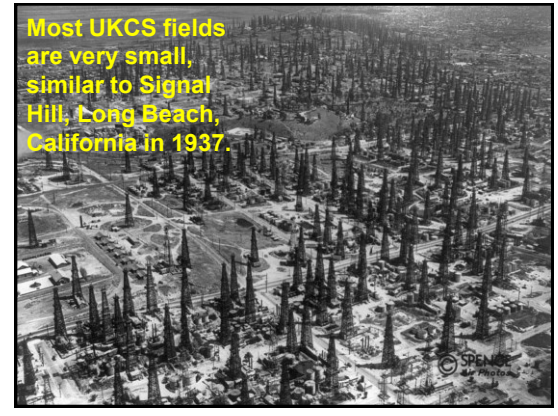
Test drilling to go ahead in Falkirk area despite fracking ban

Fracking for Scottish shale-gas:

Storm in a teacup?

Scotland's Oil





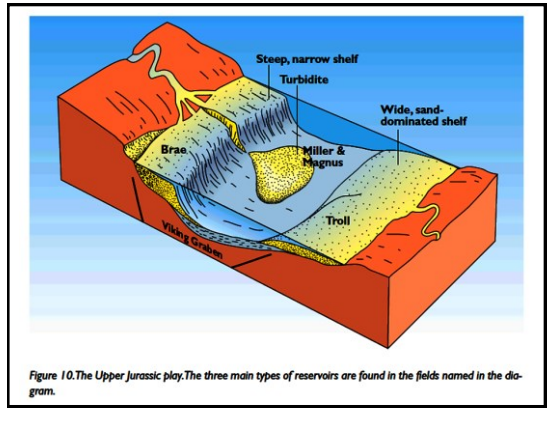
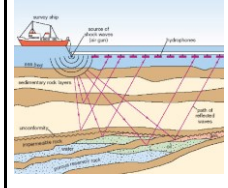


Figure 10.The Upper Jurassic play.The three main types of reservoirs are found in the fields named in the diagram.



How Does Marine Seismics Work?

1975: The first commercial 3D survey recorded in the North Sea

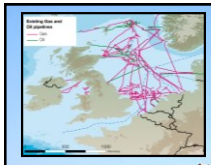
Drilling

Since 1965 3,970 exploration and appraisal wells have been drilled on the UKCS, at a cost of £58 billion.

Subsea drill bit

Distribution

Since 1966, over 45,000 km of pipelines, umbilical and cable has been Installed in the North Sea



Decommission, reef or abandon?

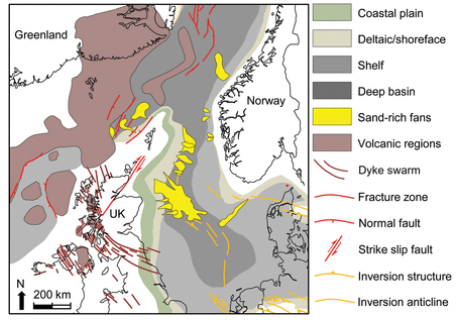
1. Successful heavy decommissioning lift of the Welland gas production platform in the southern North Sea.

3. More than 27,000 abandoned oil and gas wells lurk beneath the Gulf of Mexico

First minister accused of selecting optimistic economic forecasts to bolster his case for independence.

Alex Salmond said there can be '*little doubt that Scotland is moving into a second oil boom*'.

But the geology looks poor



Geological context: deep-marine source rocks & sand reservoirs.

Kezia Dugdale, Murdo Fraser, Willie Rennie and Patrick Harvie reacted to the GERS overspend report

Dugdale: *"People were misled by the SNP … and that is unforgivable."*

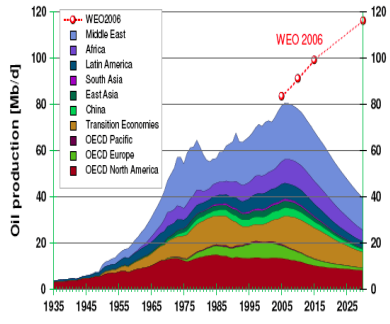
Fraser: *The [figures] shed new light on the SNP's deception."*

Rennie: "Ms Sturgeon's … credibility had been smashed to smithereens."

