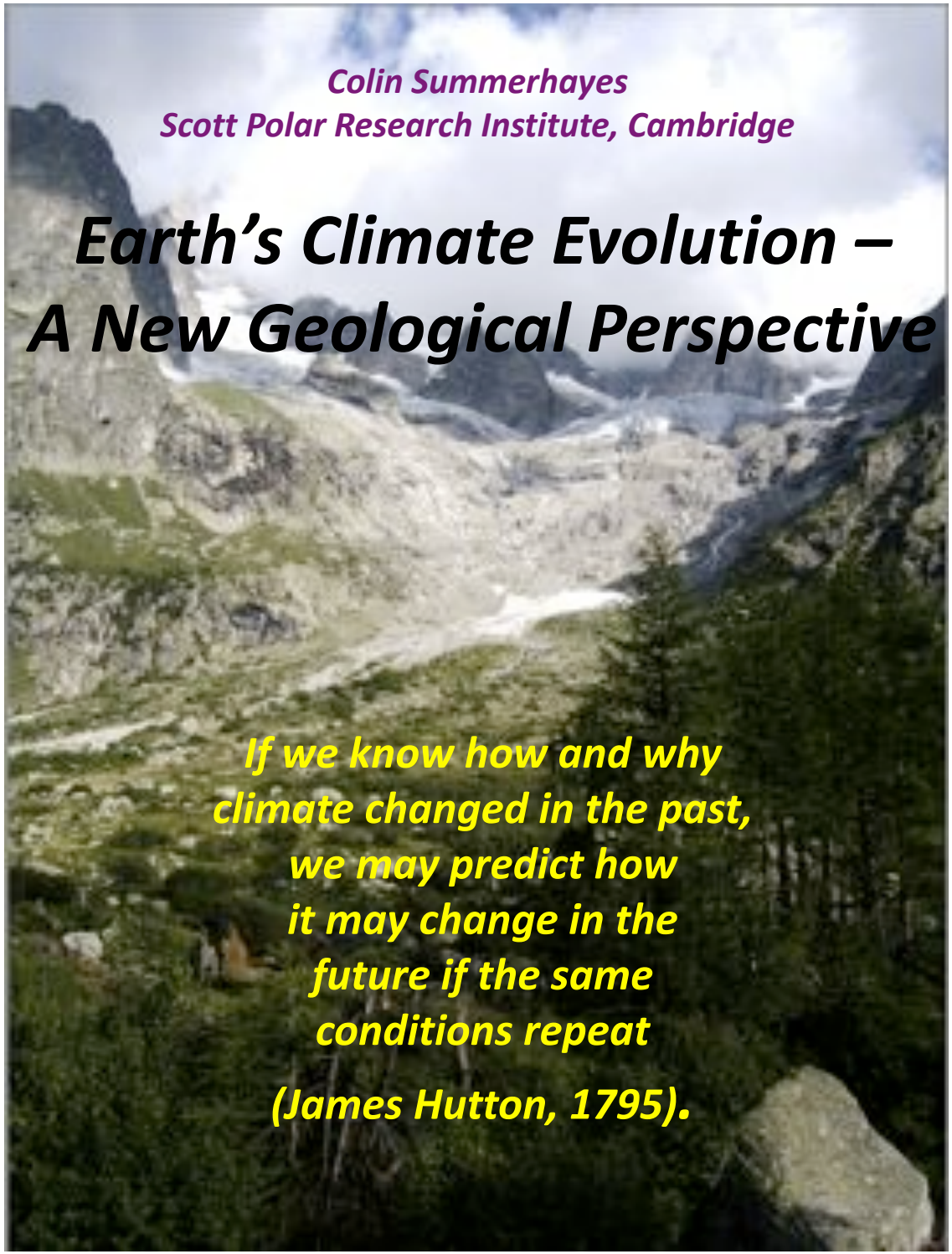
Colin Summerhayes
Scott Polar Research Institute, Cambridge

Earth's Climate Evolution – A New Geological Perspective



If we know how and why climate changed in the past, we may predict how it may change in the future if the same conditions repeat

(James Hutton, 1795).

Earth's Climate Operates Within a Narrow Envelope of Change. Drivers Include:

- ***The Sun (output increased 6% in Phanerozoic)***
- ***Plate tectonics (volcanic source of CO_2)***
- ***Chemical weathering and subduction (CO_2 sink)***
- ***Evolution of land plants (CO_2 sink)***
- ***Large Igneous Provinces (plateau basalts & CO_2)***
- ***Orbital & Axial variability (modifies heat)***
- ***Solar variability (sunspot cycles)***
- ***Internal variability (El Niño; PDO)***
- ***Single volcanic eruptions (short term cooling)***
- ***Bolide impacts (end Cretaceous)***

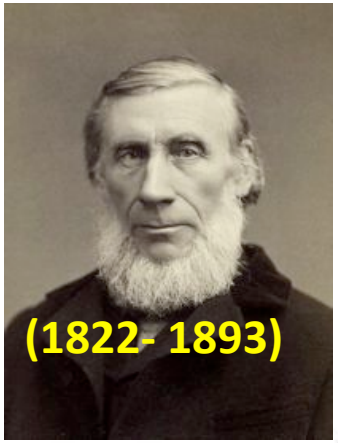
Thermostat: e.g. As temperature increases, rate of chemical weathering goes up.

CO_2 vs Temperature as Drivers of Change

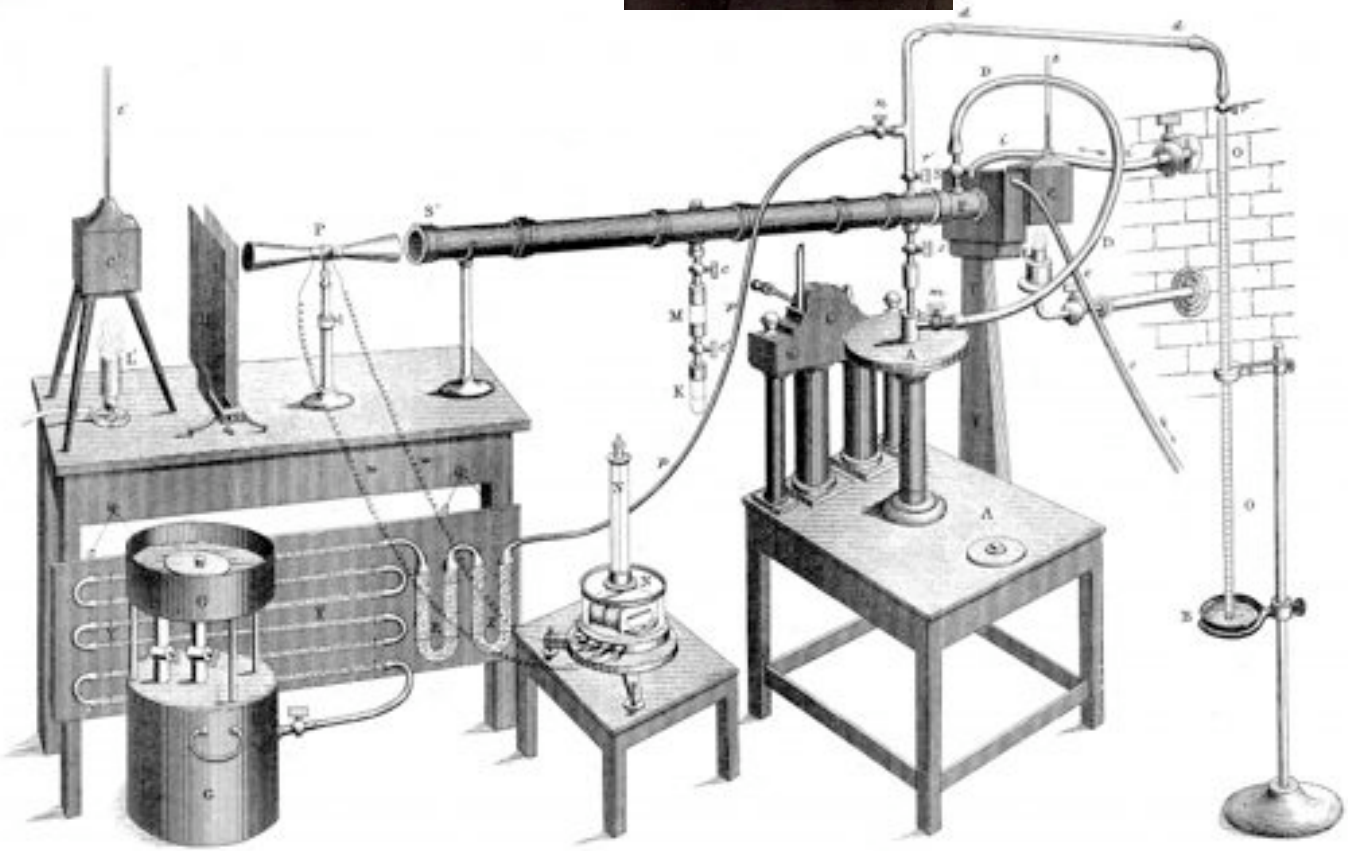
- ***We can consider CO_2 and temperature as non-identical twins. (A) CO_2 may appear first, followed by temperature; or (B) temperature may appear first followed by CO_2.***
- ***The one that comes first depends on circumstances.***
- ***E.g. in (A) plate tectonic sources commonly precede development of chemical weathering/subduction sinks.***
- ***E.g. in (B) orbital insolation raises temperature, which raises CO_2 .***
- ***In both A & B there is positive feedback between CO_2 and temperature, with H_2O feedback as well.***

The Role of Greenhouse Gases

Joseph Fourier (1824)
Air traps outgoing infrared radiation. Warms the atmosphere.

