School for Young Scientists:

“Modelling and forecasting of river flows and managing hydrological risks: towards a new generation of methods”

Moscow, Russia, 21-25 September, 2020

Climate of the past and present and its hydrological relevance

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Available online: http://www.itia.ntua.gr/2065/

Parts of the presentation

1. Prologue: My personal involvement with climate
2. Weather and climate: Definitions, meaning and historical background
3. Climate of the past
4. Climate of the present
5. Basics of climate theory
6. The energy cycle
7. The carbon cycle
8. The hydrological cycle and its alleged intensification
9. The alleged intensification of hydrological extremes
10. Dealing with the future of climate and water
11. Epilogue: Is our future dark?

1. Prologue:
My personal involvement with climate

My first paper on climate

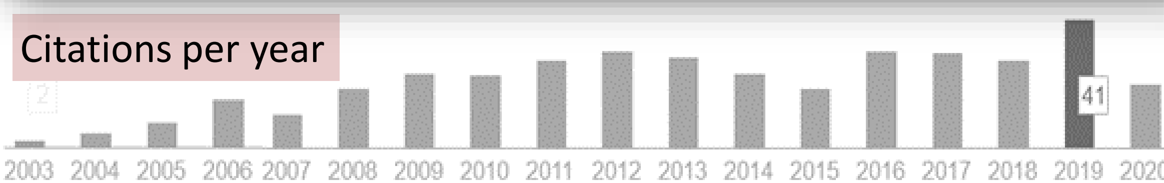
- This is my only journal paper with the term *climate change* in its title; it was rejected twice by *Water Resources Research*.
- It was accepted by *Hydrological Sciences Journal*, whose Editor, Zbigniew W. Kundzewicz, has been, at the same time, the IPCC leader for hydrology (Chairing Lead Author of the IPCC freshwater chapter in IPCC AR4 and Review Editor in IPCC AR5 & AR6).
- Later Kundzewicz, who appreciates diversity of opinion, invited me to jointly lead the Journal, which we did for more than a decade.
- The paper has now almost 400 citations.

Hydrological Sciences–Journal–des Sciences Hydrologiques, **48**(1) February 2003

Koutsoyiannis (2003)

Climate change, the Hurst phenomenon, and hydrological statistics

Citations per year



Sources of images: https://scholar.google.com/citations?user=OPA_BScAAAAJ, https://iahs.info/Publications-News/Hydrological-Sciences-Journal.do

Former Editors

Zbigniew W. Kundzewicz 1997-2015

Demetris Koutsoyiannis 2006-2017

My latest paper on climate (together with ZWK)

Koutsoyiannis and Kundewicz (2020)

Sci

MDPI

Article

Atmospheric Temperature and CO_2: Hen-Or-Egg Causality? (Version 1)

Demetris Koutsoyiannis [1,*] and Zbigniew W. Kundzewicz [2]

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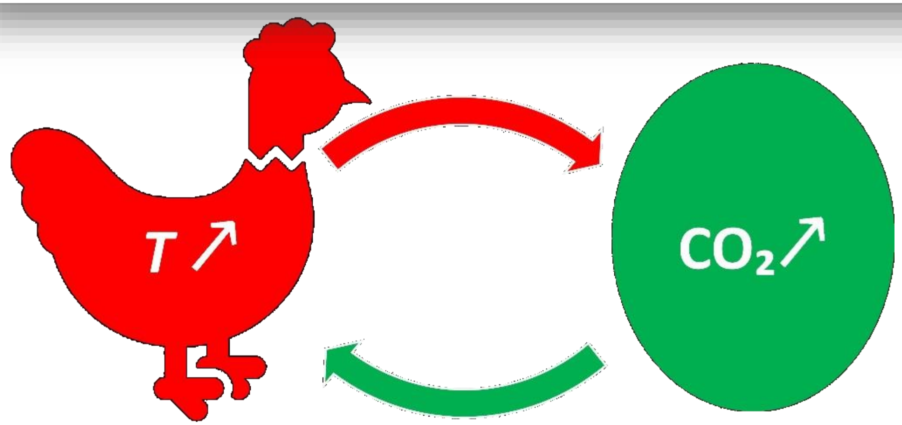
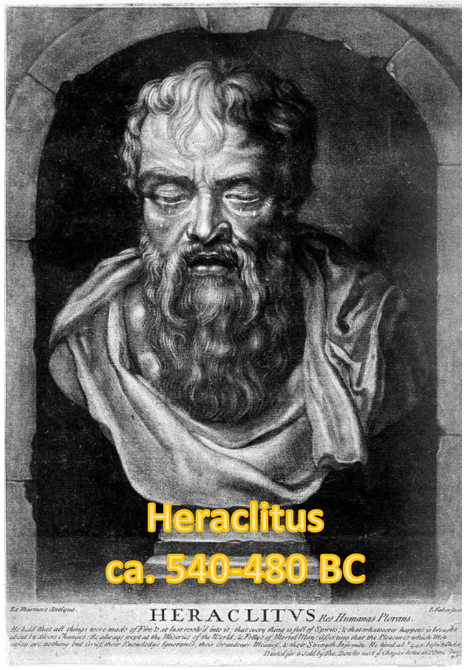
2. Institute for Agricultural and Forest Environment, Polish Academy of Sciences, 60-809 Poznań, Poland; kundzewicz@yahoo.com or zkundze@man.poznan.pl



Dialogue and dialectic: How science works (and Nature too)



- *Τὸ ἀντίξουν συμφέρον καὶ ἐκ τῶν διαφερόντων καλλίστην ἁρμονίαν καὶ πάντα κατ' ἔριν γίνεσθαι.*

  (*Opposition unites, the finest harmony springs from difference, and all comes about by strife*; Heraclitus, Fragment B 8).

- *Γίνεσθαί τε πάντα κατ᾽ ἐναντιότητα καὶ ῥεῖν τὰ ὅλα ποταμοῦ δίκην, πεπεράνθαι τε τὸ πᾶν καὶ ἕνα εἶναι κόσμον* [...] *καὶ τὴν μεταβολὴν ὁδὸν ἄνω κάτω, τόν τε κόσμον γίνεσθαι κατ᾽ αὐτήν.*

(*All things come into being by conflict of opposites, and the sum of things flows like a river. Further, all that is limited and forms one world.* [...] *Change* [is] *a pathway up and down, and this determines the evolution of the world*; Heraclitus quoted by Diogenes Laertius IX.8).