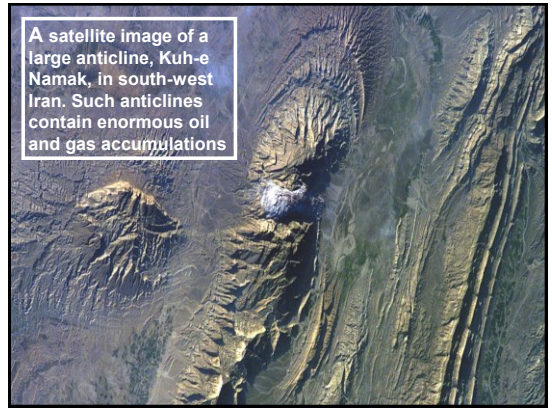
Harvie: *"Urgent need of a bold transition plan … that will make huge gains in industries like decommissioning, food production and renewables."*

Global Peak Oil:

The End of the Oil Age?

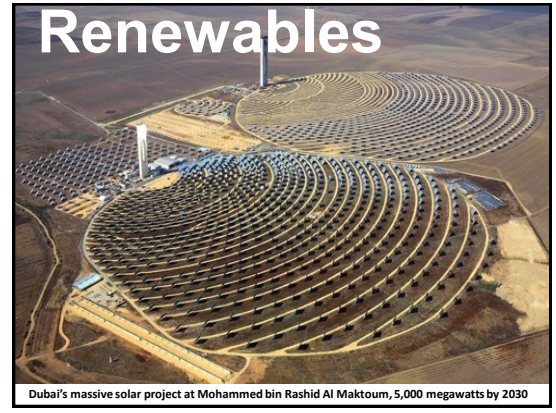


The largest point of disagreement is how much oil lies in reserve in the Persian Gulf.



A satellite image of a large anticline, Kuh-e Namak, in south-west Iran. Such anticlines contain enormous oil and gas accumulations

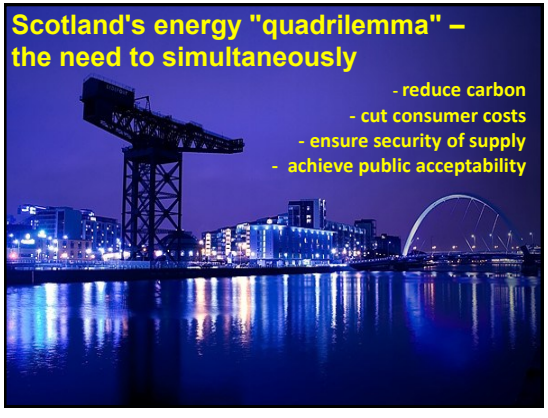
Renewables



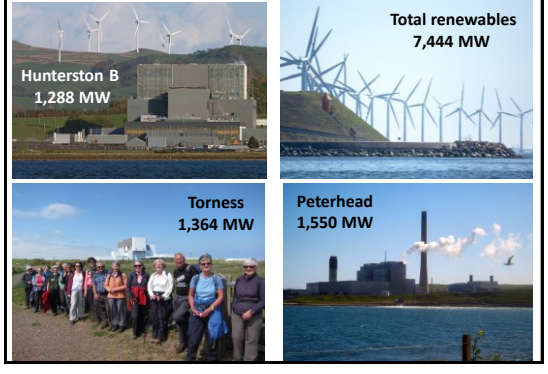
Dubai's massive solar project at Mohammed bin Rashid Al Maktoum, 5,000 megawatts by 2030

Scotland's energy "quadrilemma" – the need to simultaneously

- reduce carbon
- cut consumer costs
- ensure security of supply
- achieve public acceptability



Scottish electricity output: Nuclear vs. Gas vs. Renewables



2016: SNP pledges even tougher emissions targets!