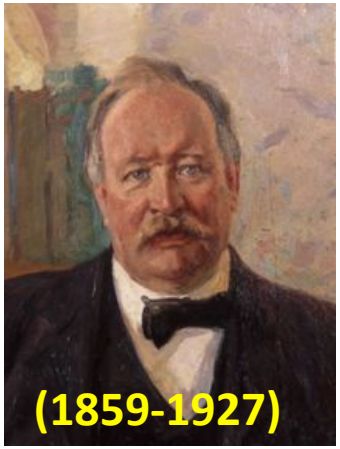


John Tyndall (1859)
H_2O, CO_2, CH_4, and O_3 could have produced *"all the mutations of climate which the researches of geologists reveal"*



Tyndall, 1959

CO_2 and Ice Ages



Svante Arrhenius (stimulated by geologist Högbom)
1896: Decrease of 0.6 x CO_2 lowers temp 5°C). Double CO_2 raises temp 4°C. Names this: "Hothouse Theory".

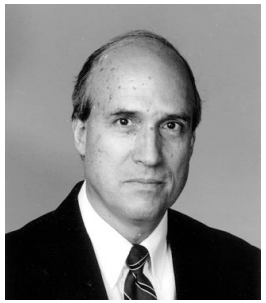
T.C. Chamberlin develops theory of Climate Change (1899).

Volcanoes ➡ CO_2 (source); chemical weathering absorbs CO_2 (sink)

Cold glacial ocean dissolves CO_2, keeps climate cool.
Warm interglacial ocean releases CO_2, keeps climate warm.

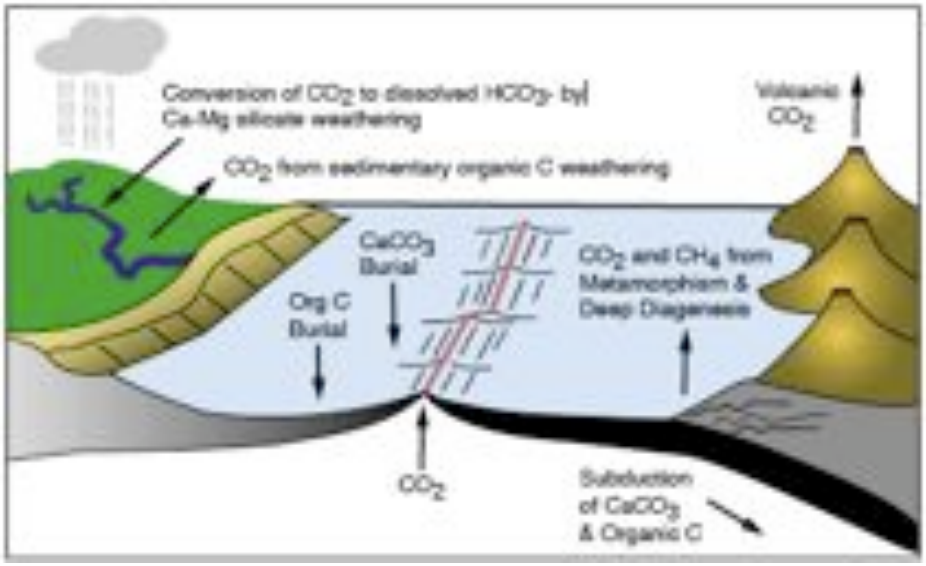
Carboniferous glaciation 300 Ma ago caused by coal extracting CO_2 from atmosphere.

Understanding the Carbon Cycle

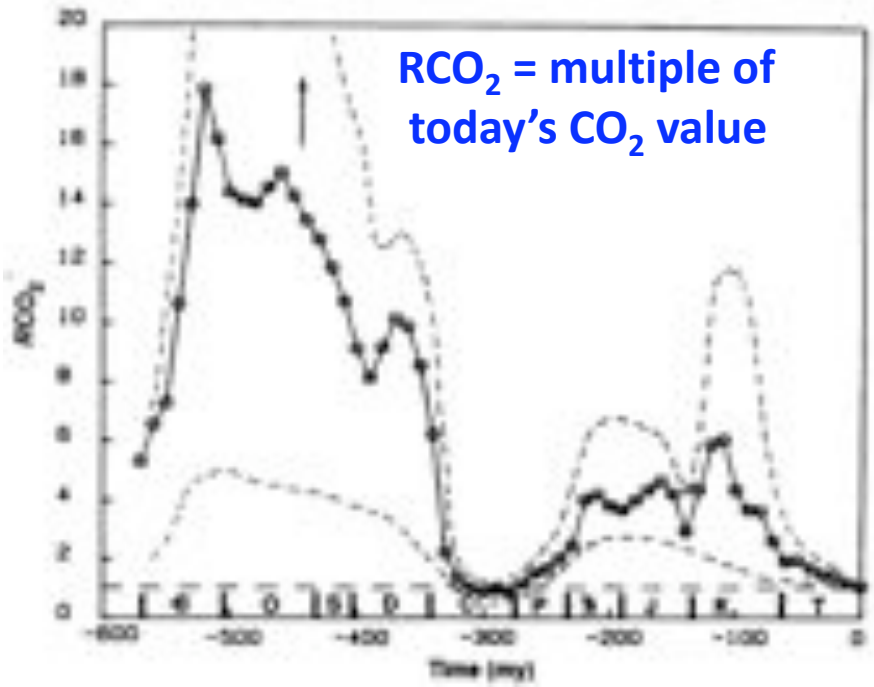


Bob Berner (1935-2015) Models Earth's Elemental Cycles

The slow carbon cycle



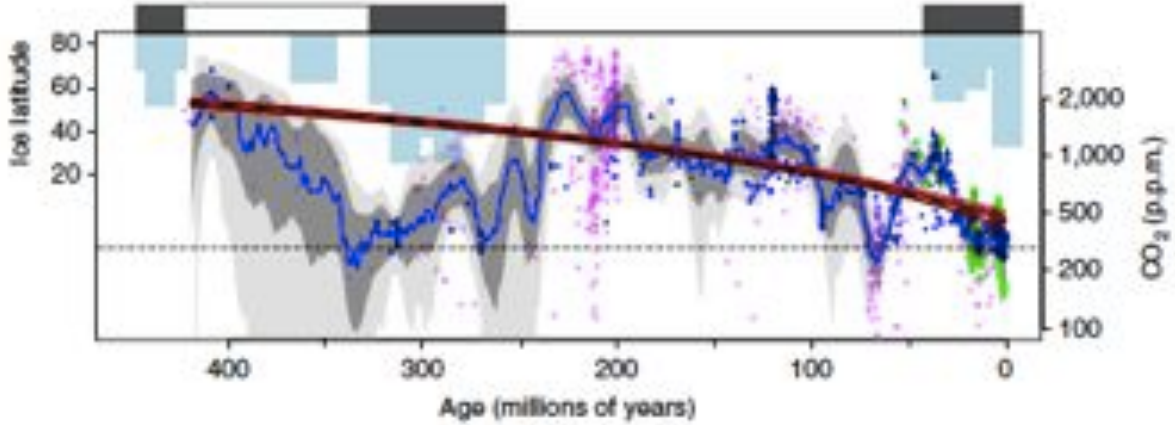
Berner, 1990



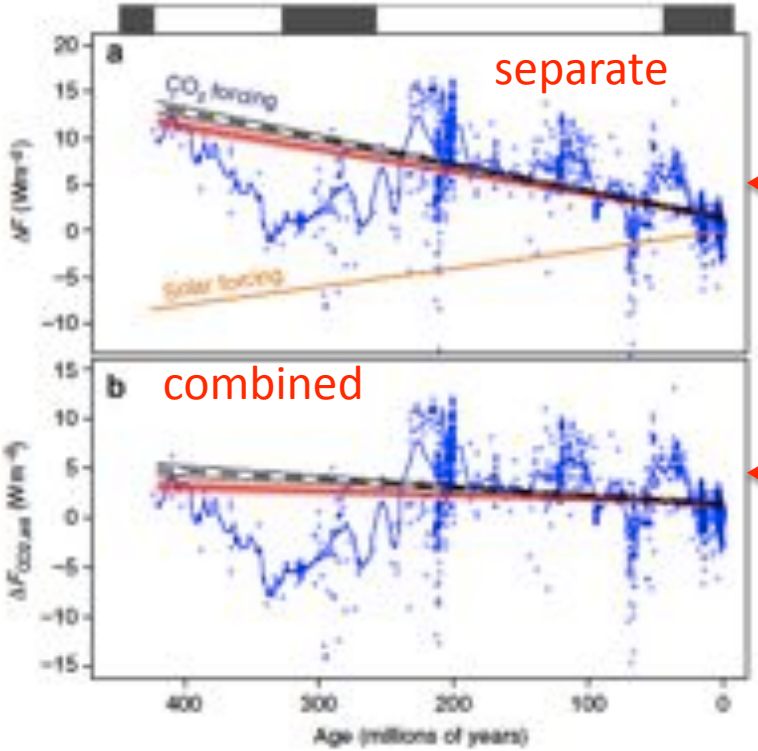
Berner, 2004, The Phanerozoic Carbon Cycle: CO_2 and O_2. Ox. Uni. Press

