Are we sure that man-made CO2 is a main cause of climatic changes?

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Unit of energy for this talk: the "**toe**" (ton of oil equivalent)

= the average heating value of 1 metric ton of oil (1000 kg = 7.33 barrels)

1 toe = 10 Gcal = 41.87 GJ = 11,630 kWh

- 1 toe at $95/bbl costs about $700;
- 1 toe of oil used in a 52% efficient oil-fired power plant yields 6,050 kWh of electricity;

Global yearly consumption of primary energy in 2013: 14 Gtoe

Average per-capita consumption of primary energy in 2007:

North America: 7.2 toe/yr

Europe : 3.8 toe/yr

World average: 1.9 toe/yr

Average retail price of 6,050 kWh of electricity in 2013

Europe: $1700 (0.28 $/kWh)

Mass.: $ 900 (0.15 $/kWh)

US average: $ 670 (0.11 $/kWh)

Outline

- HISTORICAL DATA
  - past consumption of primary energy
  - social and economic considerations
- OUTLOOK, A PLAUSIBLE SCENARIO
  - demographic growth
  - energy needs
  - mix of primary resources
  - certain and presumed energy reserves
  - CO_2 release due to energy consumption
- WHAT CAUSES CLIMATIC CHANGES?
  - global warming versus CO_2 concentrations
  - the role of solar activity

Dedication
to my thesis advisors and coauthors

Mario Silvestri
(1919-1994)
Politecnico Milano

James C. Keck
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Elias P. Gyftopoulos
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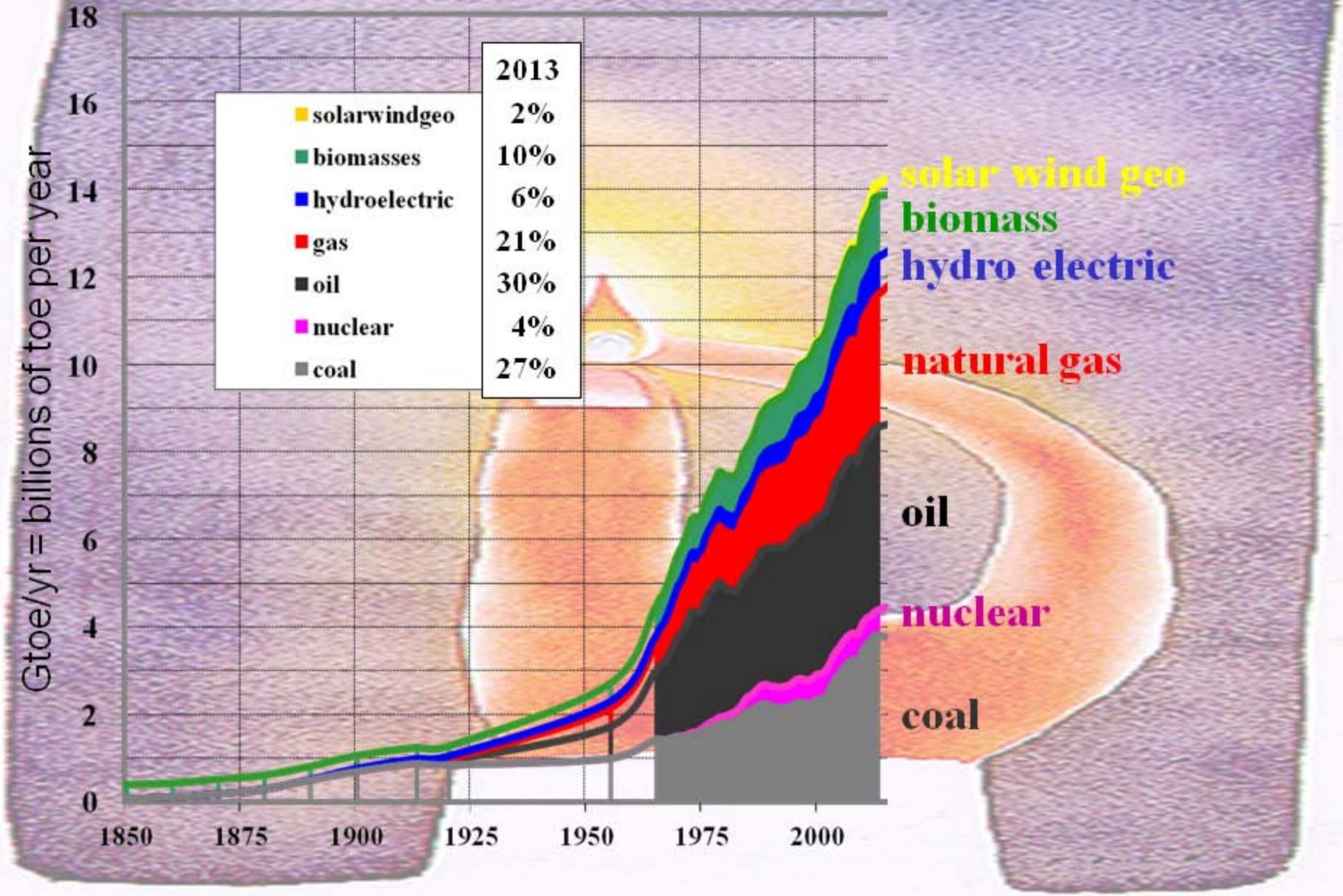
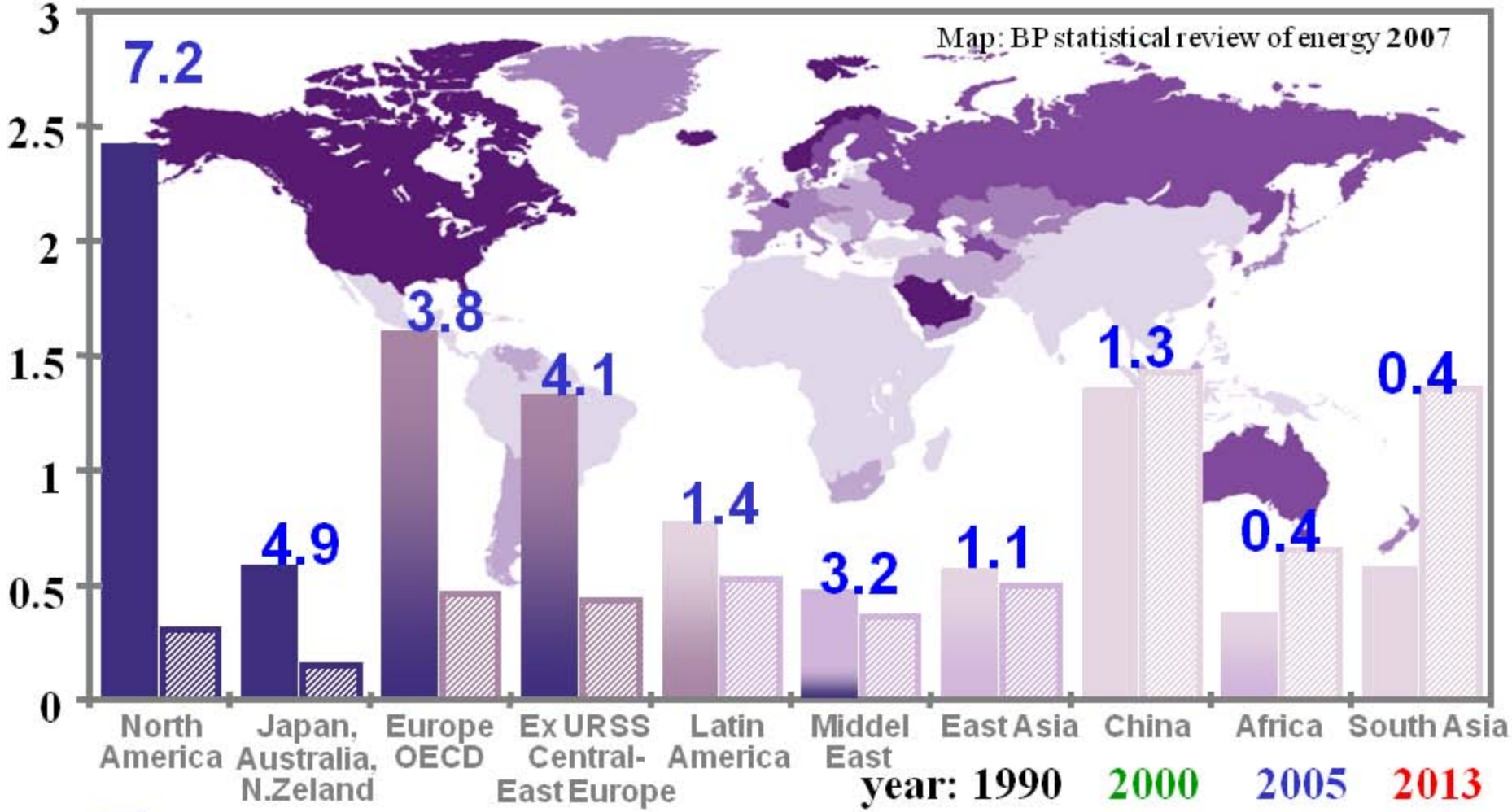
Global consumption and mix of primary energy in the last 150 years



Uneven spread of per-capita energy consumption



year:	1990	2000	2005	2013
Energy consumption (Gtoe/yr)	9.2	10.3	12.0	14.2
Pupulation (billions)	5.3	6.1	6.5	7.1
toe/yr per capita	1.74	1.73	1.85	1.99

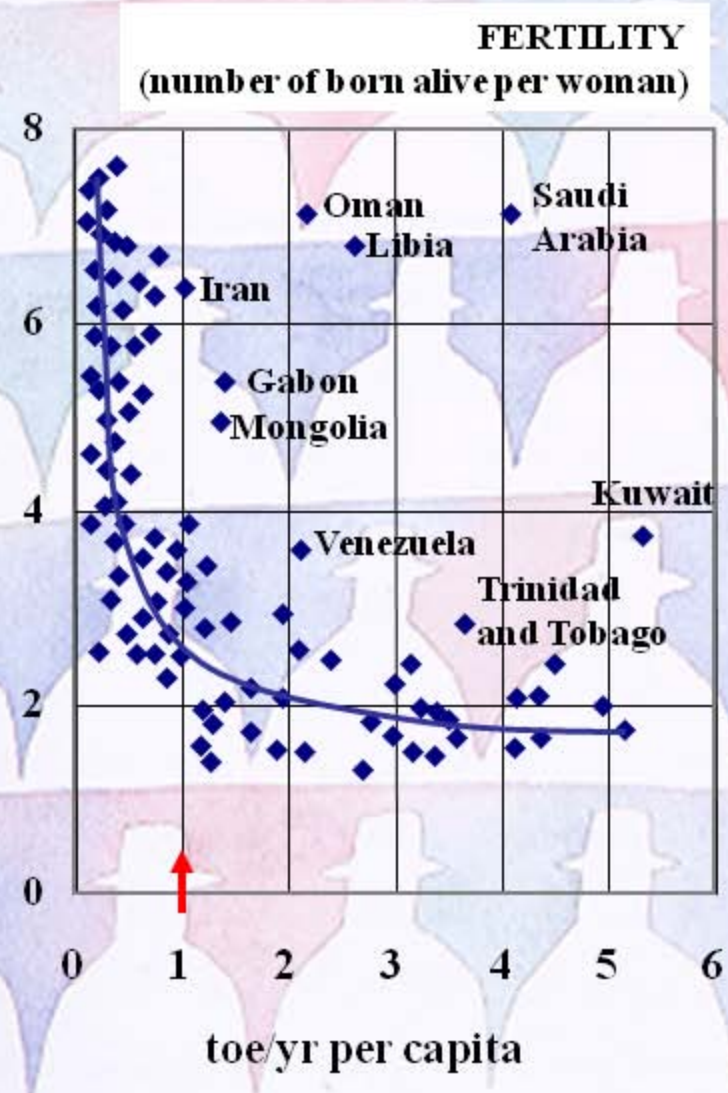
History of per-capita energy consumption

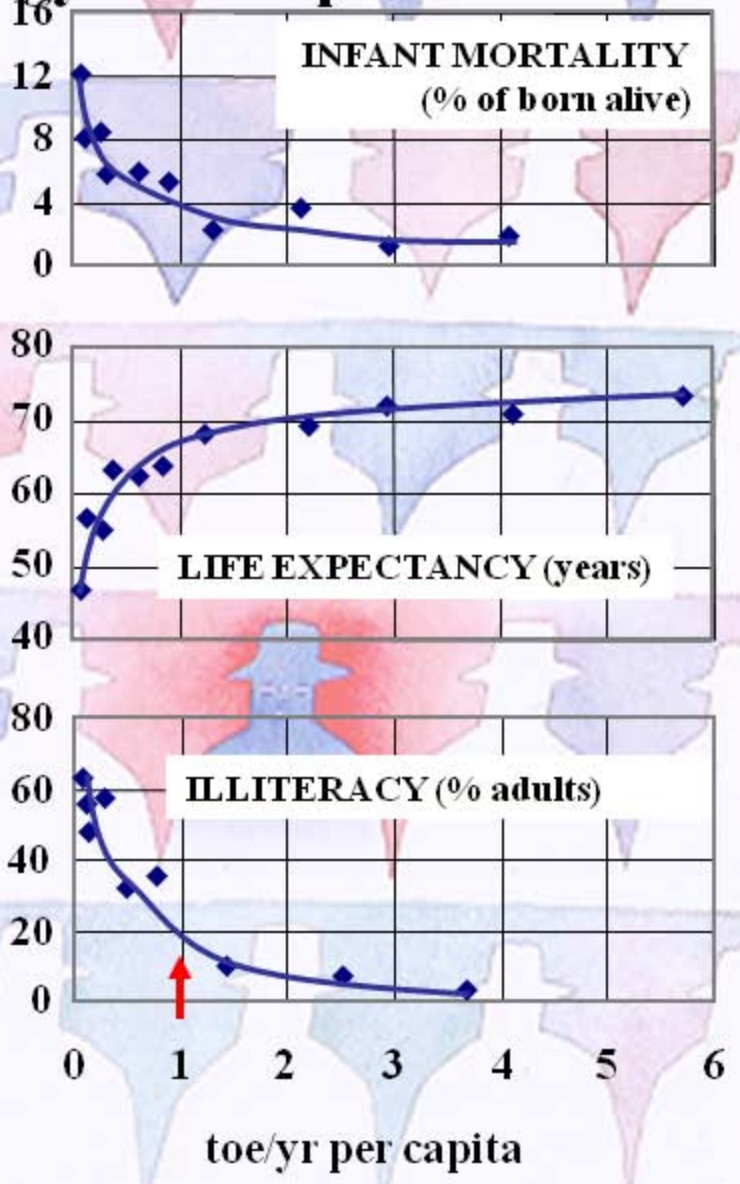
food for survival (3000 kcal/day)		0,11 toe/yr
after discovery of fire (500.000 years ago)		0,22 toe/yr
neolithic age, bronze age, iron age		0,45 toe/yr
greek-roman rural-artisan middle-age economy		0,50 toe/yr
1800 - England	⟷	0,55 toe/yr
1900 - England	industrialization ⟷	2,8 toe/yr
2000 - England		3,5 toe/yr

	agricoltural fraction of gross national product		
<1900 - Italy	66 %		0,50 toe/yr
1900 - Italy	50 %		0,50 toe/yr
1913 - Italy	42 %	⟷	0,55 toe/yr
1939 - Italy	28 %	industrialization	1,0 toe/yr
1981 - Italy	6,4 %	⟷	2,5 toe/yr
2000 - Italy	3,3 %		3,0 toe/yr

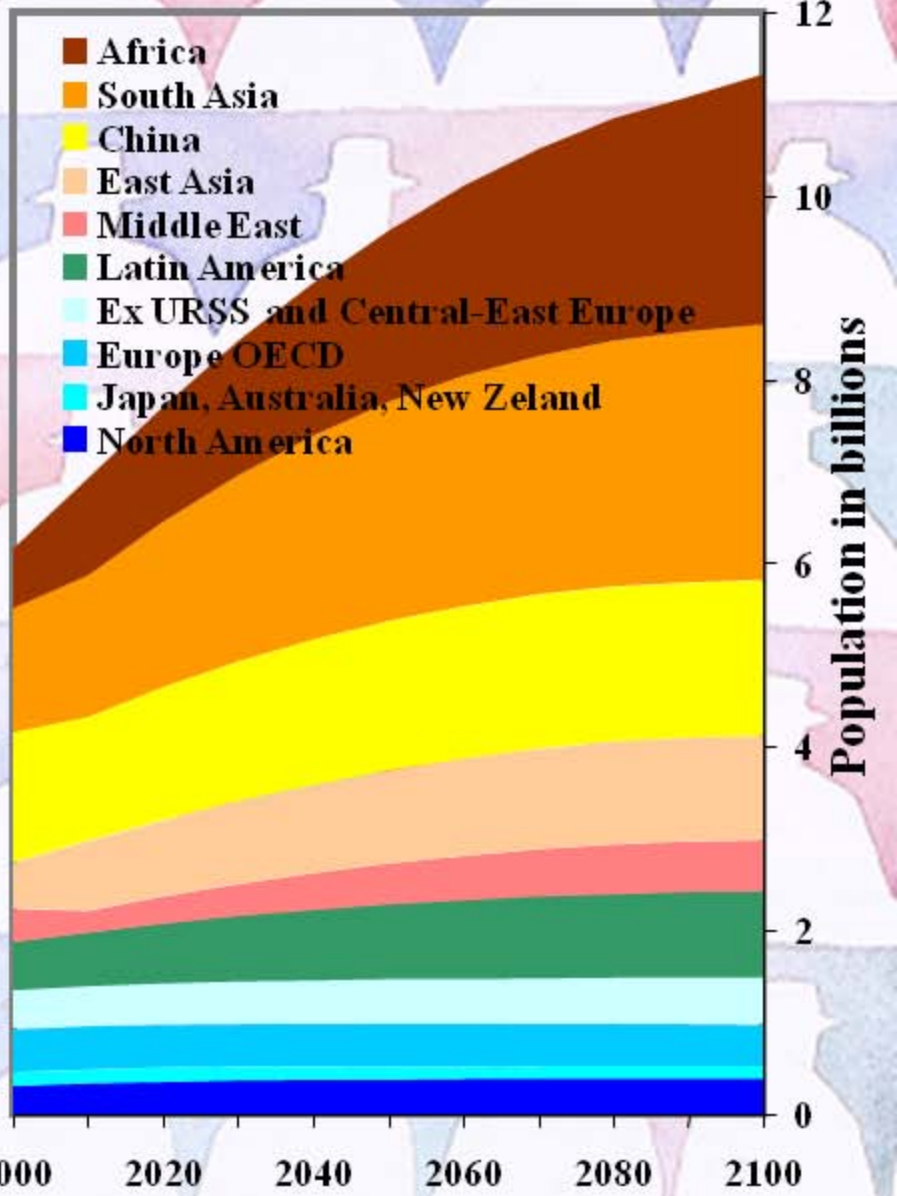
	global consumption	population	average per capita
greek-roman age	0,15 Gtep/yr	0.3 billion	0,5 toe/yr
year 2000	10,3 Gtep/yr	6.2 billion	1,7 toe/yr

Correlations between social and economic development and per-capita primary energy consumption

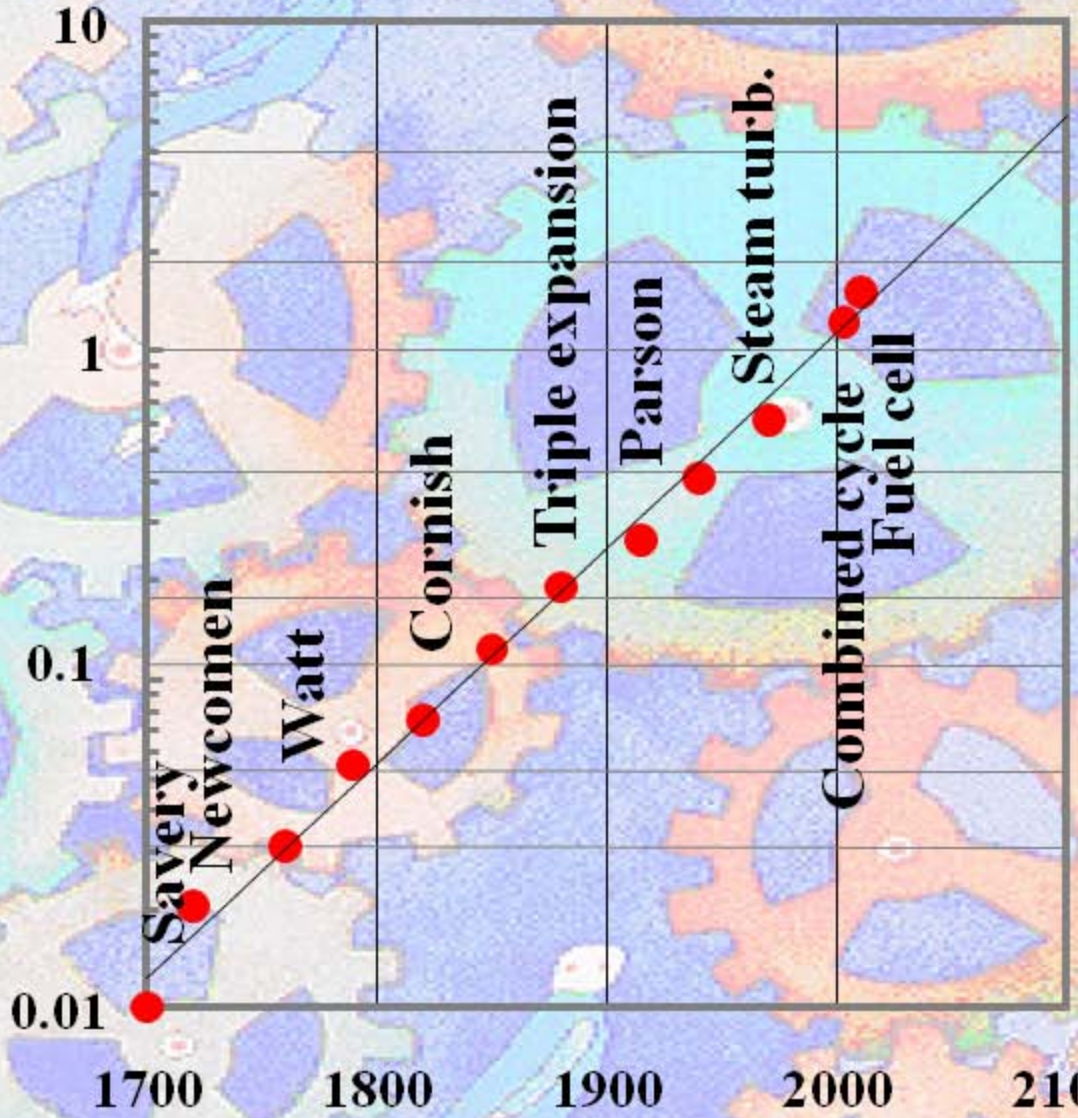




Demographic growth outlook



Role of scientific and technological research



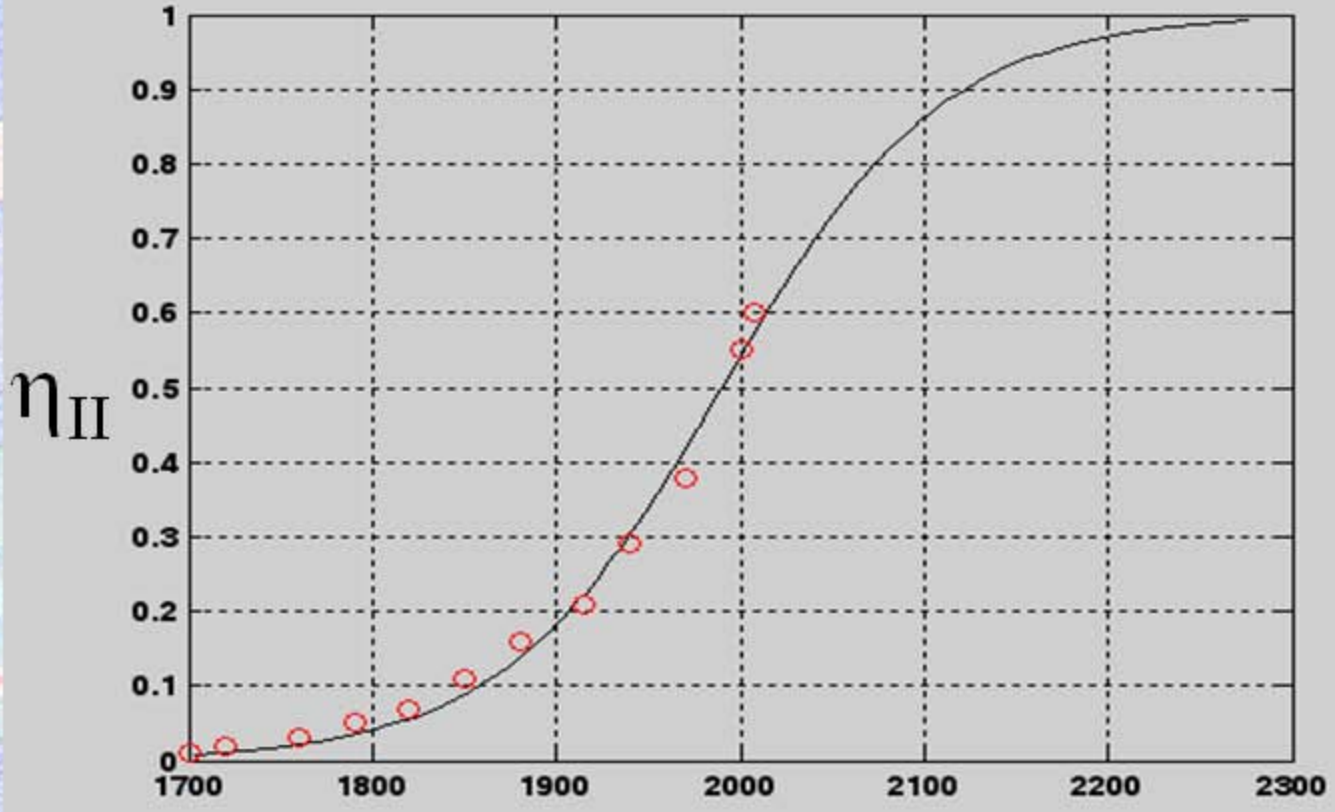
$$\frac{\eta_{II}}{1-\eta_{II}}$$

logistic scale (linearity is typical of a learning process)

η_{II}

Thermodynamic efficiency of the best-available mature technology for primary energy conversion to work or electricity

Role of scientific and technological research

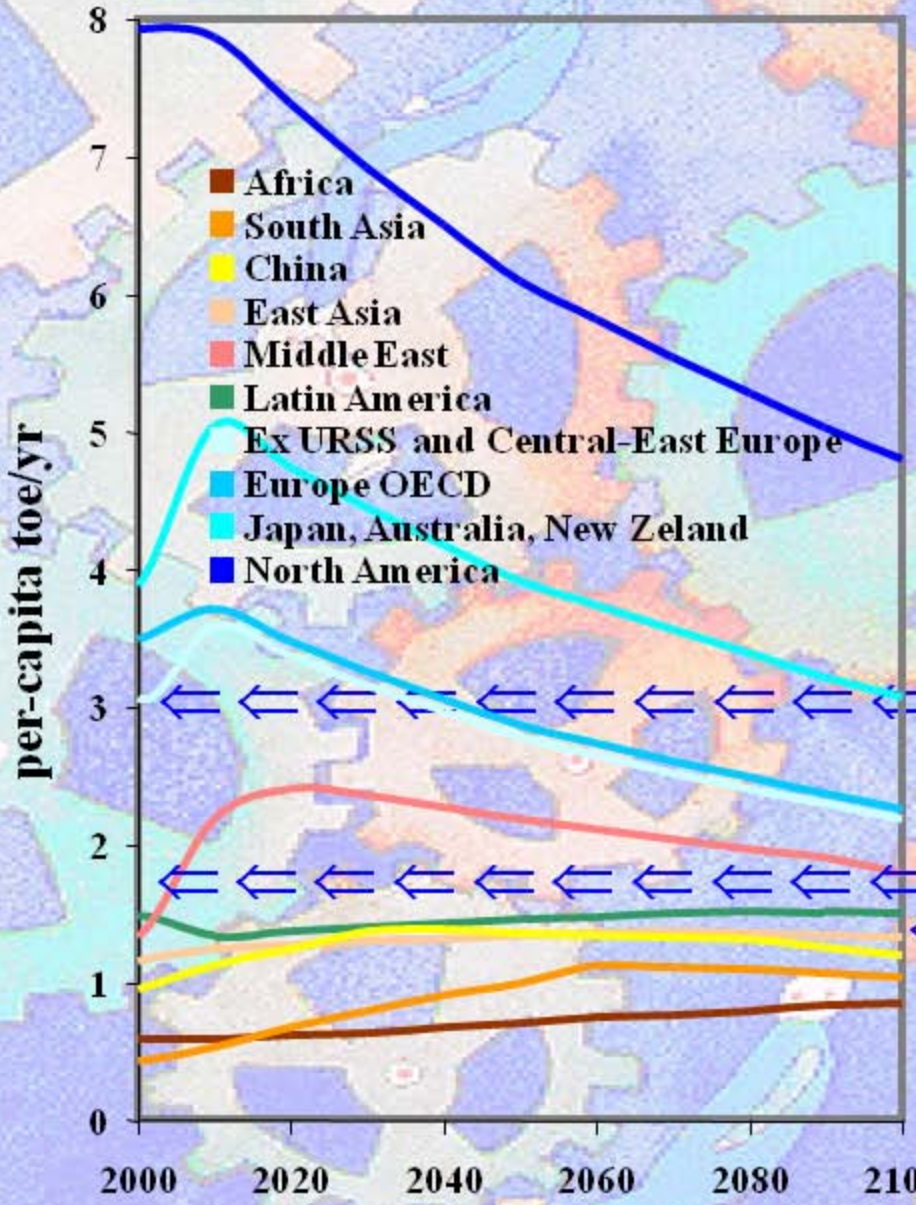


$$\frac{d\eta_{II}}{dt} = \frac{1}{\tau}\eta_{II}(1-\eta_{II}) \quad \text{with} \quad \tau \approx 60\ \text{yr}$$

η_{II}

Thermodynamic efficiency of the best-available mature technology for primary energy conversion to work or electricity

Per-capita consumption (forecast)



Net effect of :