"The re-elected SNP Government will raise Scotland's 2030 climate target to a new higher target."

Dan Barlow

MEETING THE 2030 TARGET

- An electricity system powered solely by renewables, or using carbon capture.
- Two-thirds of new cars and vans sold being electric by 2030.
- Nearly a fifth of homes fitted with heat pumps by 2030, and
- 16,000 hectares of land planted with trees each year.

scottish renewables

World's largest floating wind farm off Peterhead (30MW pilot)

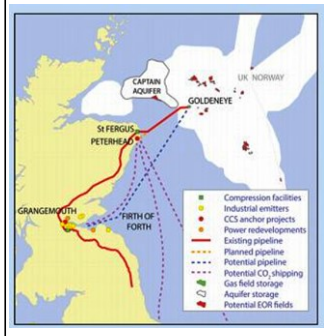
UK's largest wood fired biomass station, Lockerbie (44MW)

Europe's largest onshore wind farm, East Renfrewshire (522MW)

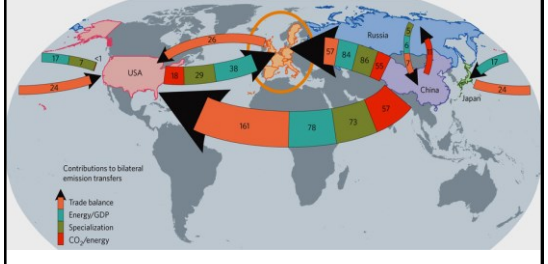
Scotland's largest solar farm: Carse of Gowrie (14MW)

CCS

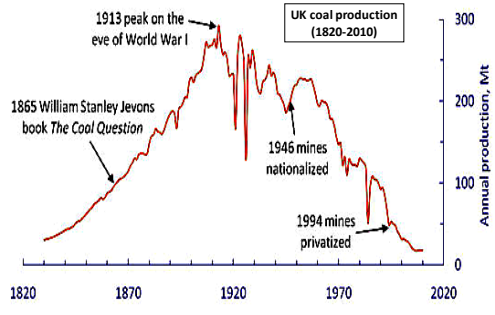
Scotland could cost-effectively become Europe's carbon capture and storage hub, building on existing pipelines and offshore infrastructure and saving on oil decommissioning costs.



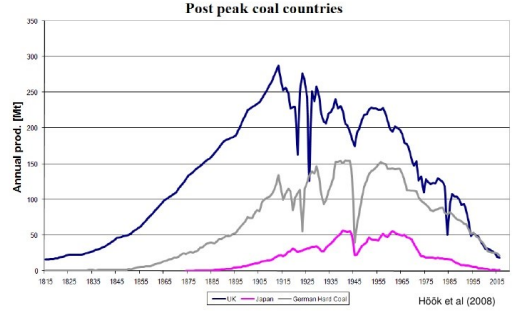
Net transfers of embodied emissions (in megatonnes of CO_2) resulting from bilateral trade.

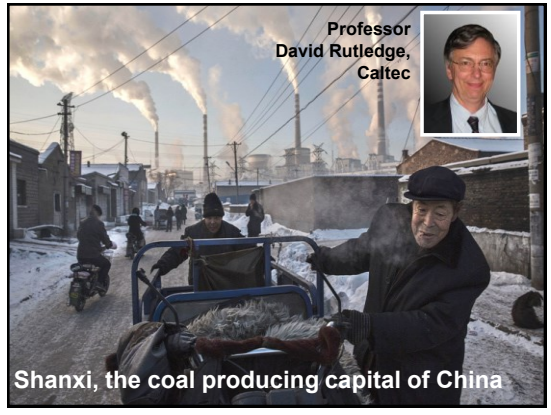


Peak Coal?

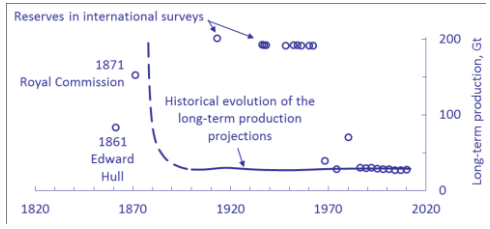


Can we apply Hubbert approach to coal?