Silicate Weathering and Evolution of Land Plants Negate Effects of TSI Increase

CO_2



Forcing

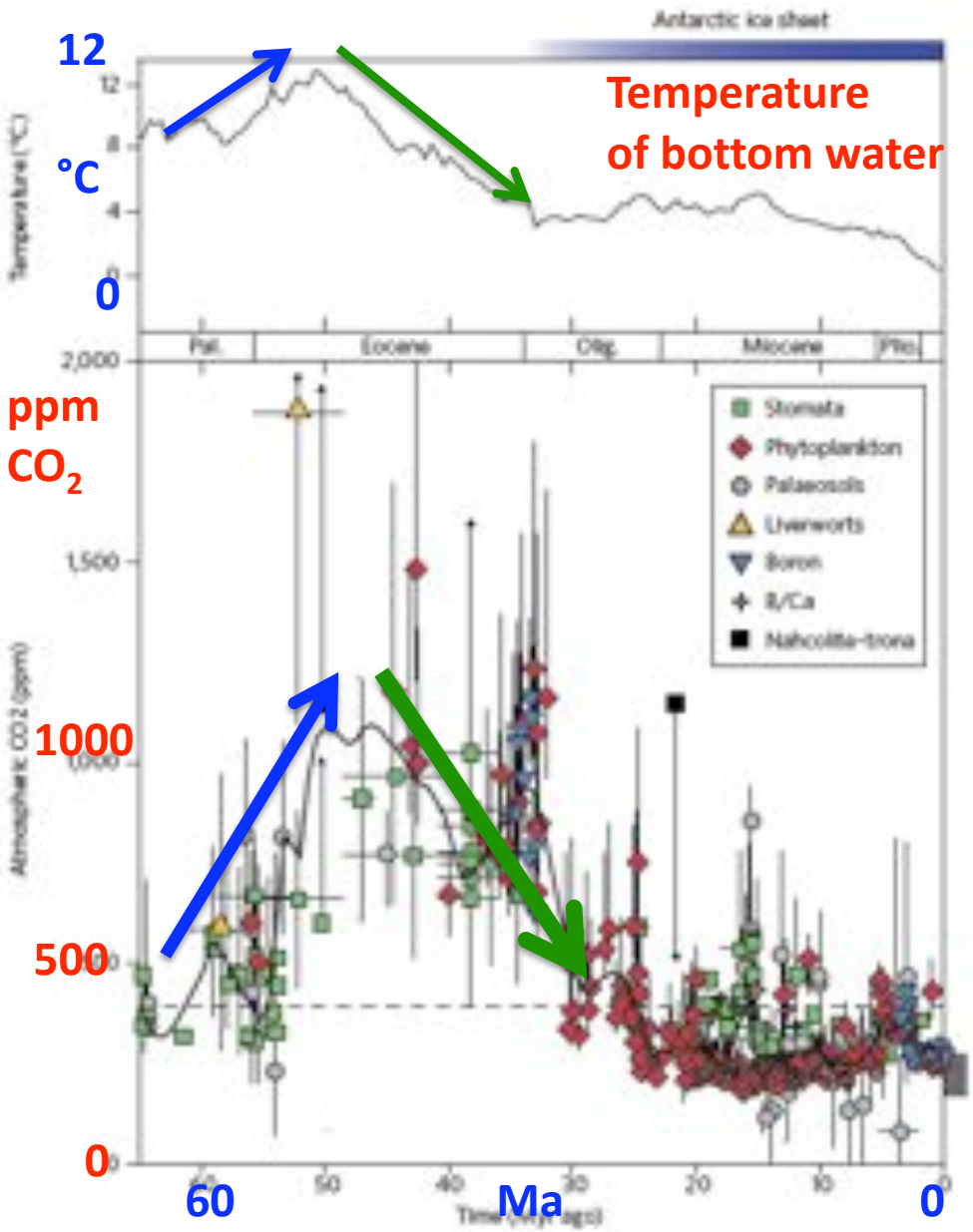


IPCC business as usual

Red = Least squares fit

Foster et al, 2017

Example - Cenozoic

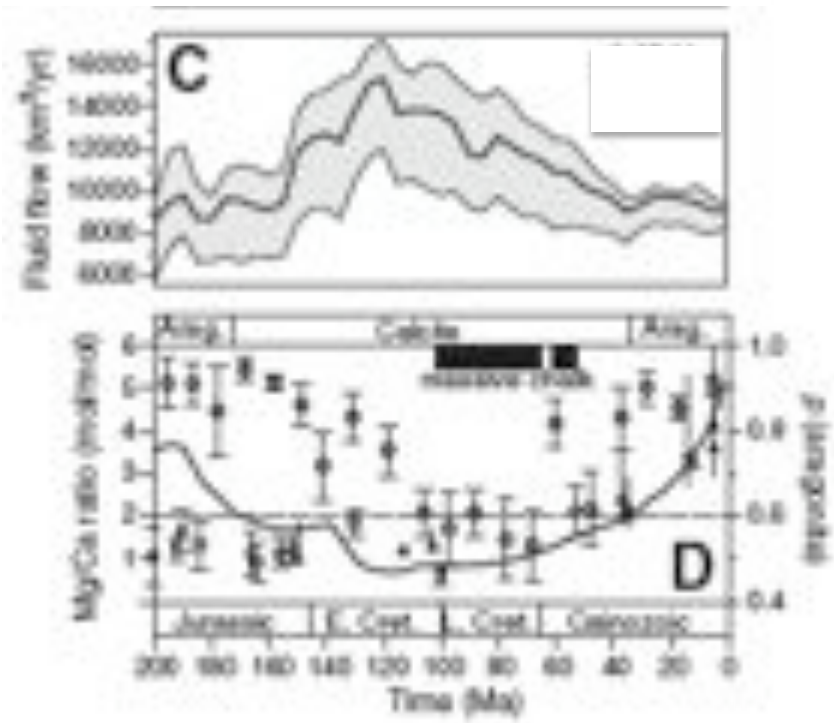


Beerling and Royer, Nature Geoscience 2011

THE SLOW CARBON CYCLE AT WORK

Sediment Composition is a Climate Clue

Reverse engineering: Seafloor chemistry tells us about atmospheric chemistry (Holland, 2003)



Larger flux of hydrothermal fluids
= volume of mid-ocean ridge
= volume of volcanic CO_2
= basalt alteration (Mg sink, Ca source)

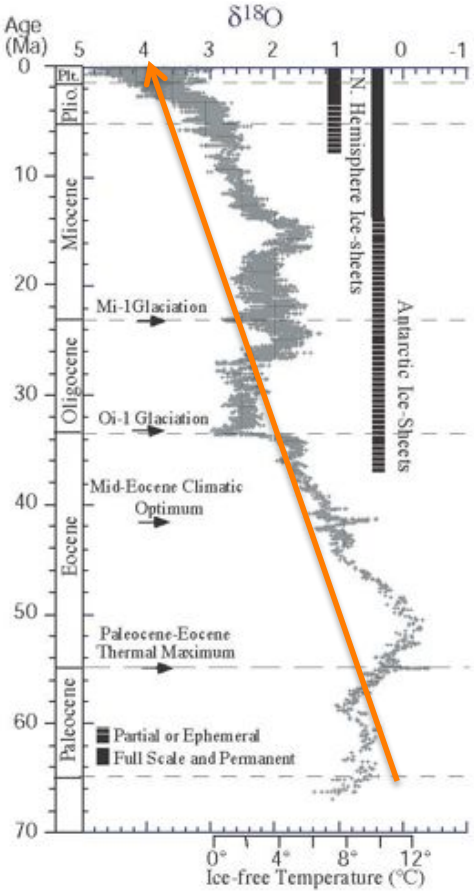
More CO_2 = WARM = Mg/Ca <2
= Low Mg Calcite (massive chalks).
Low CO_2 = COOL = Mg/Ca >2
= High Mg-calcite + Aragonite reefs (o)

ALSO - dissolving CO_2 raises CCD

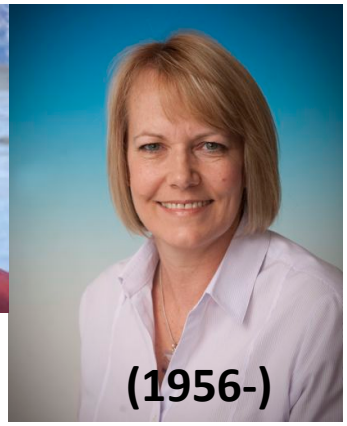
The Calcite Metronome (Zalasiewicz & Williams, 2012).

Müller et al, Geology, 2013; also see M Arthur, 1980

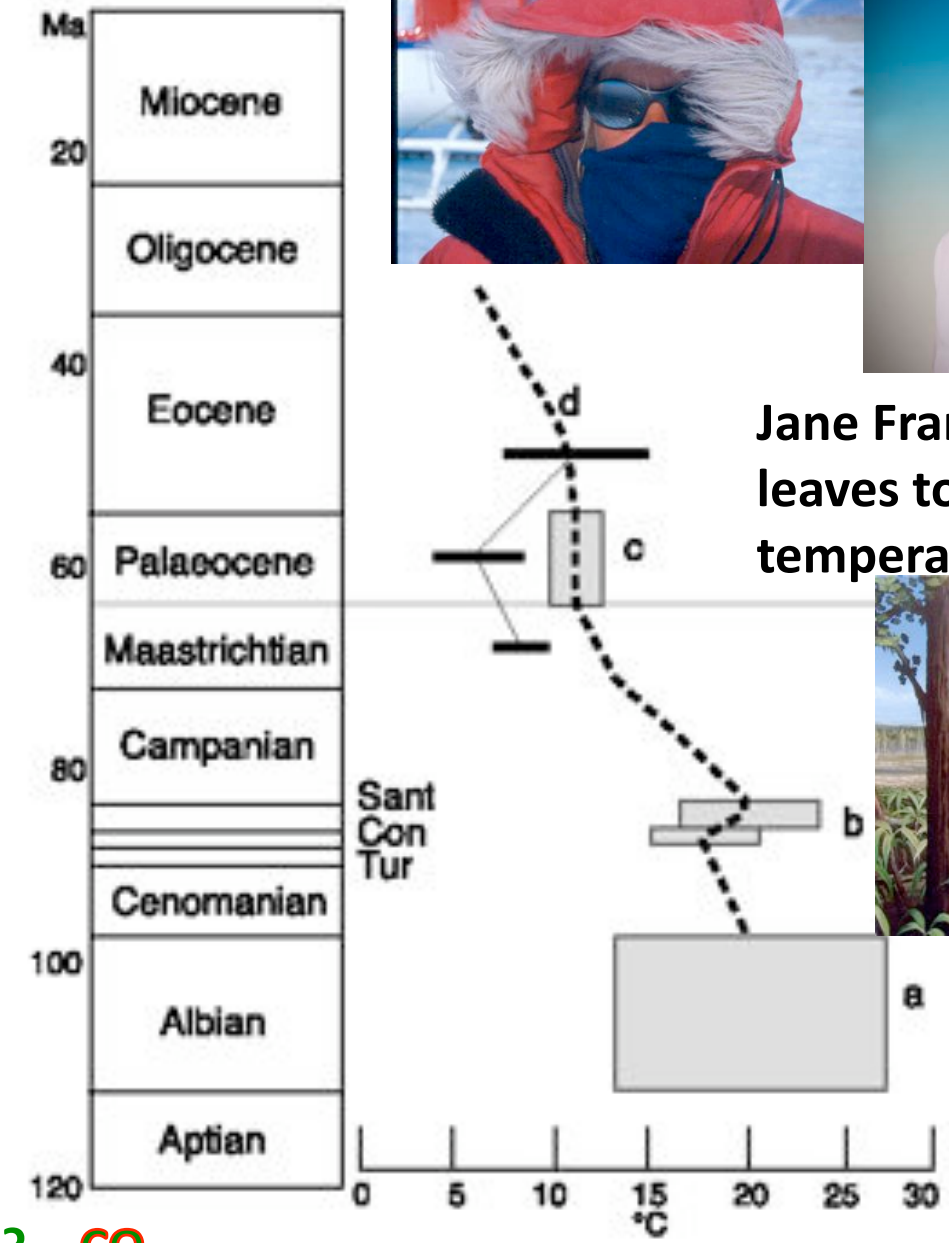
120 Ma of Earth's Thermal History



Zachos et al, 2001



Jane Francis uses fossil leaves to establish temperatures



Alexander Is. 2500 km from S Pole, 100 Ma.