Part 2
Weather and climate: Definitions, meaning and historical background

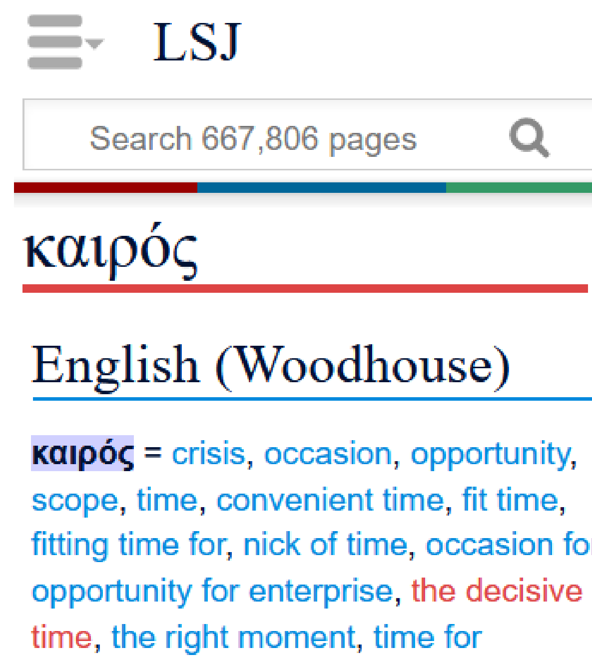
The importance of definitions

My own view:
I am not a poet.
I strongly believe that in science we should follow Luzin.

The Scientific School	The Poetic School
Ἀρχὴ παιδεύσεως ἡ τῶν ὀνομάτων ἐπίσκεψις (*The beginning of education is the inspection of names*) Socrates (from Epictetus, Discourses, I.17,12)	*What's in a name? That which we call a rose, by any other name would smell as sweet.* William Shakespeare ("Romeo and Juliet", Act 2, scene 2)
Each definition is a piece of secret ripped from Nature by the human spirit. I insist on this: any complicated thing, being illumined by definitions, being laid out in them, being broken up into pieces, will be separated Into pieces completely transparent even to a child, excluding foggy and dark parts that our intuition whispers to us while acting, separating into logical pieces, then only can we move further, towards new successes due to definitions . . . Nikolai Luzin (from Graham and Kantor, 2009)	*Let me argue that this situation* [absence of a definition] *ought not create concern and steal time from useful work. Entire fields of mathematics thrive for centuries with a clear but evolving self-image, and nothing resembling a definition.* Benoit Mandelbrot (1999, p. 14)

Weather – Tempus – Καιρός

- Weather is the state of the atmosphere at a particular time, as defined by the various meteorological elements (WMO, 1992)[1].
- The elements are meteorological variables: e.g., pressure, temperature, humidity, precipitation, cloudiness, visibility and wind.
- It is often used with respect to its effects upon life and human activities[2].
- In Greek and Romance (Neo-Latin) languages the term has also the meaning of *time*.
- In English and Greek (not in all languages), *weather* refers to short-scale (min to d) variations in the atmosphere and is distinguished from *climate*.



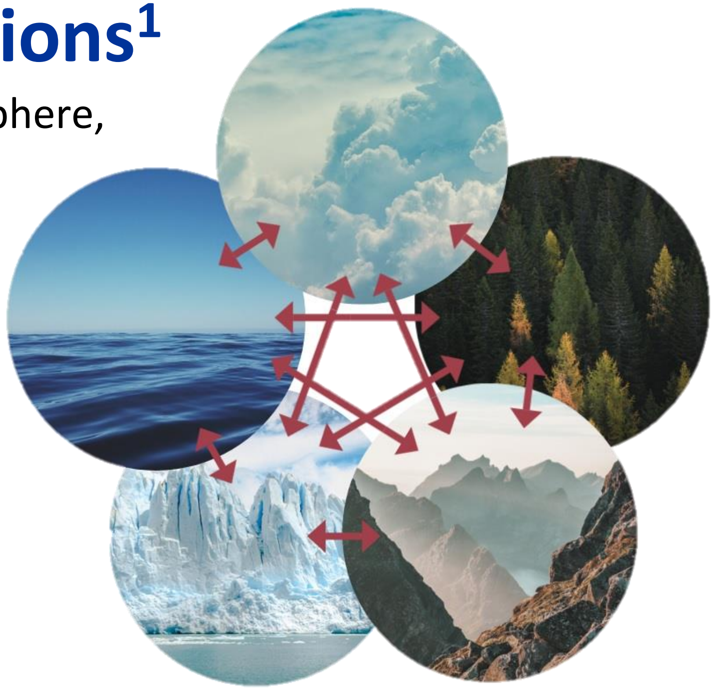
Source: https://lsj.gr/wiki/καιρός

Greek	Καιρός
Italian	Tempo
French	Temps, Météo
Spanish	Tiempo, Clima
Portuguese	Tempo, Clima
Russian	Погода

[1] See also the glossary of the NOAA's National Weather Service: https://w1.weather.gov/glossary/index.php?letter=w.
[2] Cf. the glossary of the American Meteorological Society, http://glossary.ametsoc.org/wiki/Weather

Climate < Clima < Κλίμα: Definitions[1]

- **Climate system** is the system consisting of the atmosphere, hydrosphere (including its solid phase, cryosphere), lithosphere and biosphere, which mutually interact and respond to external influences.
- **Climatic processes** are the physical, chemical and biological processes, which are produced by the interactions and responses of the climate system components through flows of energy and mass, and chemical and biological reactions.
- **Climate** is a collection of climatic processes at a specified area, stochastically characterized for a range of time scales.
- The term *process* means *change* (Kolmogorov, 1931). Thus, **climate is changing by definition.**



Source: https://en.wikipedia.org/wiki/Climate_system

- The term *stochastic* means random (i.e., unpredictable, unknowable in deterministic terms) and the term *stochastic process* means a family of stochastic (random) variables $\underline{x}(t)$ indexed by time t.
- The terms *stochastic characterization* and *stochastics* collectively refer to the scientific areas of *probability*, *statistics* and *stochastic processes*.
- The term *hydroclimatic* is used to give more emphasis on the hydrological processes.