+ industrialization of least developed countries

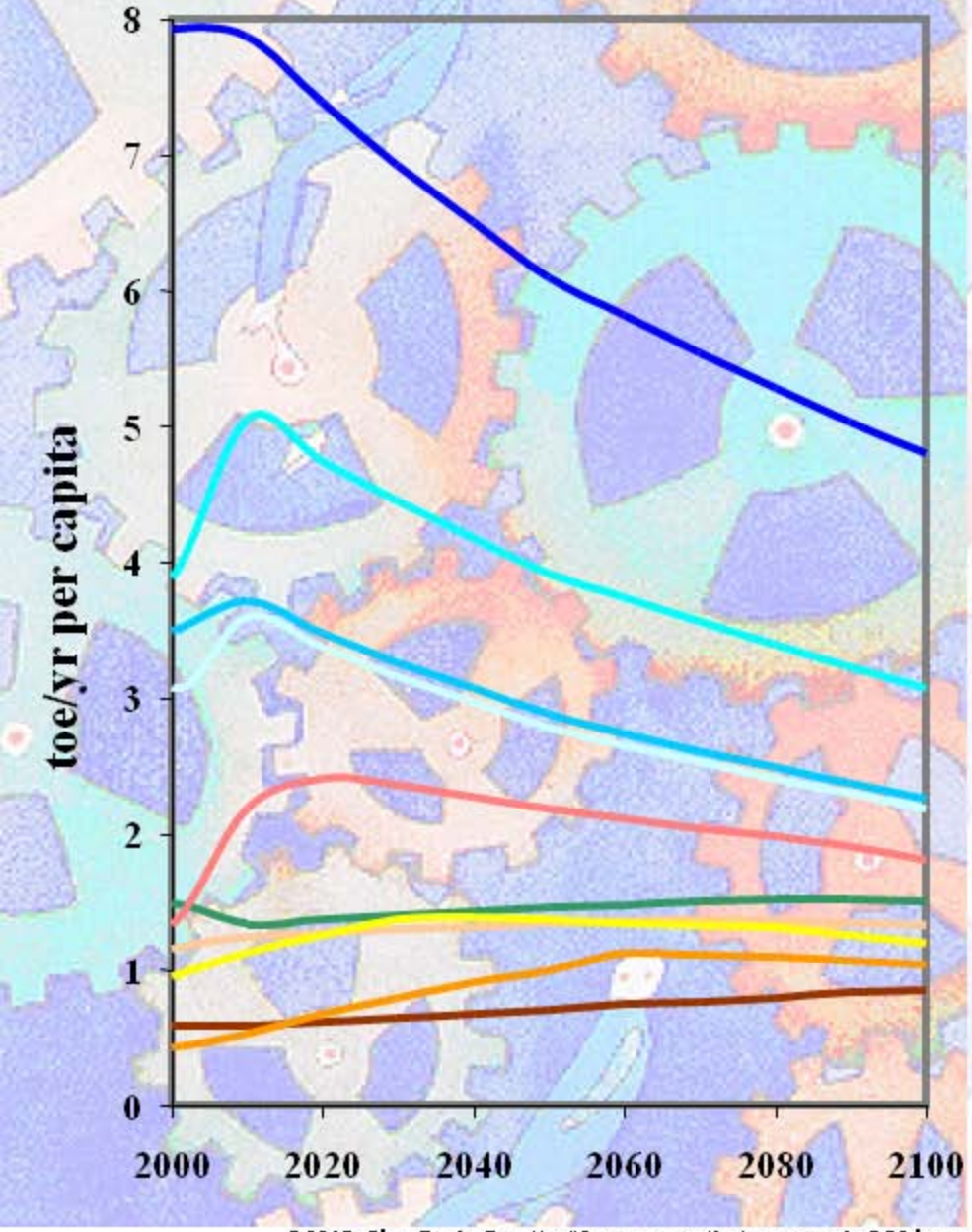
– social and technological improvements in "from well to final use" efficiency

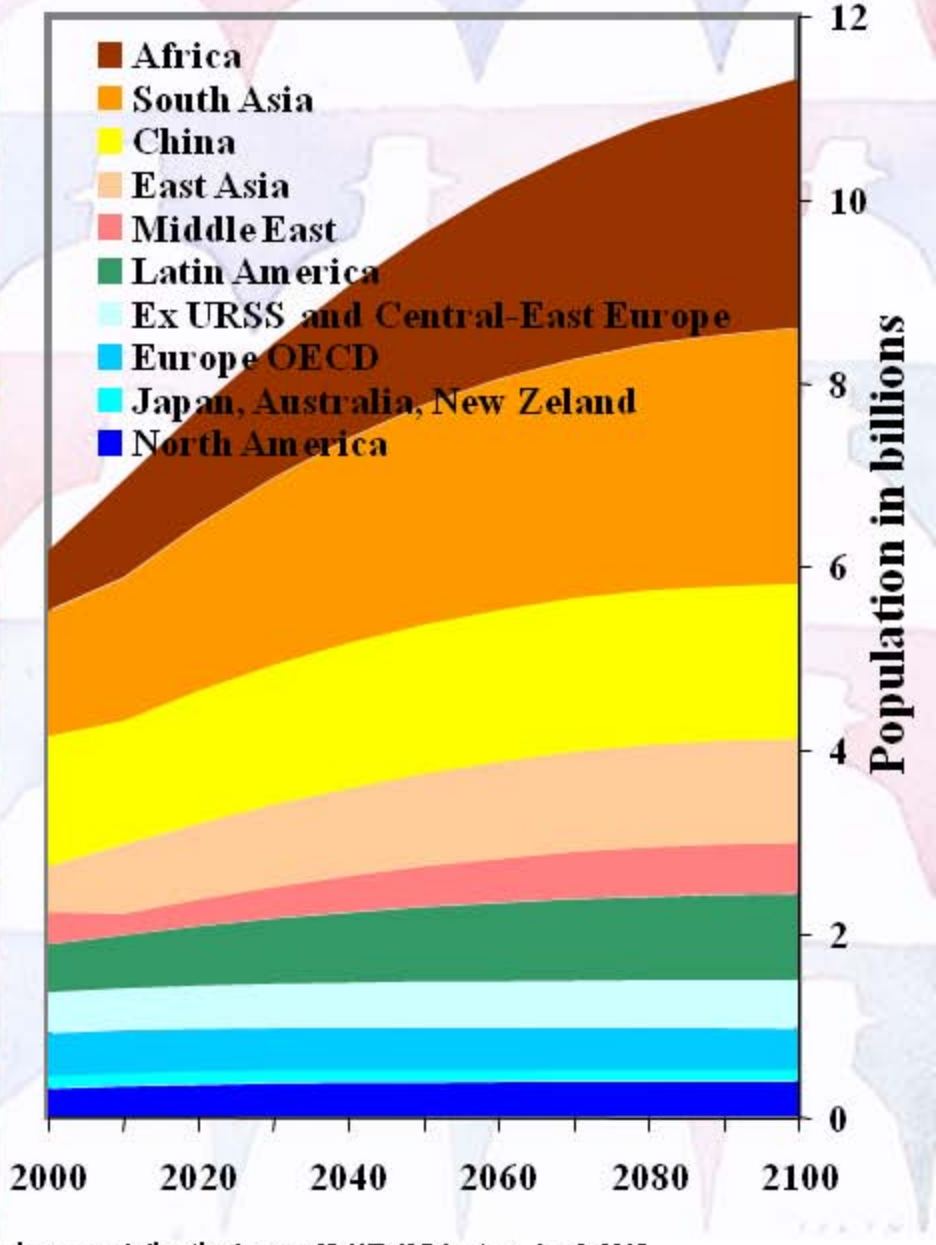
Current average standard for industrialized countries

2000 world average

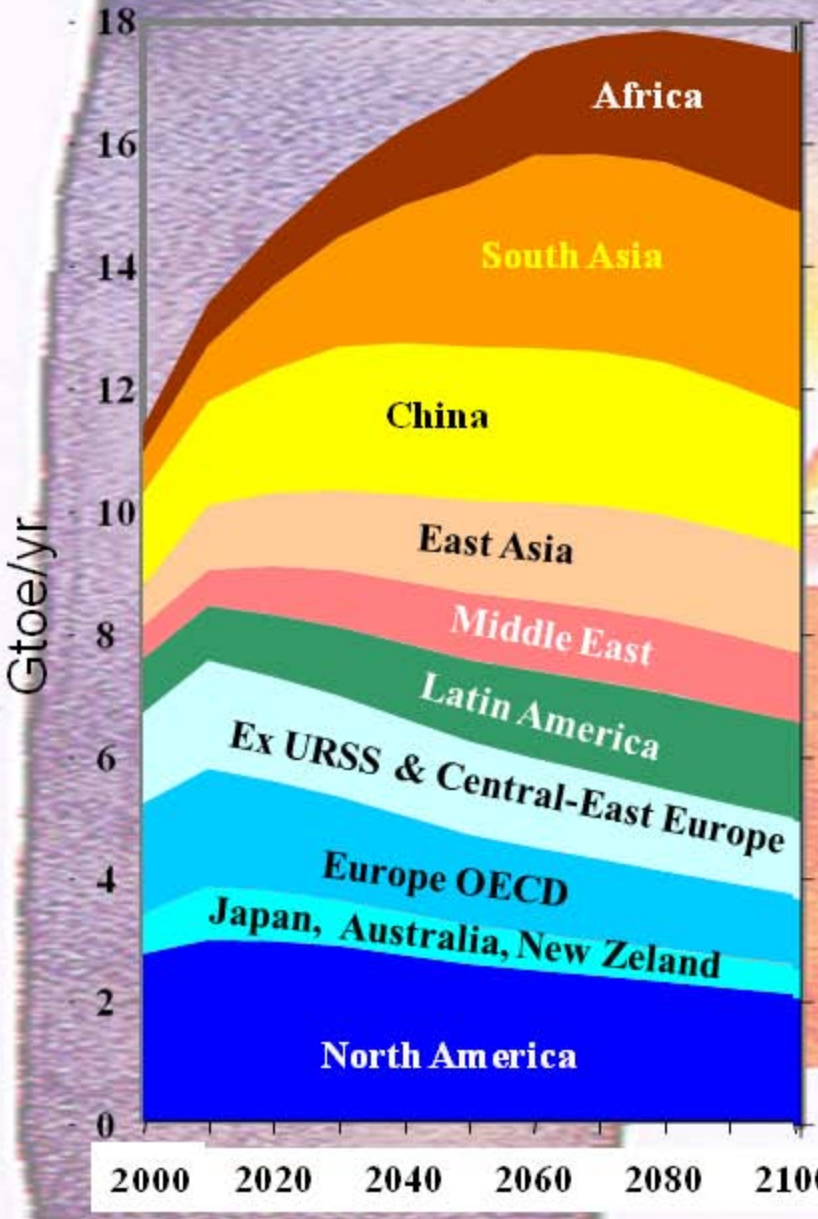
2100 world average

Per-capita consumption x population = ...

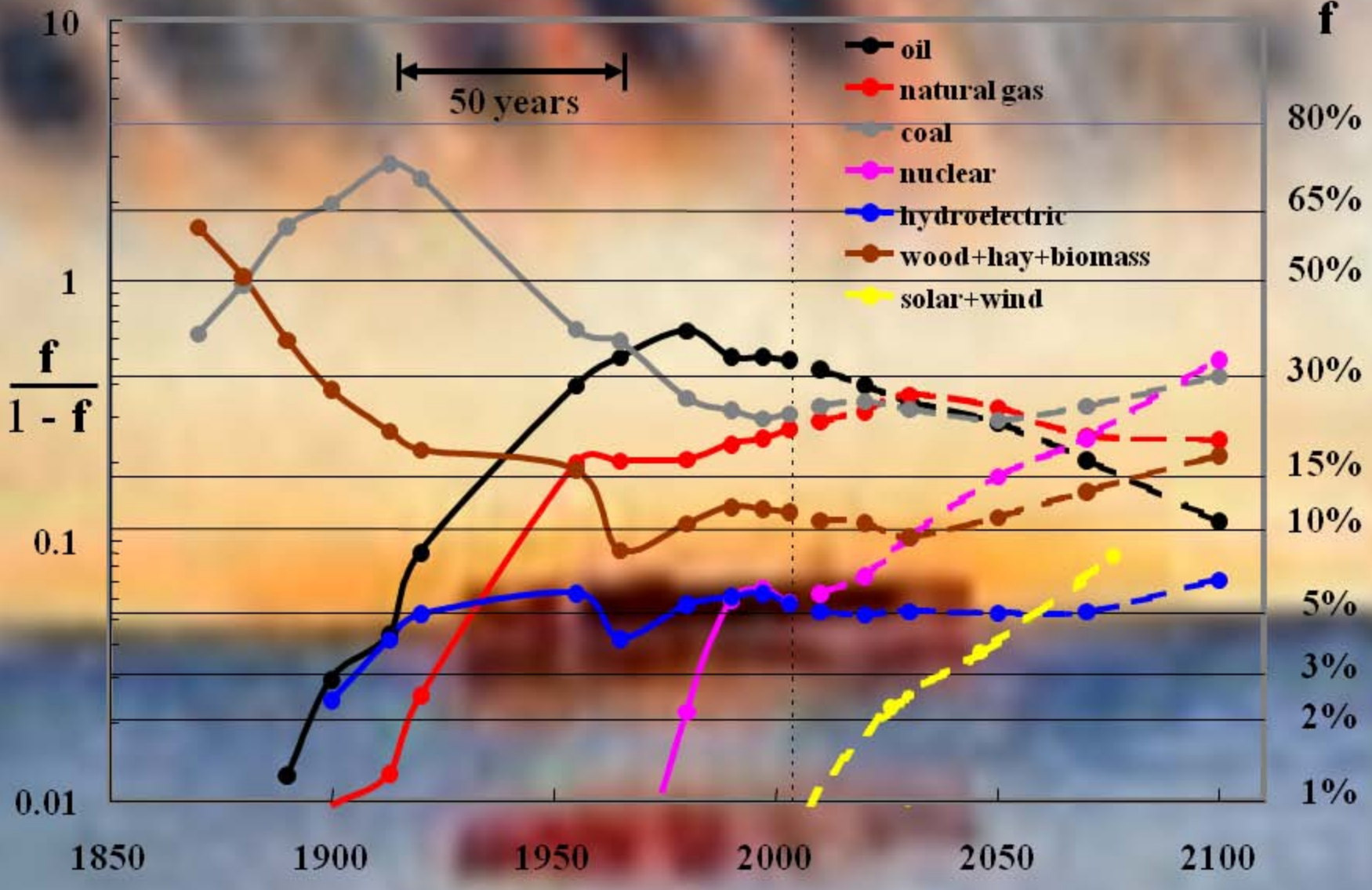




… = global primary energy consumption (outlook)



System's inertia: history and outlook of market shares



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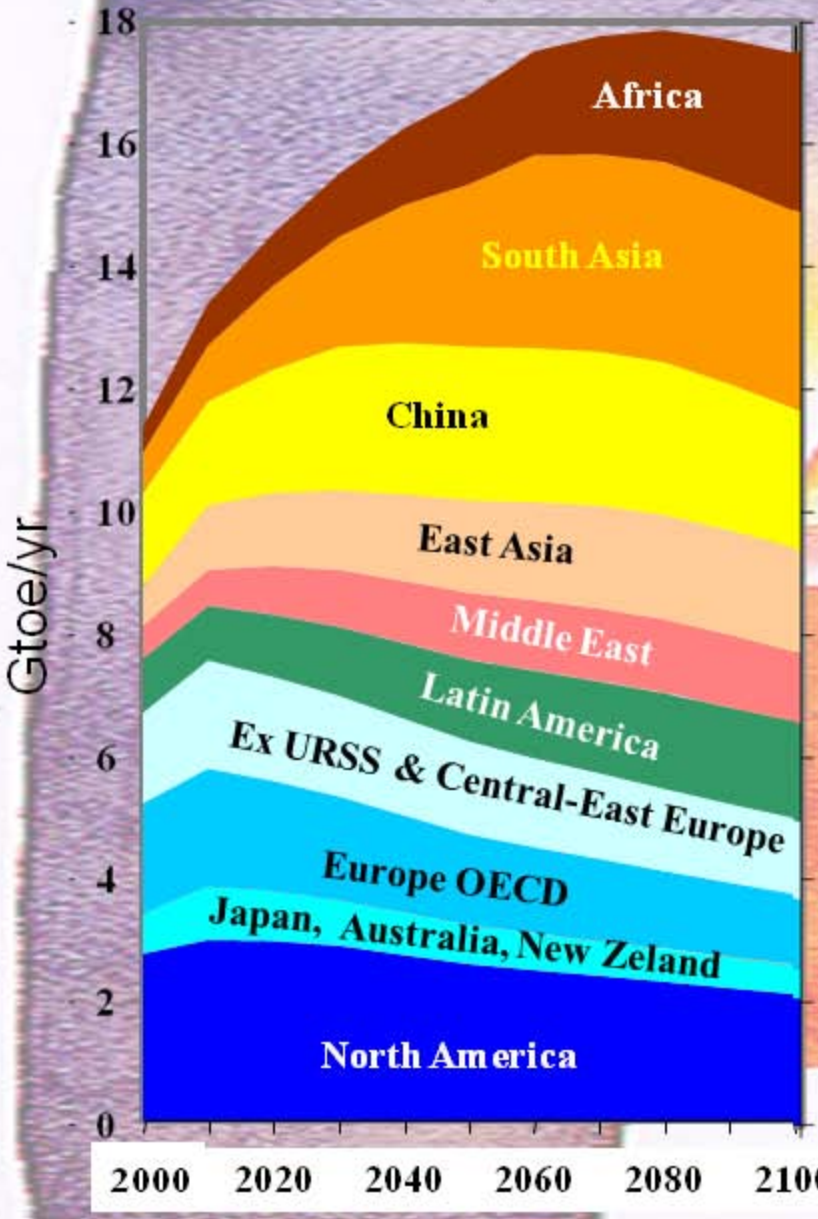

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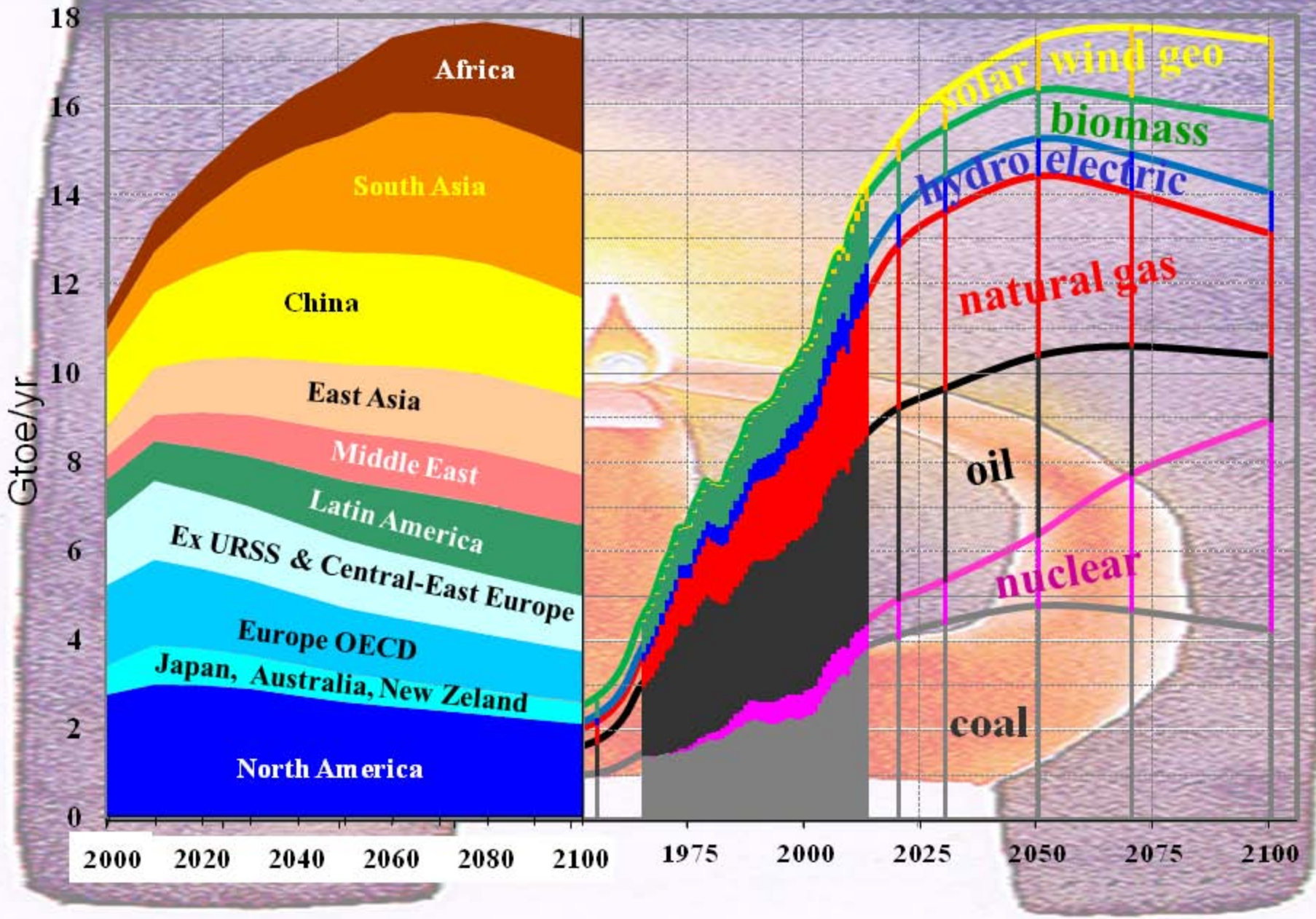

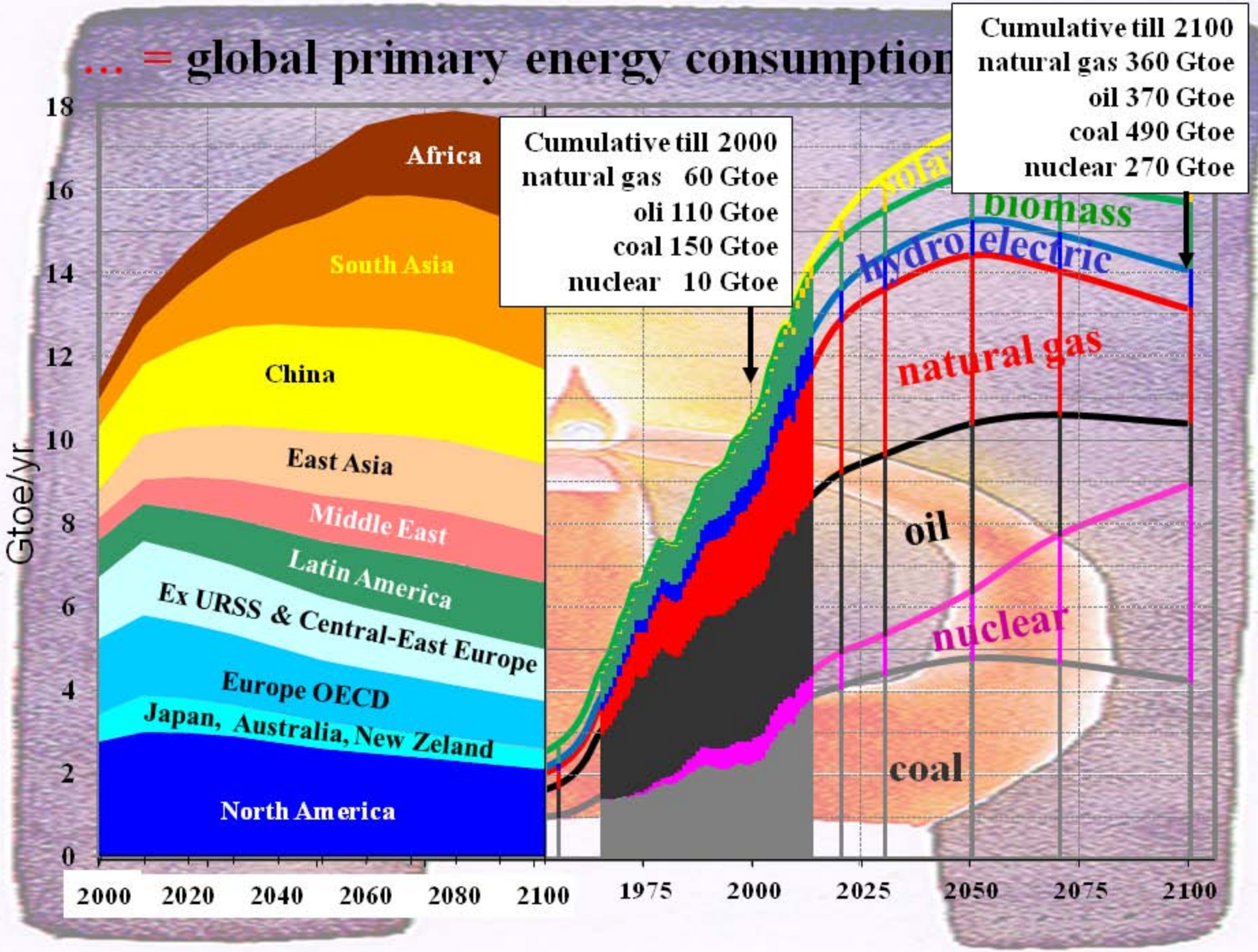

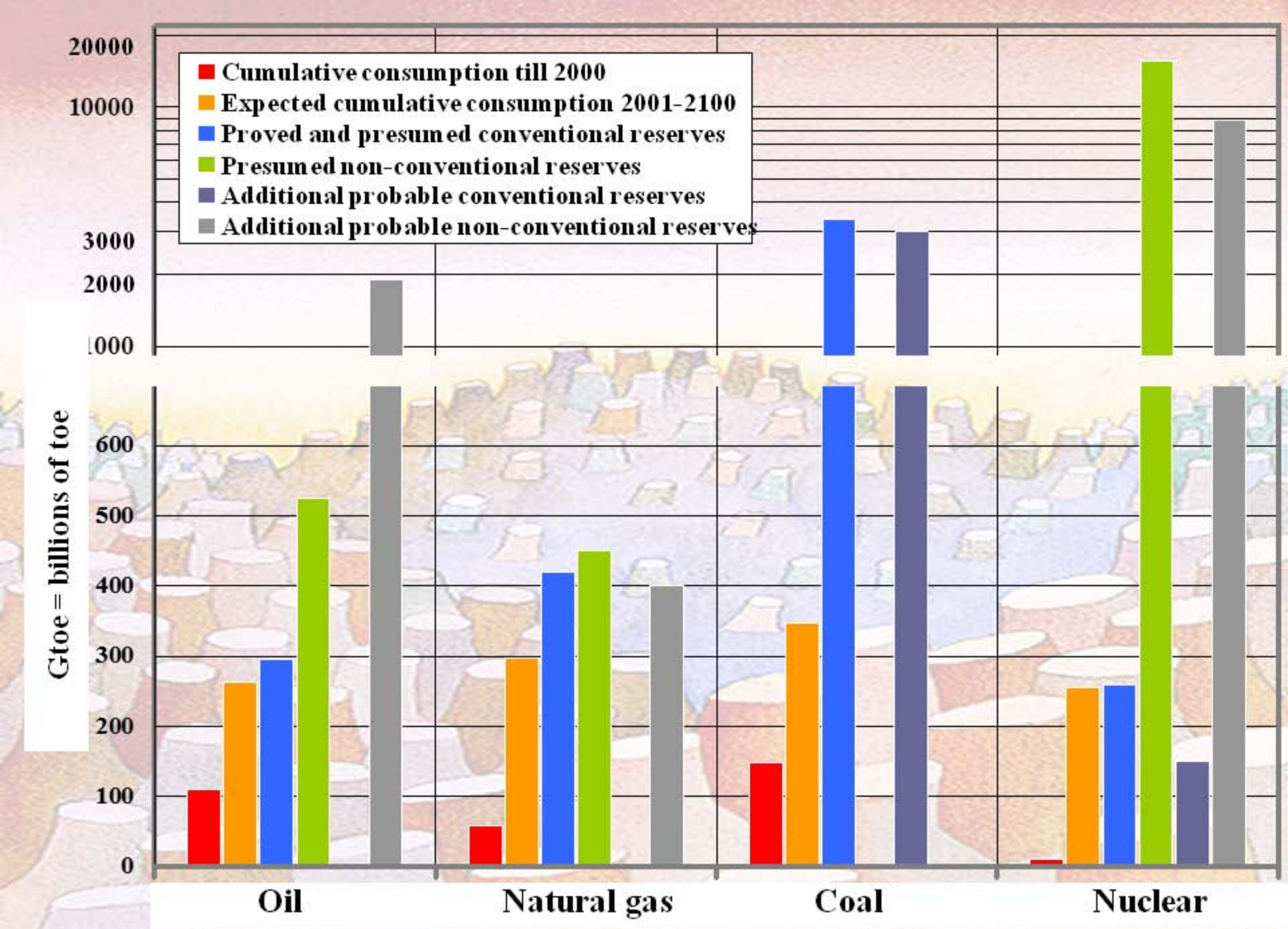

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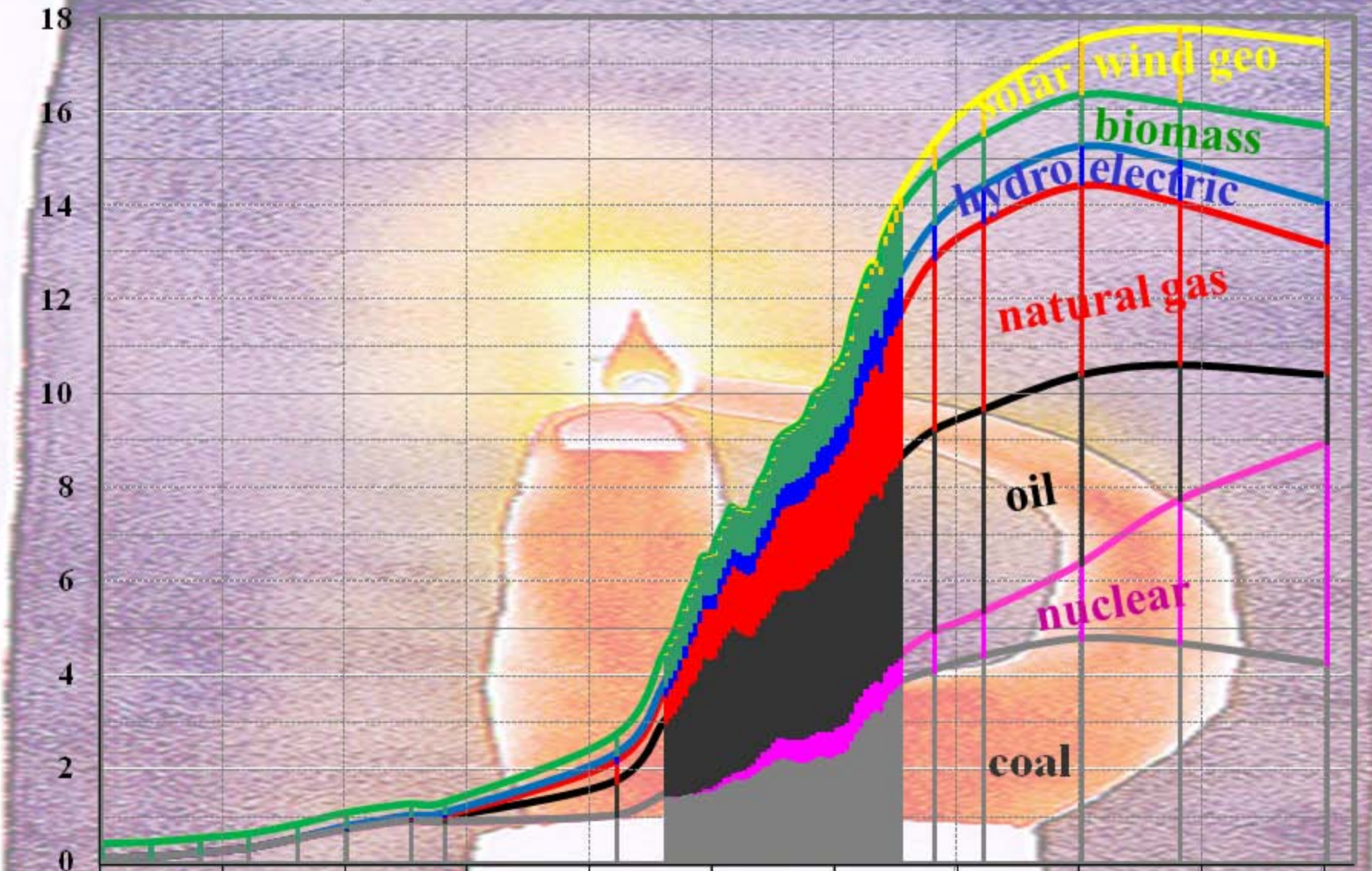
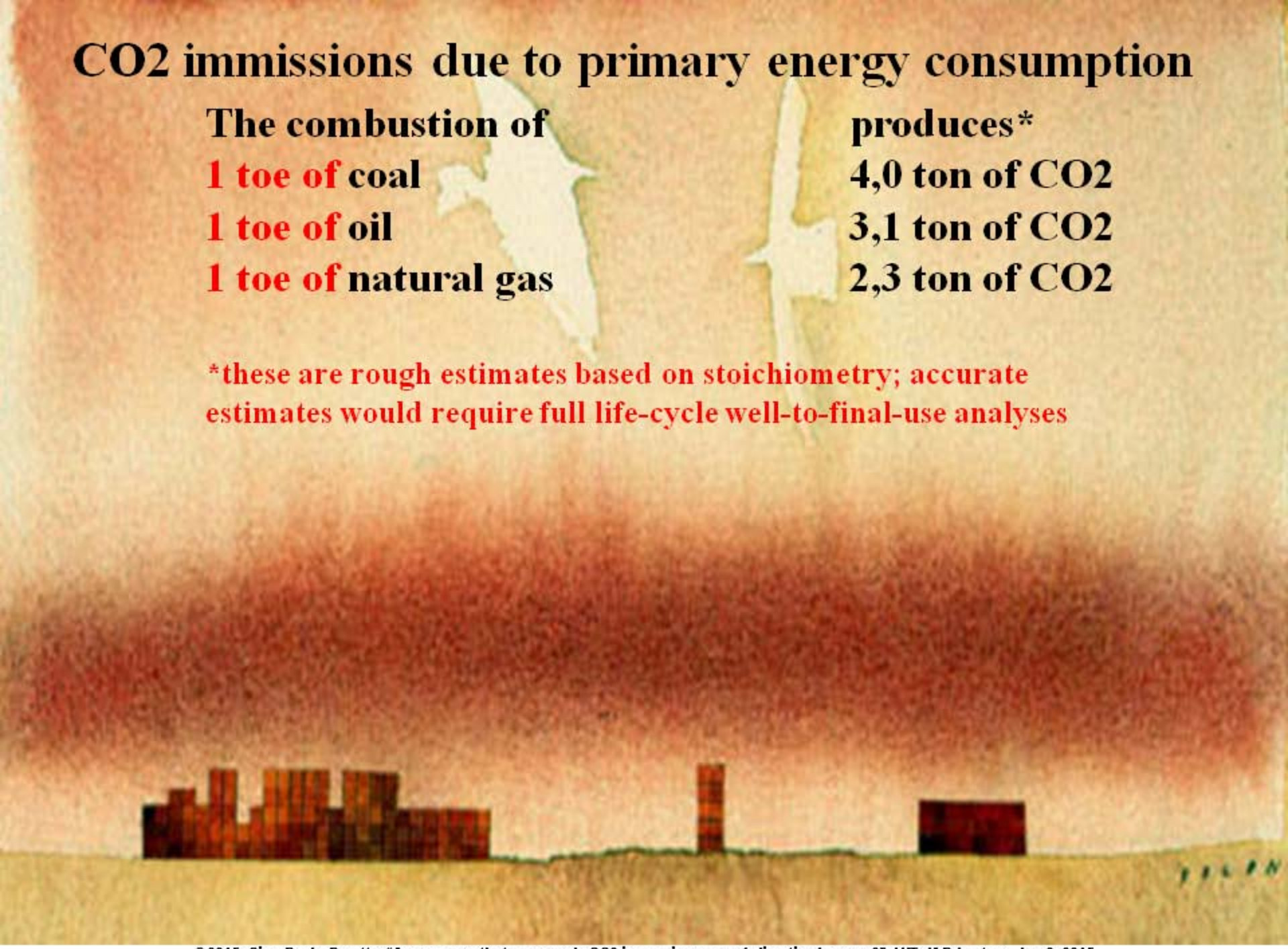