INDEPENDENT MEASURES AGREE

BUT: Solar radiation Increased by 6% from 600 Ma to present.

So WHY THE COOLING? – CO_2

(Francis and Poole, 2002)

Climate Catastrophe at 55 Ma: Analog for Tomorrow?

Massive injection of 1000+ Gt Carbon.

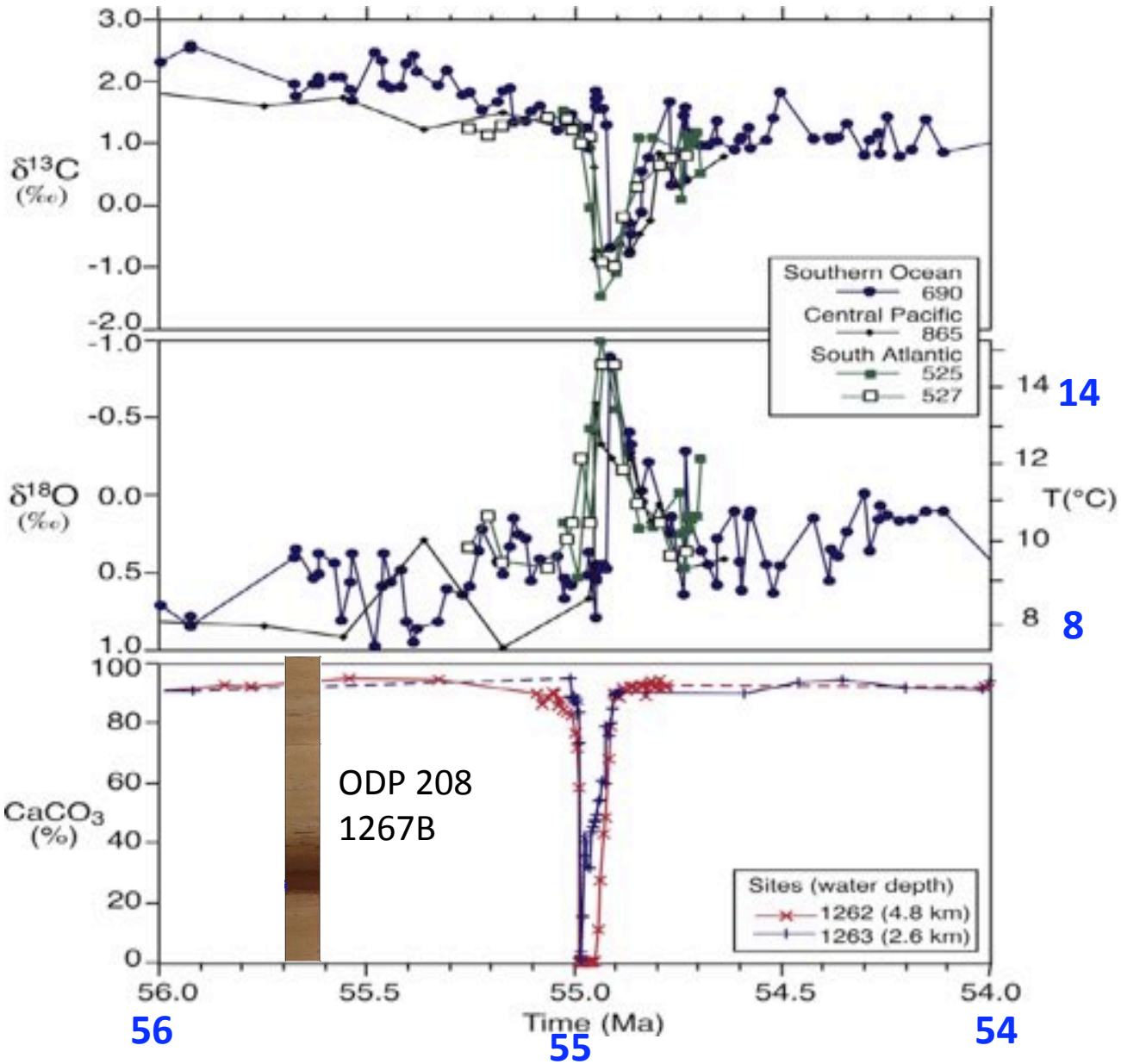
Temperature up 5-6°C

Slow recovery

Acidification of bottom water dissolves $CaCO_3$; kills benthic organisms. Corals die.

Sea level up c.12m.

THE SLOW CARBON CYCLE AT WORK

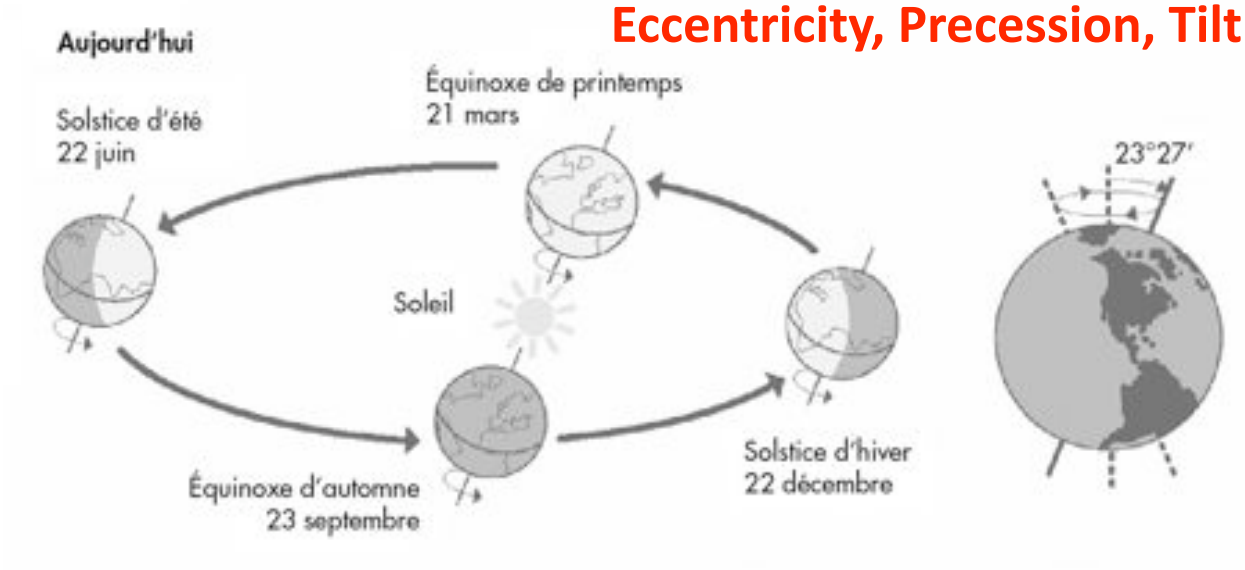


IPCC WG-1, 2007, based on Zachos et al, 2008

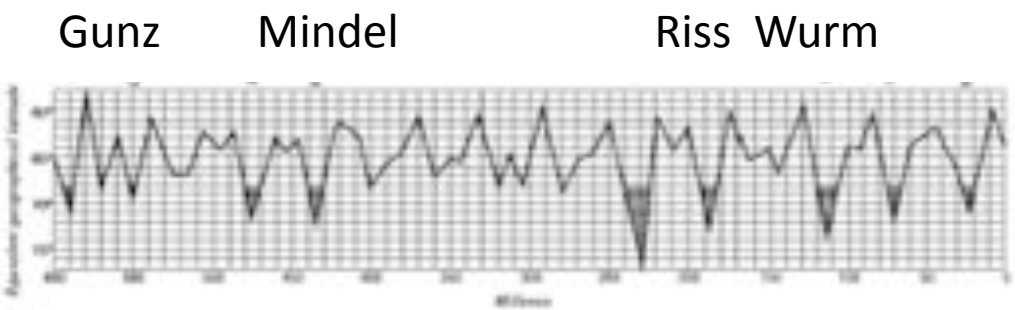
The Climate Clock:
Predictable Astronomical Controls on Climate

Milutin Milankovitch

Eccentricity, Precession, Tilt



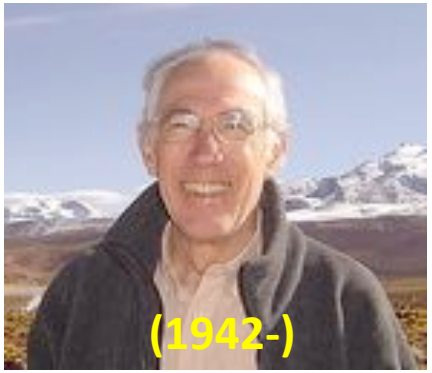
Converted astronomical calculations into variations in climate.