[1] My definitions (Koutsoyiannis, 2021) are based on, but are not identical to, common ones in the literature (see next slides).

Climate < Clima < Κλίμα: History

- Aristotle (384–322 BC) in his *Meteorologica* describes the climates on Earth in connection with latitude but he does not use the term *climate*. Instead, he uses the term *crasis* (*κρᾶσις*, literally meaning mixing, blending, temperament; cf. *εὔκρατος*, *εὐκρασία*).
- The term *climate* (*κλίμα*, plural *κλίματα*) was coined as a geographical term by the astronomer Hipparchus (190 –120 BC; founder of trigonometry). It originates from the verb *κλίνειν*, meaning 'to incline' and denoted the angle of inclination of the celestial sphere and the terrestrial latitude characterized by this angle.
- Hipparchus's Table of Climates is described by Stabo the Geographer (63 BC – AD 24), from whom it becomes clear that the *Climata* of that Table are just latitudes of several cities, from 16° to 58°N (see Shcheglov, 2007, for a reconstruction of the Table).
- Furthermore Strabo, defined the five climatic zones, *torrid* (*διακεκαυμένη*), two *temperate* (*εὔκρατοι*) and two *frigid* (*κατεψυγμέναι*), as we use them to date.

LSJ

Search 667,806 pages

κλίμα

English (LSJ)

[ῐ, cf. *Scymn.521*], ατος, τό, (κλίνω)

A inclination, slope of ground, ἑκάτερον τὸ κ. τῶν ὀρῶν *Plb.2.16.3*; ἡ πόλις τῷ ὅλῳ κ. τέτραπται πρὸς τὰς ἄρκτους *Id.7.6.1*, etc.; scarp, *Apollod.Poliorc.140.7*.

Russian (Dvoretsky)

κλίμα: ατος (ῐ) τό κλίνω

1) склон, скат, спуск: ἑκάτερον τὸ κ. Polyb. оба склона (горы);

2) страна света, климатический пояс (βόρειον Arst.; ὑπάρκτιον Plut.; ἐν τοῖς κλίμασι τούτοις NT): τὰ πρὸς μεσημβρίαν κλίματα τῆς Μηδίας Polyb. южные области Мидии.

Source: https://lsj.gr/wiki/κλίμα

Climate < Clima < Κλίμα: Contemporary history

- The term *climate* was used with the ancient Greek geographical meaning until at least 1700. The term *climatology* appears after 1800.
- With the increasing collection of meteorological measurements, the term *climate* acquires a statistical character as the average weather. Indeed, the geographer A.J. Herbertson (1907) in his book entitled “*Outlines of Physiography, an Introduction to the Study of the Earth*”, gave the following definition of climate, based on weather (but also distinguishing it from weather):

  > *By climate we mean the average weather as ascertained by many years' observations. Climate also takes into account the extreme weather experienced during that period. Climate is what on an average we may expect, weather is what we actually get.*

- Herbertson also defined climatic regions of the world based on statistics of temperature and rainfall distribution.
- Herbertson’s work was influential for the famous and most widely used Köppen (1918) climate classification; this includes six main zones and eleven climates which are on the same general scale as Herbertson's (Stamp, 1957).

Climate < Clima < Κλίμα: Some modern definitions

- Definition by the USA National Weather Service, Climate Prediction Center (https://www.cpc.ncep.noaa.gov/products/outreach/glossary.shtml#C):

  Climate – The average of weather over at least a 30-year period. Note that the climate taken over different periods of time (30 years, 1000 years) may be different. The old saying is climate is what we expect and weather is what we get.

- Definition by the American Meteorological Society (http://glossary.ametsoc.org/wiki/Climate):

  Climate – The slowly varying aspects of the atmosphere–hydrosphere–land surface system. It is typically characterized in terms of suitable averages of the climate system over periods of a month or more, taking into consideration the variability in time of these averaged quantities. Climatic classifications include the spatial variation of these time-averaged variables. Beginning with the view of local climate as little more than the annual course of long-term averages of surface temperature and precipitation, the concept of climate has broadened and evolved in recent decades in response to the increased understanding of the underlying processes that determine climate and its variability.

- Definition by the IPCC (2013)

  Climate – Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Some remarks on climate’s modern definitions

- Why “*at least a 30-year period*”? Is there anything special with the 30 years?
  - This reflects a historical belief that 30 years are enough to smooth out “random” weather components and establish a constant mean. In turn, this reflects a perception of a constant climate—and a hope that 30 years would be enough for a climatic quantity to get stabilized to a constant value. It can be conjectured that the number 30 stems from the central limit theorem and in particular the common (albeit wrong) belief that the sampling distribution of the mean is normal for sample sizes over 30 (e.g. Hoffman, 2015). Such a perception roughly harmonizes with classical statistics of independent events.
  - This perception is further reflected in the term anomaly (from the Greek ανωμαλία, meaning abnormality), commonly used in climatology to express the difference from the mean.
  - Thus, the dominant idea is that a constant climate would be the norm and a deviation from the norm would be an abnormality, perhaps caused by an external agent.
  - The entire line of thought is incorrect.
- Why “*climate taken over different periods of time (30 years, 1000 years)* [is] *different*”?
  - The obvious reply is: Because different 30-year periods have different climates. This contradicts the tacit belief of constancy and harmonizes with the perception of an ever-changing climate.
- Is Herbertson’s idea, “*climate is what we expect, weather is what we get*”, correct?
  - **No**. A correct reformulation would be “*weather is what we get immediately, climate is what we get if we keep expecting for a long time*” (Koutsoyiannis, 2011).