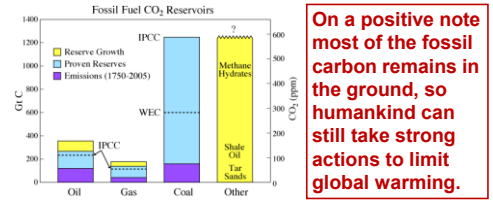


Historical Projections Compared with Reserves



- Produced only 19% of the 1871 Royal Commission reserves + cumulative
- Criteria chosen were too optimistic—1-ft seams, 4,000-ft depth
- Severe downgrade of reserves in 1968—late in the cycle ($t_{87\%}$)

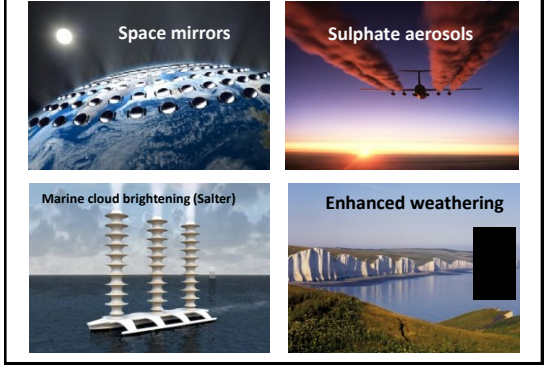
164

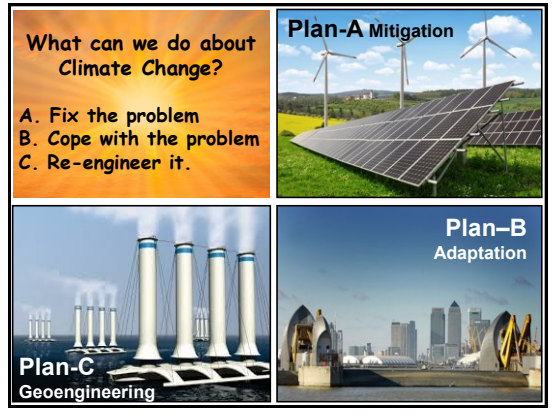


On a positive note most of the fossil carbon remains in the ground, so humankind can still take strong actions to limit global warming.

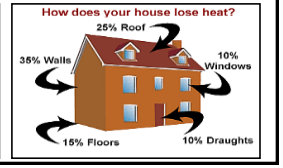
The carbon reserves map demonstrates the inequitable distribution of proven fossil fuels, and helps visualisation of likely diplomatic problems associated with fossil carbon divestment.

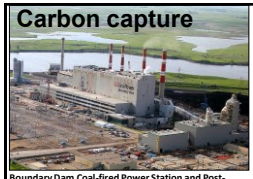
4a. Can science fix climate change





Mitigation: Seeks to reduce the sources, or enhance the sinks of greenhouse gases in order to stabilize CO_2 levels





Boundary Dam Coal-fired Power Station and Post-combustion CCS.

Forest clearing in Johar.

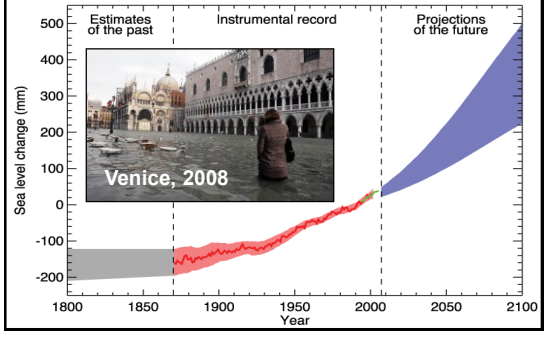
Biochar - a carbon-rich product, created by the slow burning of plant material with no oxygen.