CO_2 immissions due to primary energy consumption

The combustion of	produces*
1 toe of coal	4,0 ton of CO_2
1 toe of oil	3,1 ton of CO_2
1 toe of natural gas	2,3 ton of CO_2

*these are rough estimates based on stoichiometry; accurate estimates would require full life-cycle well-to-final-use analyses



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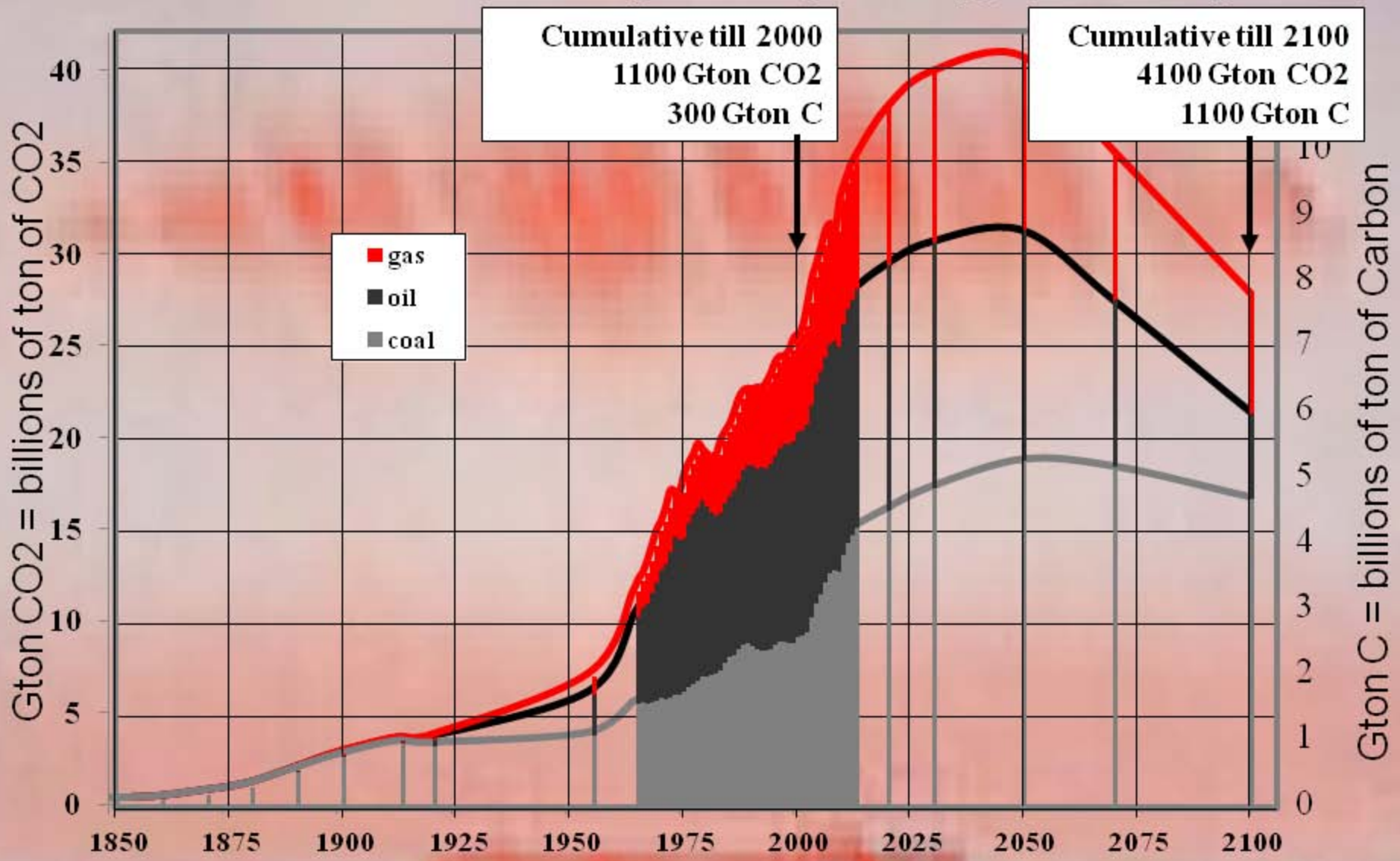

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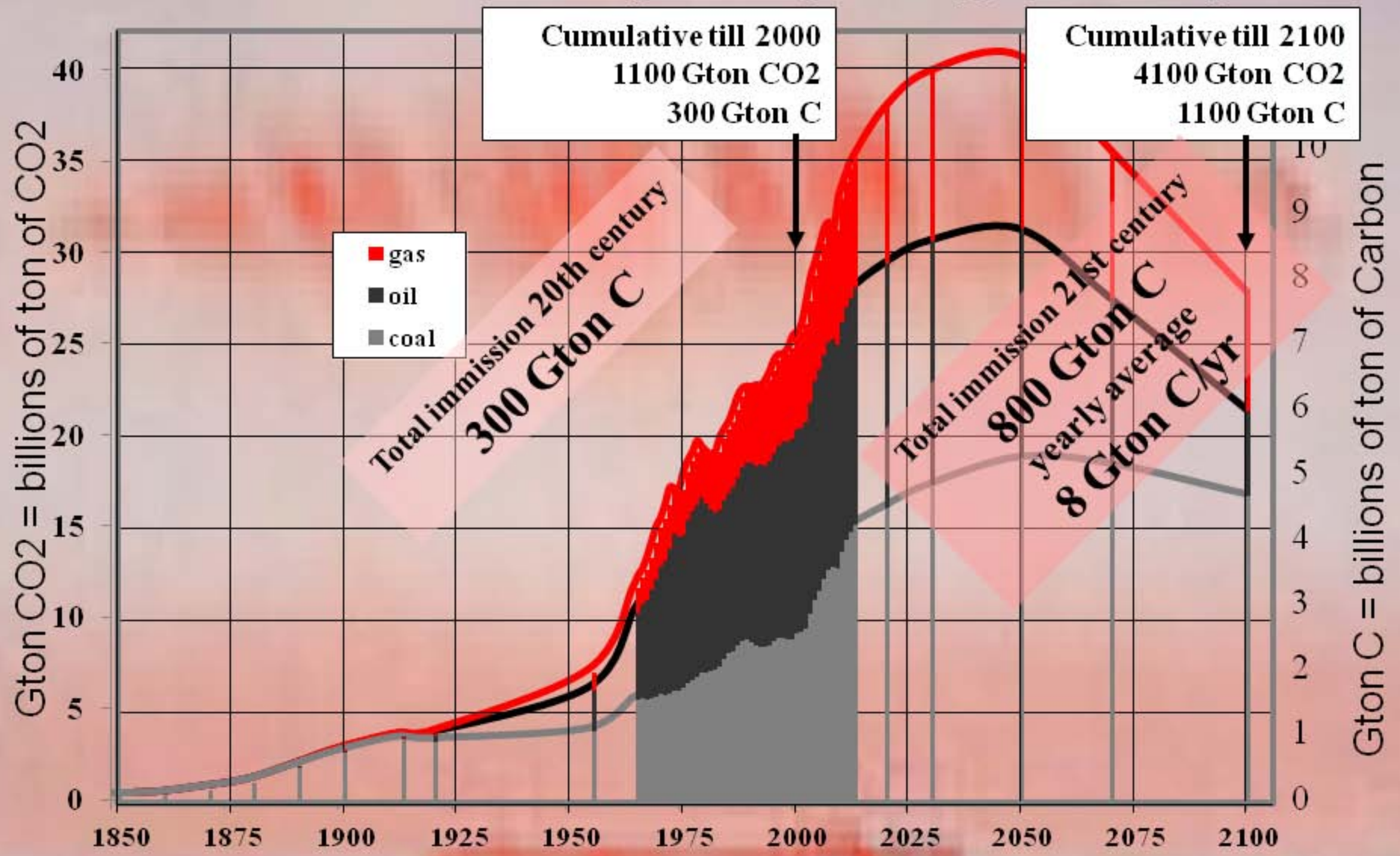
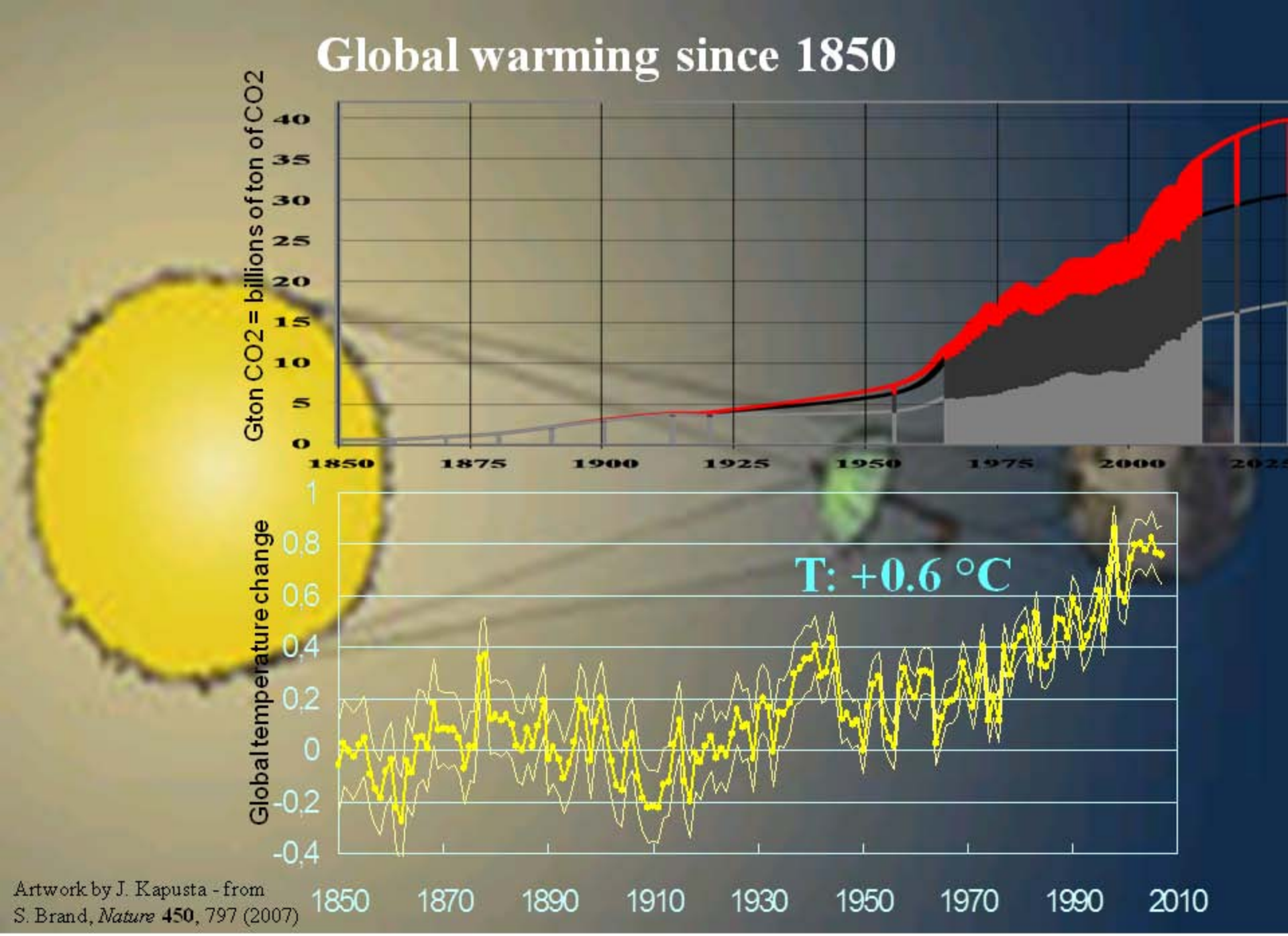
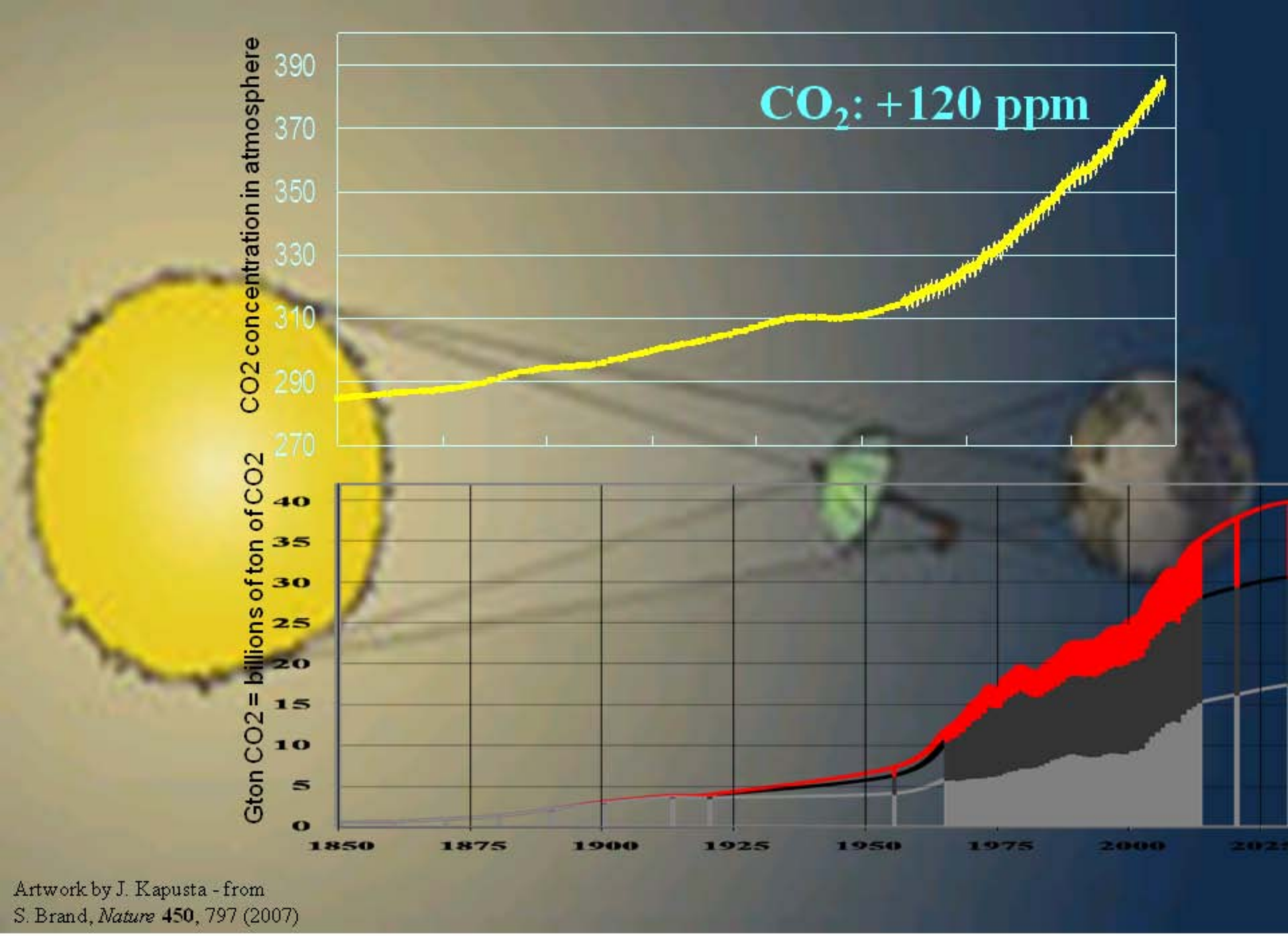


Global warming since 1850



Artwork by J. Kapusta - from
S. Brand, *Nature* **450**, 797 (2007)



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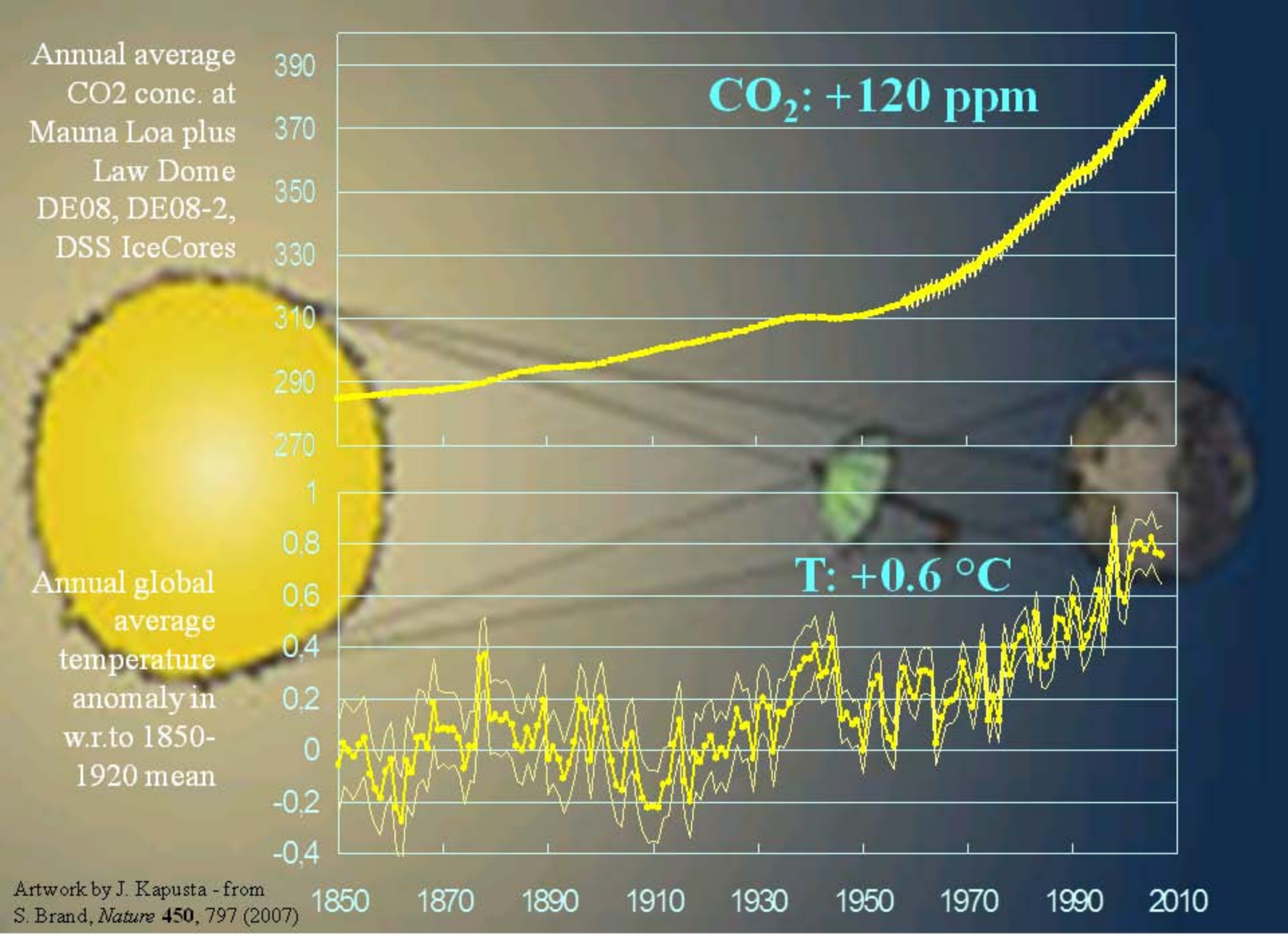
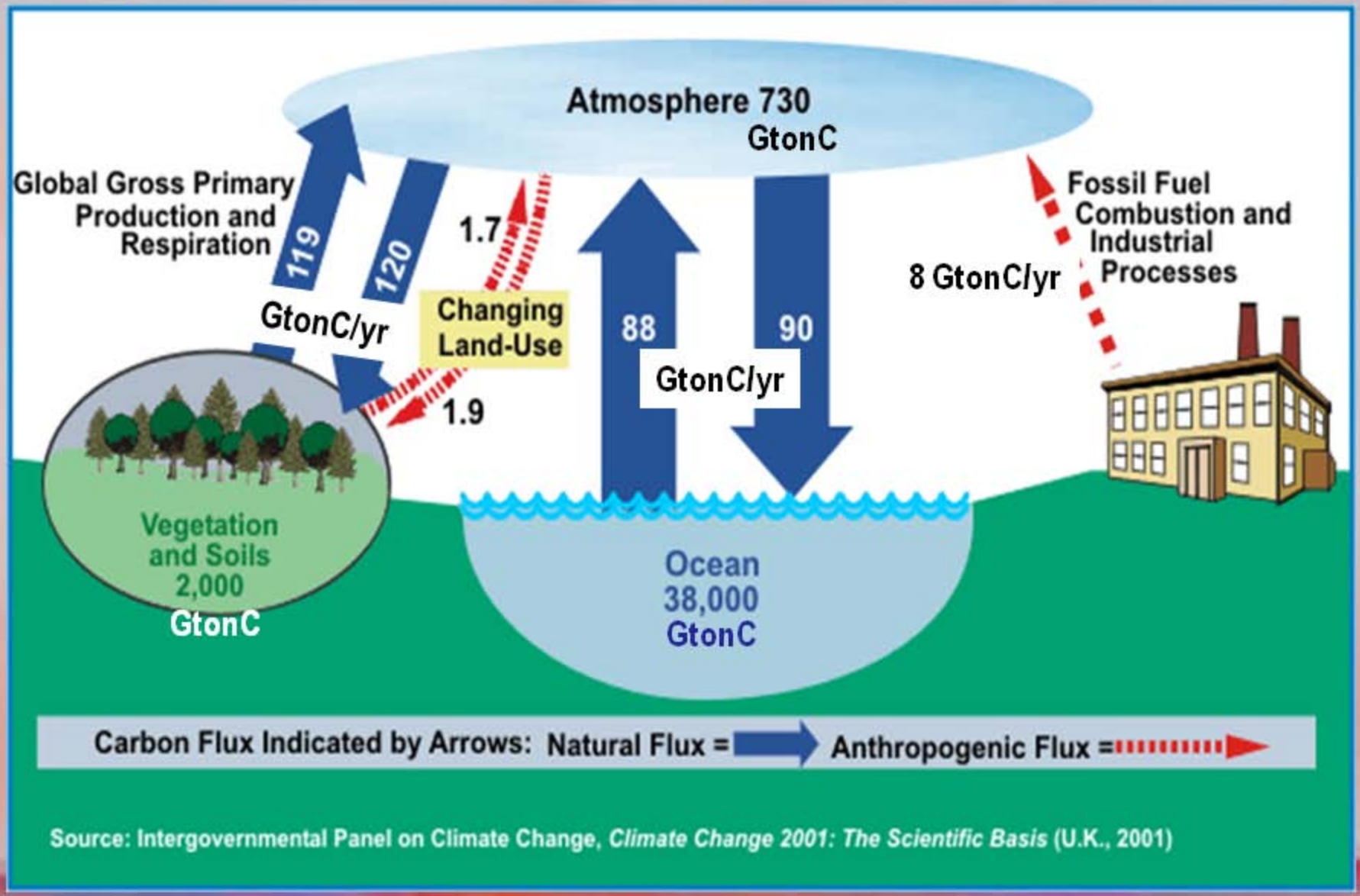
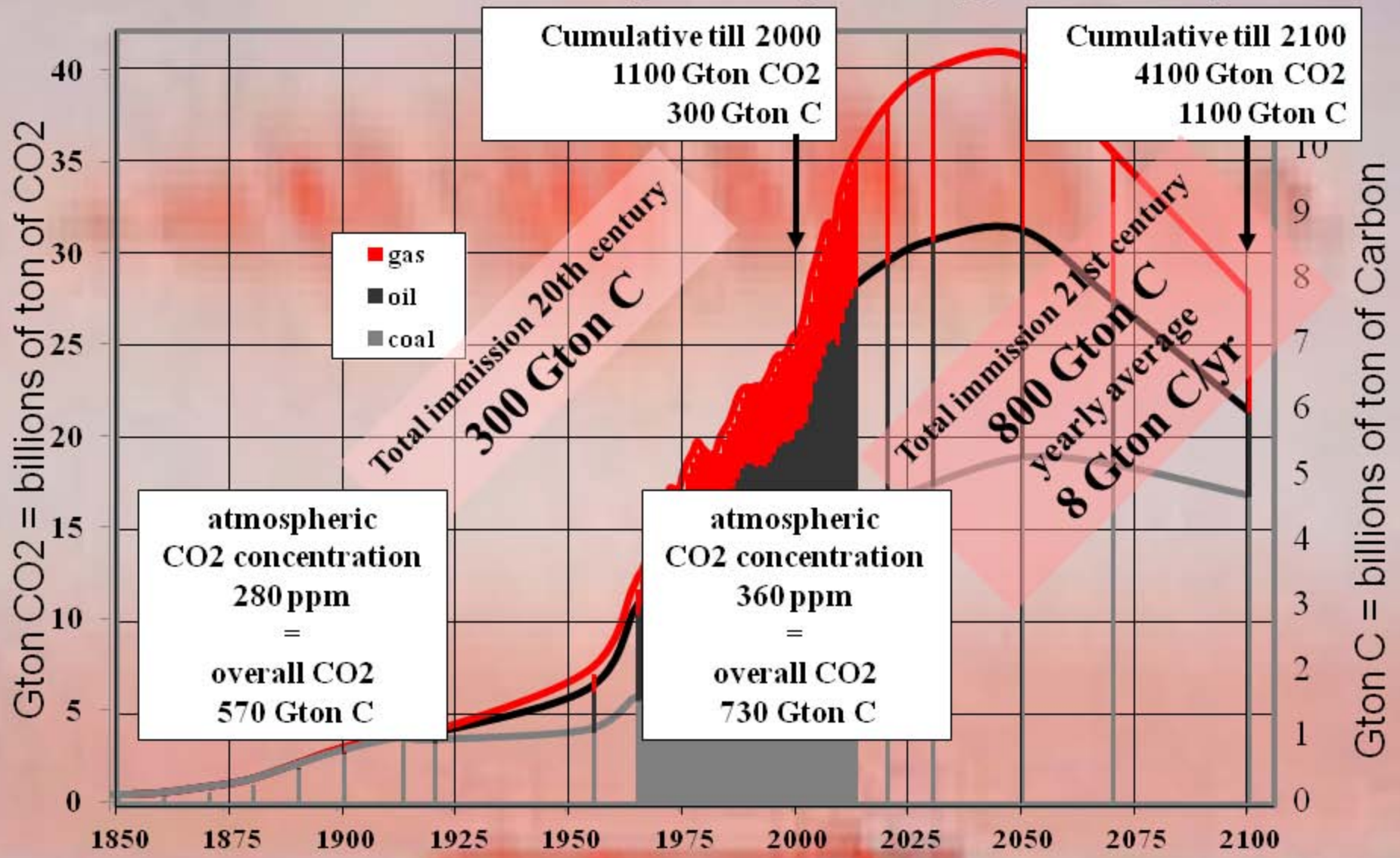


Energy related anthropic immissions are relatively small compared to the natural carbon exchanges and reserves of CO2 on Earth



Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (U.K., 2001)

CO2 immissions due to primary energy consumption



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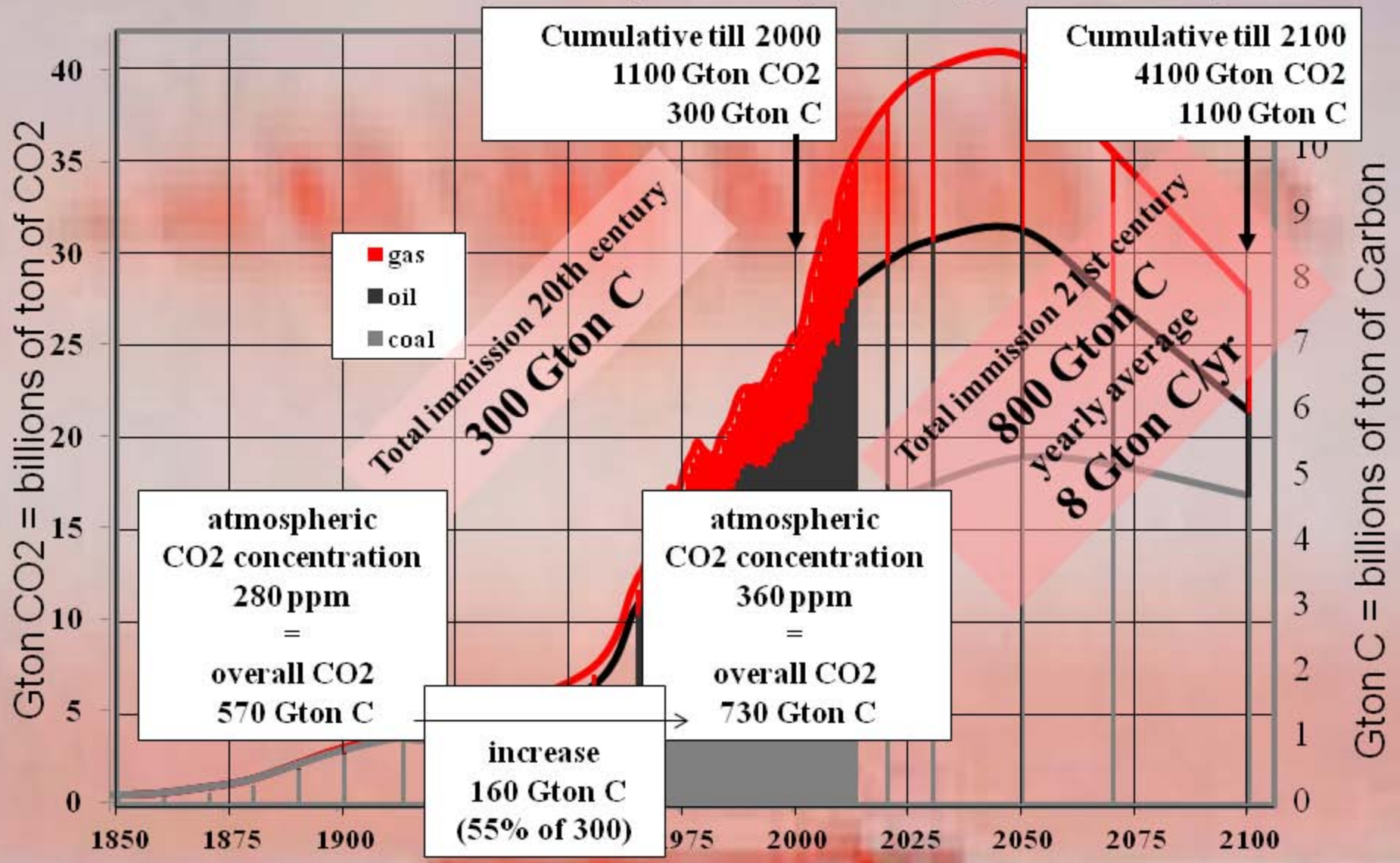