The meaning of “climate change”

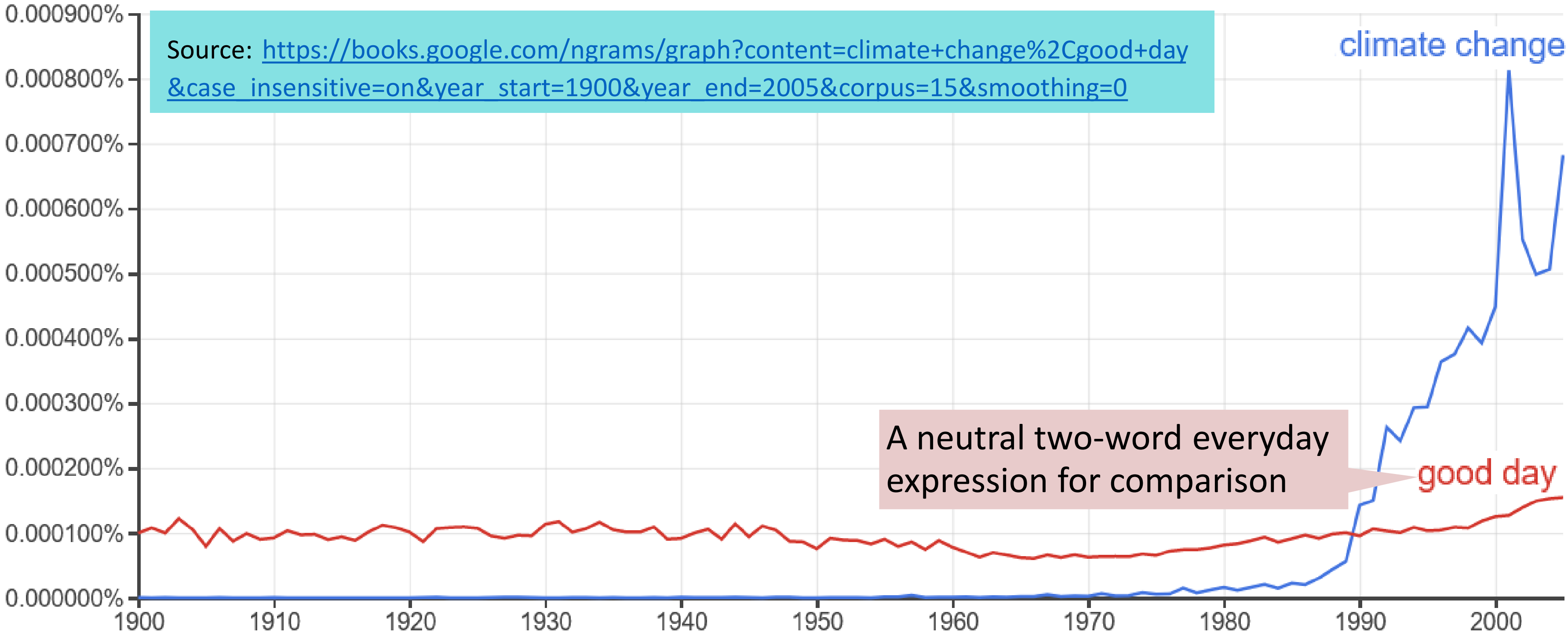
- In scientific terms, the content of the term *climate change* is almost equivalent to that of *weather change* or even *time change* (climate is changing as is weather and time).
- Thus, “*the term 'climate change' is a misleading popular slogan*” (Vit Klemes[†]) and serves political aims. It is not a scientific term.
- Even according to the IPPC’s (2013) definition, its meaning is ambiguous:

  Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.

  Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: ‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods’. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

[†] 1932-2010; https://motls.blogspot.com/2011/03/vit-klemes-1932-2010.html

Evolution of the use of the term “climate change”



- The graph shows the evolution of the frequency of appearance of the term “climate change” in the millions of books archived by Google Books. The neutral term “good day” is used as a reference for comparison.
- The term appeared in the 1970s.
- It looks that after 1990 climate change became more important than good day.

The launch of the Climate Change Agenda

NEWS RELEASE

BUREAU OF PUBLIC AFFAIRS

US Department of State
Office of Media Services

U.N. Speech Text:
CHALLENGES OF INTERDEPENDENCE
REVIEWED BY SECRETARY KISSINGER

April 15, 1974

FOR IMMEDIATE RELEASE

SEP 26 1975

Address by Secretary of State
Henry A. Kissinger before the
Sixth Special Session of the
United Nations General Assembly
New York, N.Y., April 15, 1974.

Mr. President, Mr. Secretary General, distinguished d...
and gentlemen.

WORLD METEOROLOGICAL ORGANIZATION

EXECUTIVE COMMITTEE

TWENTY-SIXTH SESSION, GENEVA, 1974

Distr.: RESTRICTED

EC-XXVI/Doc. 70
(23.V.1974)

ITEM 5.6 (3)

Original: ENGLISH

ENVIRONMENTAL POLLUTION AND OTHER ENVIRONMENTAL QUESTIONS

Implications of possible climatic changes

(Presented by the Secretary-General)

Summary

This document conveys to the Executive Committee a request from the Government of the United States of America to consider the problem of the implications of possible climatic changes on the well-being of man. The present WMO activities in this field are reviewed

Reproduced from Lewin (2017)

- Henry Kissinger, the then powerful Secretary of State and National Security Advisor of USA raised the issue of "climatic changes" in the UN Assembly in 1974.
- WMO reacted immediately (in a month).

Kissinger (1974)

-- The poorest nations, already beset by man-made disasters, have been threatened by a natural one: the possibility of climatic changes in the monsoon belt and perhaps throughout the world. The implications for global food and population policies are ominous. The United States proposes that the International Council of Scientific Unions and the World Meteorological Organization urgently investigate this problem and offer guidelines for immediate international action.

WMO (1974)

Implications of possible climatic changes

5.6.25 The Executive Committee discussed a request from the Government of the United States of America to consider certain problems of climatic change in relation to the current and planned activities of WMO. This request had stemmed from a statement made by the Secretary-of-State at the sixth special session of the United Nations General Assembly in which he had called attention to the possibility of climatic changes which could have serious implications for global food and population policies. In this connexion, the Committee also noted the decision of the second session of the Governing Council of UNEP that the Executive Director should continue his activities relating to "outer limits", particularly climatic change.