Steven's Croft in Lockerbie - the UK's largest wood fired biomass station, supplies the electrical needs of 70,000 Scottish homes.

Plan-B: Adaptation

Seeks to reduce the vulnerability of social and biological systems and thus to offset the effects of global warming

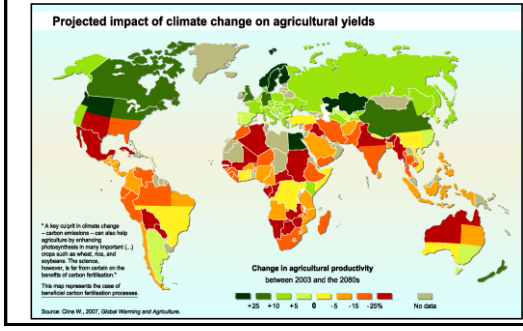
Sea level: Keep on building higher and higher barriers as the oceans rise



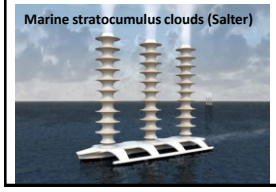
Infrastructure:

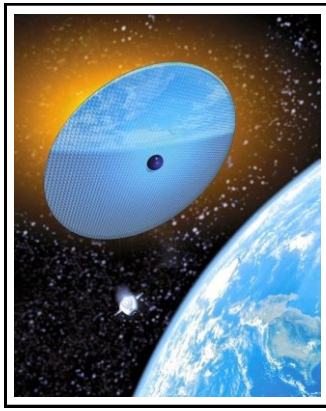
keep on repairing the damage caused by more and more extreme weather events

Food security: Try to keep on improving water supplies, and keep developing more and more new cultivars and new crop varieties as the climate changes



Plan-C: Geoengineering



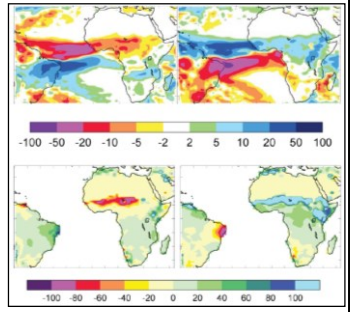


Edward Teller et al. (1997)

Small-angle-scattering system, using modest quantities of either conductors or dielectrics ($50–500 billion), in deep space.

Climate impacts of stratospheric aerosol geoengineering

There is a growing realisation that it is unlikely that stratospheric sulphate will be distributed evenly between the two hemispheres owing to the Brewer Dobson circulation.



The change in annual mean precipitation (mm month^{-1}) and the percentage change in the Net Primary Productivity for scenarios where SO_2 is injected into either the northern hemisphere or the southern hemisphere.

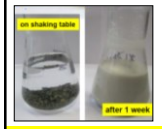
ENHANCED CHEMICAL WEATHERING AS A GEOENGINEERING STRATEGY TO REDUCE ATMOSPHERIC CARBON DIOXIDE
Jens Hartmann et al. May, 2013

(left) A "hardpan" of carbonate formed on waste slag mounds at former steelworks in Consett, United Ki precipitation in waters egressing from a waste landfill in Scunthorpe steelworks (photograph courtesy of e). In both cases, rainwater has percolated through the material (dissolving Ca^{2+} and Mg^{2+}) and cor e precipitation of carbonate

CO_2 Mineralisation Project to turn released carbon into commercial products.

Industrial flue gas is fed into a high temperature and high pressure environment to create a reaction between the CO_2 and chemical solutions and produce useful mineral-based products.