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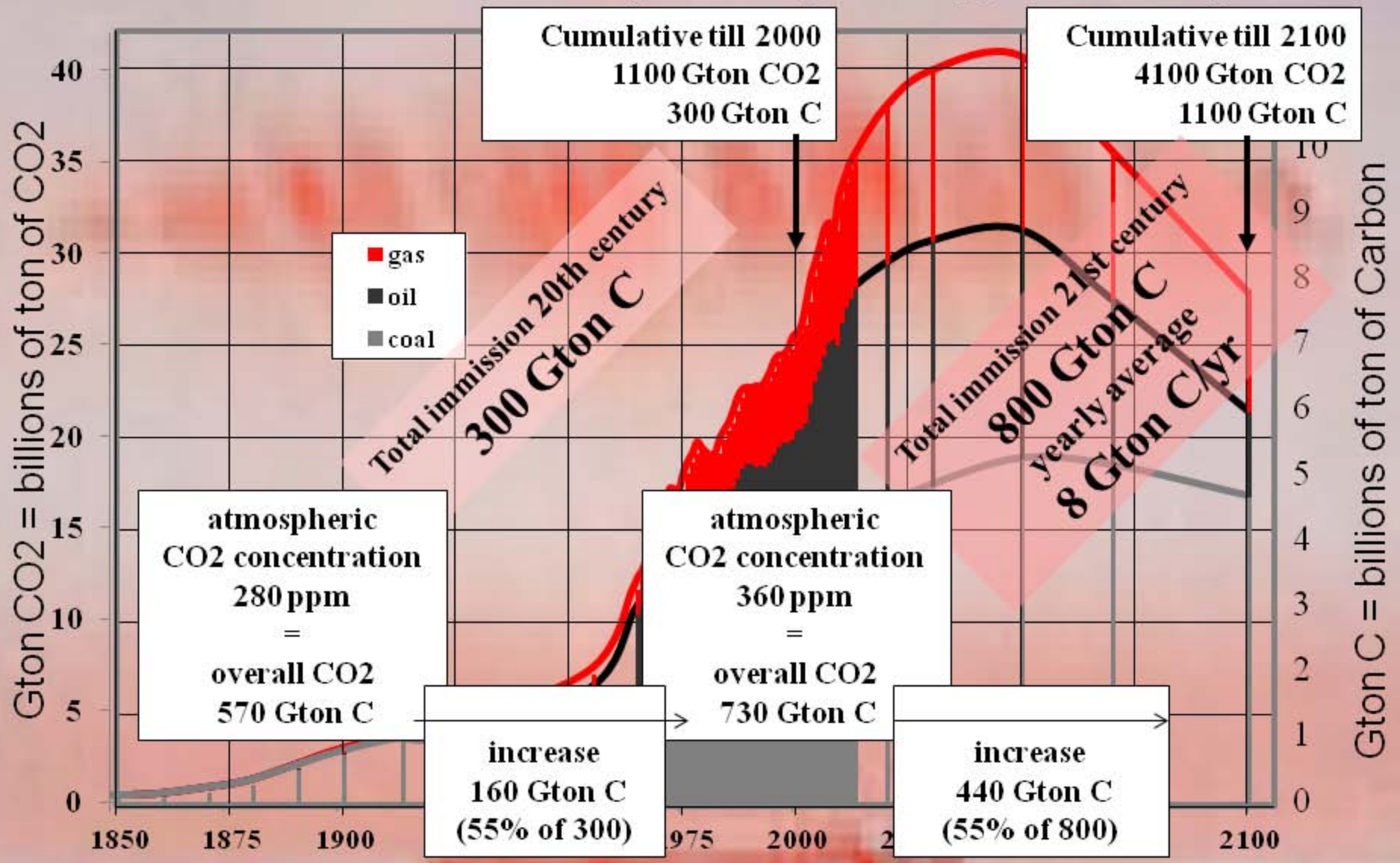

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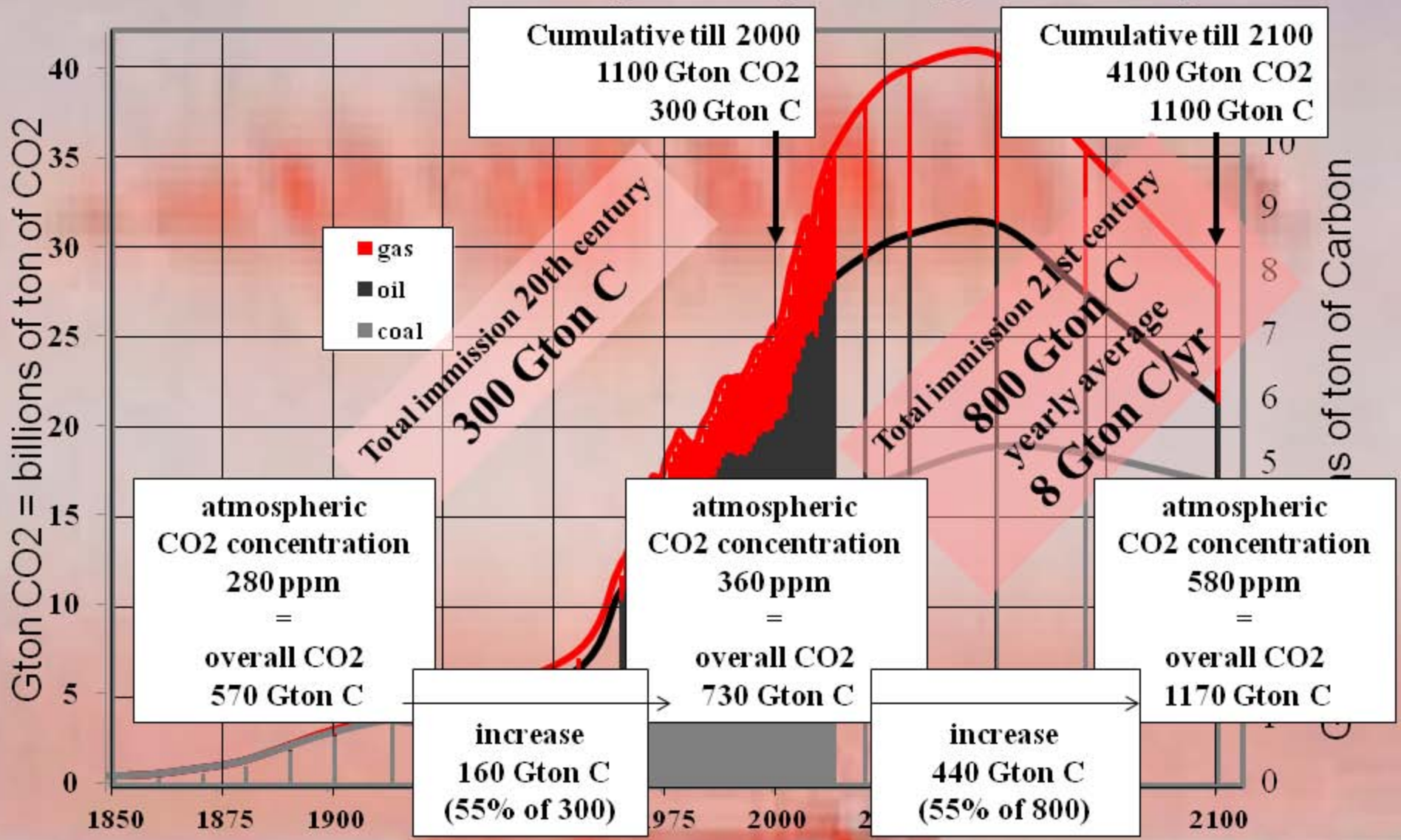

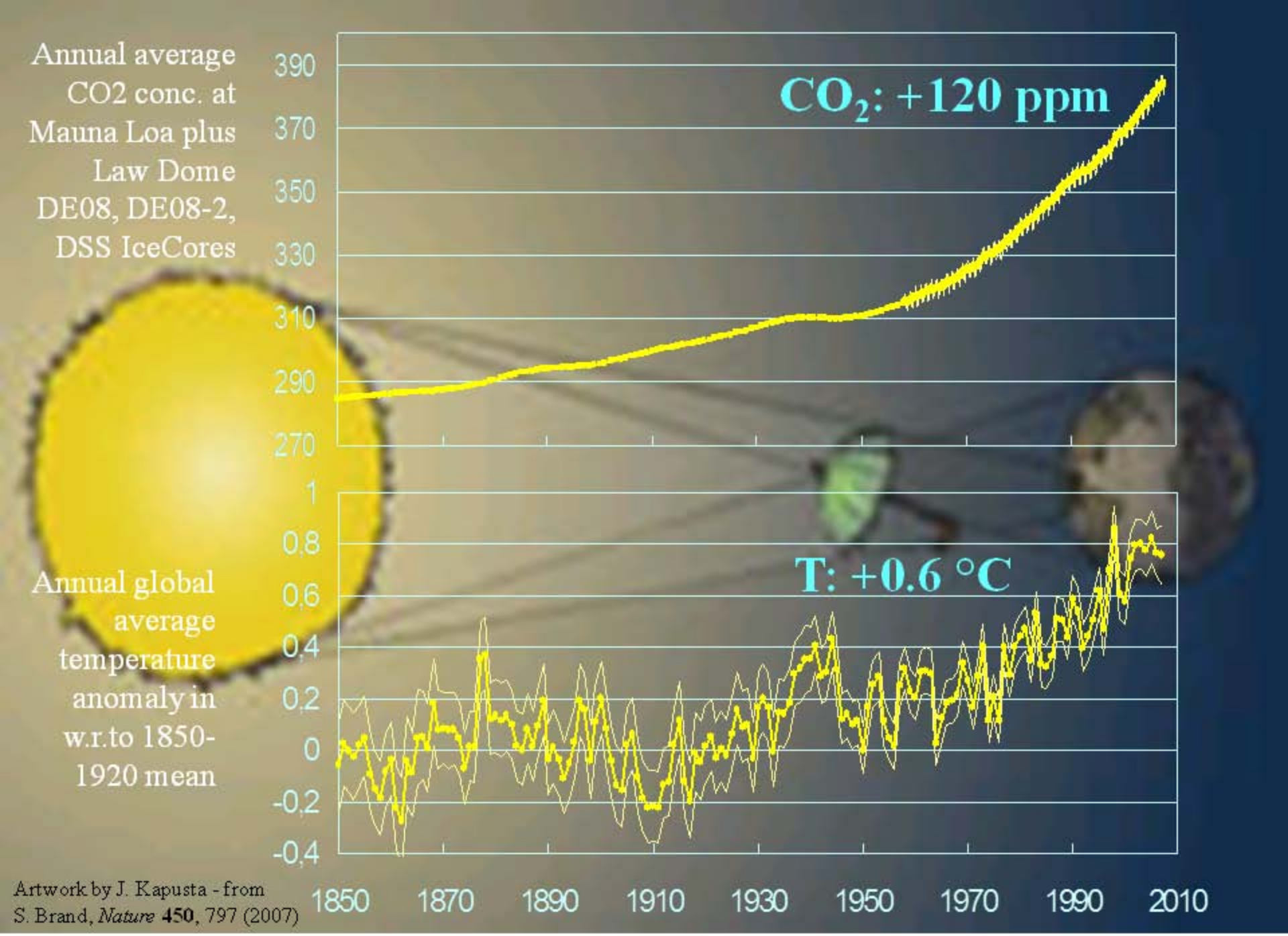

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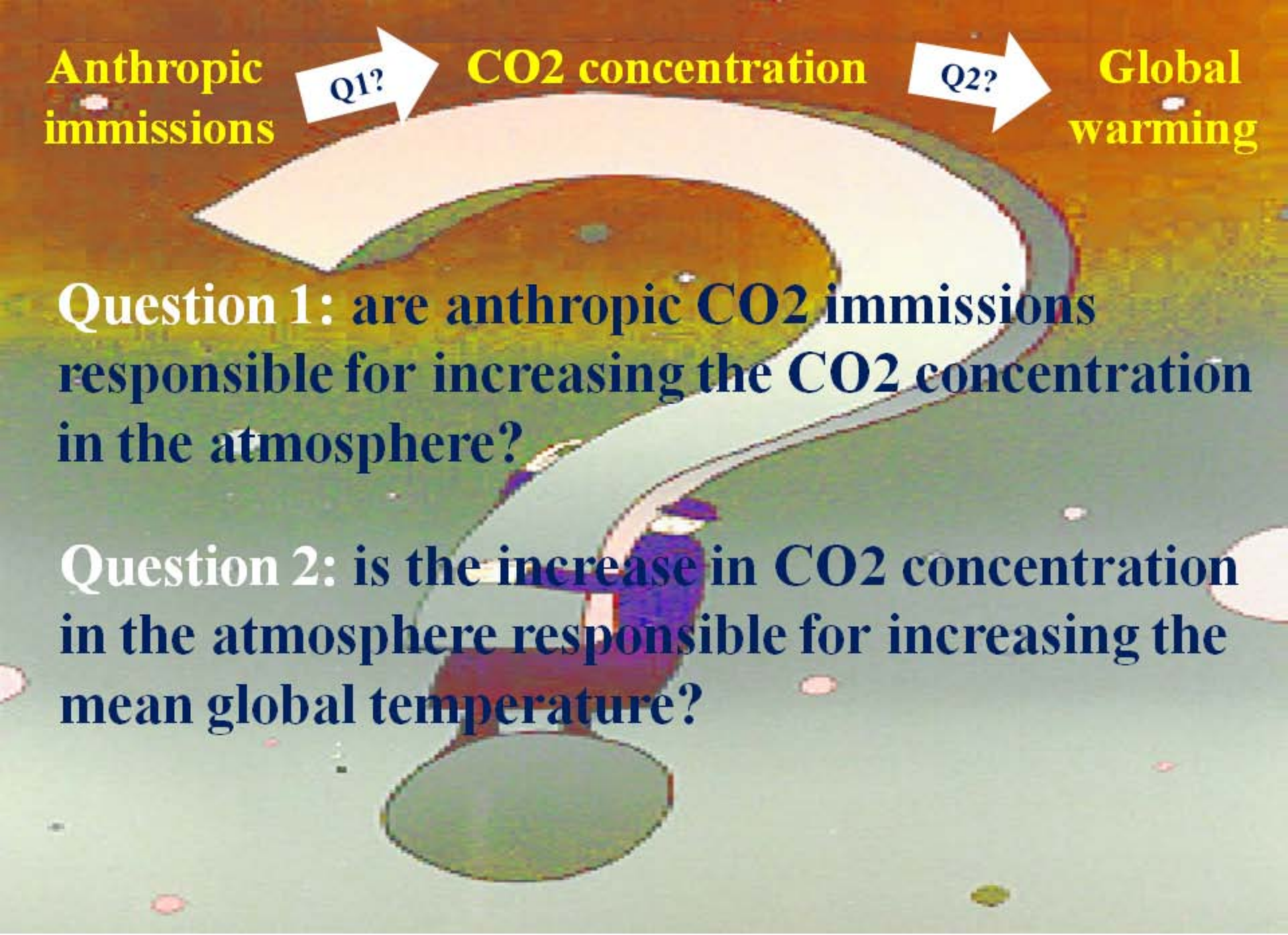
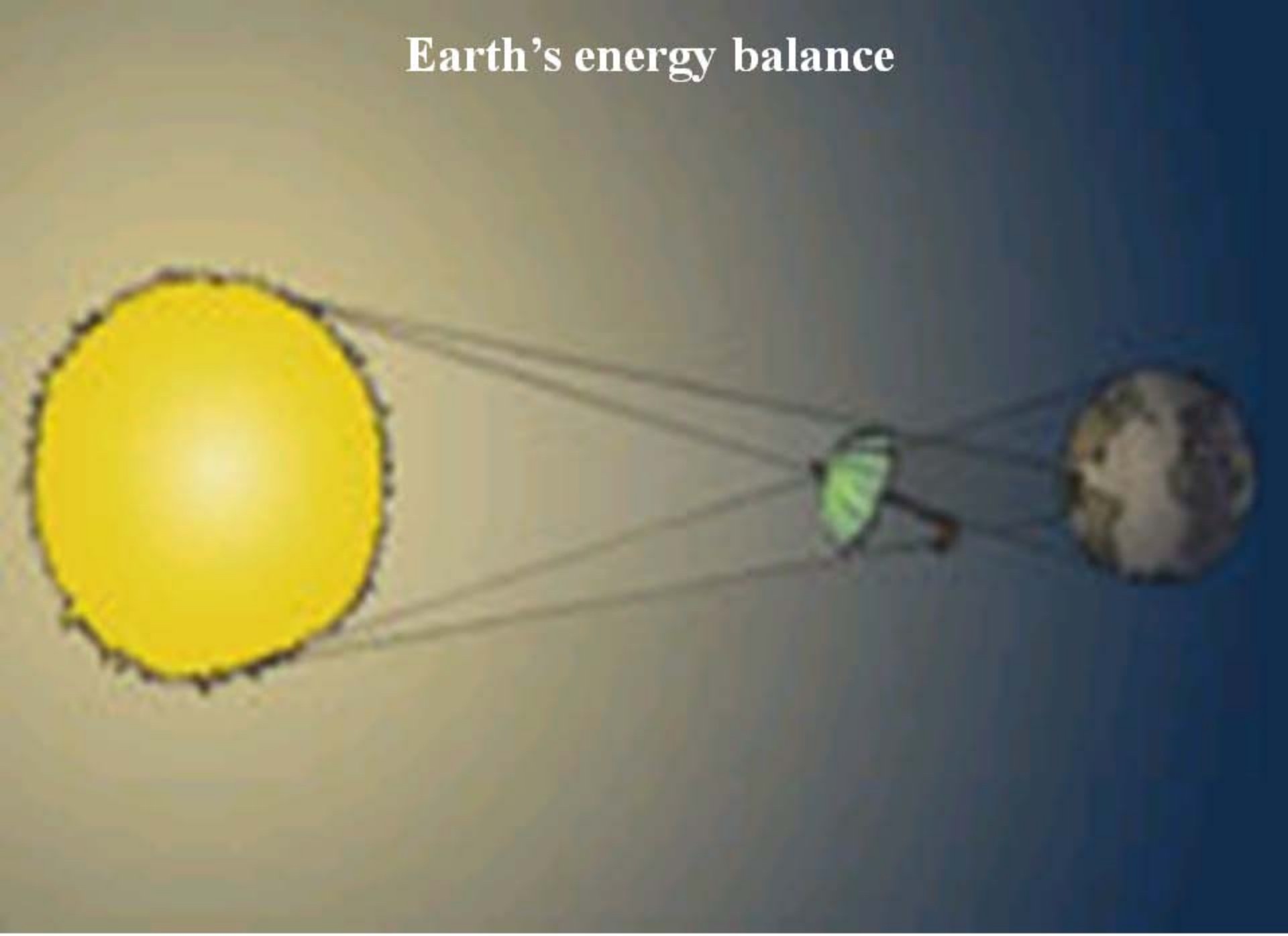
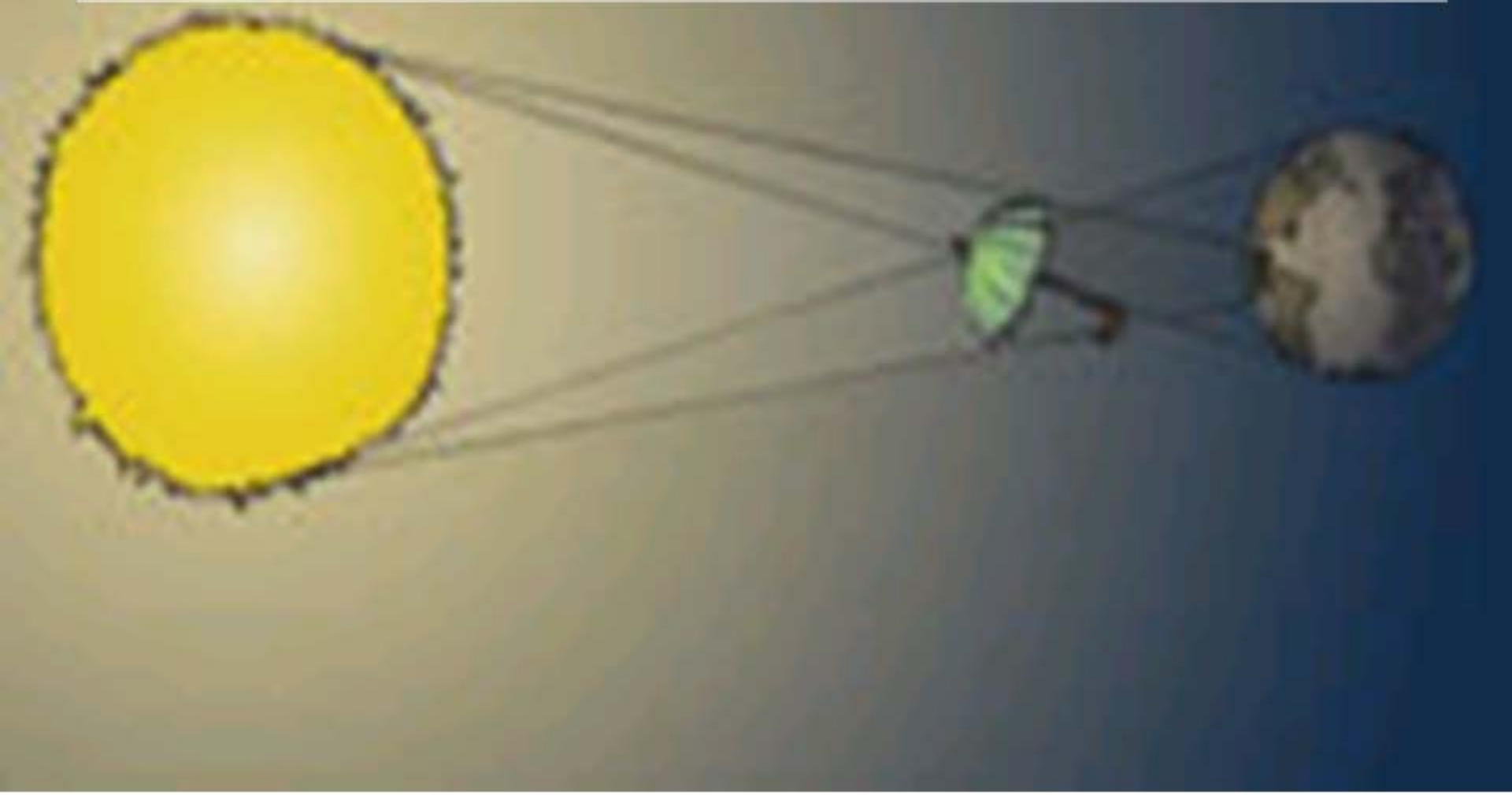


Earth's energy balance



Earth's energy balance

- Solar radiation — $I_0 = 1367\ W/m^2$
- Albedo (about 32% gets reflected away) — $I_{eff} = 930\ W/m^2$



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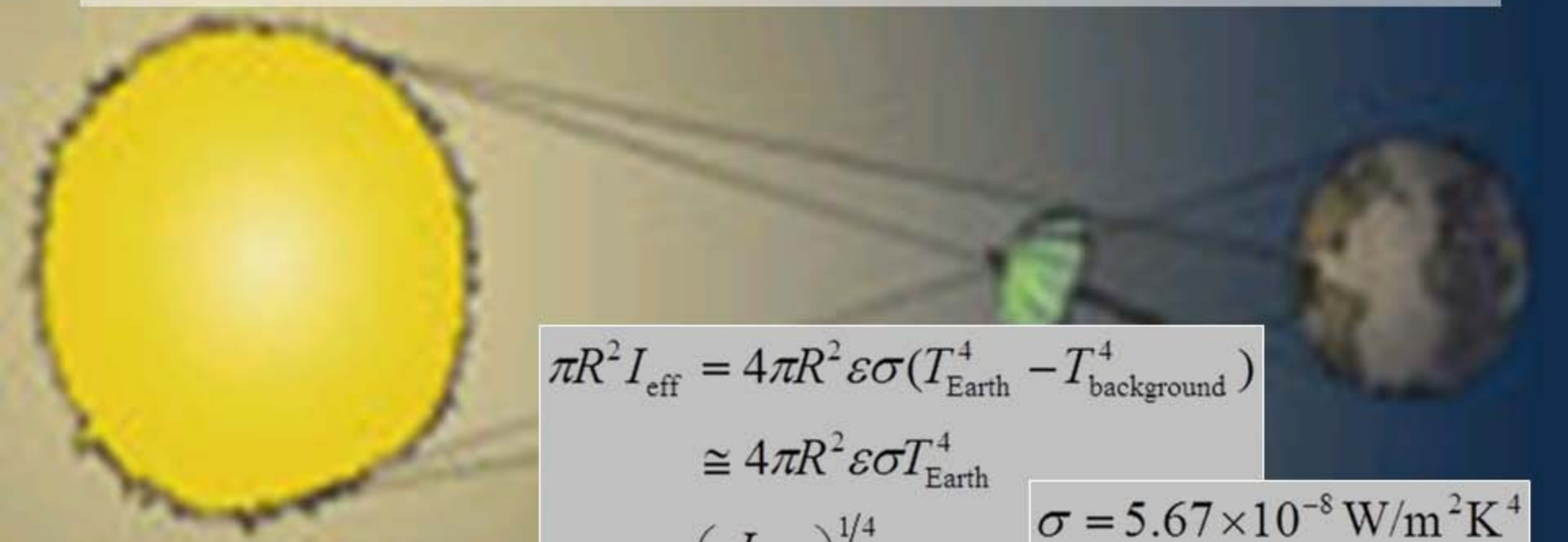

$$\pi R^2 I_{\text{eff}} = 4\pi R^2 \varepsilon\sigma (T_{\text{Earth}}^4 - T_{\text{background}}^4)$$

$$\cong 4\pi R^2 \varepsilon\sigma T_{\text{Earth}}^4$$

$$T_{\text{Earth}} = \left(\frac{I_{\text{eff}}}{4\varepsilon\sigma} \right)^{1/4}$$

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

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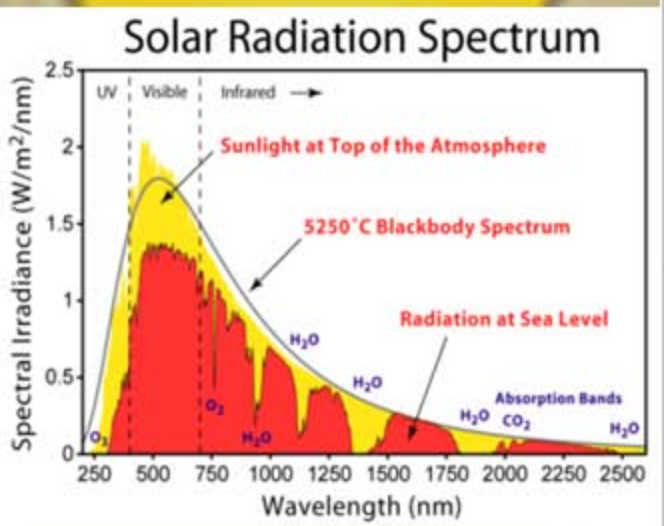

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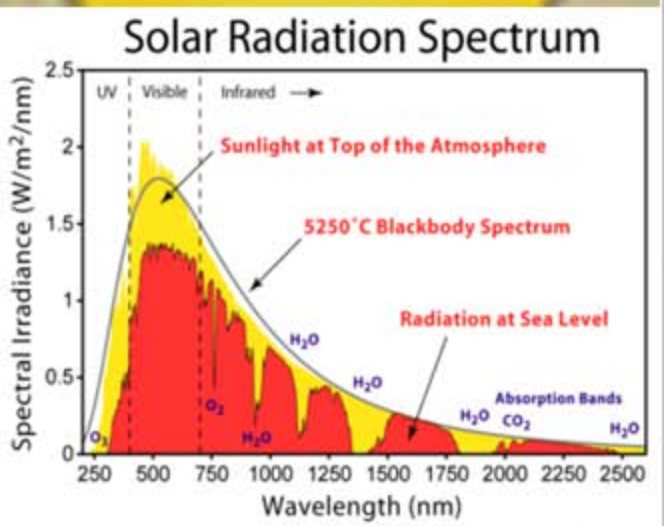

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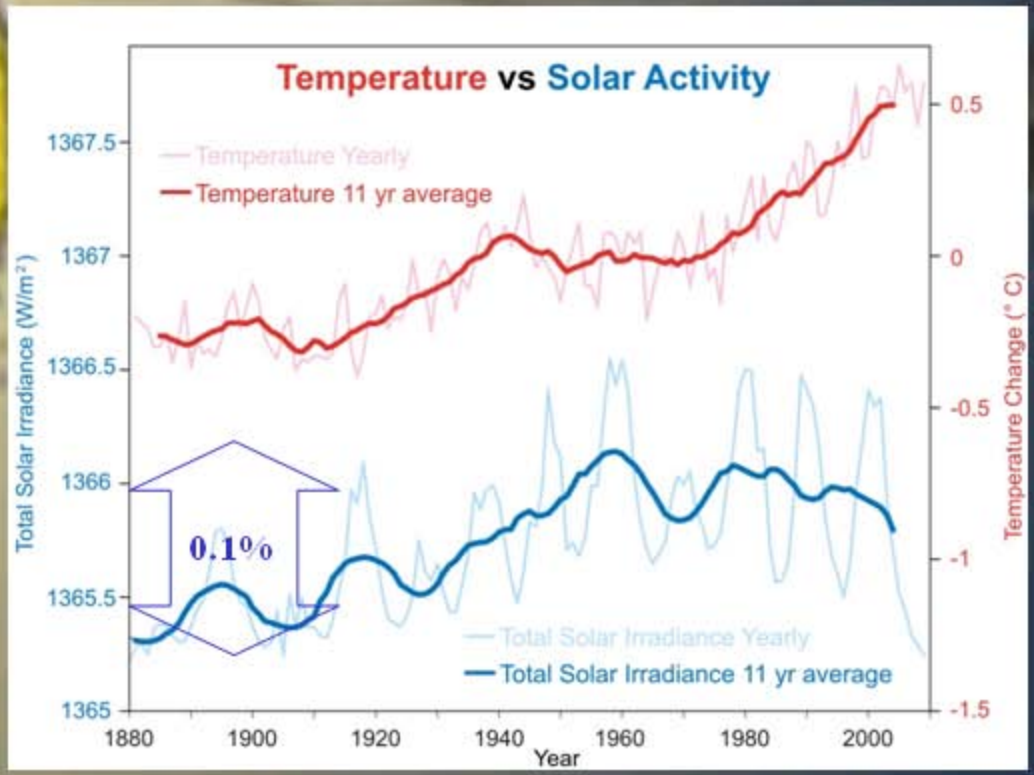
- Measured variations in I_0 are less than 0.1%