Scientists get involved immediately: NOAA, Oct. 1974

Photo: Carl Purcell, AID

CLIMATE: A KEY TO THE WORLD'S FOOD SUPPLY

BY PATRICK HUGHES

"The poorest nations, already beset by man-made disasters, have been threatened by a natural one: the possibility of climatic changes in the monsoon belt and perhaps throughout the world. The implications for global food and population policies are ominous. . . ."

HENRY KISSINGER, Address before the UN General Assembly, April 15, 1974

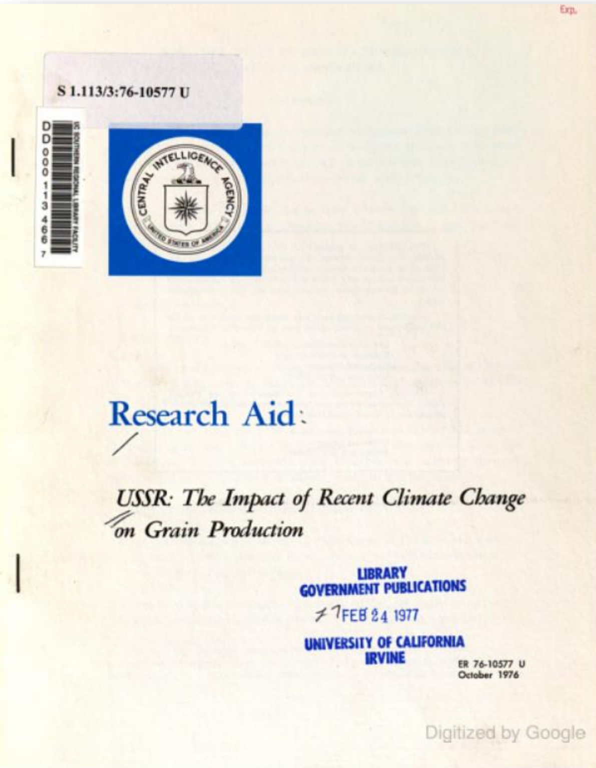
Hughes (1974)

- Was the climate alert about **global cooling or global warming**?
- The answer was not categorical and in fact did not matter.
- **What did matter was the alert per se**.

Both the Little Ice Age and our own climatic era are relatively minor variations superimposed on long-term fluctuations between cold, glacial and warm, relatively brief, interglacial periods of the ice age in which we are now living. For most of the Earth's history our planet had no permanent ice cover. For more than two million years now, however, we have had permanent ice fields which alternately expand and contract. The last major glacial period ended about 10,000 years ago. Some climatologists think that the present cooling trend may be the start of a slide into another period of major glaciation, popularly called an "ice age."

Many other scientists disagree. J. Murray Mitchell, Jr., of the Environmental Data Service, a world authority on climatic change, comments, "We observe these trends, and we know they are real. But we can't find the central tendency, we just don't know how long they will last." Mitchell himself suspects that the present cooling trend will reverse itself rather soon.

The first book with a title containing "climate change"



CIA (1976)

A cold-war report referring to USSR, in which climate change is the **cooling** of the Northern Hemisphere since 1940.

Introduction

8. The world's climate and the possible effect of a change in climate on food production is receiving increased attention. In particular, the drought and subsequent famine in the Sahelian zone of North Africa during the late 1960s and early 1970s has focused world attention on the implications of climate change. According to evidence gathered by climatologists, the Northern Hemisphere has been cooling since the mid-1940s. This cooling may have been responsible for the widespread failure during the 1960s of the rain-producing monsoons in the grain-growing regions that lie south of the tropical deserts.

9. In the USSR, a grain crop shortfall in 1972 and subsequent massive imports drew attention to the potentially precarious situation some grain-producing countries in the North Temperate Zone might face because of climate fluctuations. Bounded to the north by cold temperatures and to the south by deserts, the grain-growing region of the USSR has a high potential for disastrous weather should the boundaries of these unfavorable climates shift.

10. Little has been done to evaluate the effect that this climate change has had on food production in the temperate latitudes. This report (1) discusses the nature of climate and climate change, (2) uses detailed meteorological data to measure changes in the climate in the USSR grain belt, and (3) estimates the impact of the climate change on grain production since 1962.

USSR: Average Annual Change in All Grain Production, 1962-74

	Grain Area[1] (Million Hectares)	Average Increase in All Grain Production (Million Metric Tons/Year)	Caused by Climate Change (Million Metric Tons/Year)
Total	112.0	6.84	3.50
Baltics	2.2	0.28	0.05
Belorussia	2.8	0.42	0.01
Ukraine	16.7	1.62	0.94
Moldavia	0.9	0.11	0.03
RSFSR	71.3	3.49	1.71
Kazakhstan	18.1	0.92	0.76