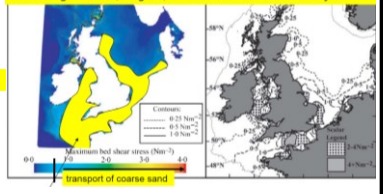
Mitigation of CO_2 emissions by fast weathering of olivine in high-energy seas



Lab and flume experiment

400,000 tonne mega-carrier

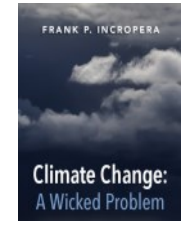
Weathering of a 1 cm thick carpet of olivine grains spread out over an area of *35,000 km²* would suffice to compensate CO_2 produced by fossil fuel burning in France, Belgium, Netherlands and the UK in one year



$Mg_2SiO_4 + 4\,CO_2 + 4\,H_2O \rightarrow 2\,Mg^{2+} + 4\,HCO_3^- + H_4SiO_4$

4b. Staving off catastrophic climate change

Climate change is a super wicked problem

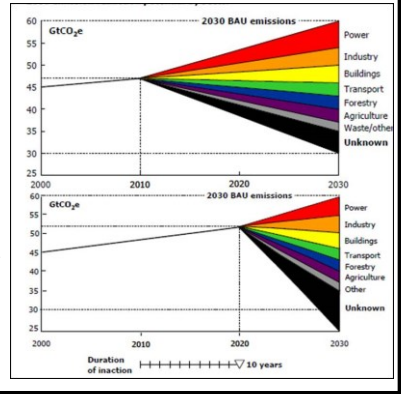


1. Wicked problems are
   - difficult to clearly define,
   - have many interdependencies,
   - are often multi-causal,
   - socially complex,
   - not stable - as the understanding of the problem is constantly evolving.
2. Attempts to address wicked problems
   - often lead to unforeseen consequences
   - as they exist in complex systems that exhibit unpredictable, emergent behaviour.
3. Wicked problems are often difficult or impossible to resolve because of their incomplete, contradictory, and changing requirements
   - there is often no right or wrong response,
   - many are characterised by chronic policy failures,
   - the solution hardly ever sits within the remit of any single organisation.
4. In short it is the social complexity, rather than technical complexity that is overwhelming.

The Science and Politics of Wedges

Seven "stabilization wedges" as envisioned by Socolow & Pacala.

Although much of the needed technology and know-how exists, the real key lies in how to rapidly deploy it in our power plants, buildings, factories and vehicles, and improving land management practices, given the profound inertia in our social, political and economic infrastructure.



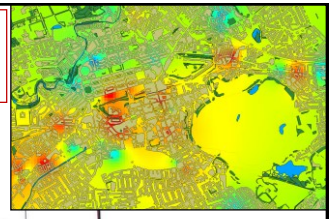
What can we do?

- **Maximize opportunities and co-benefits**
  - reduce air-pollution
  - improve energy efficiencies
- **Research & innovation**
  - geoengineering
- **Adaptation**
  - local planning, assisting disadvantaged nations
- **Carbon tax**
  - revenue neutral Pigovian tax

Air pollution kills 5.5 million people a year worldwide, mostly from strokes and heart attacks.

Air pollution in Edinburgh

Air pollution concentrations are so high they are regularly breaking national safety standards. 80% of urban air pollution is caused by road traffic.



Edinburgh St Leonards. Site ID: ED3. (The nearest main road, Pleasance is approximately 35m away.)

Traffic-Related Pollutants in Urban Centres: A Case Study of the Seagate, Dundee.

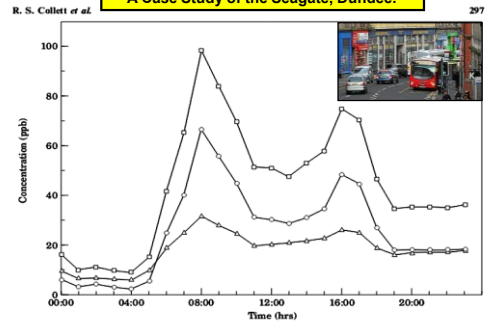
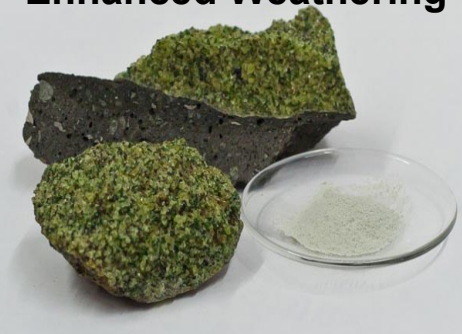


Figure 4. Graph showing the average weekday, daily variation in ambient NO (○), NO_2 (△) and NO_x (□) from hourly averaged values.