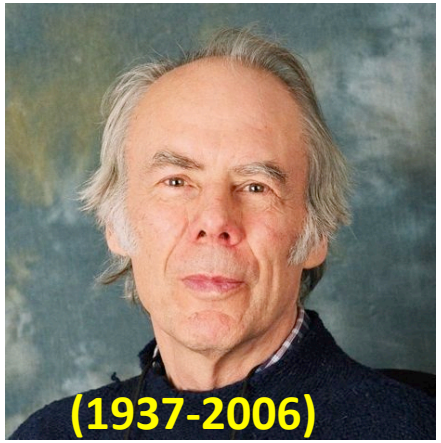
Insolation at 65°N in June past 600Ka.

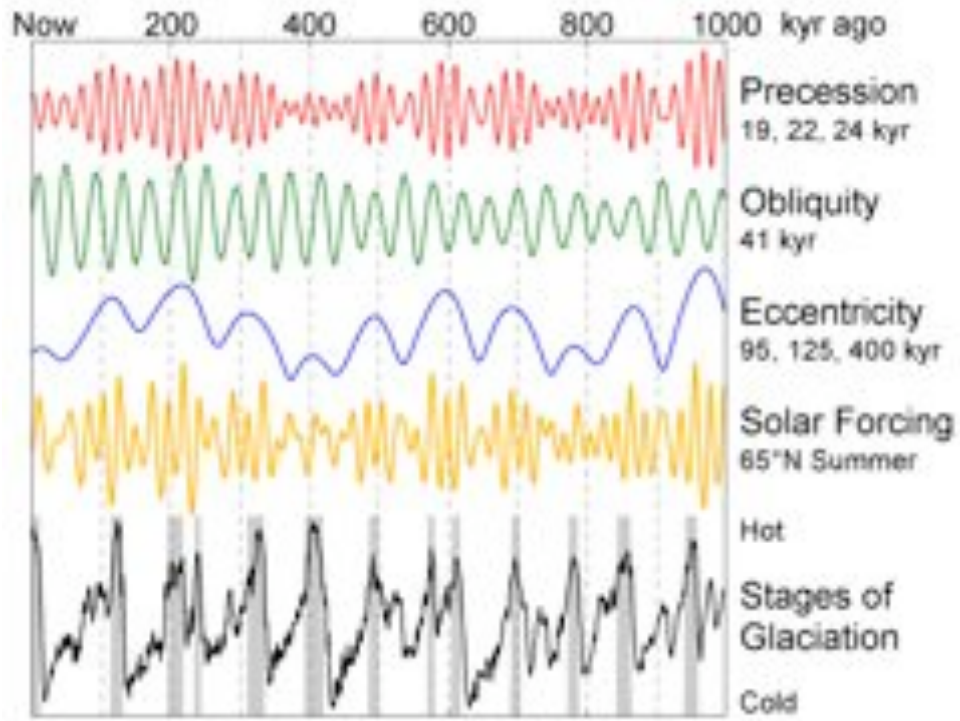
Long cold summers
Initiated glaciation

The Orbital – Climate Connection

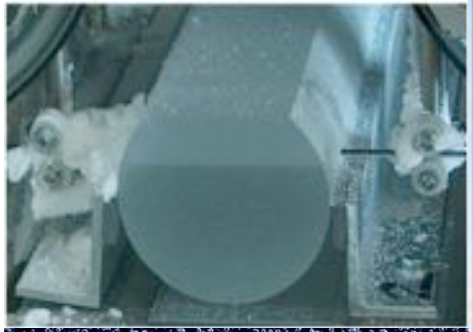


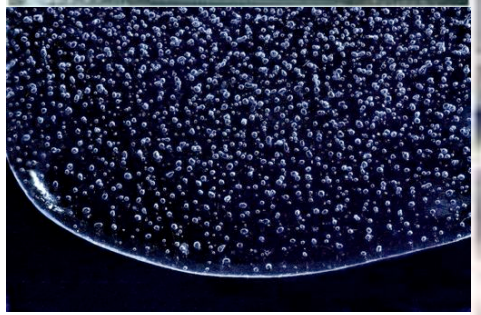
André Berger refines Milankovitch calculations (1970s).





Nick Shackleton links ocean temperature to orbital changes in marine sediments (1976) (with Hays and Imbrie).





CO_2 now outside natural envelope

400

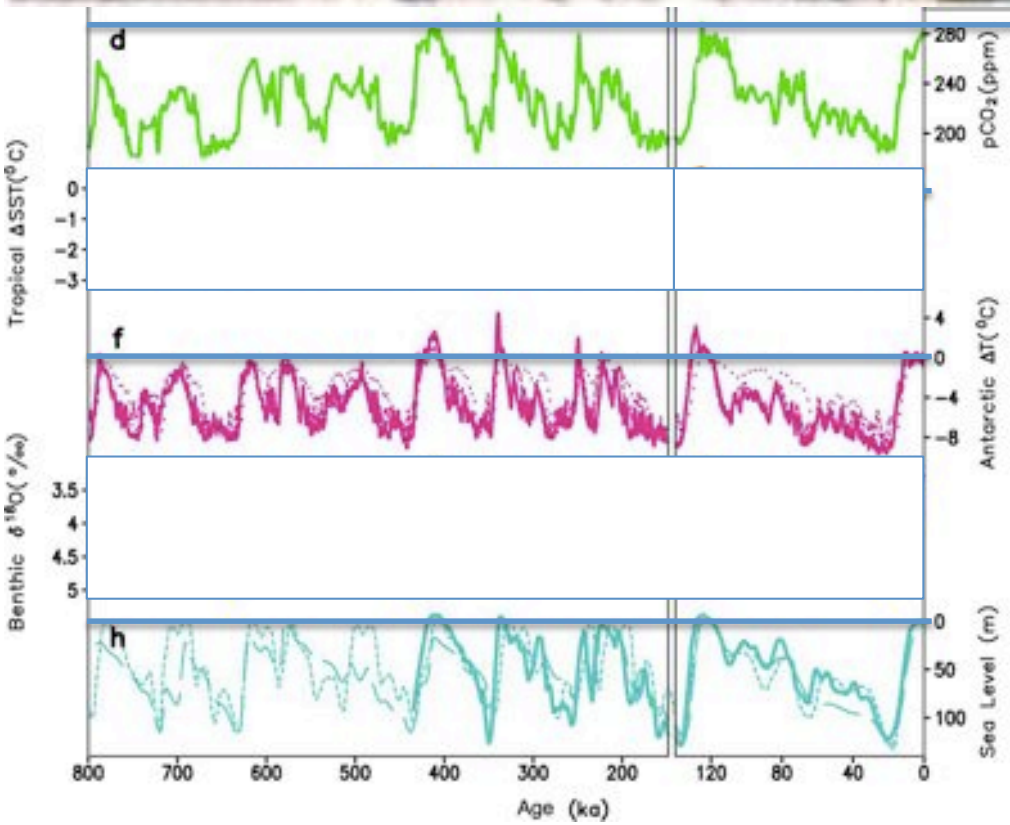
280

CO_2 accelerates warming

CO_2 is secondary cause (30-50% of temp rise)

Orbital change is main cause

Solid lines = data
Dashed = models



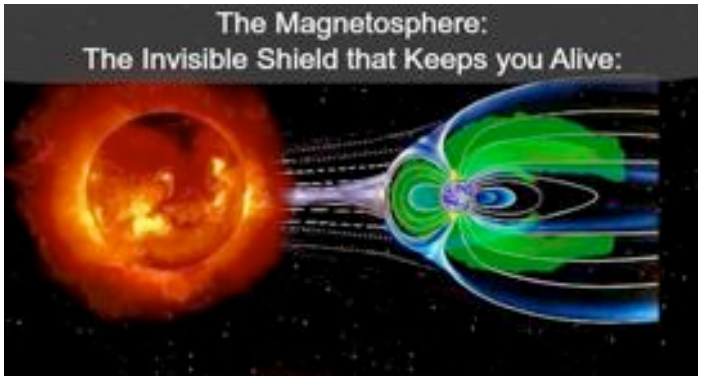
9°C range (polar)
4°C global.
Last interglacial +2-3°C

SL = -130m at LGM = +4 to +9m

IPCC 2013 AR5 Fig 5.3

Changes In Solar Output Also Affect Climate

- **When there are lots of sunspots**  **solar wind (ejected plasma) is strong.**



- **The solar wind deflects cosmic rays.**

- **Cosmic Rays form ^{14}C and ^{10}Be isotopes, captured by ice cores/tree rings.**

- **The isotopes show sunspot variation in the past.**

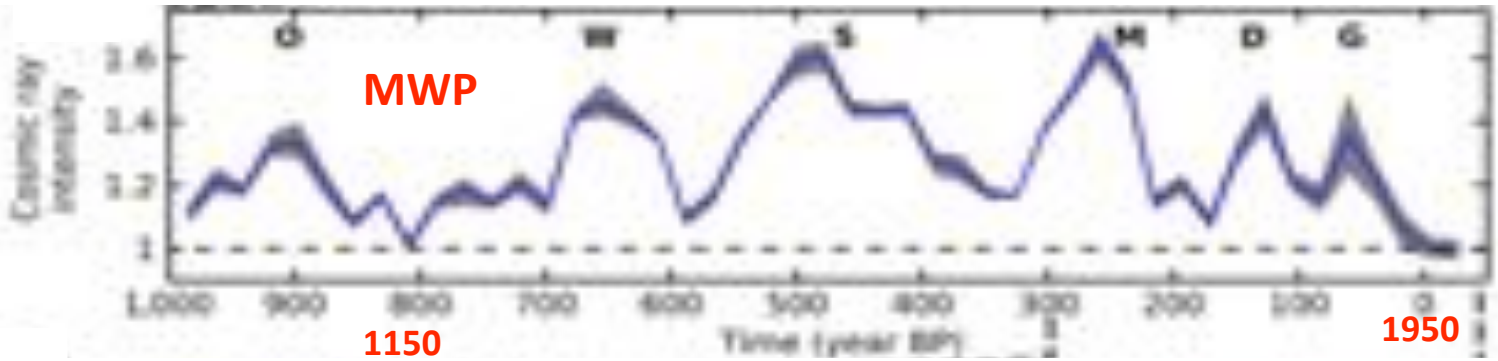
http://25.media.tumblr.com/cc5e0188b54dac9a521693bbef51ca1e/tumblr_my4l616V7i1ri1icuo1_1280.jpg