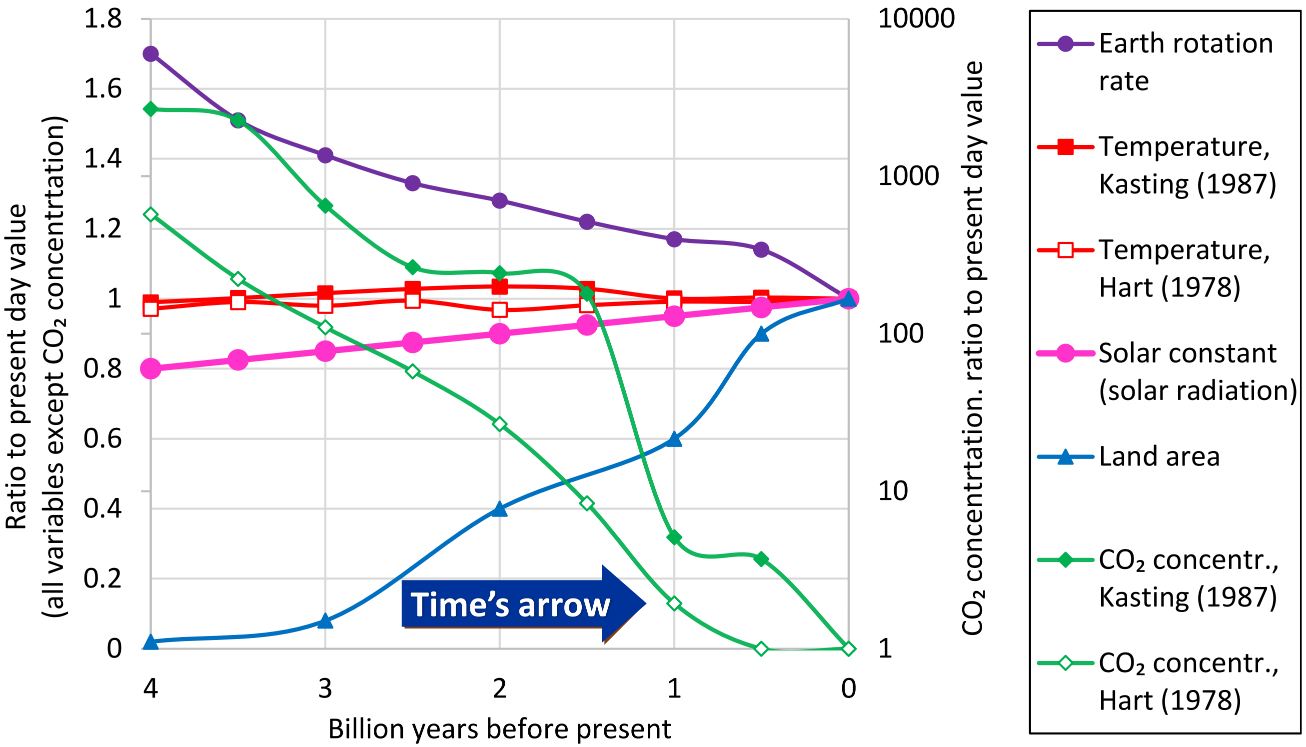
A necessary clarification ending Part 2

- “Climate change” is a political agenda—not anything scientifically sound.
- What follows purports to be scientific—not political.
- I have also conducted research on the political, historical and socio-economic aspects of the Climate Change Agenda.
- Those in the audience interested in my latter research are invited to visit my presentation (Koutsoyiannis 2020b):

The political origin of the Climate Change Agenda
http://www.itia.ntua.gr/2035/

Part 3
Climate of the past

“Πάντα ρεῖ”[1] & “Μεταβάλλει τῷ χρόνῳ πάντα”[2] Changes on Earth since the appearance of earliest life, 4 billion years ago



The graph has been constructed from estimates by Kuhn et al. (1989). Temperature is expressed in K and corresponds to 35° latitude; a change in the temperature ratio by 0.01 corresponds to ~2.9 K.

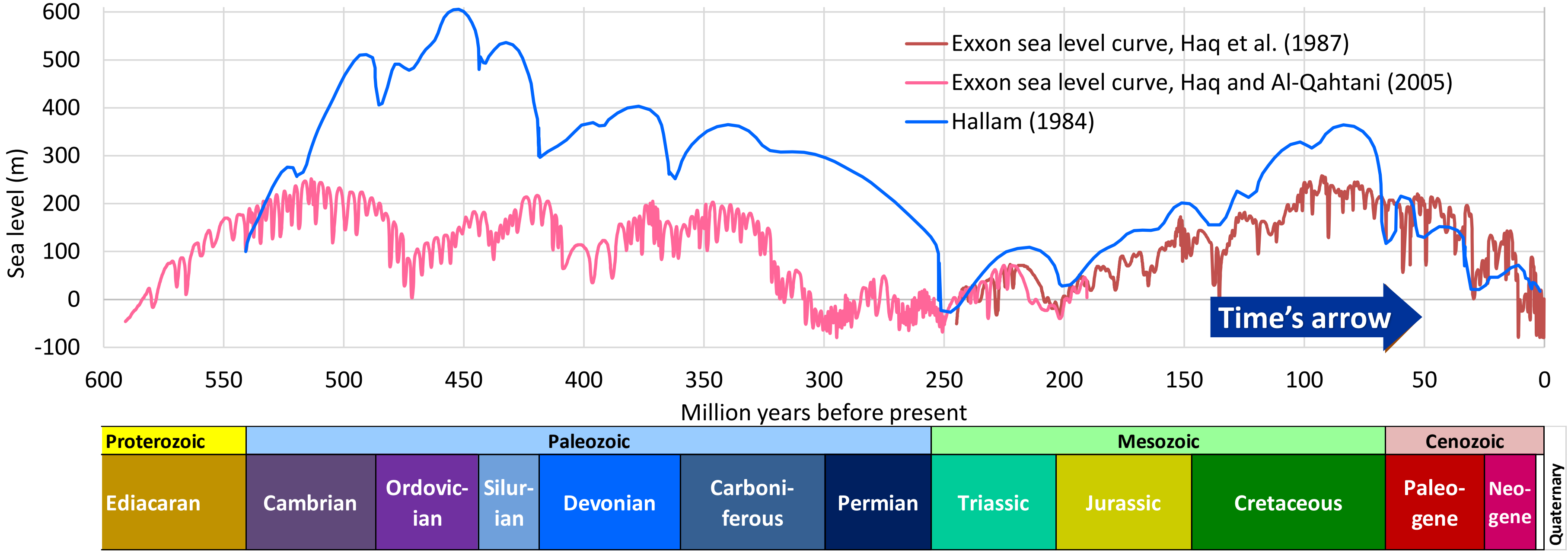
Although the estimates are dated and uncertain, evidence shows existence of liquid water on Earth even in the early period, when the solar activity was smaller by 20-25%. This is known as the faint young Sun problem (Feulner, 2012).

______

[1] “Everything flows” Heraclitus, quoted in Plato’s Cratylus, 339-340

[2] “Everything changes in course of time”, Aristotle, *Meteorologica*, I.14, 353a 16

Sea level during the Phanerozoic



Phanerozoic = Paleozoic + Mesozoic + Cenozoic. High sea level suggests high temperature.