Enhanced Weathering



Olivine from the Eifel, Germany and some ground dunite powder.

Stratospheric sulfate injections with commercial aircraft

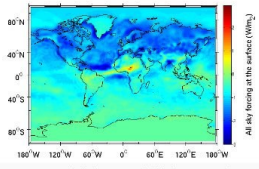


Figure 2. . Global mean of all-sky aerosol forcing at the surface when intercontinental flight routes are in the lower stratosphere and the sulfur content of the fuel is 50 times the current level. [3]

- Commercial aircraft could be used to deliever sulfate into stratosphere by increasing fuel sulfur content and the flight altitude of inter-continental flights
- The sulfur content of the fuel should be increased to about 50 times the current level to have a significant cooling effect
- The cooling effect would be confined to the Northern Hemisphere

Injecting aerosols into the stratosphere mimics the cooling effects of volcanoes

Paul J. Crutzen - Nobel Lecture

Nobel Lecture, December 8, 1995

My Life with O_3, NO_x and Other YZO_xs

"Awarded for work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone."

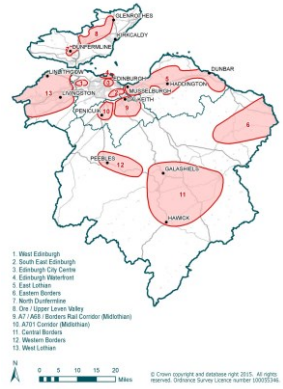
Urban sprawl - Aerial view of the north west (1/8th) of Livingston

SESplan

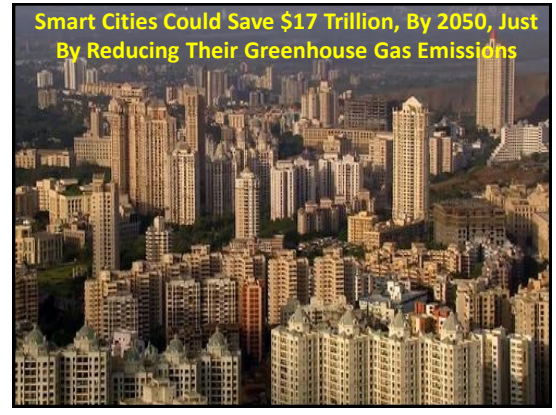
The Strategic Development Planning Authority for Edinburgh and South East Scotland

A Vision for Edinburgh and South East Scotland

Over the next 20 years the predicted growth in the number of households in the area is 25%. The city of Edinburgh, East and West Lothian, Midlothian, the Borders and Fife will be the region's main population growth areas. In short, in just the next 10 years more than 100,000 new homes will be needed.

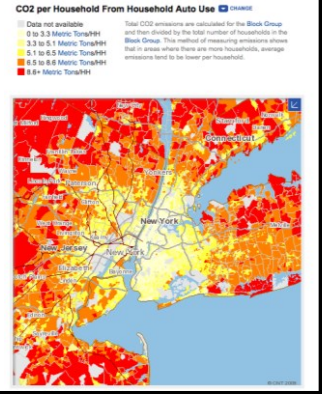


Smart Cities Could Save $17 Trillion, By 2050, Just By Reducing Their Greenhouse Gas Emissions



Cities are a big source of greenhouse gases.

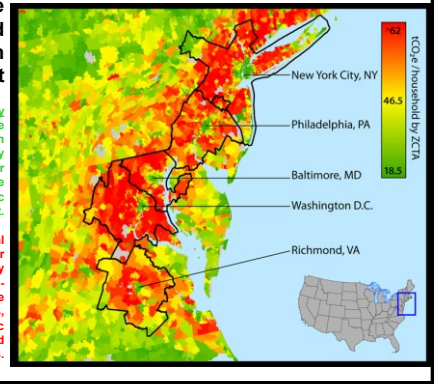
However, annual emissions per household are half of those in the less efficient, car-dependent suburbs.