Solar Variability Past 1000 Years

Sunspot Min = Cosmic Ray Max = Strong ^{10}Be and ^{14}C = cold

Sunspot Max = Cosmic Ray Min = Weak ^{10}Be and ^{14}C = warm

Little Ice Age



Cold

Warm

Ups and downs = 208-year Suess Cycle, 88-year Gleissberg Cycle

THIS IS THE NATURAL ENVELOPE OF SOLAR CHANGE

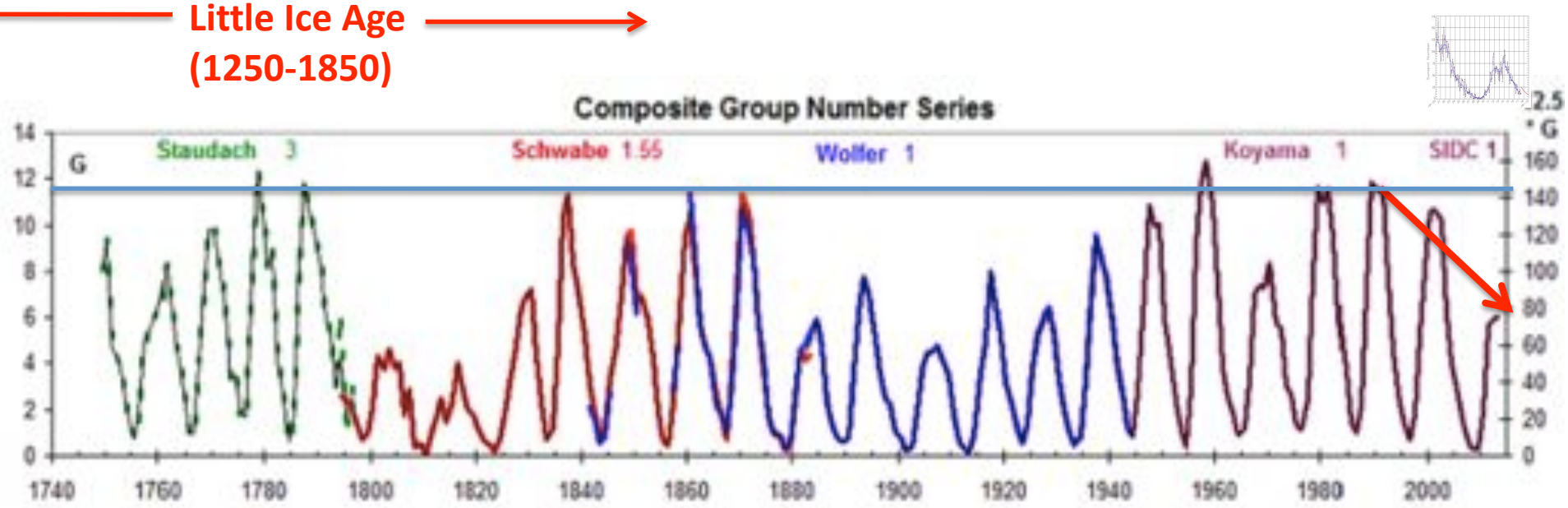
Steinhilber et al, PNAS 109(16) (2013)

Group Sunspot Numbers Since 1740 (REVISED)

THE NATURAL ENVELOPE OF SOLAR CHANGE

Harvests better in warm periods (maximum sunspots)

Little Ice Age (1250-1850)



Dalton Minimum

Gleissberg Minimum

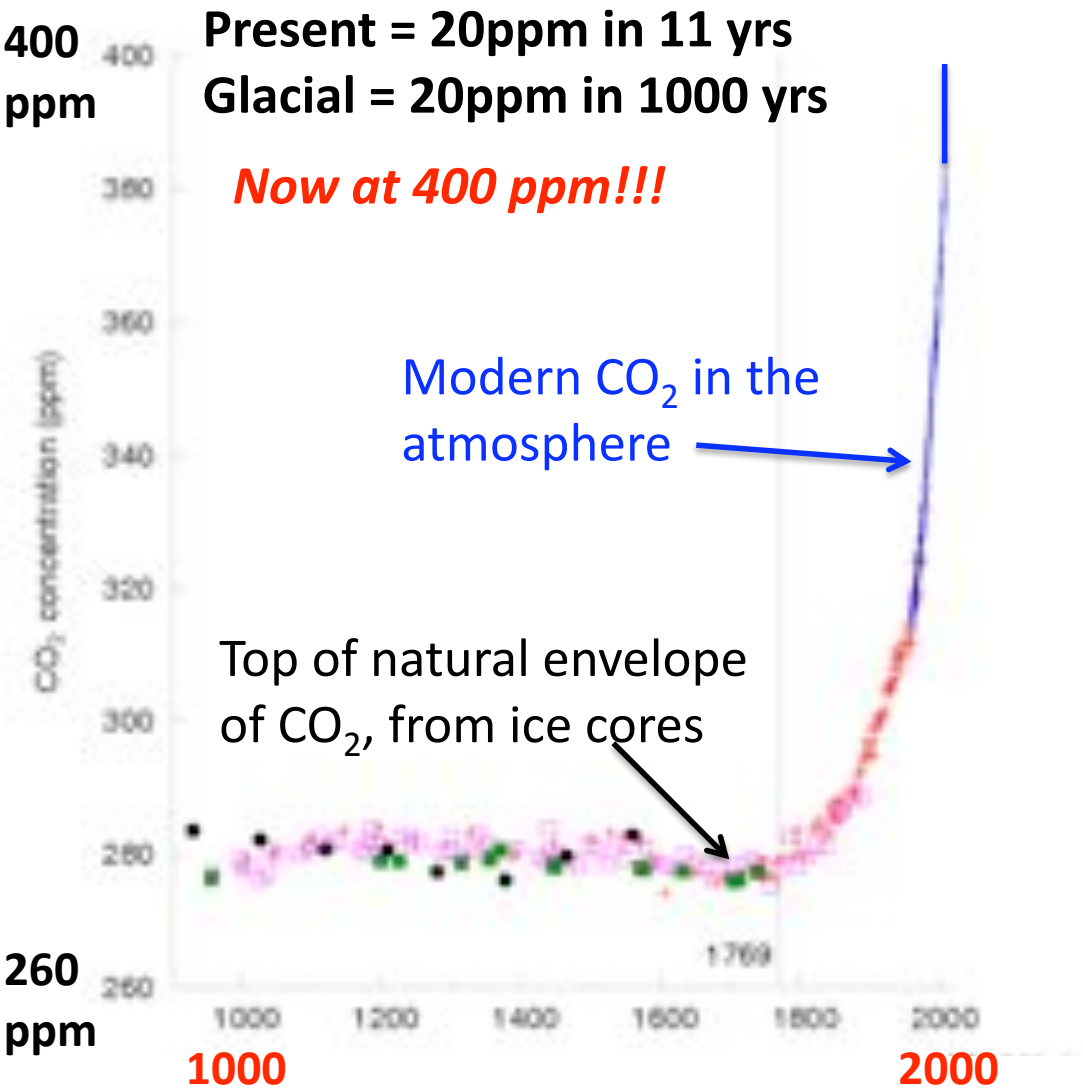
Should be cooling now, but we are not

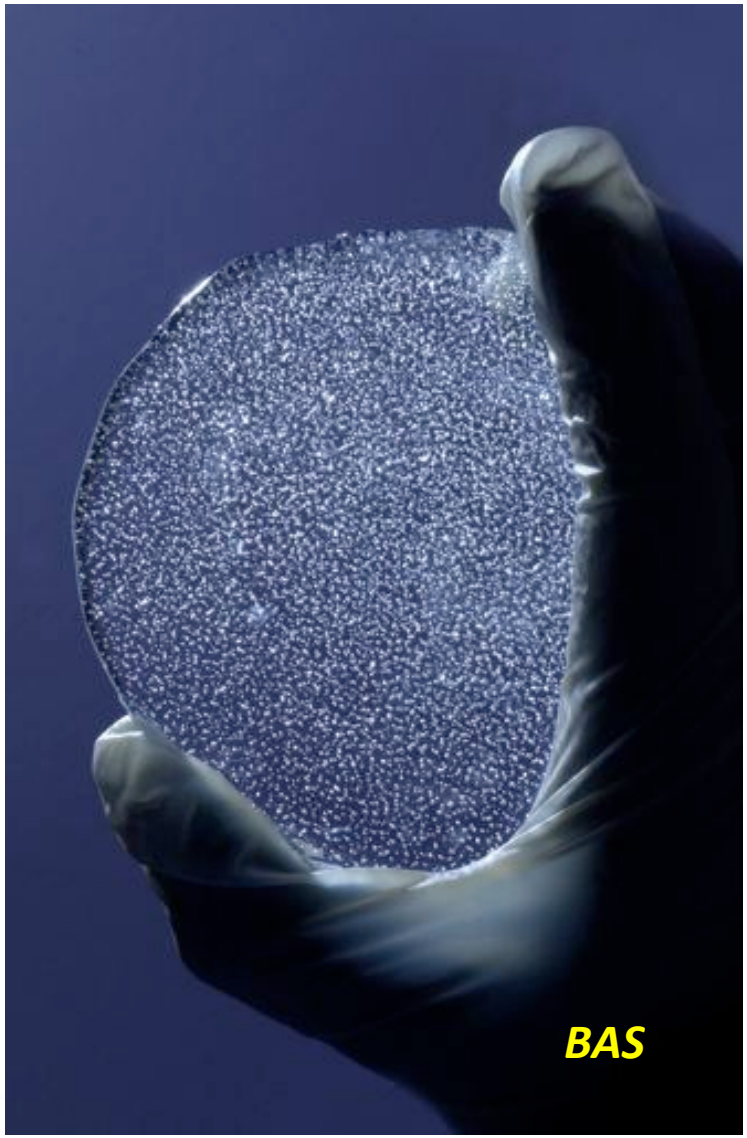
Note – modern solar output (1950-2000) not significantly different from 1840-1870, or 1780-1790.