CO2 effect as a greenhouse gas

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- With pre-industrial greenhouse gases (1750) $T_1 = 288\ K\ (+15°C) = T_0 + 33°C$
- Corresponds to an additional radiation $I = I_0 + F = 1367 + 144\ W/m^2$
- F, called radiative Forcing, $F = 144\ W/m^2$ $T_1 - T_0 = 33°C$

can be split between the main greenhouse gases

64%	due to water vapor	92 W/m²	21°C
21%	due to CO_2	30 W/m²	7°C
15%	due to CH4, N2O, other	22 W/m²	5°C

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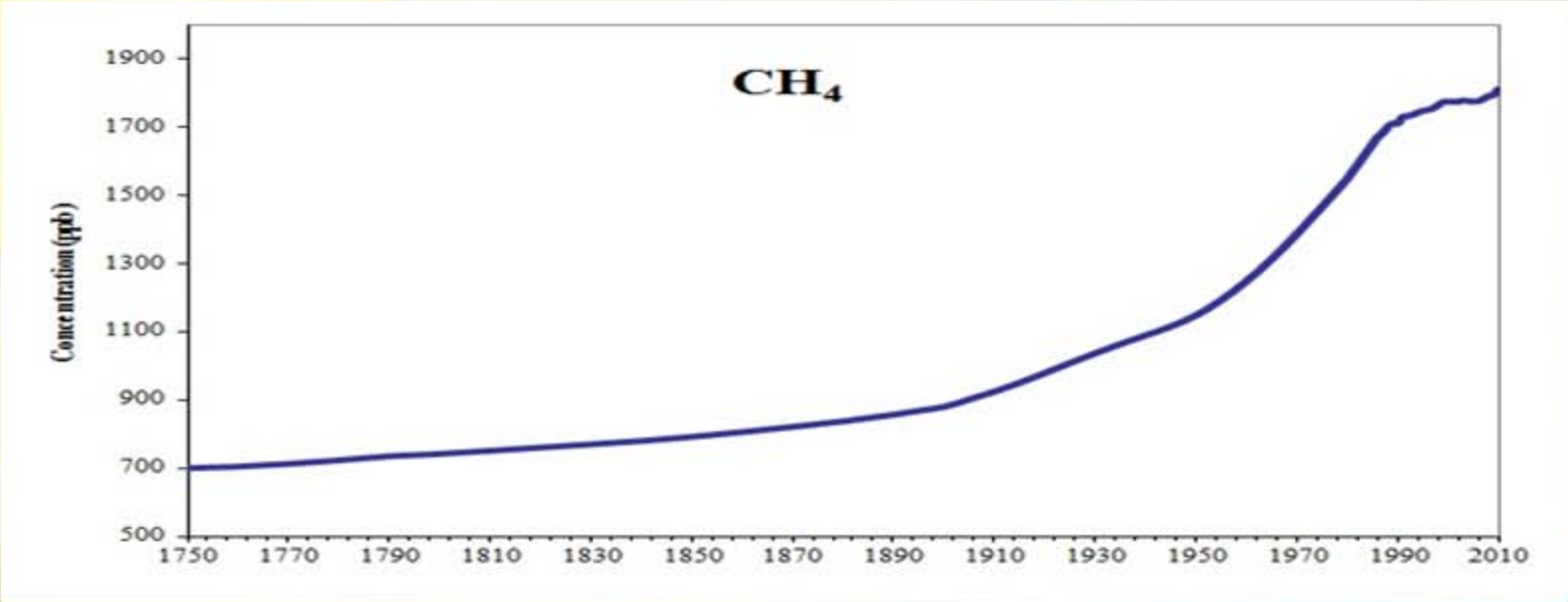

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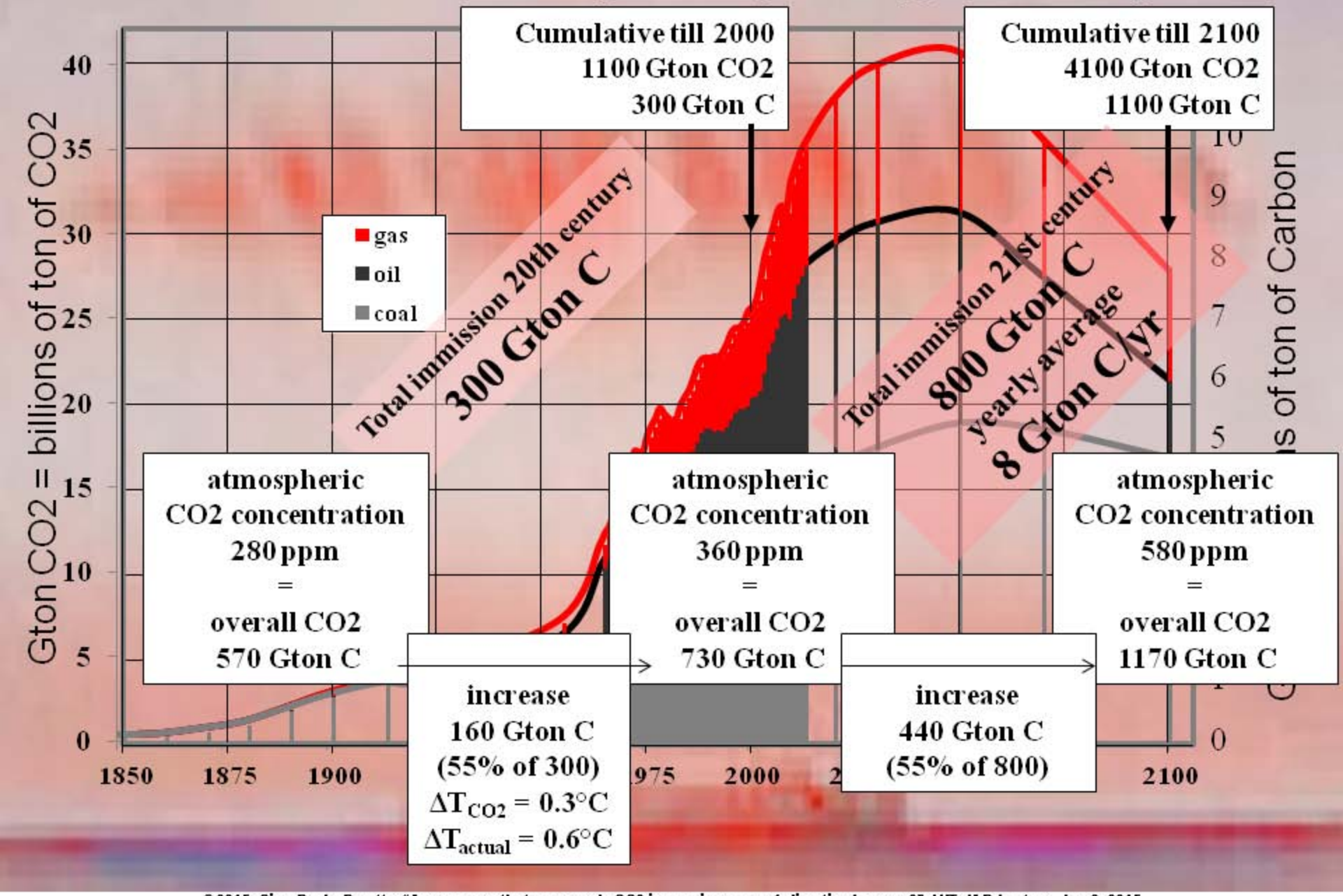
- IPCC formula

$$F - F_0 = 5.35 \ln(C/C_0)$$

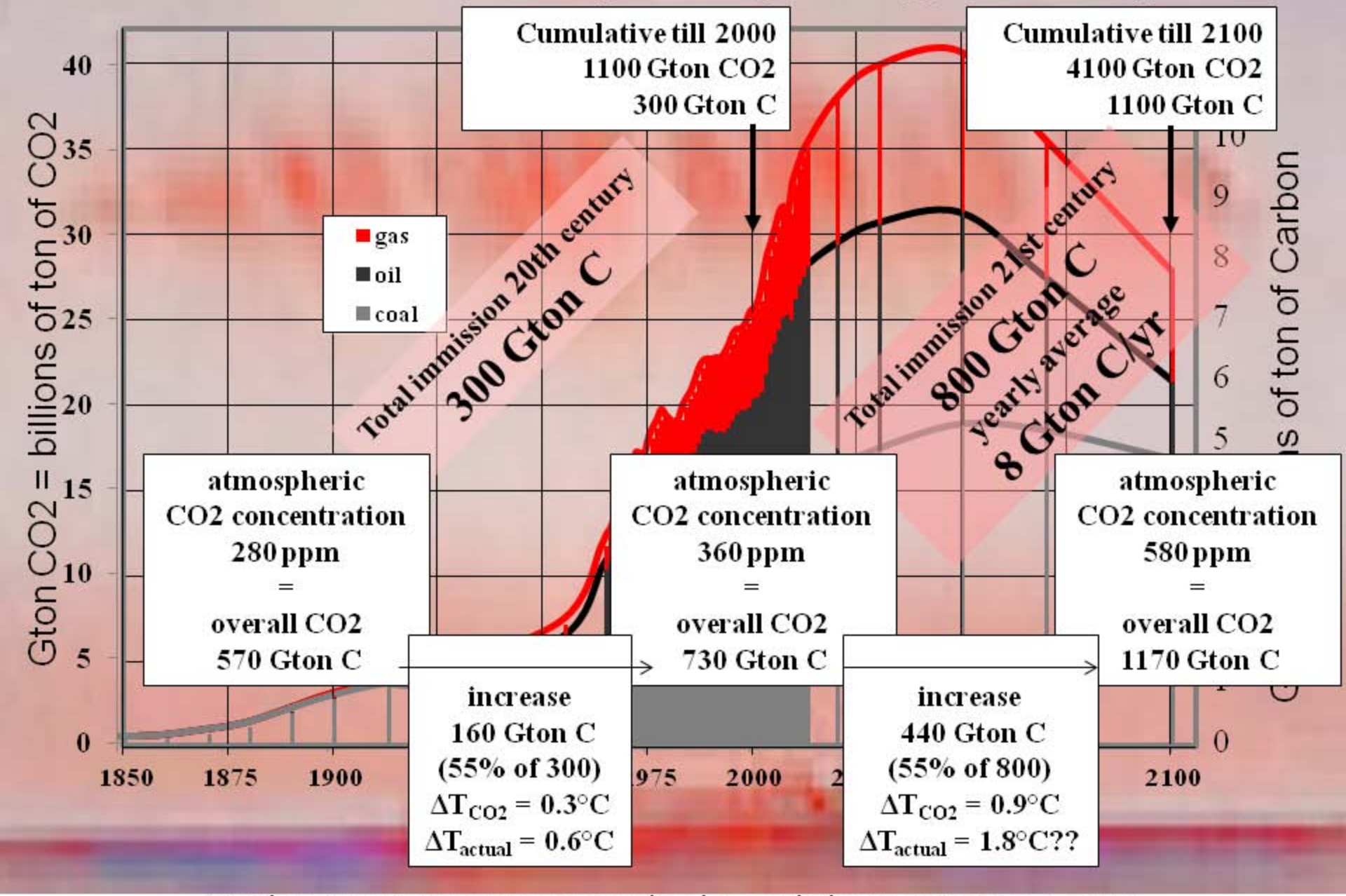
- $F_{2000} - F_{1850} = 5.35 \ln(360/280) = 1.35$ for CO2 during 20th century
- $1.35 * 33/144 = \underline{0.3°C}$ therefore CO2 accounts for <u>only half of the 0.6°C</u> increase

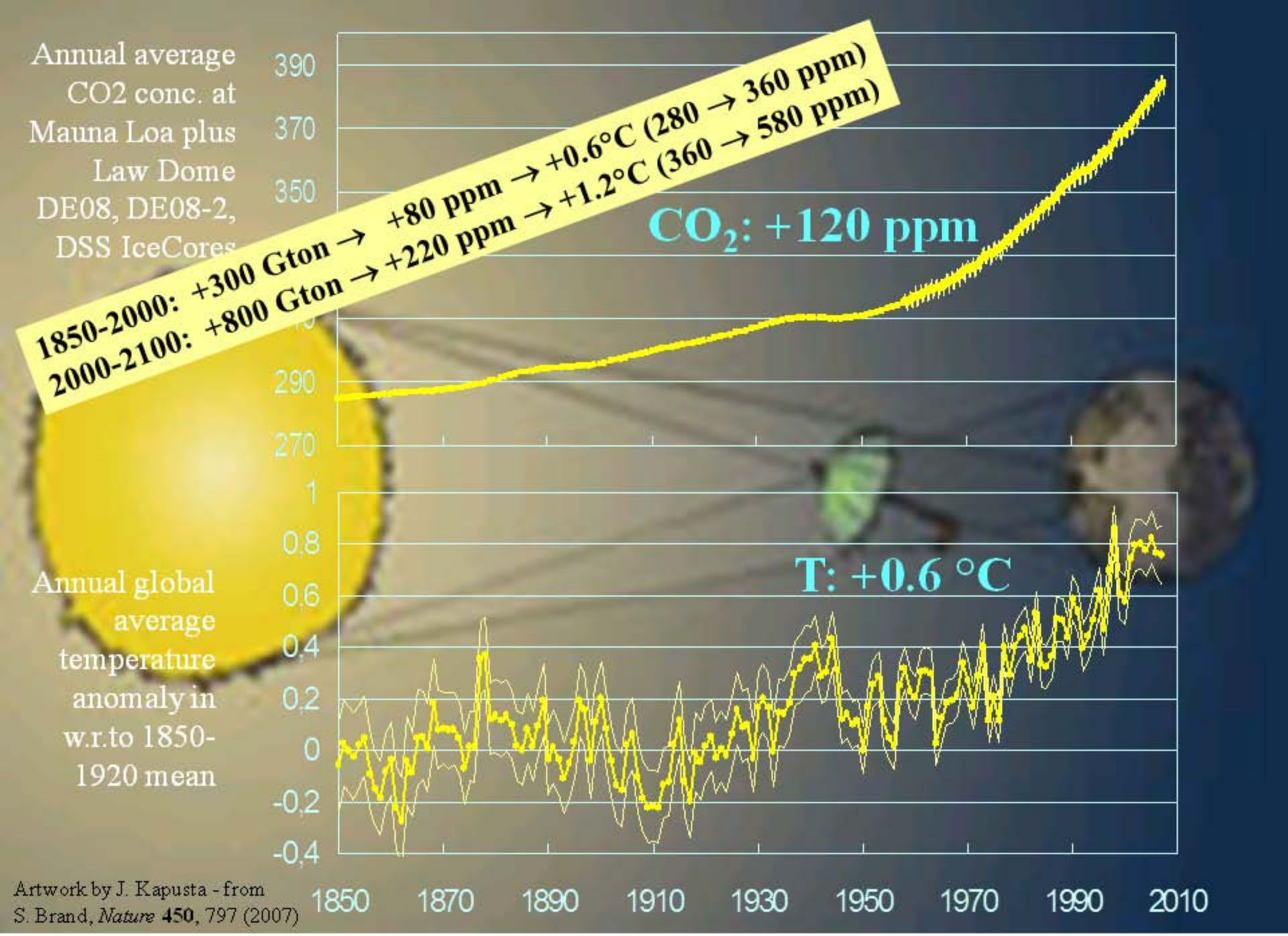
- $F_{2100} - F_{1850} = 5.35 \ln(580/280) = 3.89$ for CO2 during 20th+21th century
- $3.89 * 33/144 = \underline{0.9°C}$ is the estimate of $T_{2100} - T_{1850}$ due to CO2 immissions

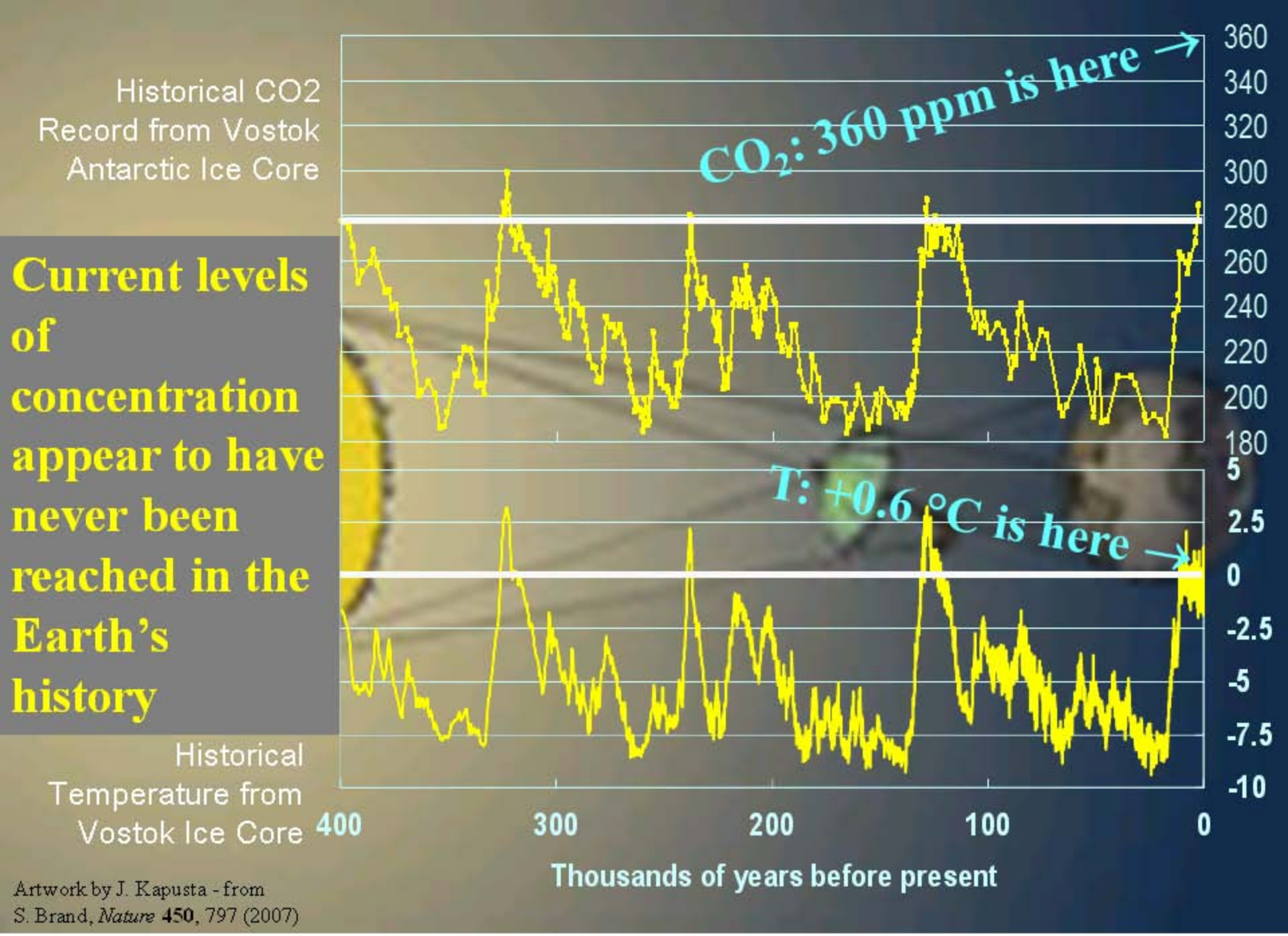
CO2 immissions due to primary energy consumption



CO2 immissions due to primary energy consumption

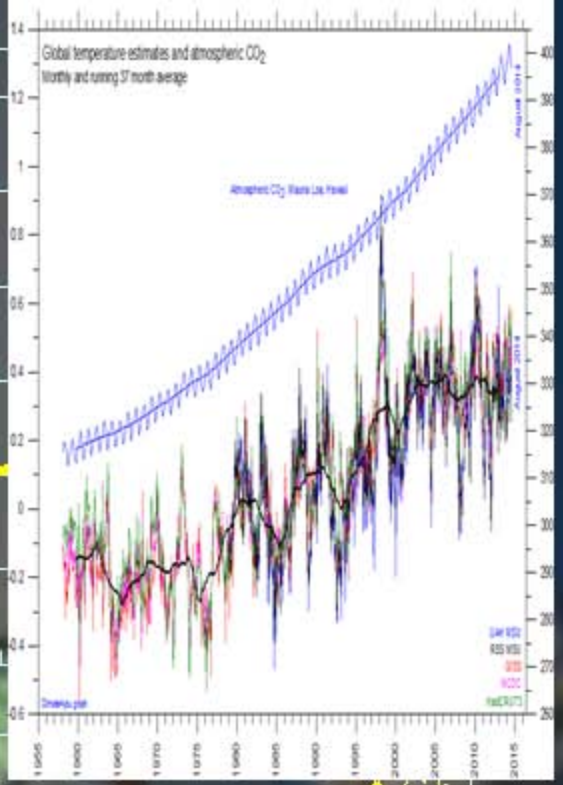






Annual average CO2 conc. at Mauna Loa plus Law Dome DE08, DE08-2,

CO_2: +120 ppm



However… correlation appears weaker in the last two decades

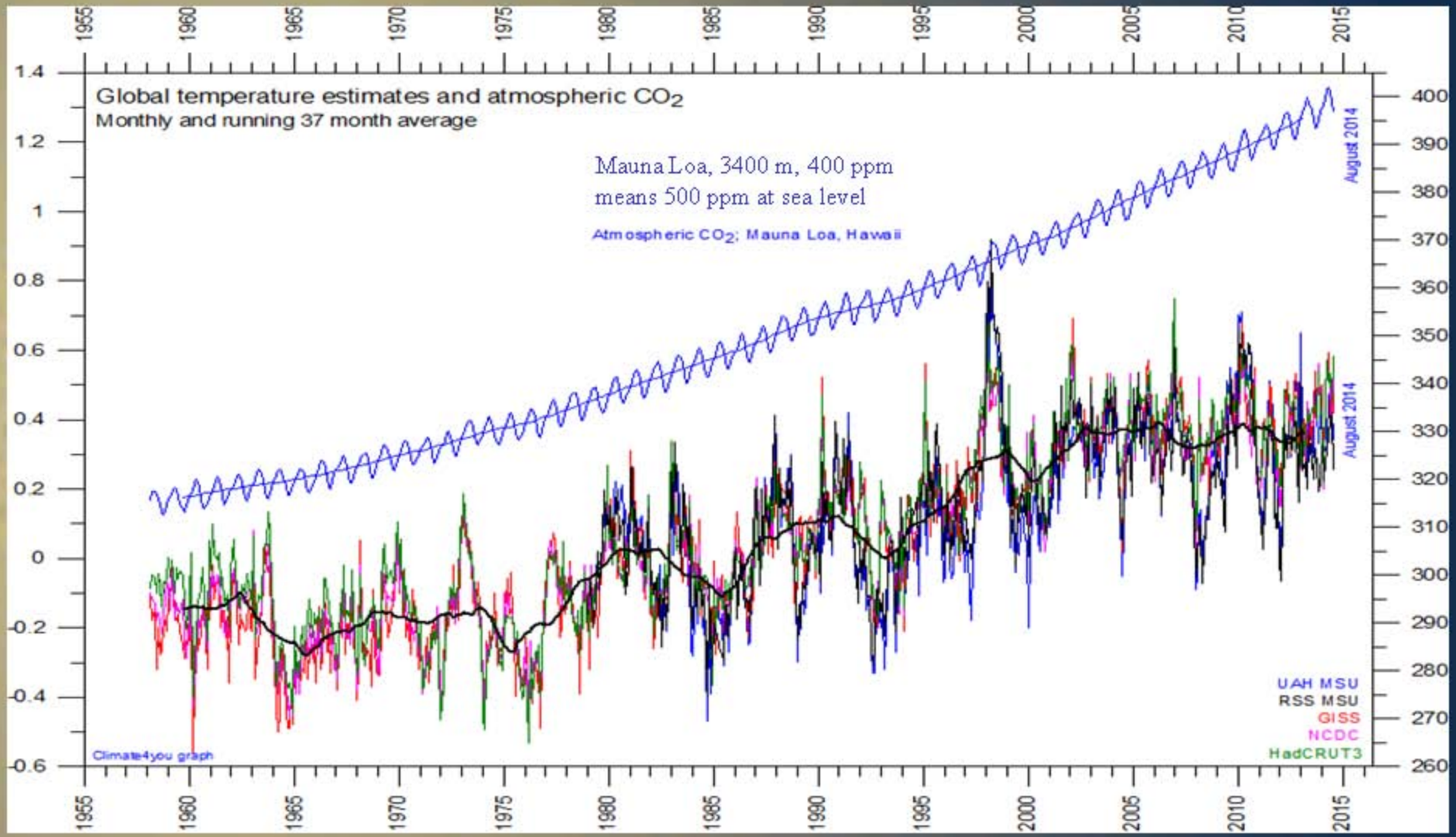
Annual global average temperature anomaly in w.r.to 1850-1920 mean

T: +0.6 °C

390
370
350
0.6
0.4
0.2
0
-0.2
-0.4
1850 1870 1890 1910 1930 1950 1970 1990 2010

Artwork by J. Kapusta - from S. Brand, *Nature* **450**, 797 (2007)

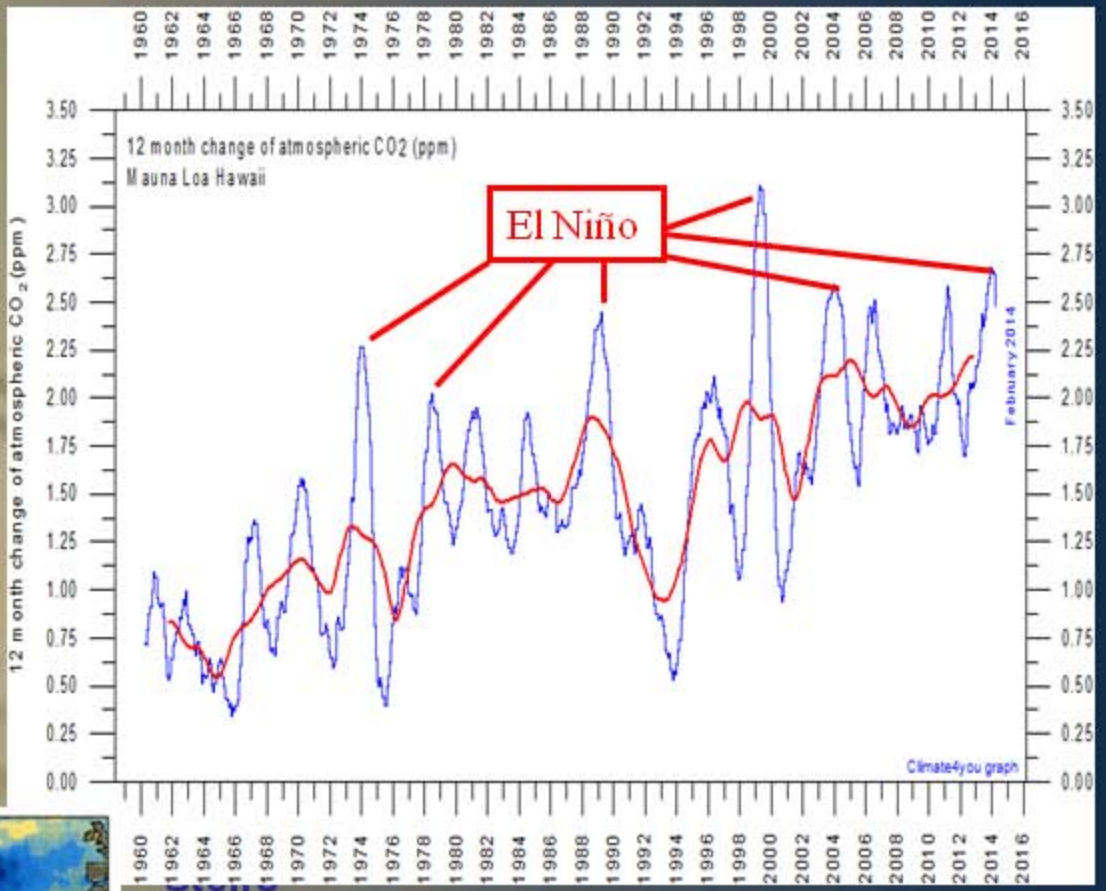
Correlation appears weaker in last two decades

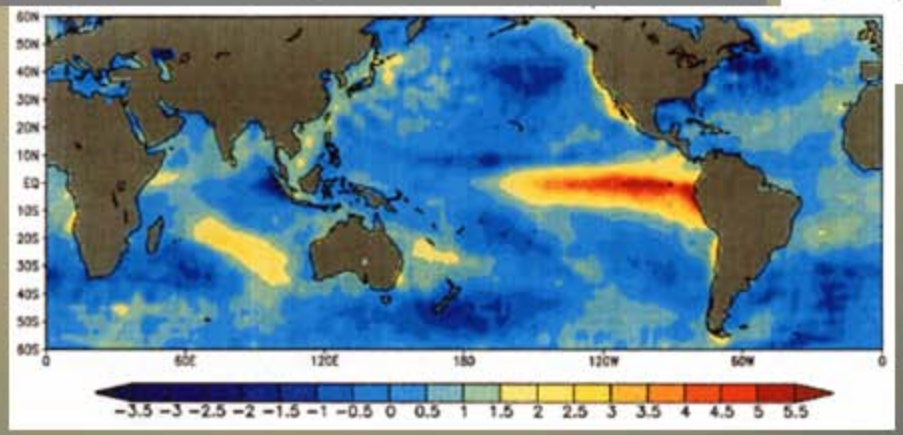


Irregular fine variations in CO2 concentration

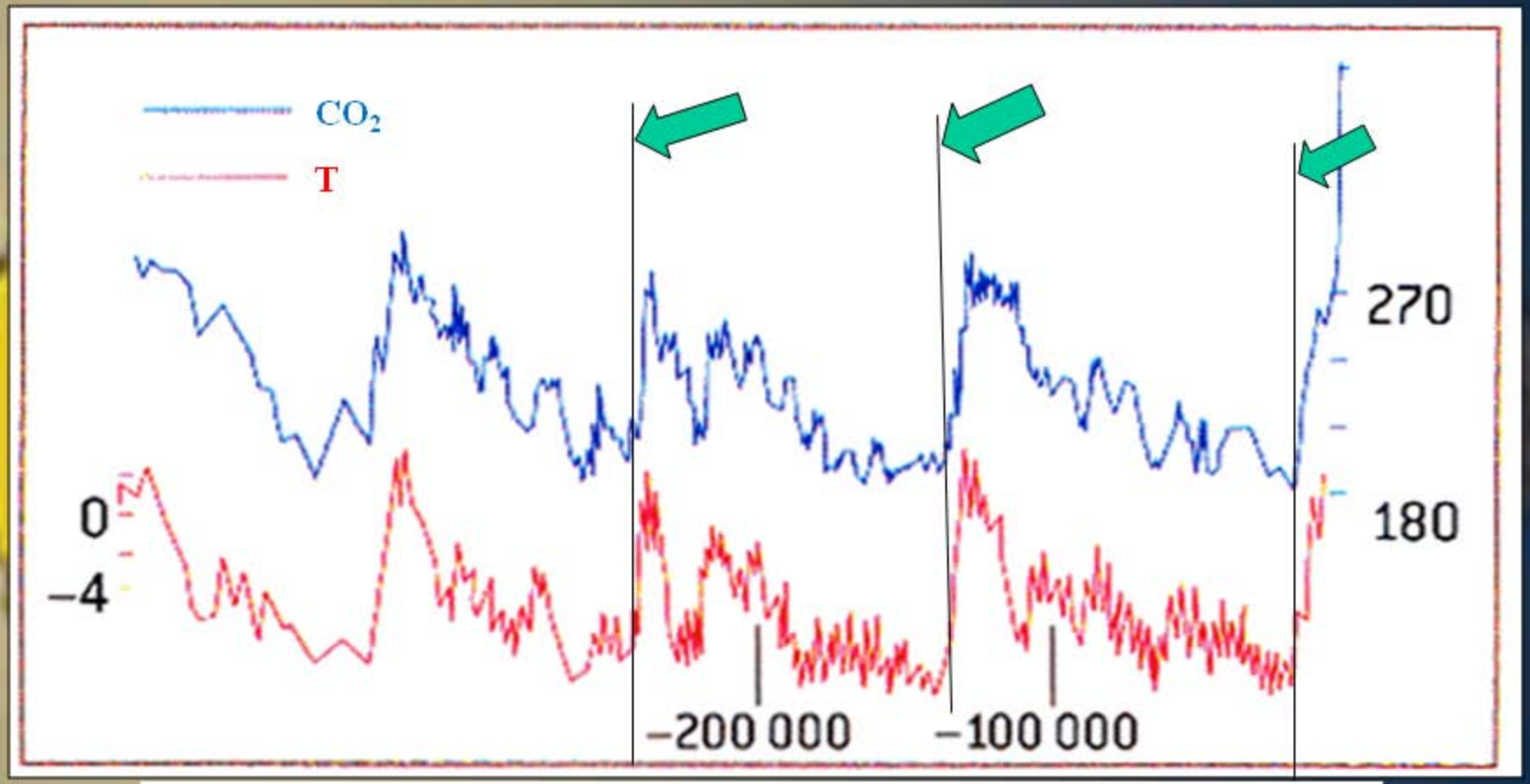
Anthropic immissions are steady,
fine variations in concentration are not as regular.