Digitized data sources:

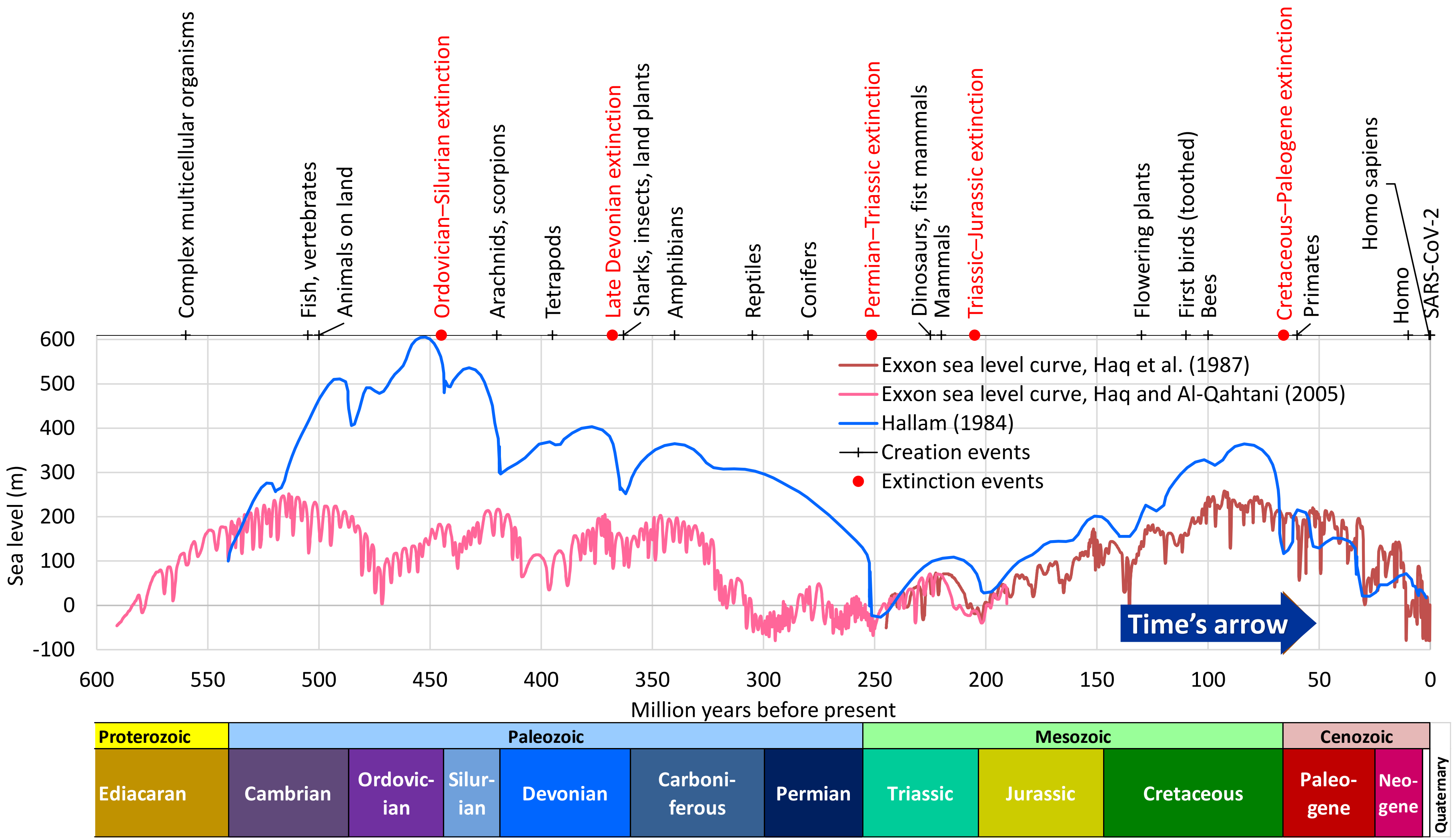
For Haq et al. (1987): https://figshare.com/articles/Haq_sea_level_curve/1005016.

For Haq and Al-Qahtani (2005): https://web.archive.org/web/20080720140054/http://hydro.geosc.psu.edu/Sed_html/exxon.sea; Note though that it has discrepancies from the graph in Miller et al. (2005).

For Hallam (1984), data were digitized in this study using chronologies of geologic eras from the International Commission on Stratigraphy, https://stratigraphy.org/chart.