Clette, Svalgaard, et al, Solar and Stellar Astrophysics (2014; figure provided by F Clette)

We Are Transforming the Atmosphere

Rising population increases emissions & warms the planet



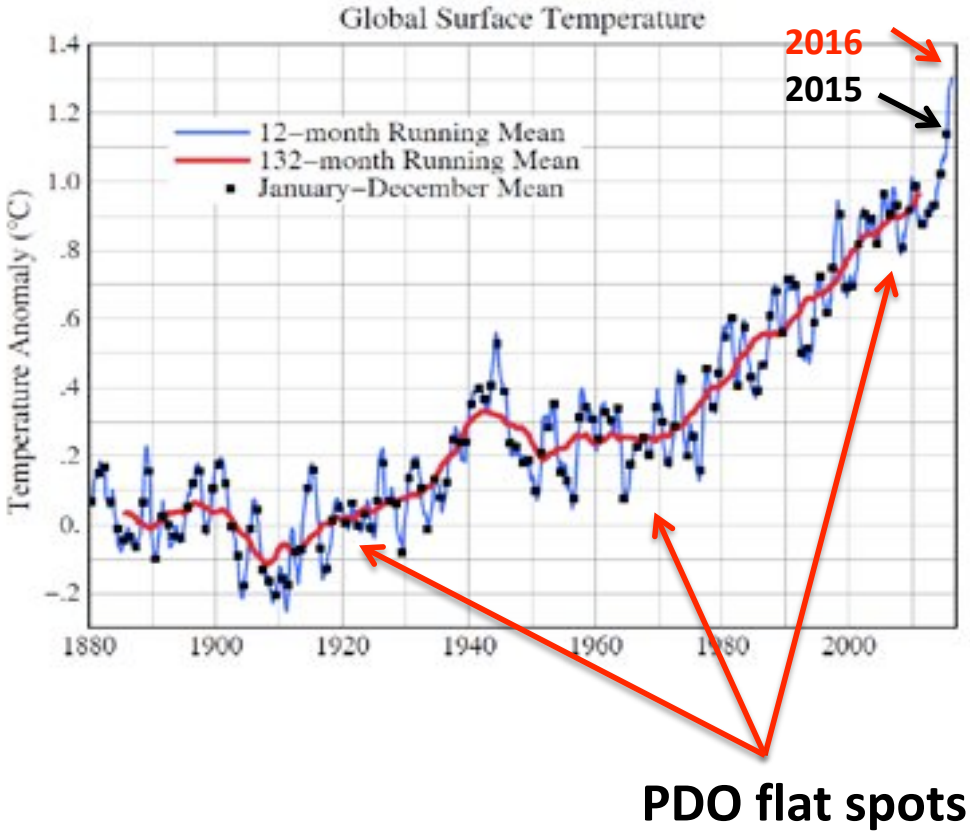


David MacKay, 2009, 'Sustainable Energy Without the Hot Air'

Global Temperature Trend

Trend driven by rising emissions.

Variability driven by: Sunspots, Aerosols, El Niños, La Niñas, PDO, and Volcanoes

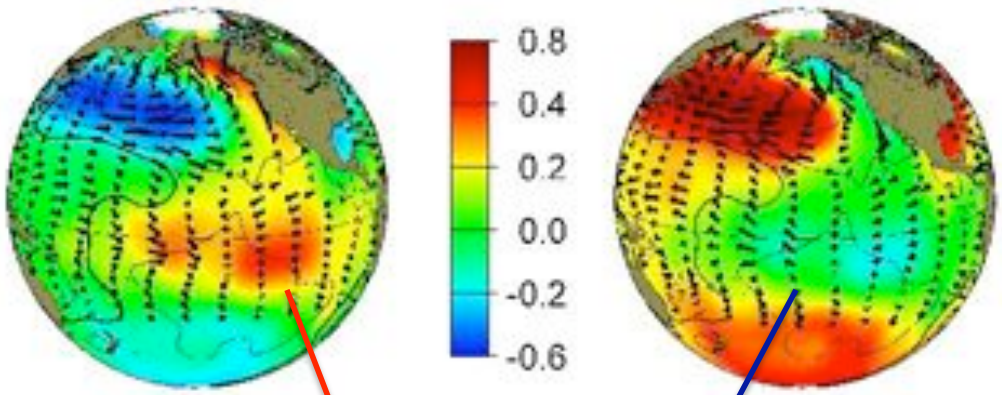


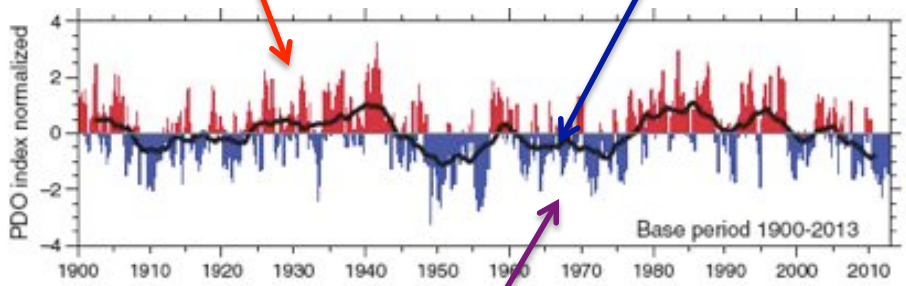
Hansen, 2016

Natural Oscillations Contribute to Flat Spots

Pacific Decadal Oscillation

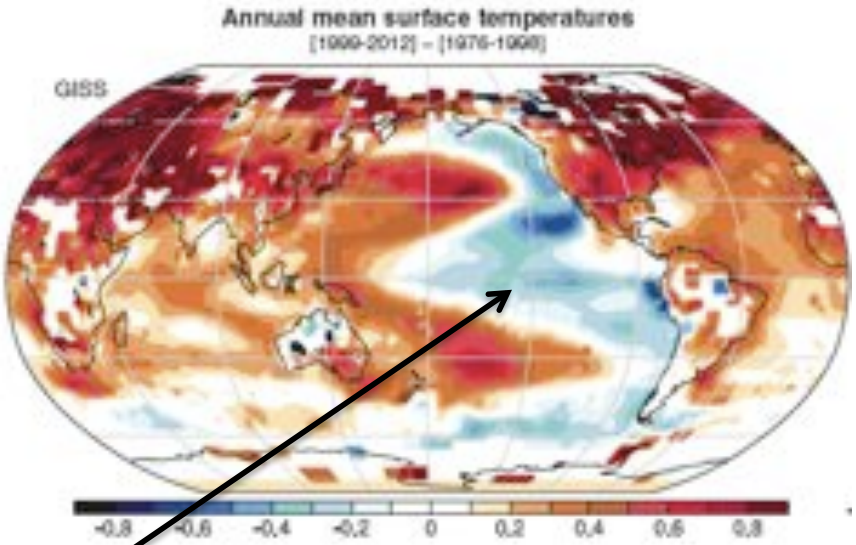
Positive **Negative**





Index = similar to El Niño/La Niña, but longer time-scale 15-25 years

THE LAST DECADE



Pacific cooling cools globe like an extended La Niña.

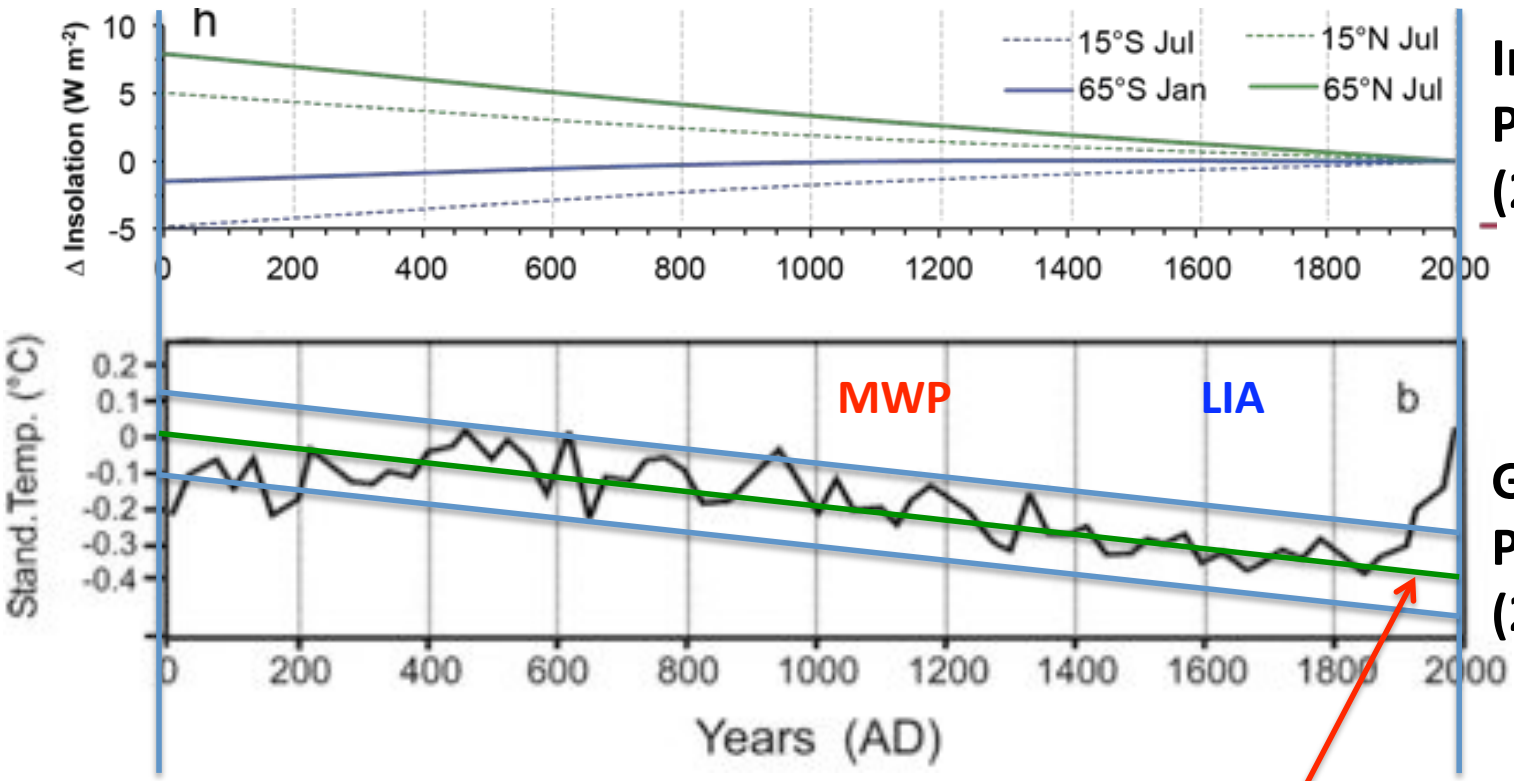
BUT – everywhere else warms. If it wasn't for this local effect, we'd be a lot warmer.