Very much affected by the natural periodic phenomenon known as El Niño (involves ocean-atmosphere interactions)





Long-time historical correlation is good but CO2 seems to lag behind T, not viceversa!



At 240000 before present, temperature increase is before CO_2 increase by about 800 years.

Artwork by J. Kapusta - from
S. Brand, *Nature* **450**, 797 (2007)

The phase relation between atmospheric carbon dioxide and global temperature

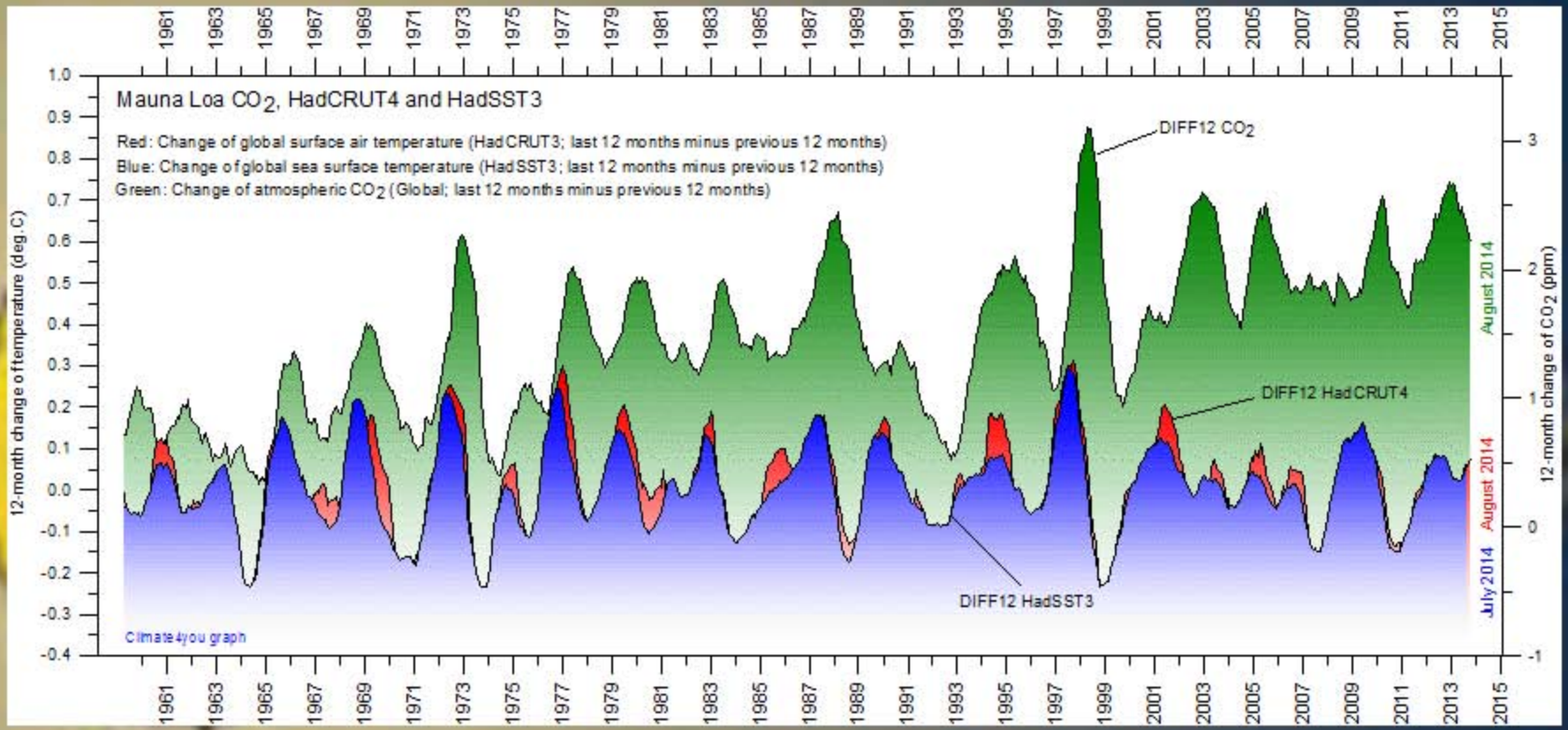
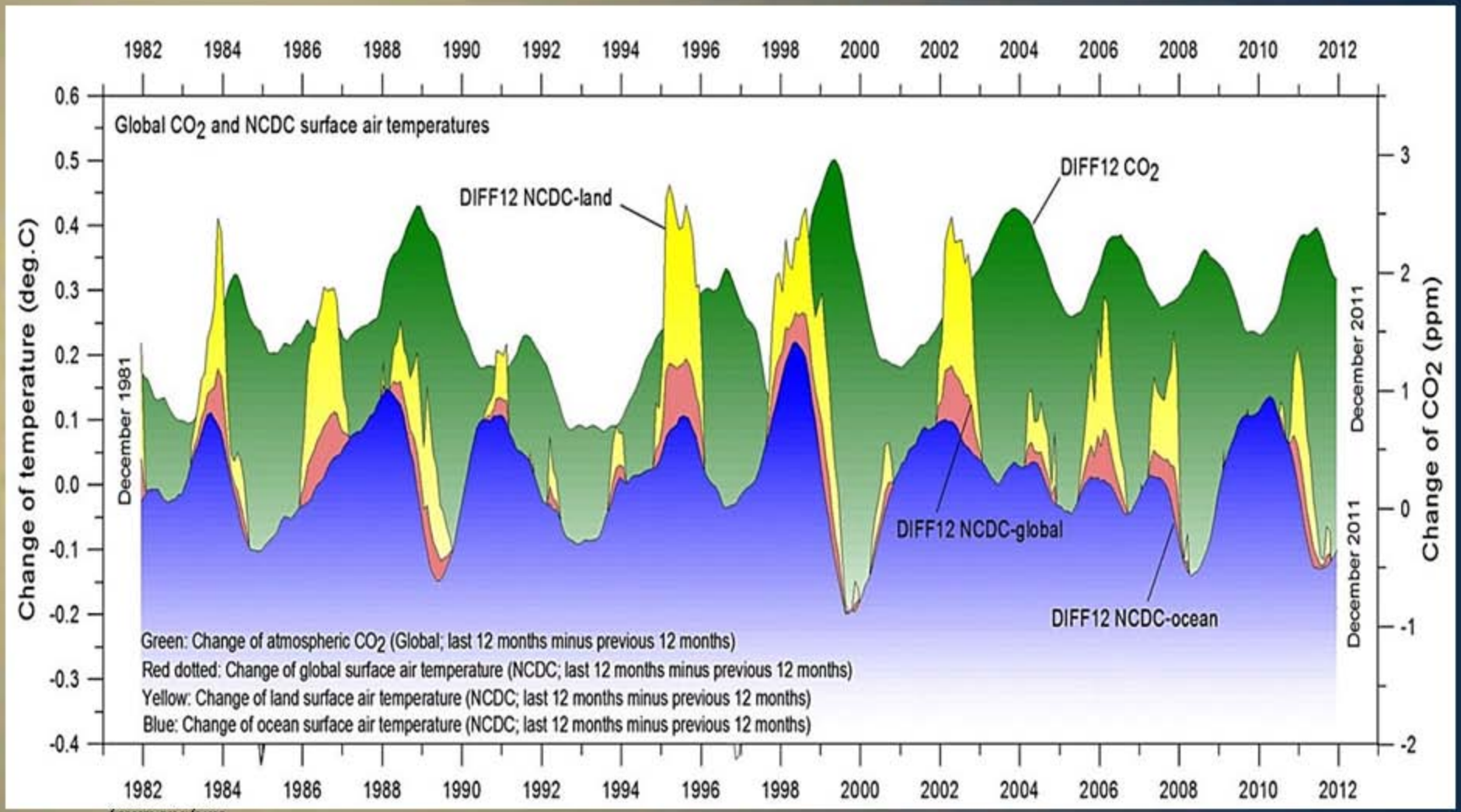


Figure taken from http://www.climate4you.com/. Ice cores show atmospheric CO_2 variations to lag behind atmospheric temperature changes on a century to millennium scale, but modern temperature is expected to lag changes in atmospheric CO_2, as the atmospheric temperature increase since about 1975 generally is assumed to be caused by the modern increase in CO_2. The maximum positive correlation between CO_2 and temperature is found for ***CO_2 lagging 11–12 months in relation to global sea surface temperature, 9.5–10 months to global surface air temperature****, and about 9 months to global lower troposphere temperature.*

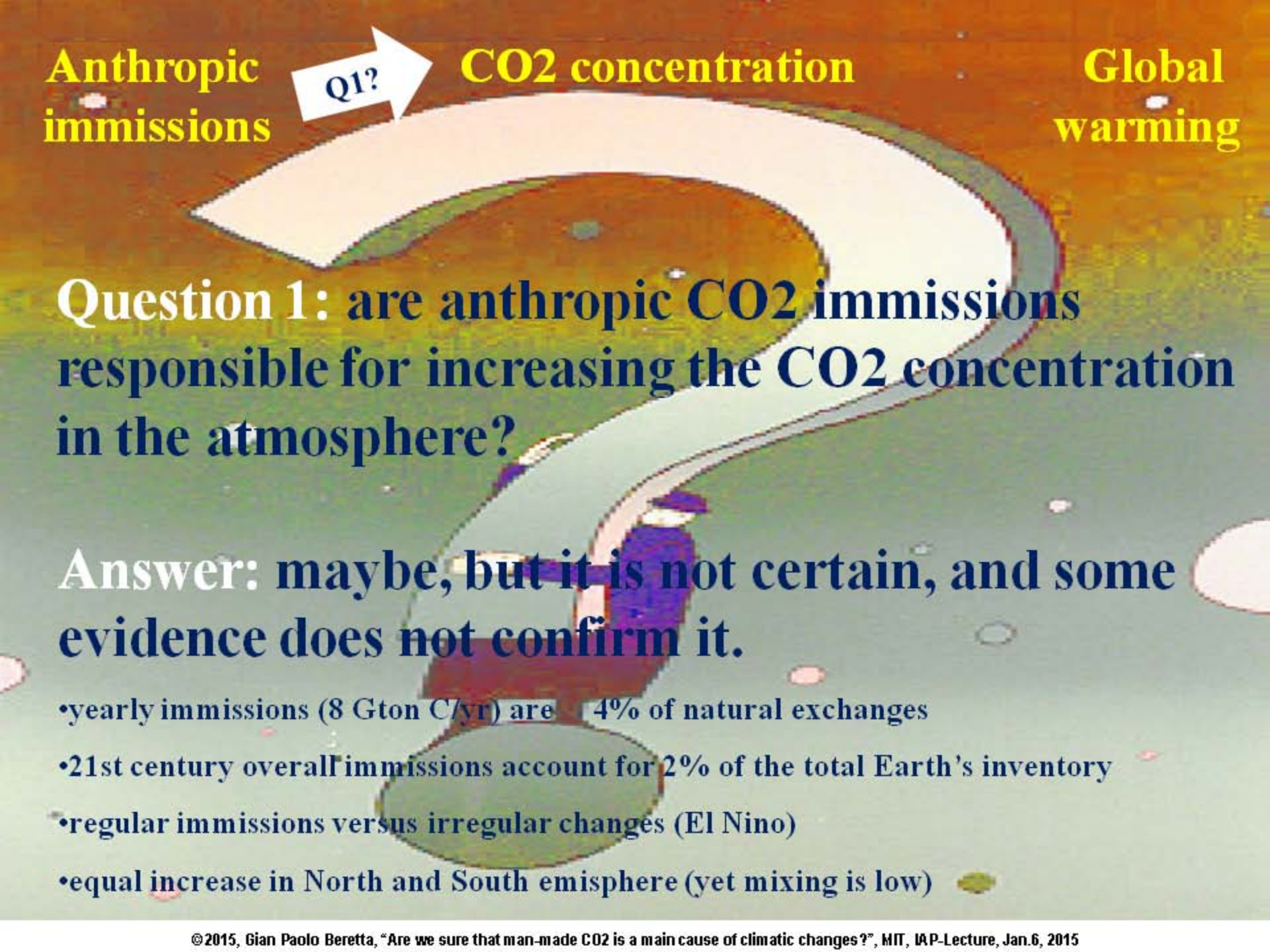
(last 50 years)

The phase relation between atmospheric carbon dioxide and global temperature



temperature.

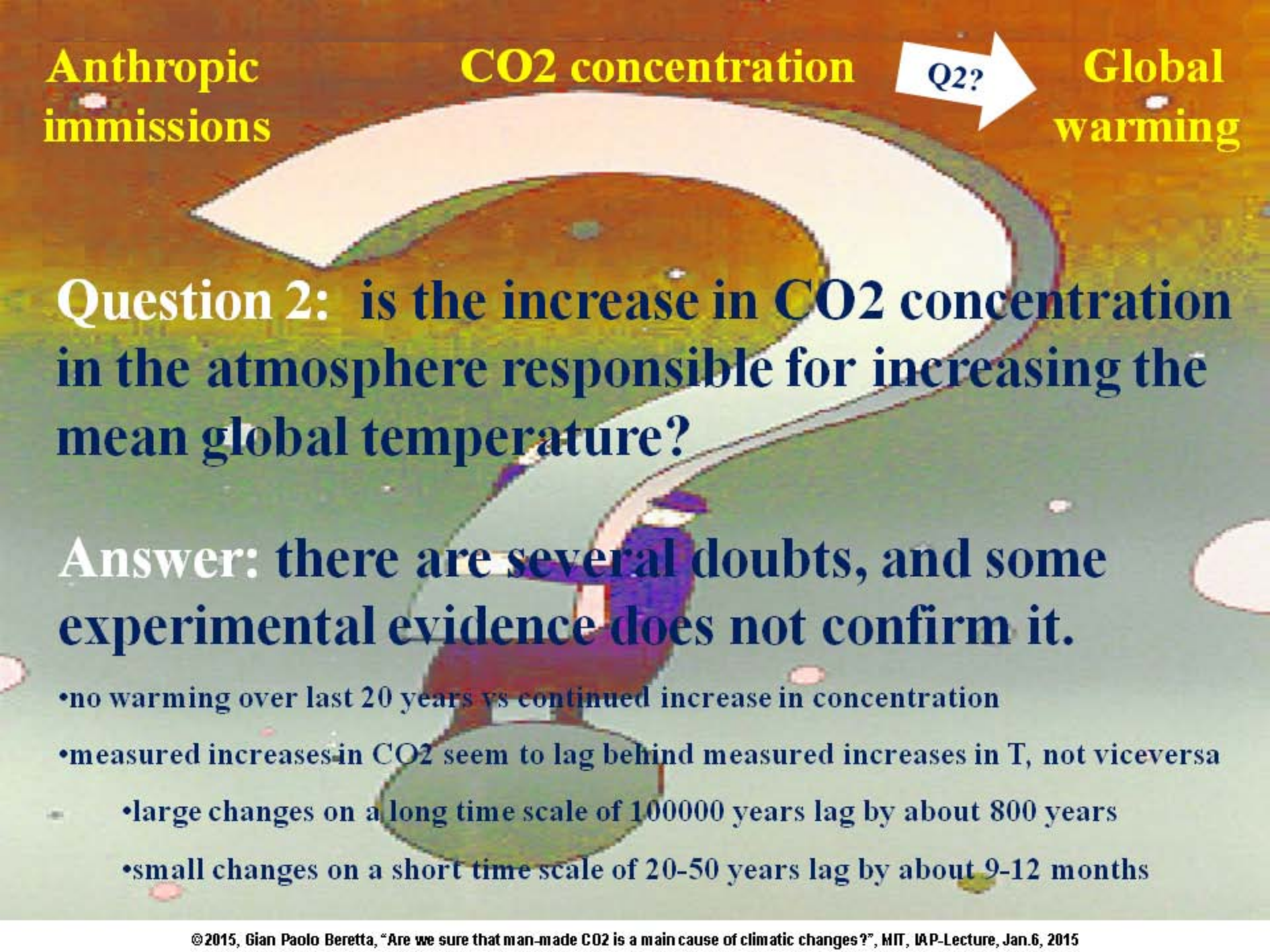
(last 20 years)



Question 1: are anthropic CO2 immissions responsible for increasing the CO2 concentration in the atmosphere?

Answer: maybe, but it is not certain, and some evidence does not confirm it.

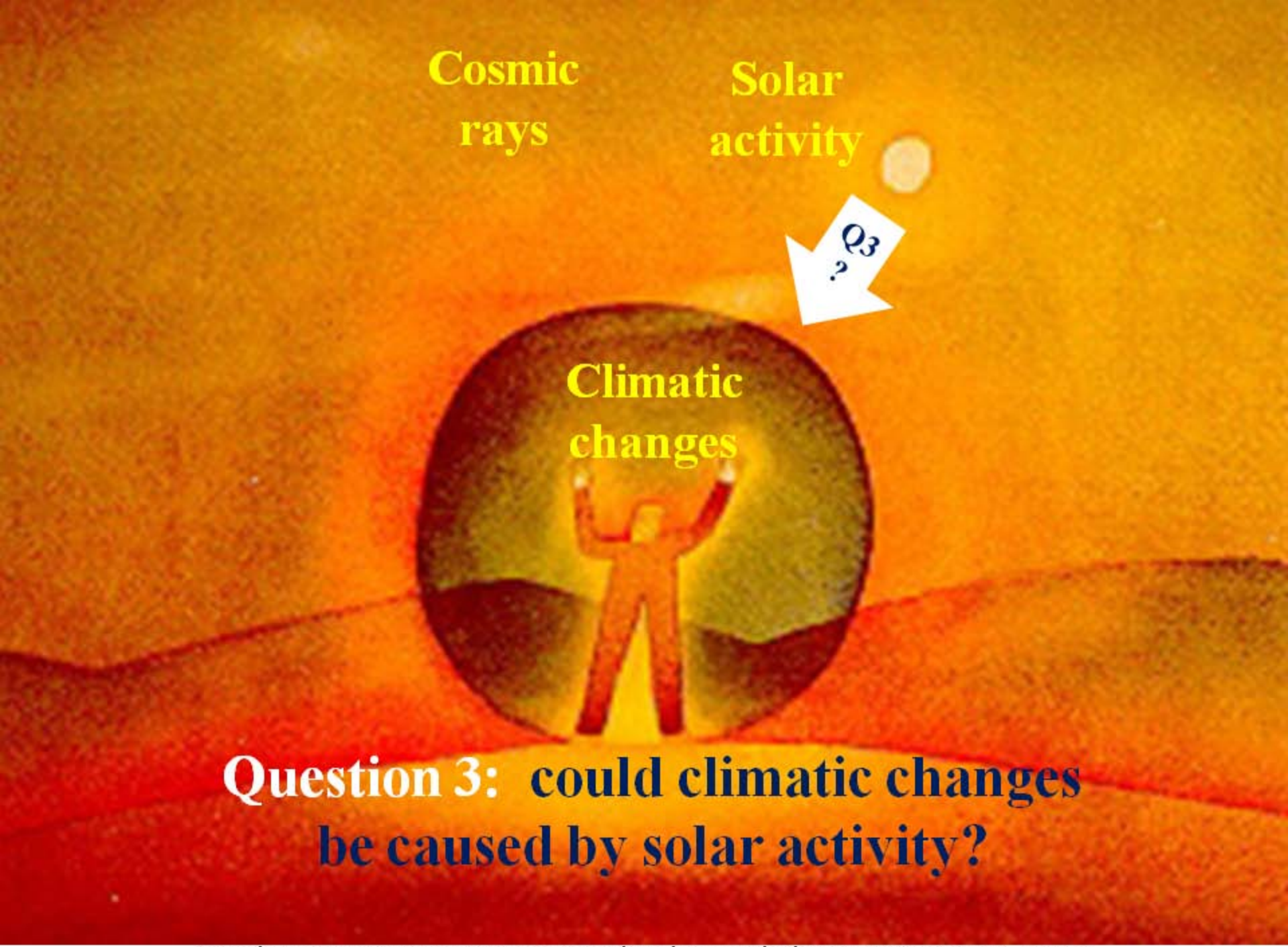
- yearly immissions (8 Gton C/yr) are 4% of natural exchanges
- 21st century overall immissions account for 2% of the total Earth's inventory
- regular immissions versus irregular changes (El Nino)
- equal increase in North and South emisphere (yet mixing is low)



Question 2: is the increase in CO2 concentration in the atmosphere responsible for increasing the mean global temperature?

Answer: there are several doubts, and some experimental evidence does not confirm it.

- no warming over last 20 years vs continued increase in concentration
- measured increases in CO2 seem to lag behind measured increases in T, not viceversa
  - large changes on a long time scale of 100000 years lag by about 800 years
  - small changes on a short time scale of 20-50 years lag by about 9-12 months



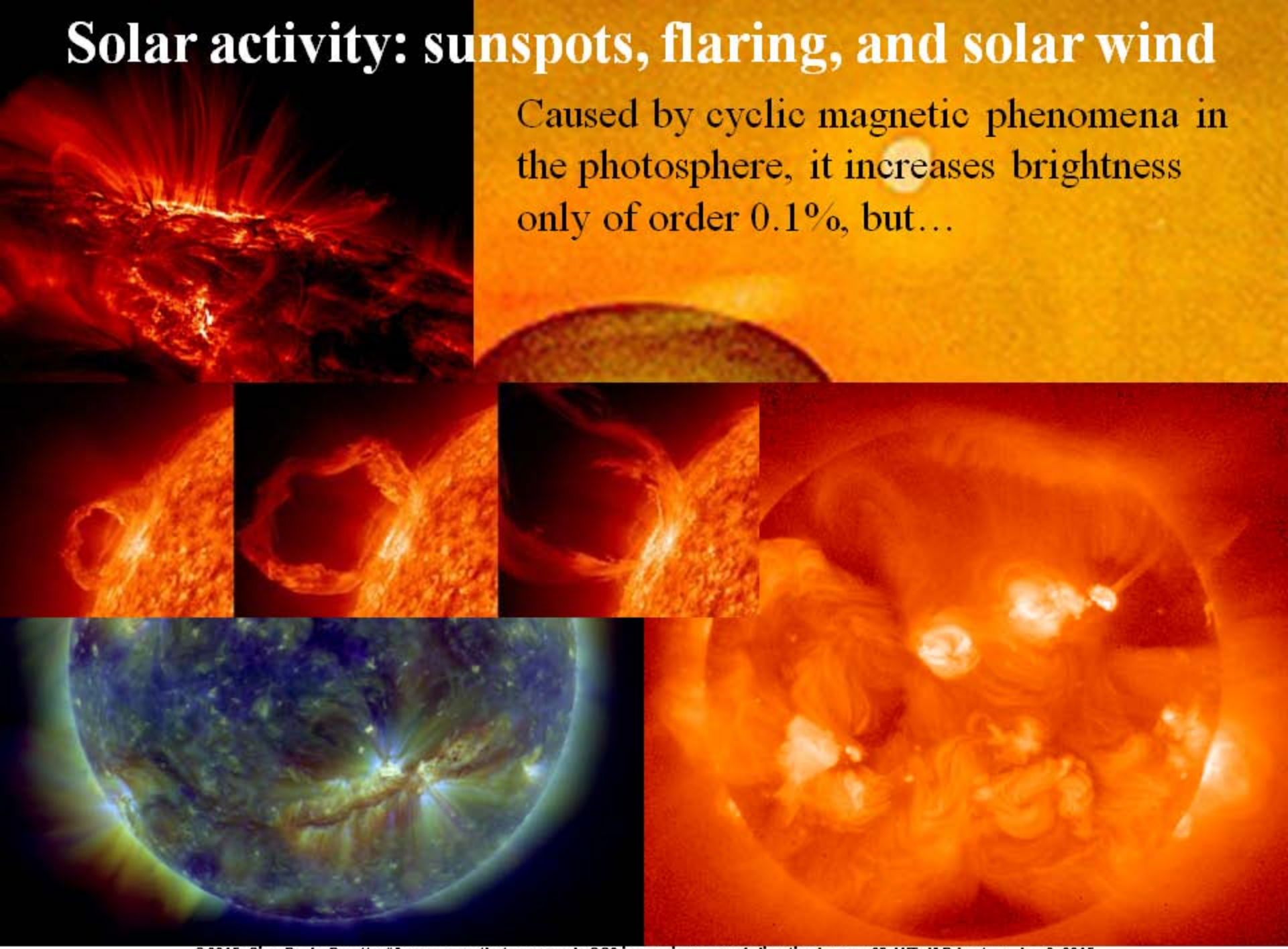
Question 3: could climatic changes be caused by solar activity?

Some preliminary observations:

- during the last few decades also other planets (Mars, Jupiter, Neptune and Pluto) and their satellites have shown clear signs of warming
  - Mars +0.65°C in the last 30 years
  - data seem well correlated with Earth's data
- measured variations in solar irradiance (0.1%) cannot explain such large changes
- changes have been attributed to albedo variations

Solar activity: sunspots, flaring, and solar wind

Caused by cyclic magnetic phenomena in the photosphere, it increases brightness only of order 0.1%, but…



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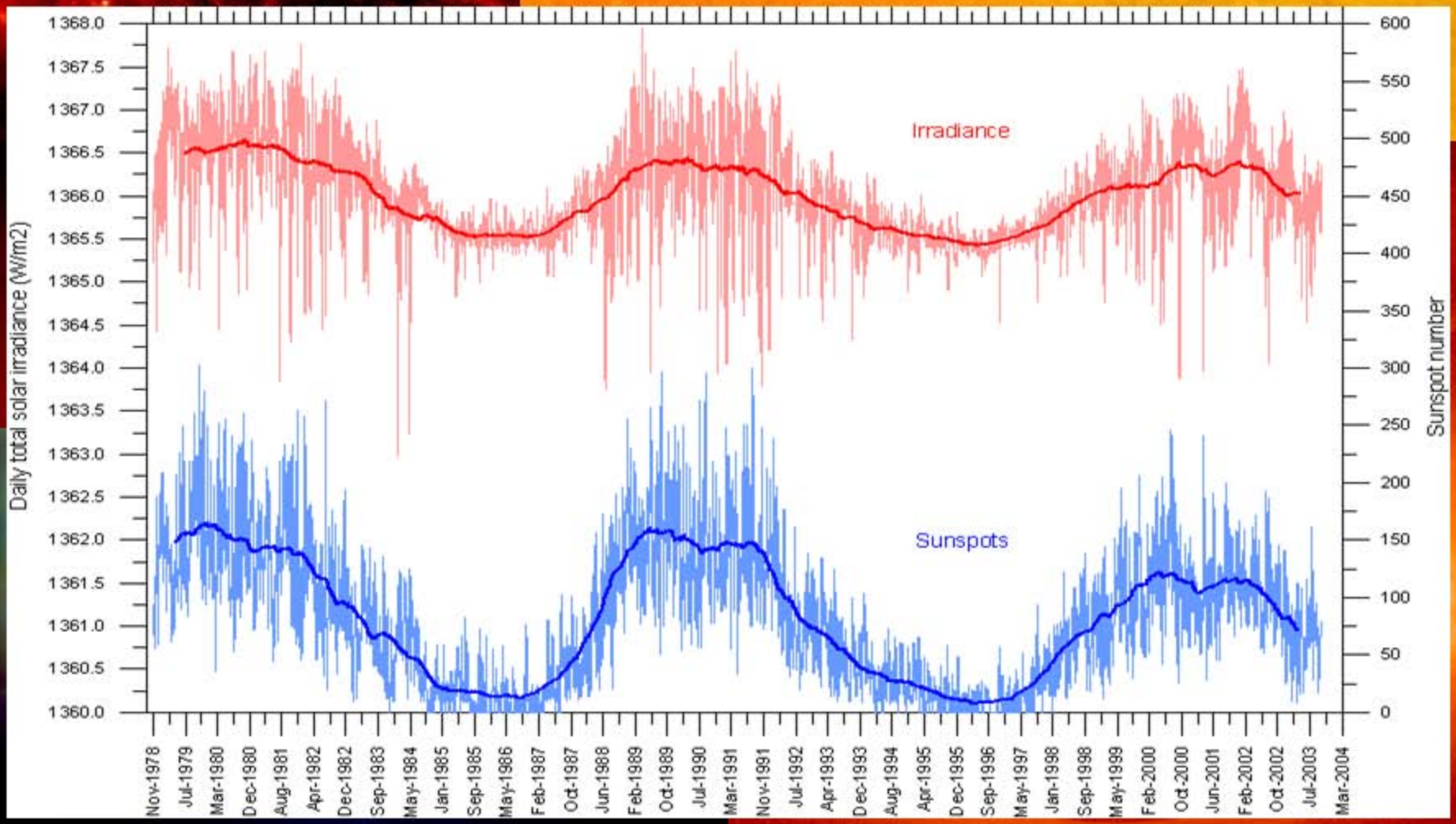
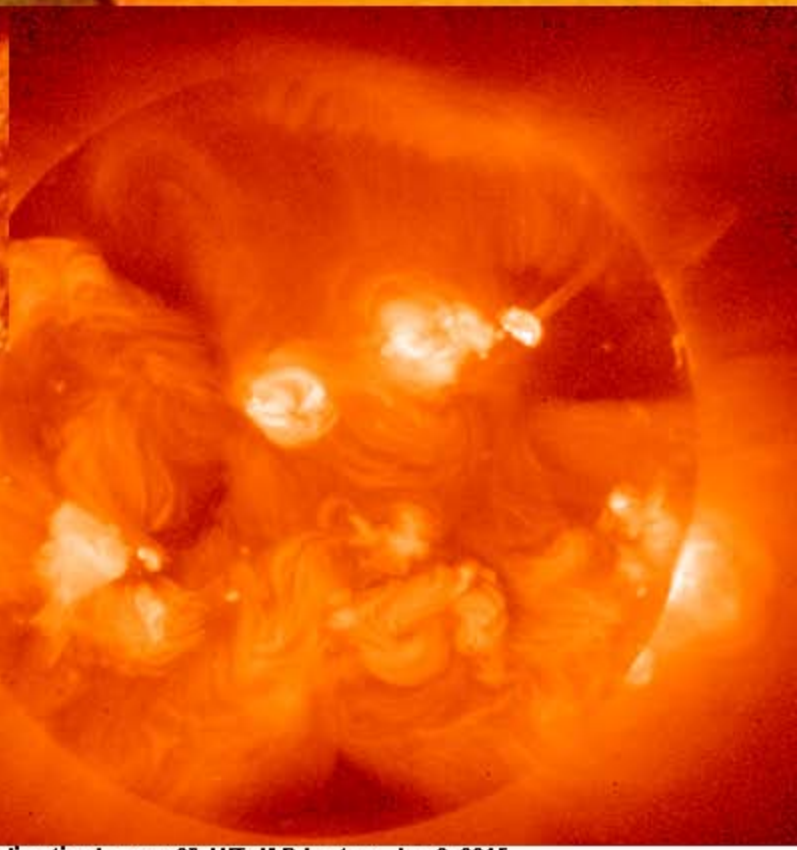
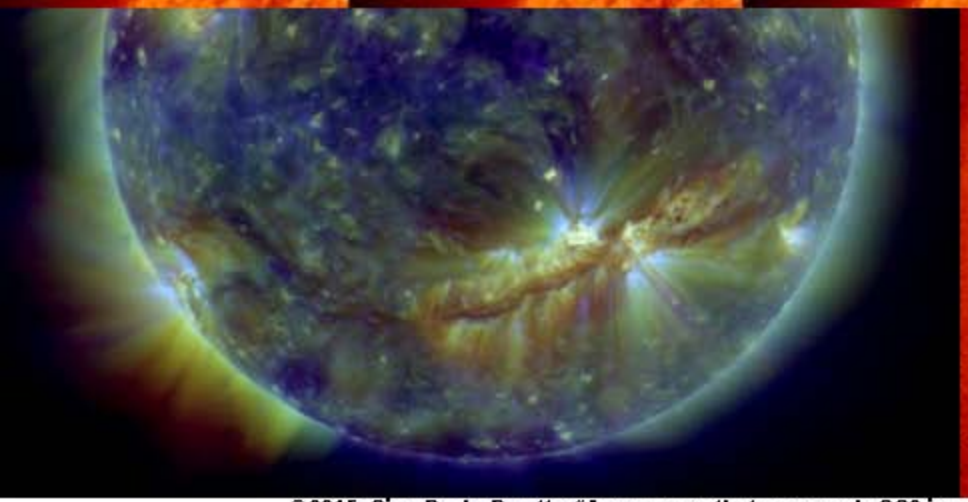