Average Household Carbon Footprint

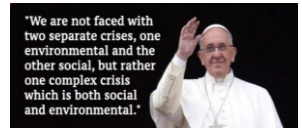
Inner city residents have lower carbon footprints as they live in smaller homes and use more public transport.

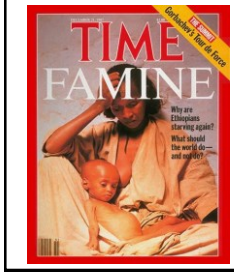
Suburbs are ideal candidates for energy efficiency technologies:- whole home energy upgrades, solar photovoltaic systems and electric vehicles.



Mass transit is a key ingredient in a sustainable, low-carbon transport future

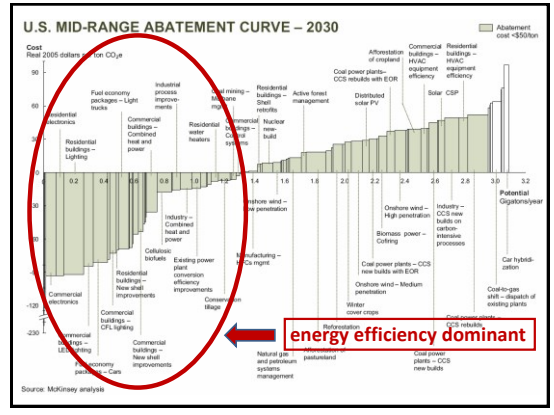
Climate and development with a focus on the global south.



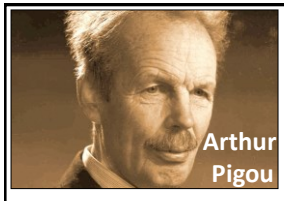


Debt Relief:

Debt relief to developing nations, with the caveat that funds previously allocated to finance debt go instead toward investing in infrastructure and to other climate change adaption & mitigation efforts.

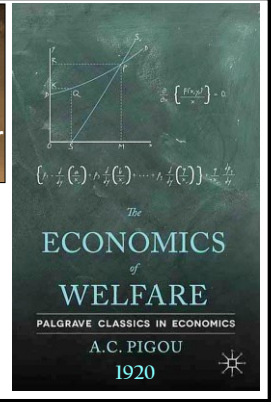


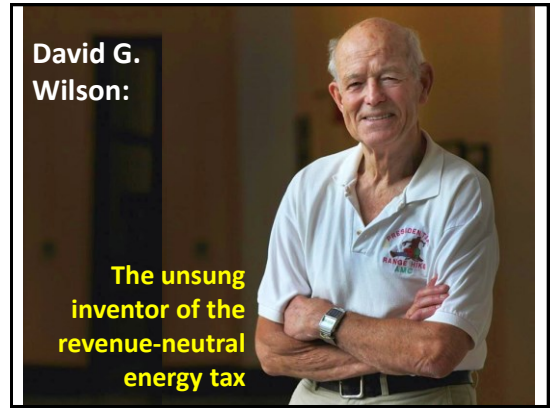
Wake Up! Climate Change Solution For Sale. $68 Billion RoyThompson @edin.com



A Pigovian tax is a levy on an environmental externality (damage) as an incentive to avert the costs (to society).

In a true market economy a Pigovian tax is the most efficient and effective way to correct a negative externality.





Carbon Fee & Dividend

(A smart carbon tax)

- All money collected is returned to households
  (None goes to the politicians)
- Innovation & investment in low-carbon technologies stimulated by Adam Smith's invisible hand
- Simple and inexpensive to administer
- Scope for corruption greatly reduced
- Gradual, so predictable for business
- Can receive bipartisan political support

Having flogged for 21 years, the dead horse of legally binding emission targets, the UN should close that chapter and try something new.