http://jisao.washington.edu/pdo/

Trenberth and Fasullo, 2013

Insolation Control on Average Planetary Temperature
Past 2000 Years

Natural Envelope of Temperature Combines Orbital Insolation (STRONG) with Solar Variability (WEAK)



Insolation PAGES 2k (2013)

Global PAGES 2ky (2013)

Temperatures Moved Outside Natural Envelope After 1970.
Plants emerging from under Baffin Island Ice last saw daylight 4000 BC.

Wanner et al, JGSL 2015

Earth's Climate Evolution (2015)

CO_2 Emissions Cut Across Orbital Insolation & Sunspots

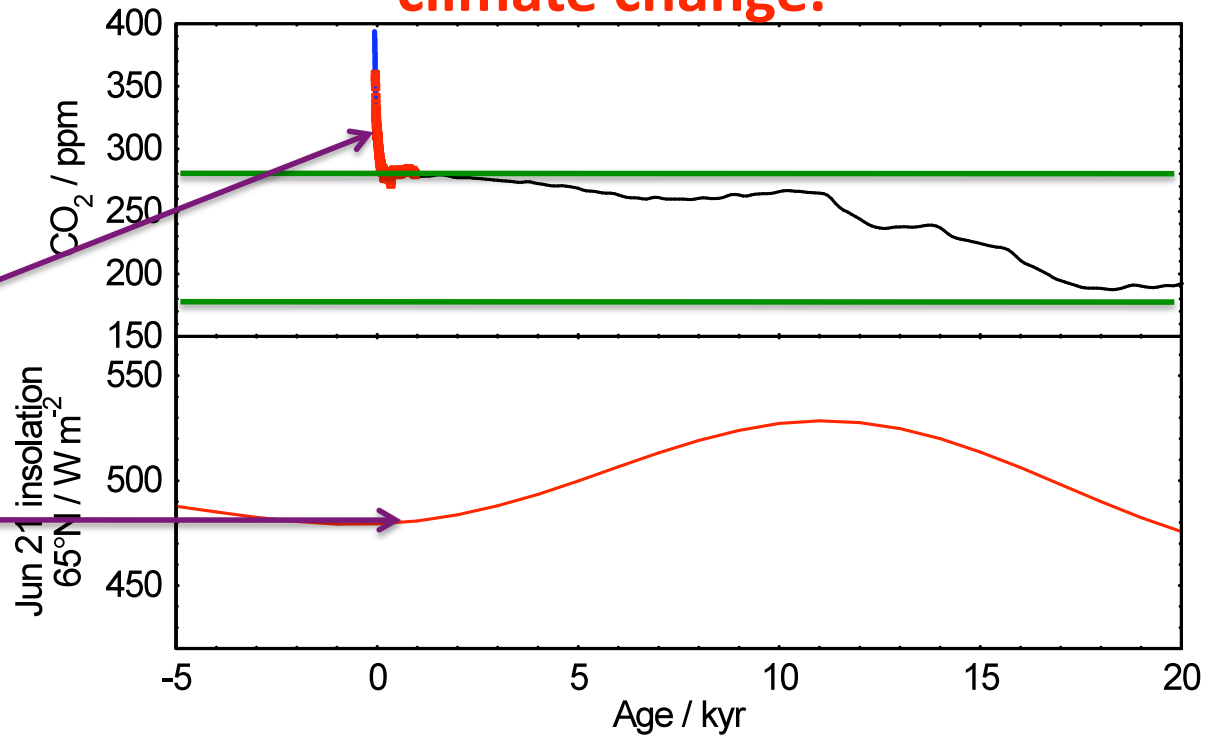
We should still be in the Little Ice Age.

Greenhouse warming has pushed us outside the natural envelope of climate change.

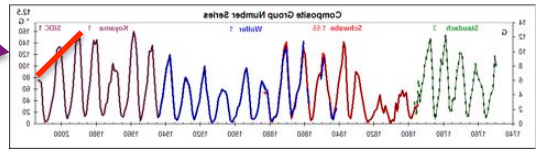
TRENDS

UP

DOWN



DOWN



2015 1740

Source E Wolff, Cambridge; modified from http://www.geolsoc.org.uk/climaterecord (2013)

Geology tells us CO_2 ↑ = T°C ↑ + sea level ↑

This is a technological problem

It calls for a technological solution

It is an engineering challenge

Solutions include:

Solar

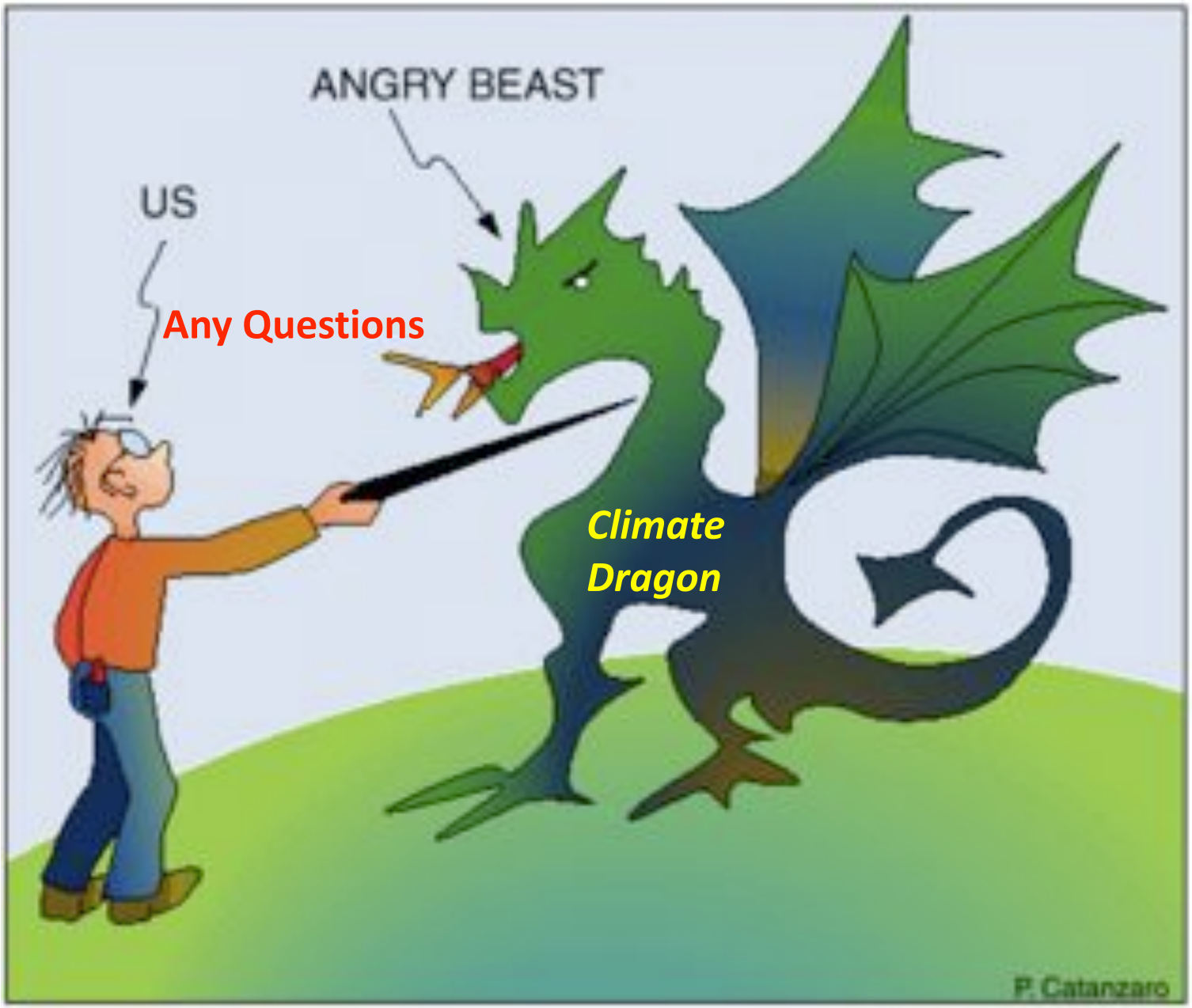
Wind

CCS

Nuclear

Massive electricity storage

Massive drive for Energy Efficiency



W. S. Broecker, "What If the Conveyor Were to Shut Down? Reflections on a Possible Outcome of the Great Global Experiment," *GSA Today 9(1):1-7 (January 1999) Figure 5.*