Solar activity: sunspots, flaring, and solar wind

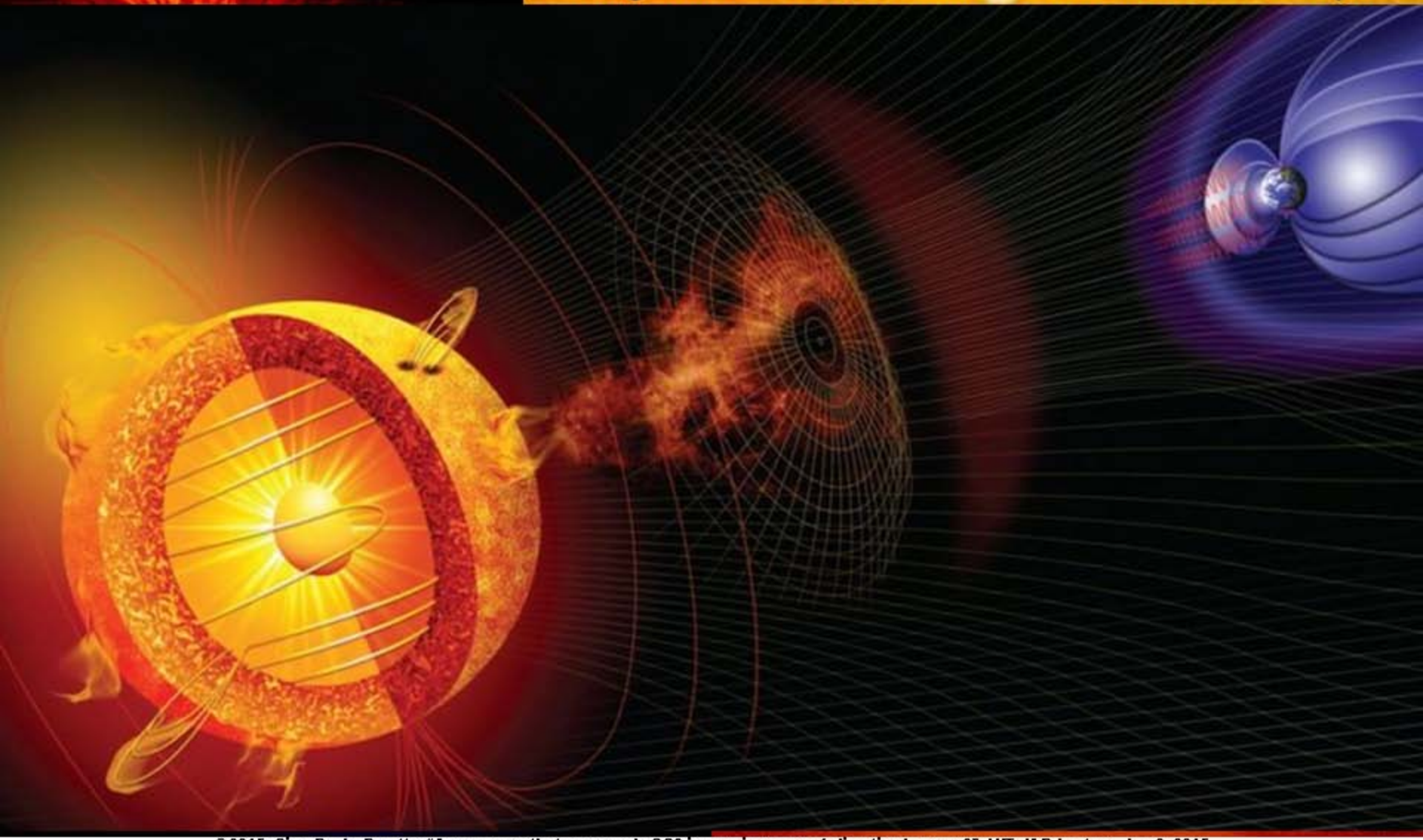
Caused by cyclic magnetic phenomena in the photosphere, it increases brightness only of order 0.1%, but it produces flares and solar wind (charged particles reaching the Earth and the other Planets).





Solar activity: sunspots, flaring, and solar wind

Solar wind, deflected by the Earth's magnetic field, shields it from cosmic rays.



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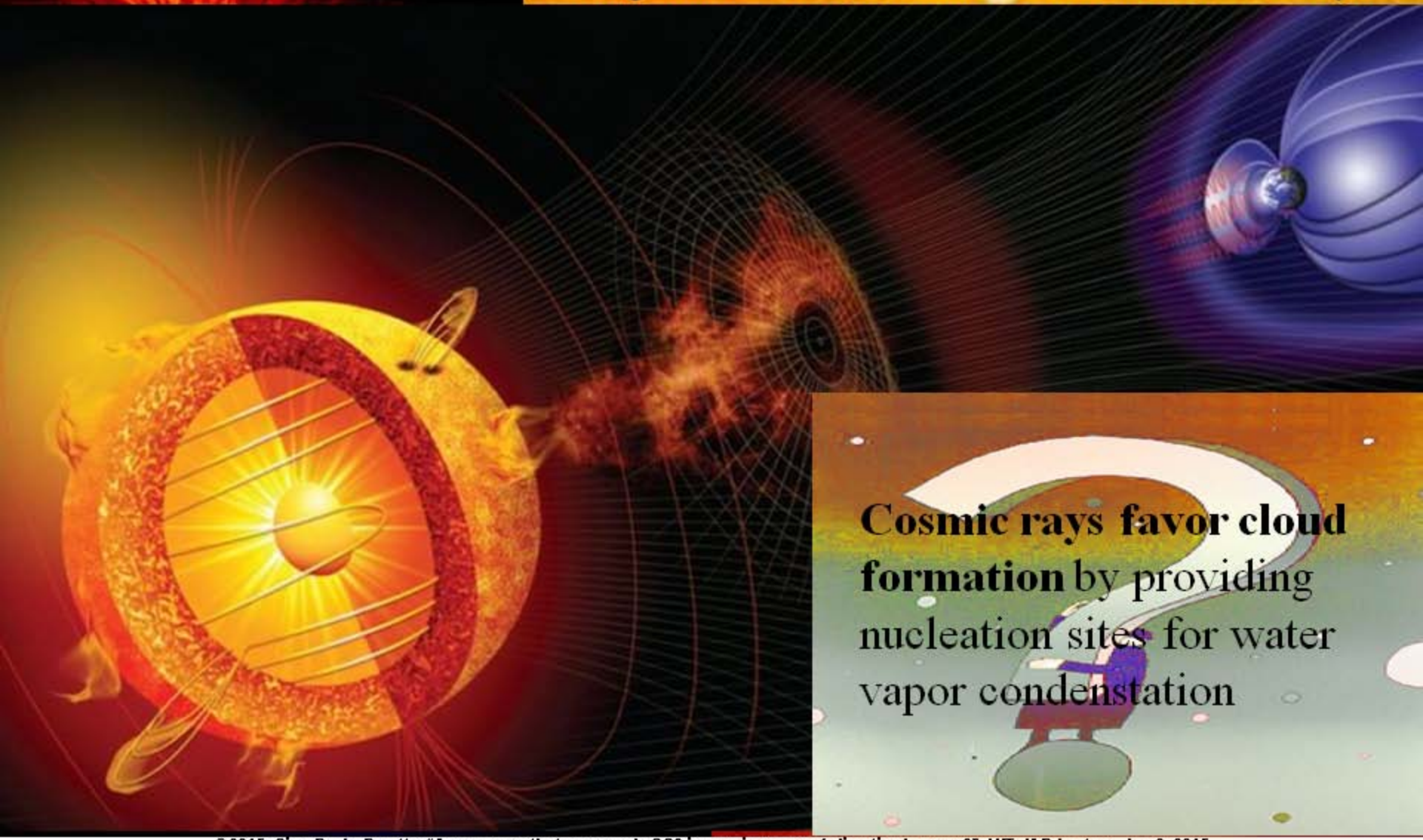

Cosmic rays favor cloud formation by providing nucleation sites for water vapor condenstation

Solar activity: sunspots, flaring, and solar wind

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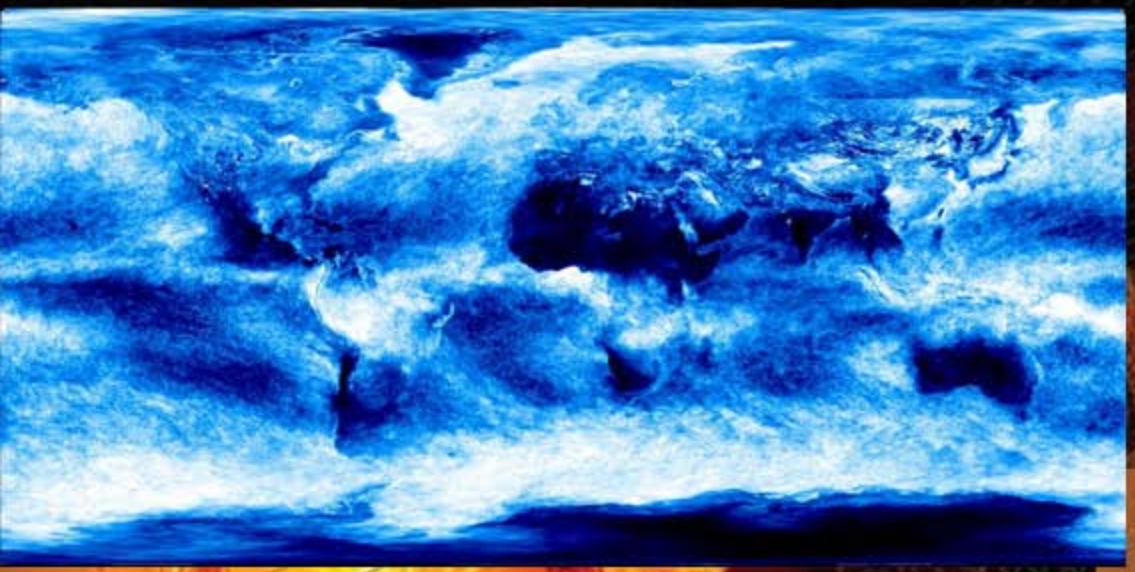
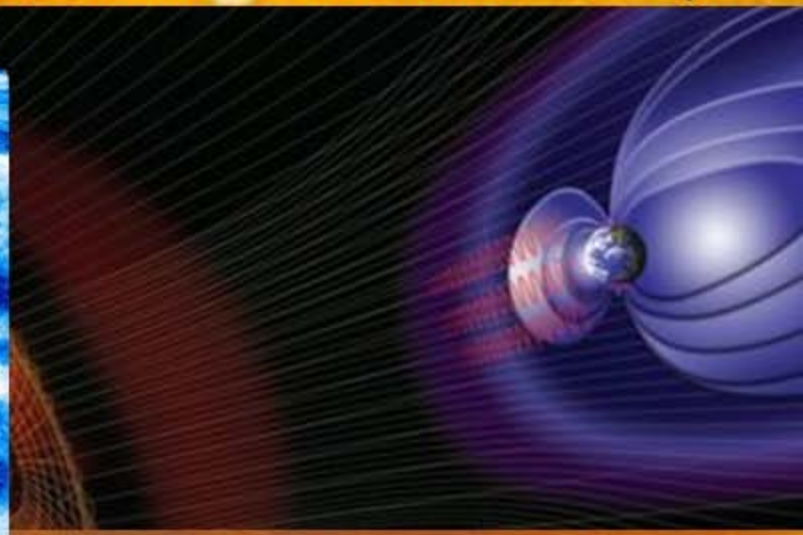
Clouds albedo





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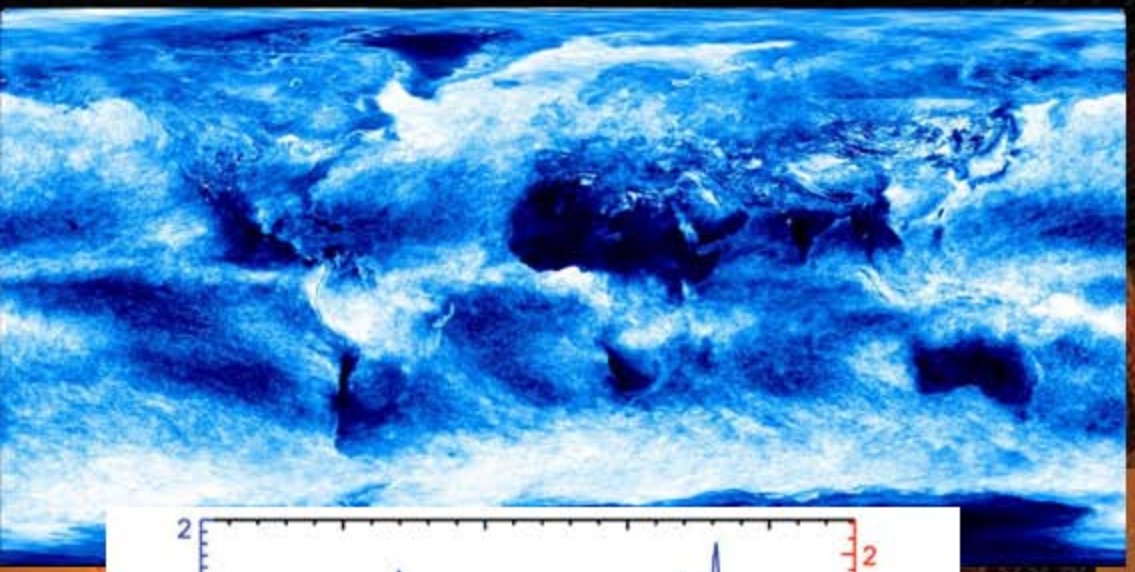
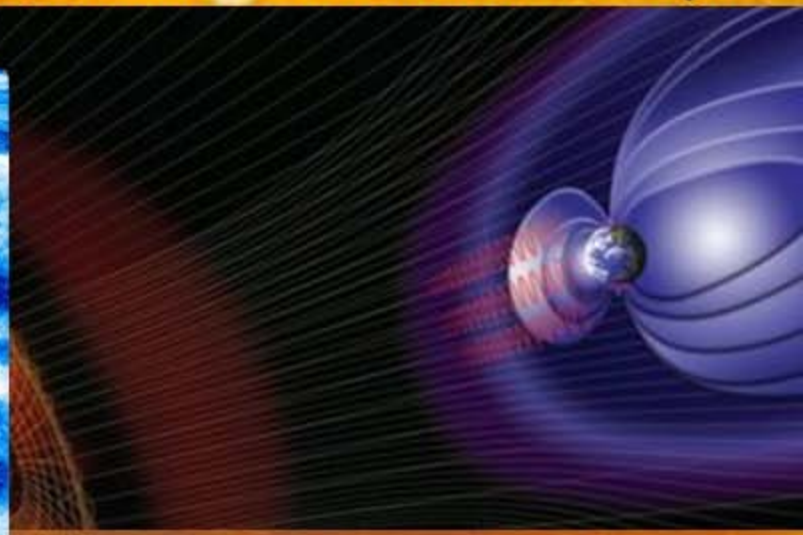
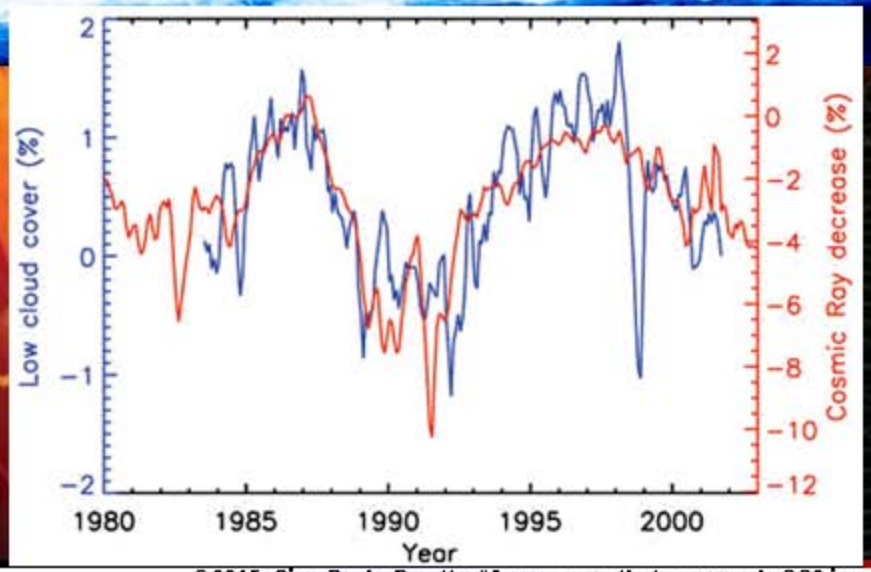


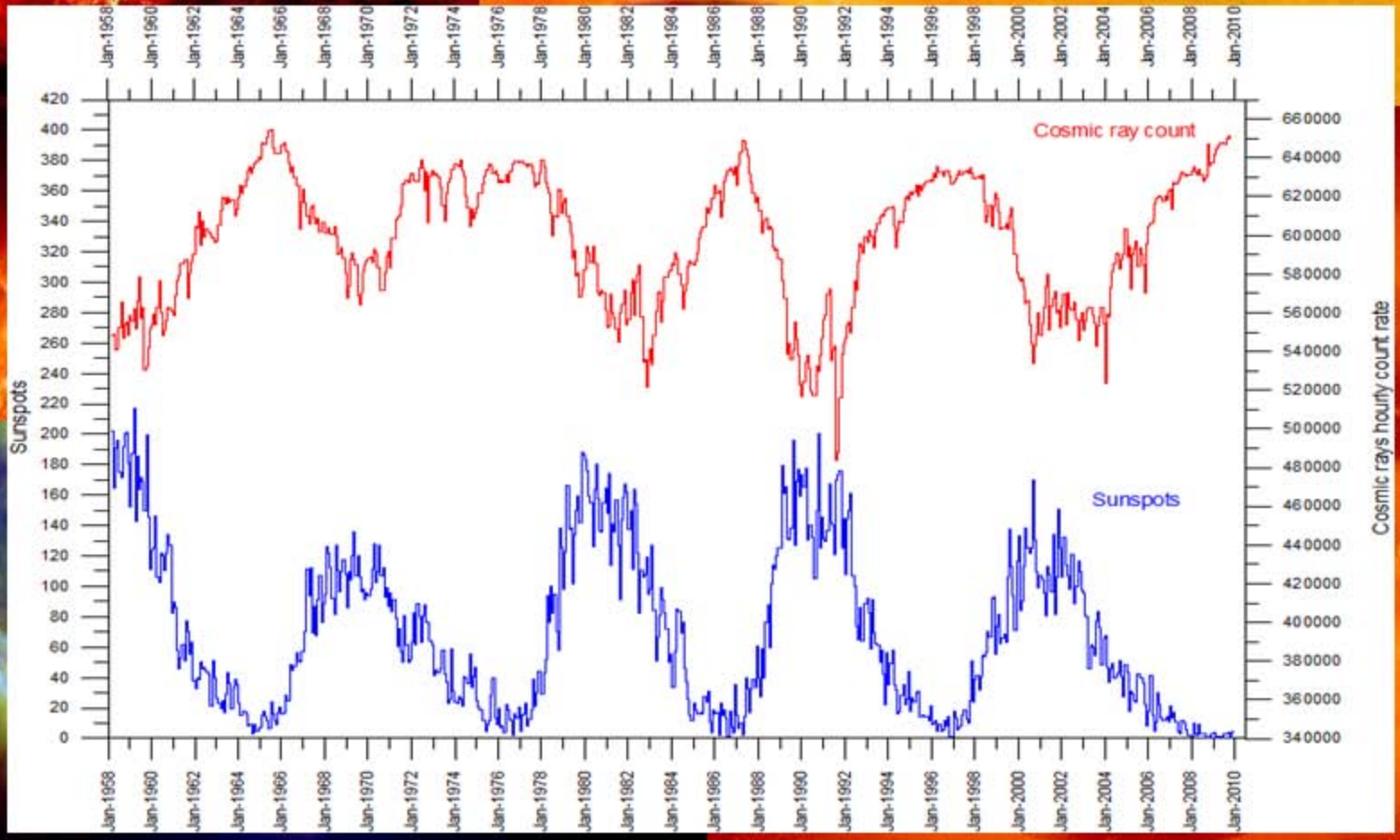




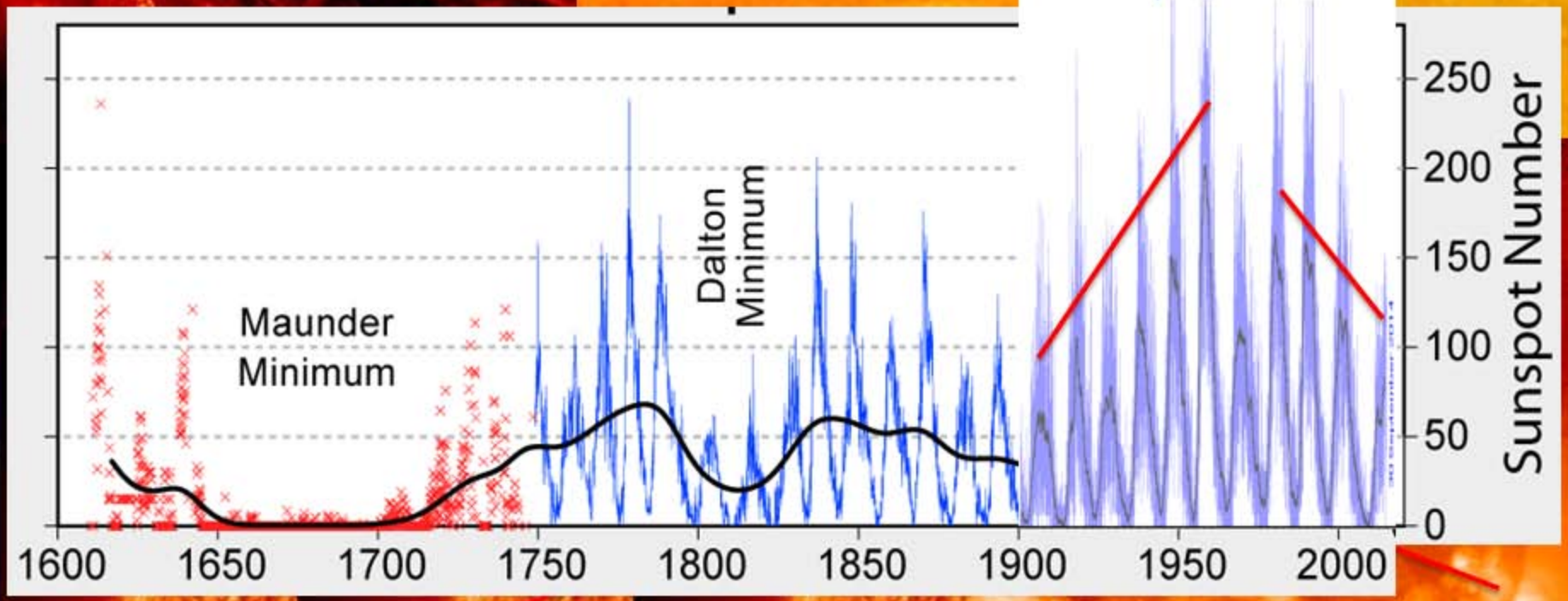
Cosmic rays favor cloud formation by providing nucleation sites for water vapor condenstation.

Solar activity: sunspots, flaring, and solar wind

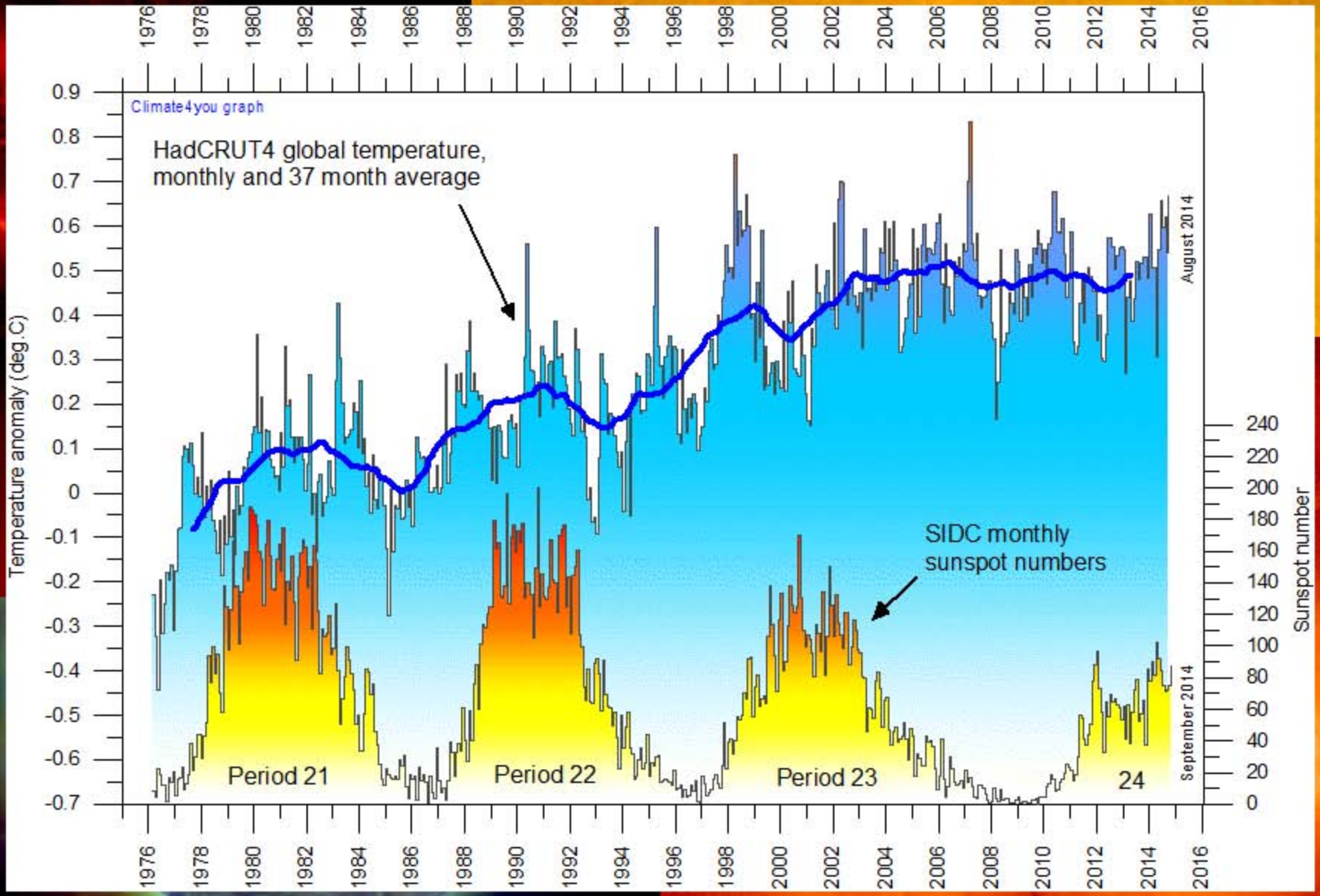
more sunspots → more solar activity → more solar wind → fewer cosmic rays → fewer clouds → smaller albedo → more effective solar heating → global warming.

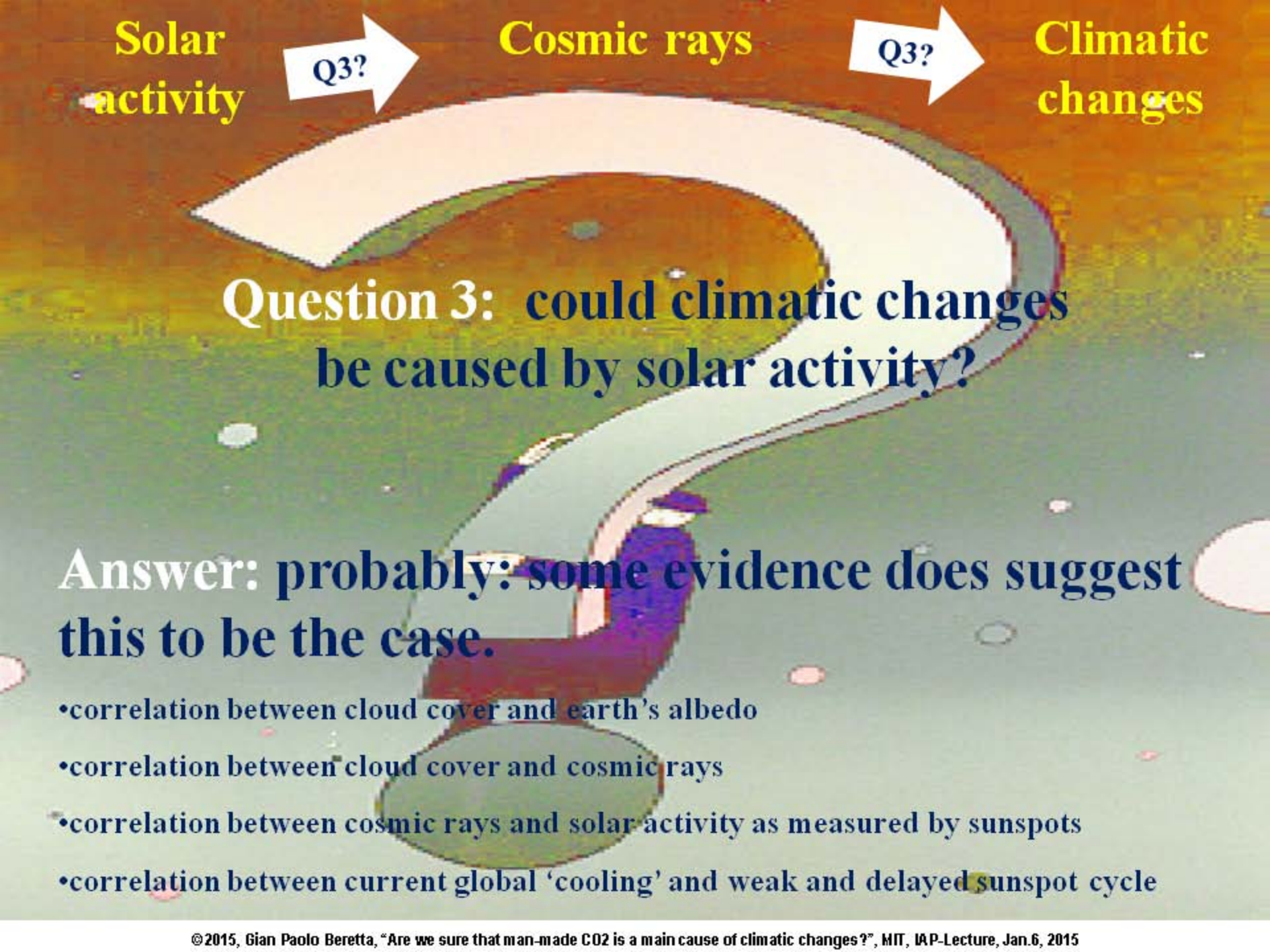


Solar activity: sunspots, flaring, and solar wind



Solar activity: currently weak and delayed cycle

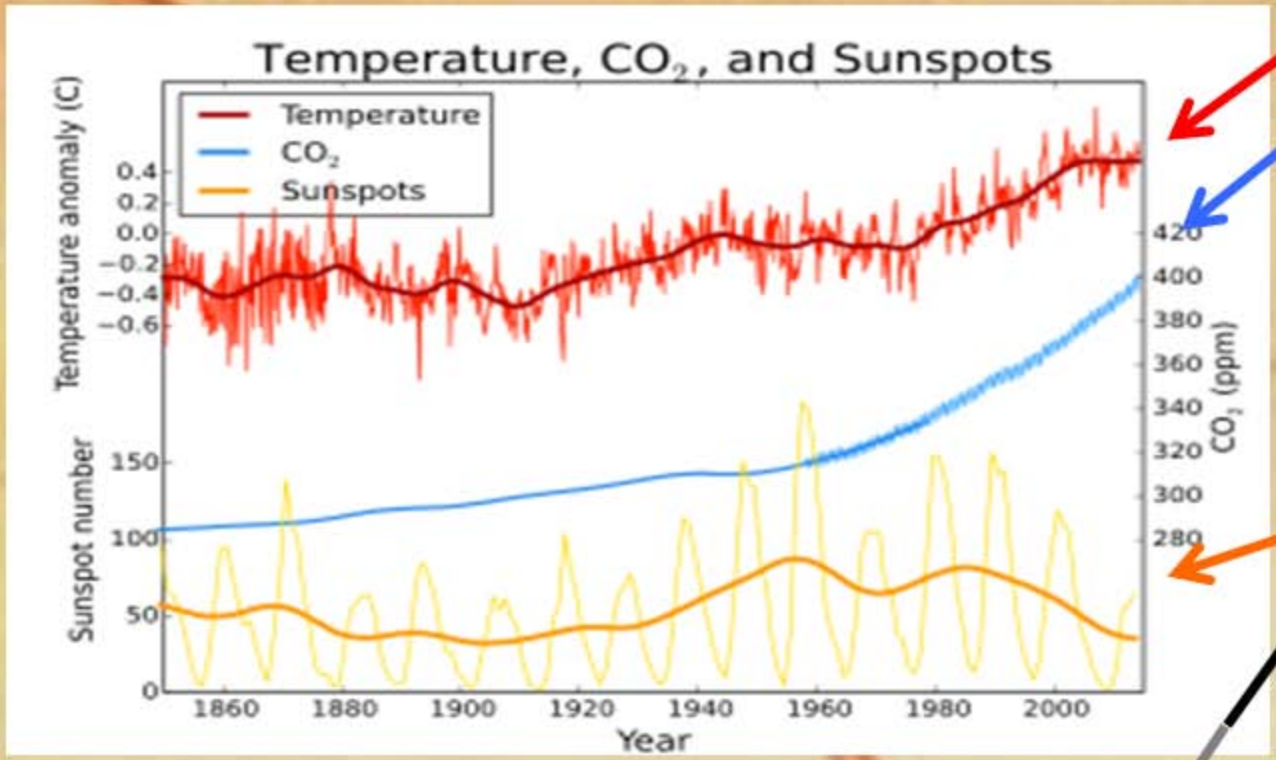




Question 3: could climatic changes be caused by solar activity?

Answer: probably: some evidence does suggest this to be the case.

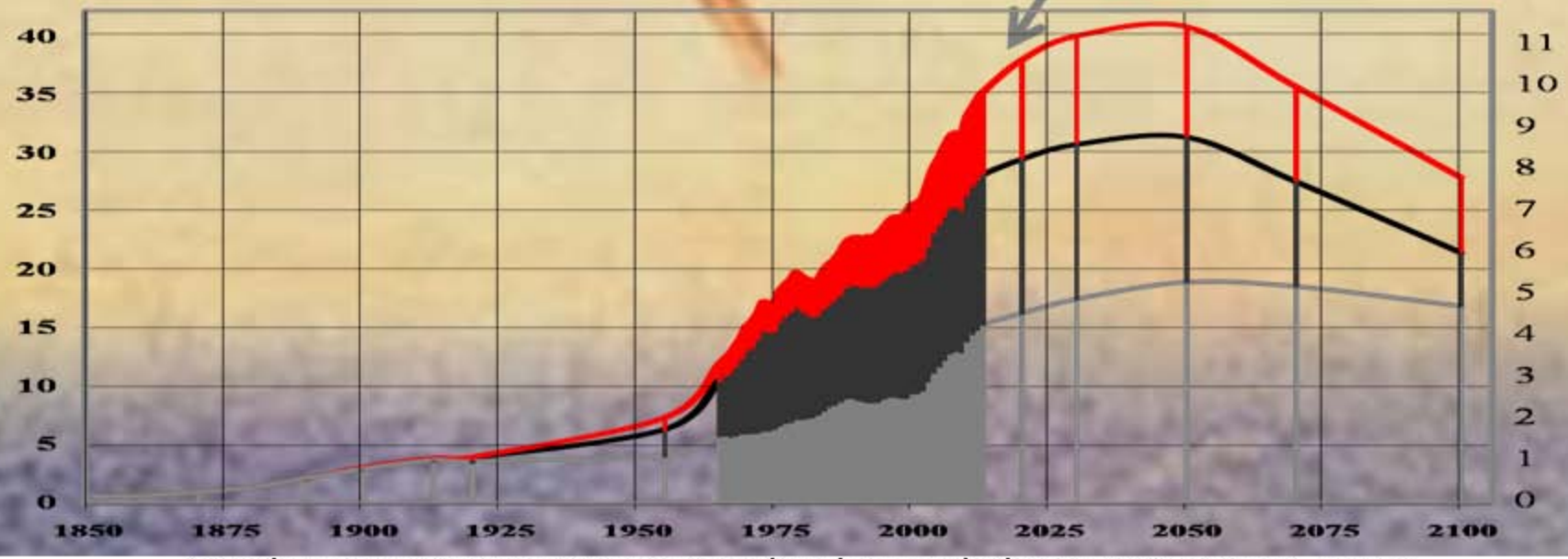
- correlation between cloud cover and earth's albedo
- correlation between cloud cover and cosmic rays
- correlation between cosmic rays and solar activity as measured by sunspots
- correlation between current global 'cooling' and weak and delayed sunspot cycle



T and
CO2 concentrations are
INTEGRATED effects of
several phenomena

Complex **modeling**
(requiring assumptions on
many many factors)

Solar activity and
CO2 immissions are <u>just</u>
<u>two</u> INSTANTANEOUS
forcing effects

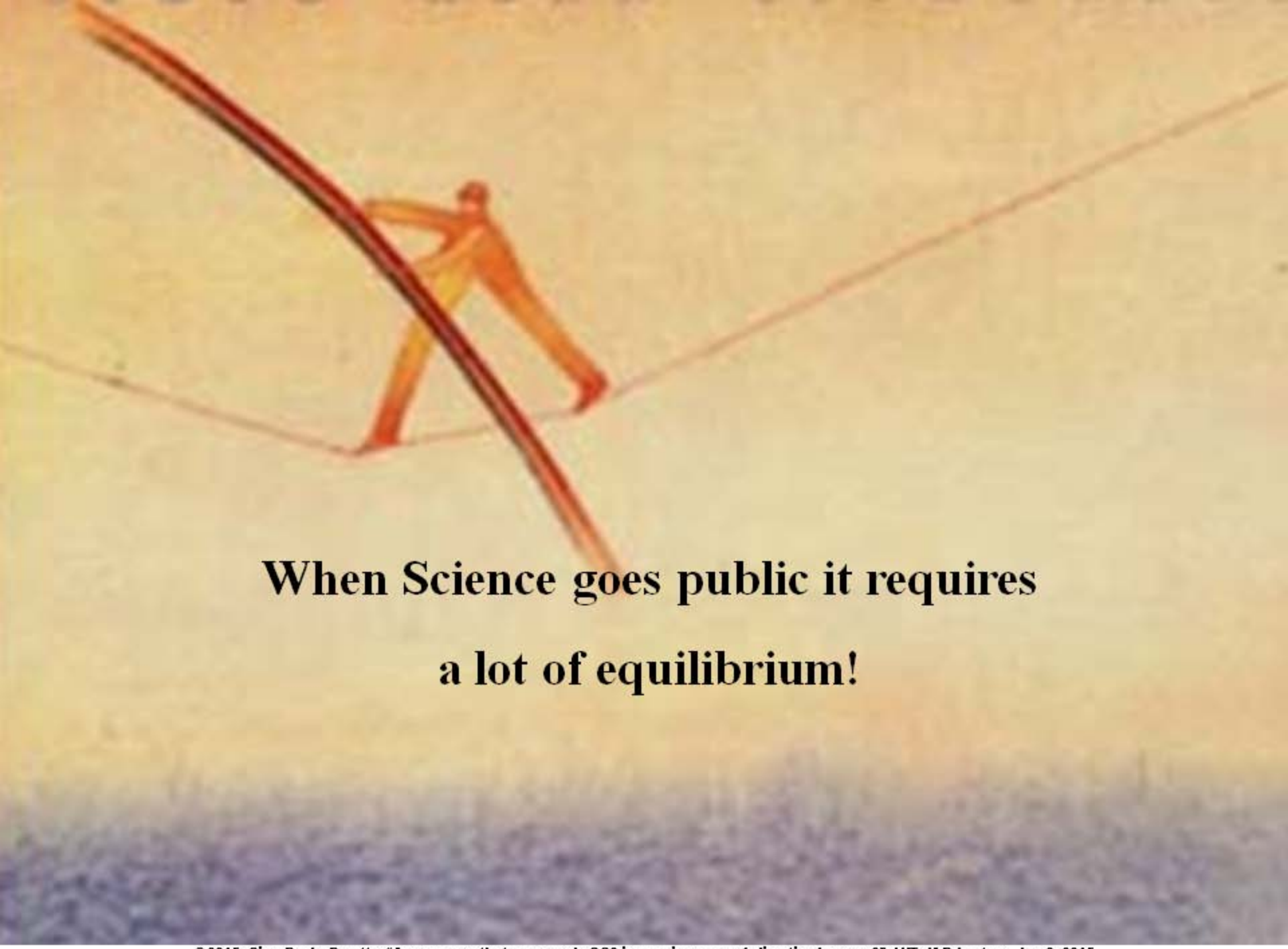


Sustainable development is tricky!

False hopes on single and simple solutions,
are fed on bad information and cheap futurology.
They cause waste of resources.

Examples:

- the 'mirage' of a hydrogen economy
- market distortions due to impulsive energy policies



Has a serious alert been called for climatic changes?

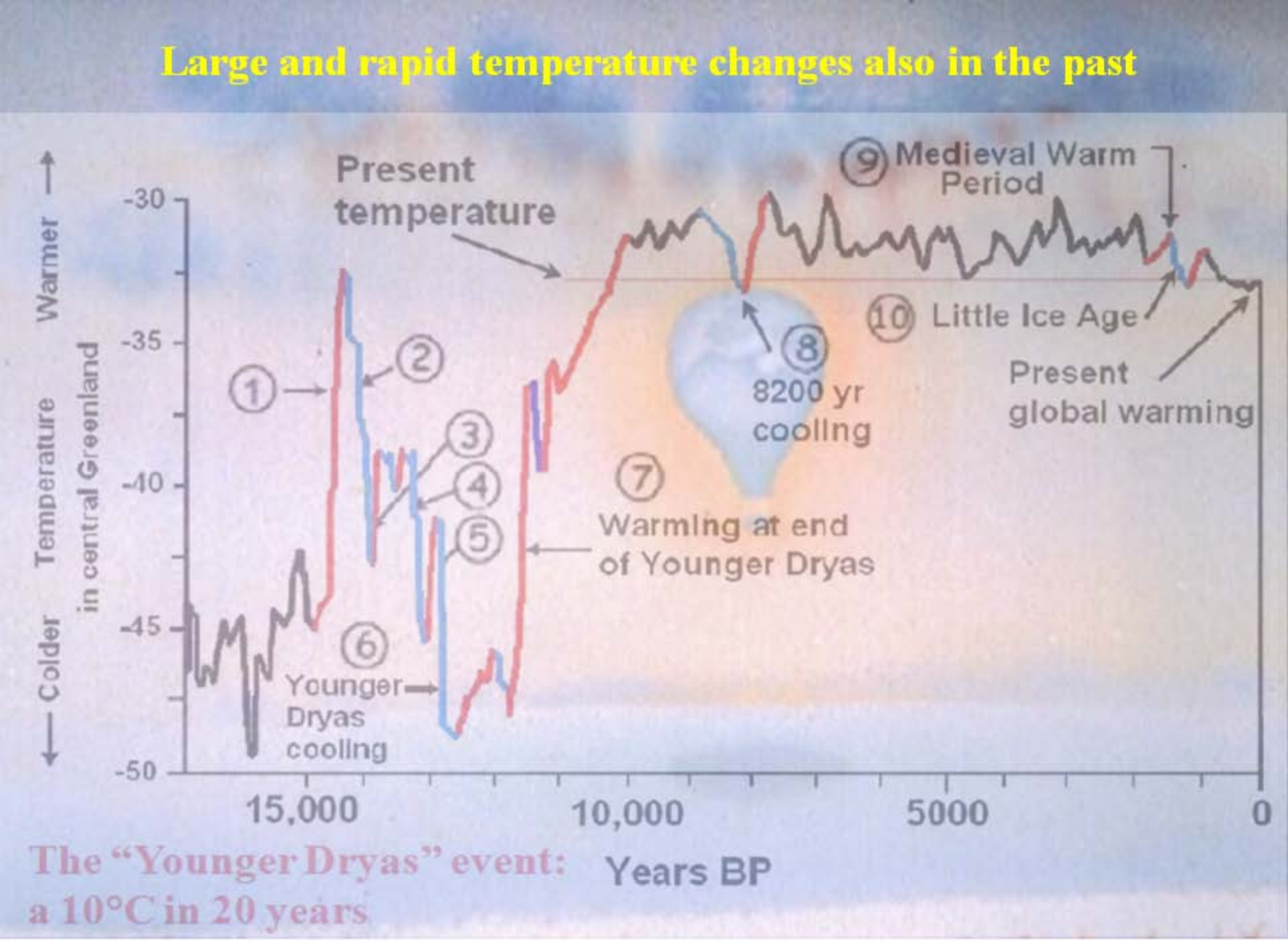
Climate change is not felt as the most important problem for the future of human kind. There are other more serious priorities (Copenhagen Consensus 2012):

- **- malnutrition in poor countries**
- **- alphabetization**
- **- deseases (malaria, tuberculosis, AIDS in particular)**
- **- availability of vaccins (Ebola?)**

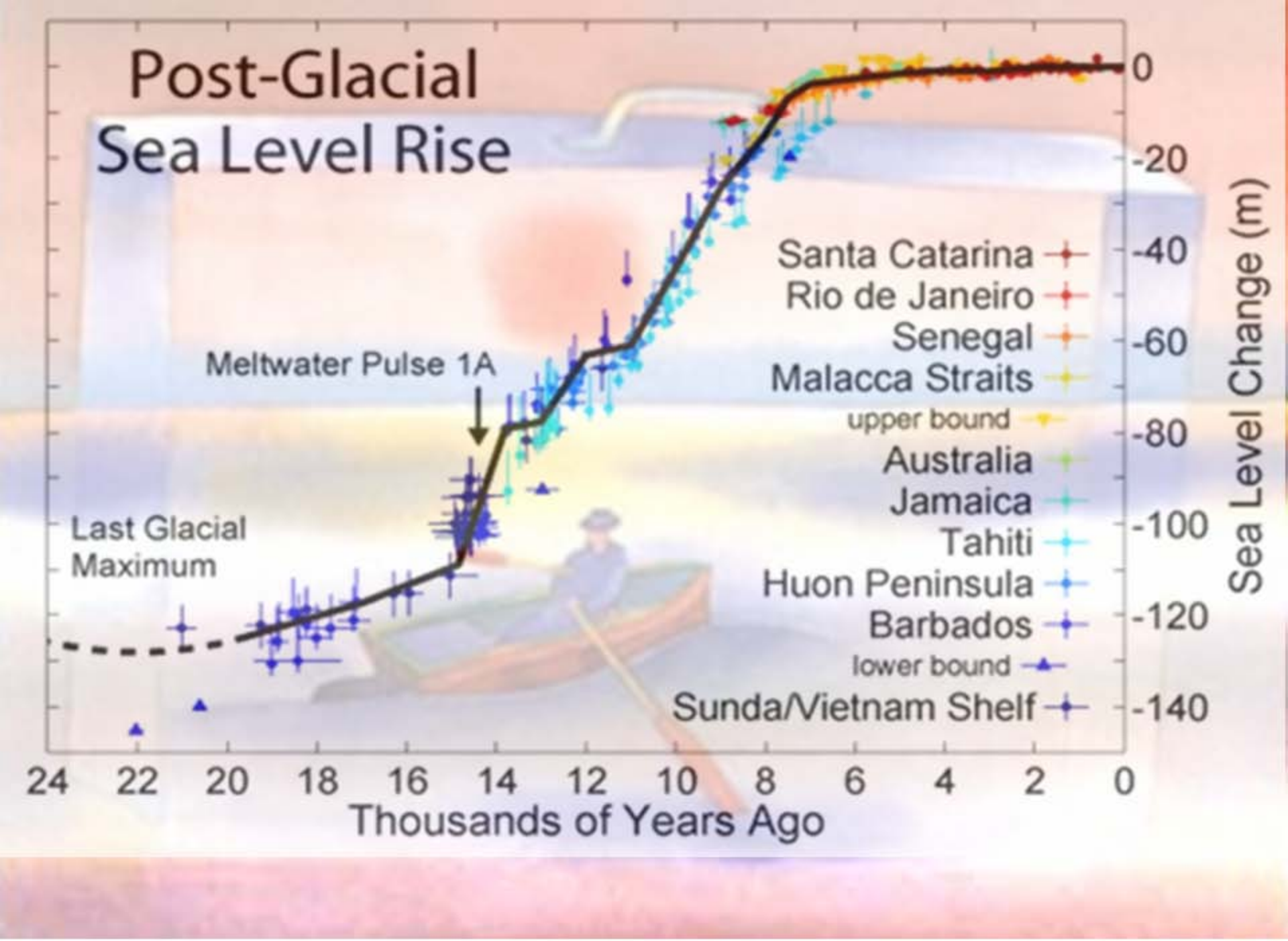
Limiting the effects of climate change is only listed as the 6° position (not cited as global warming)

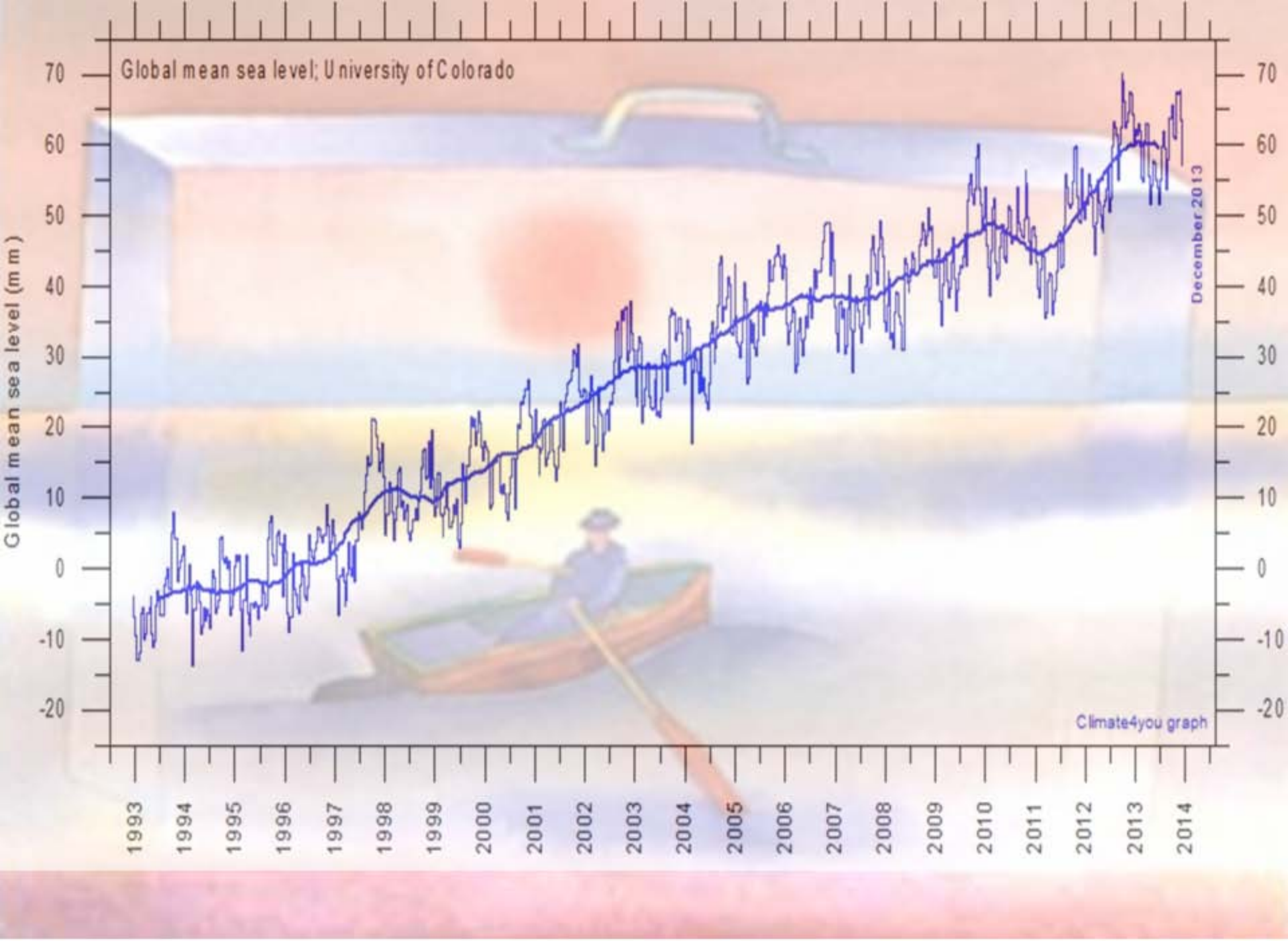
It appears that climate change, among the many problems that afflict humankind, is still felt as a minor problem.

Large and rapid temperature changes also in the past



The "Younger Dryas" event: a 10°C in 20 years

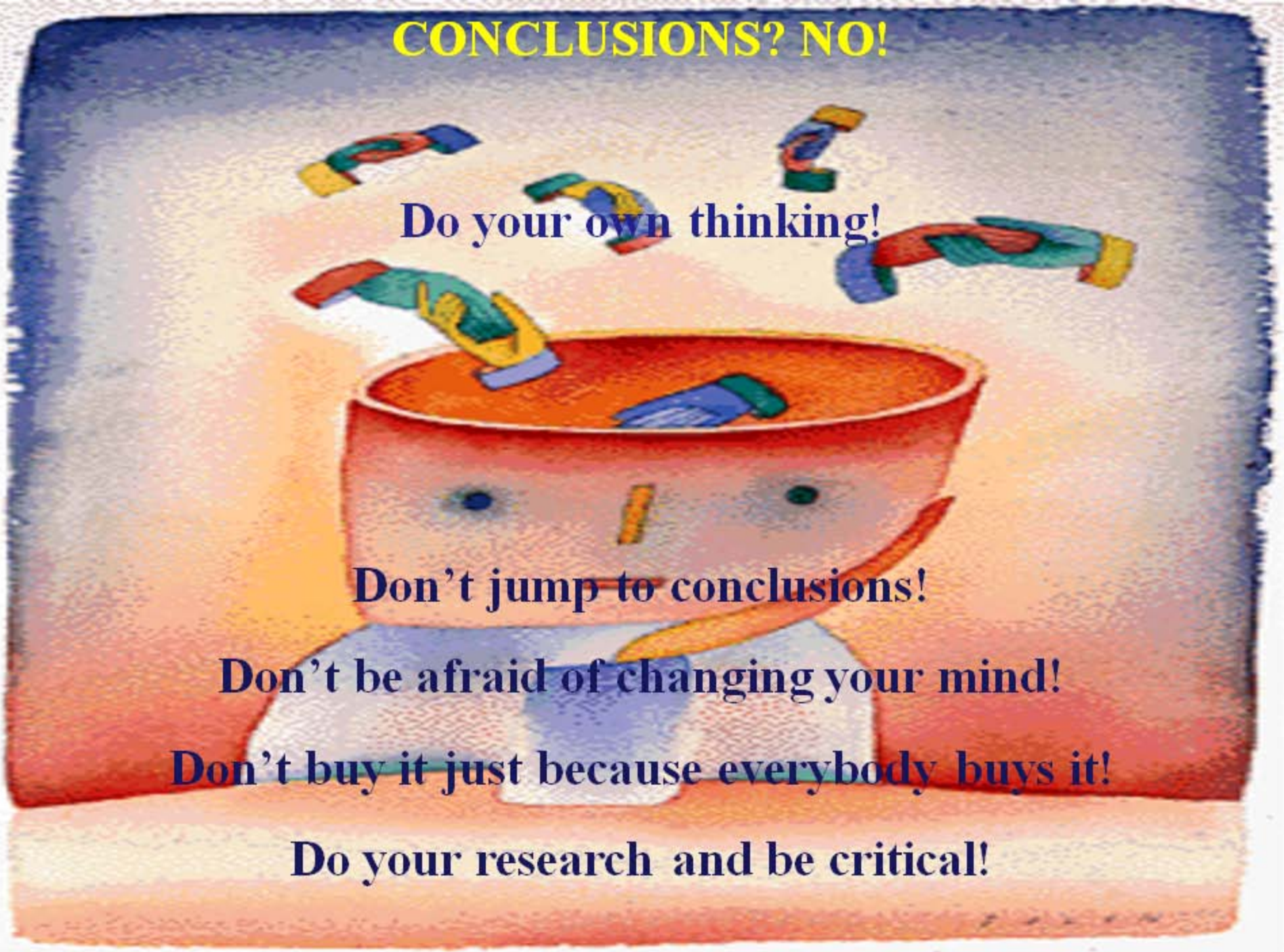


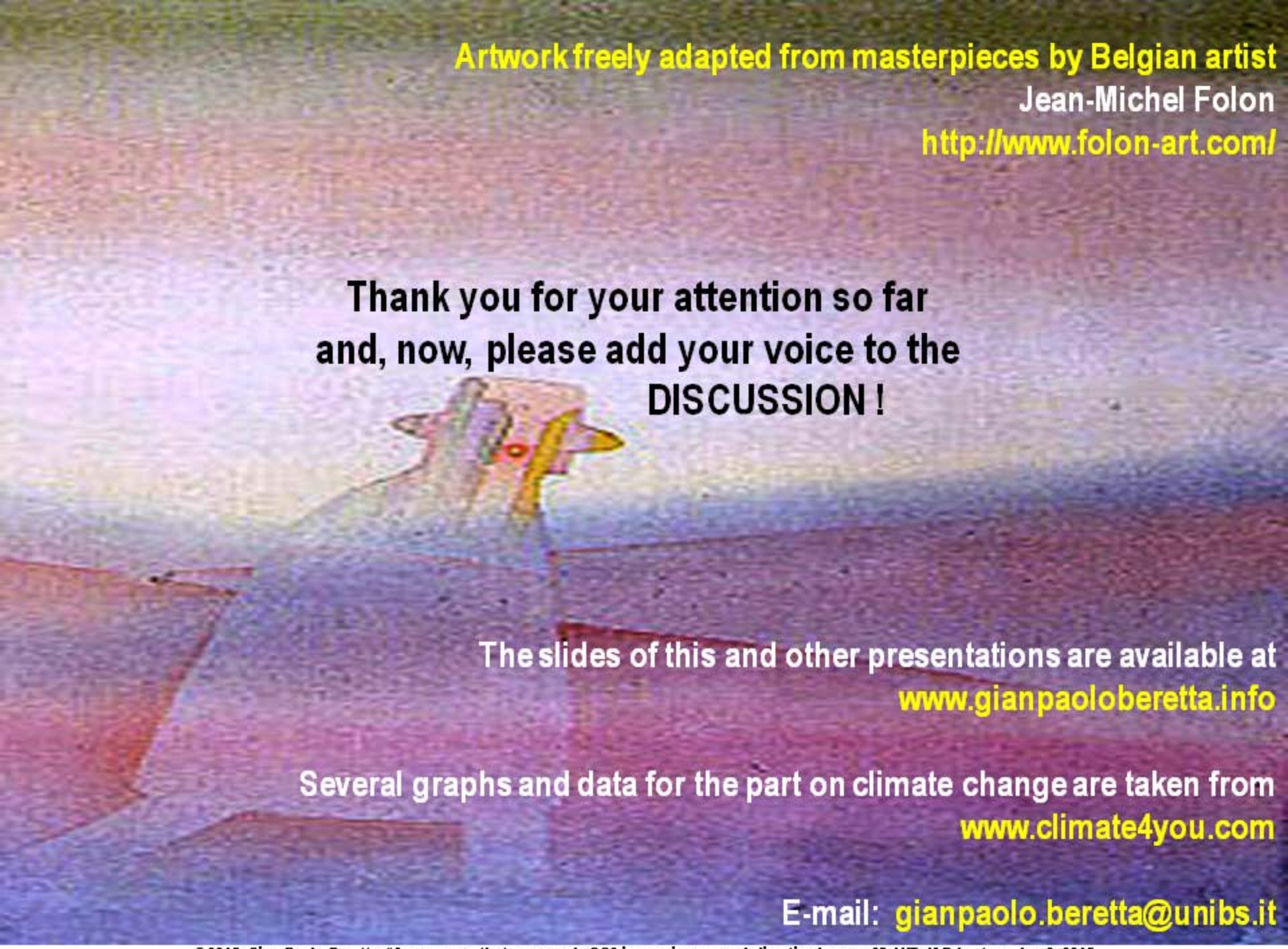


What should we do?

- The primary objective should be to get prepared to *control and limit the predictable damages* that will be caused by climate change, whether it be of anthropogenic or natural origin.
- Do only what is within *proved human reach* to contain, control, or reduce causes of global warming.
- The objective cannot be reduced to just that of reducing anthropic CO_2 immissions (because there is no certainty that they are a main cause of global warming).

CONCLUSIONS? NO!





- Proposing Activities
- See Browse Listings for this year's IAP activities
- **IAP Activity Attendance Sheet**

Non-Credit Activities: IAP Activity Attendance Sheet

Per the Report of the IAP Subcommittee, a request was made to collect some data on attendance of non-credit activities by Undergraduates and Graduate students during IAP. Please take 2 minutes to complete this short questionnaire.

Activity Date 1/6/15 **Activity Title** Are we sure that man-made CO2 is a main cause of climatic cha

Total Attendance X **# Grad Students** X **# Undergrad students** X

Of undergrads, please write the number of attendees per class year: **1stYear** X , **2nd year** X , **3rd year** X , **4th year** X

Of student attendees, how many are also taking a for credit class? X

Name of Person Recording Attendance Gian Paolo Beretta

Email Address for Person Recording Attendance beretta@mit.edu

To **send this form** , hit the submit button, or **reset it** to clear and begin again.