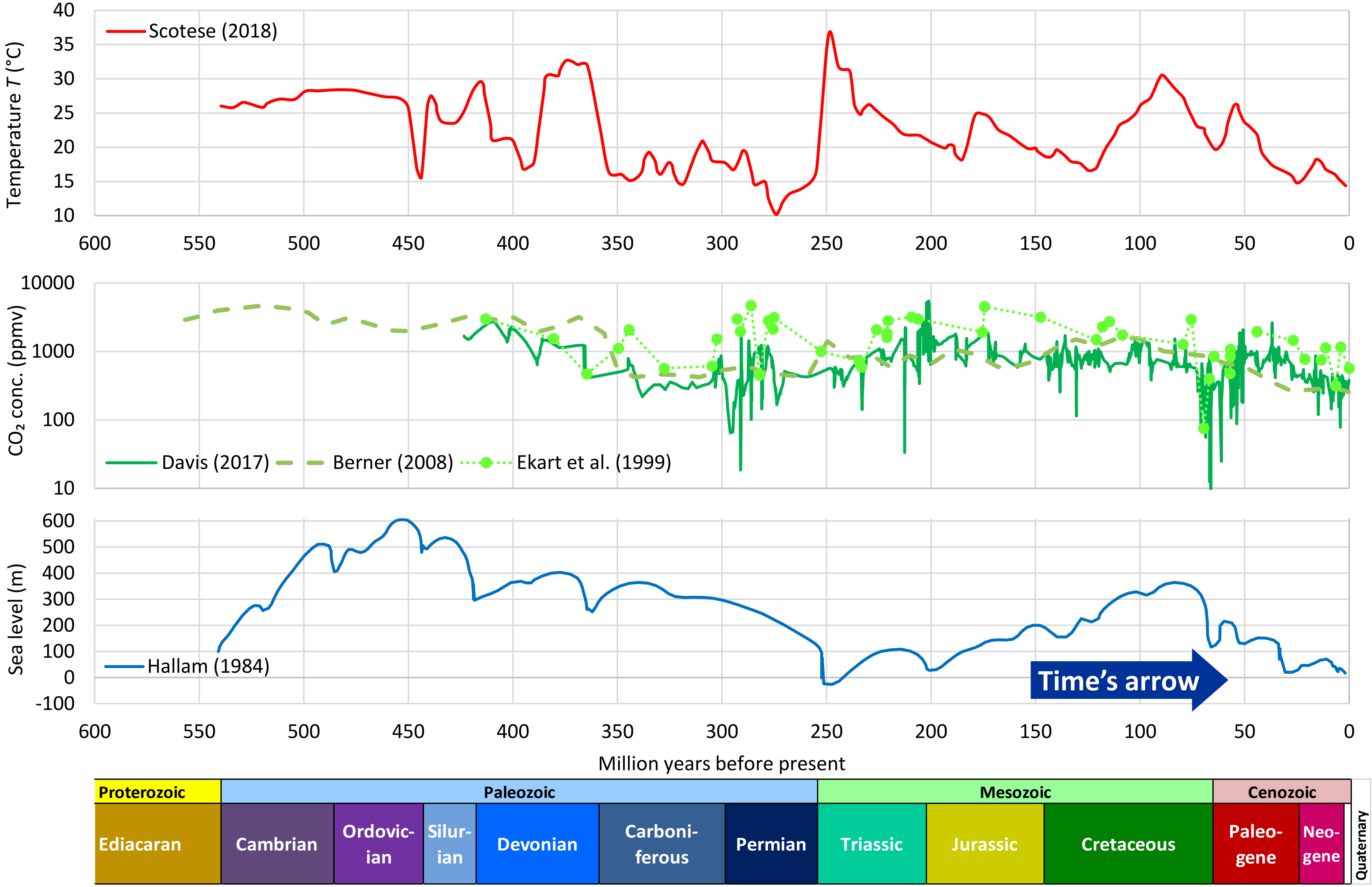
For other reconstructions see van der Meer (2017).

Life evolution and sea level during the Phanerozoic



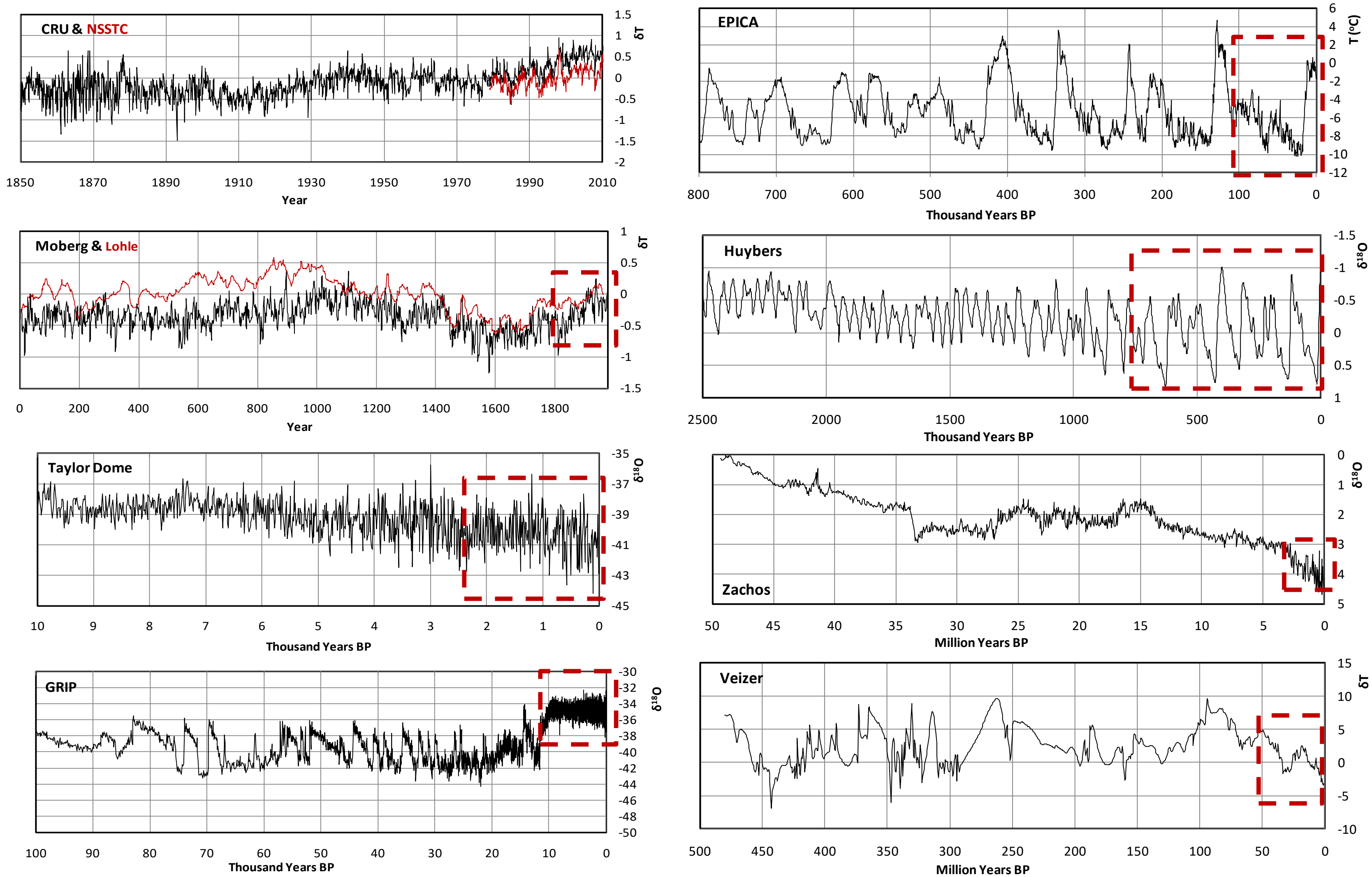
- Q: When did extinction happen? On temperature rise or fall?

Co-evolution of temperature, CO_2 concentration and sea level in the Phanerozoic

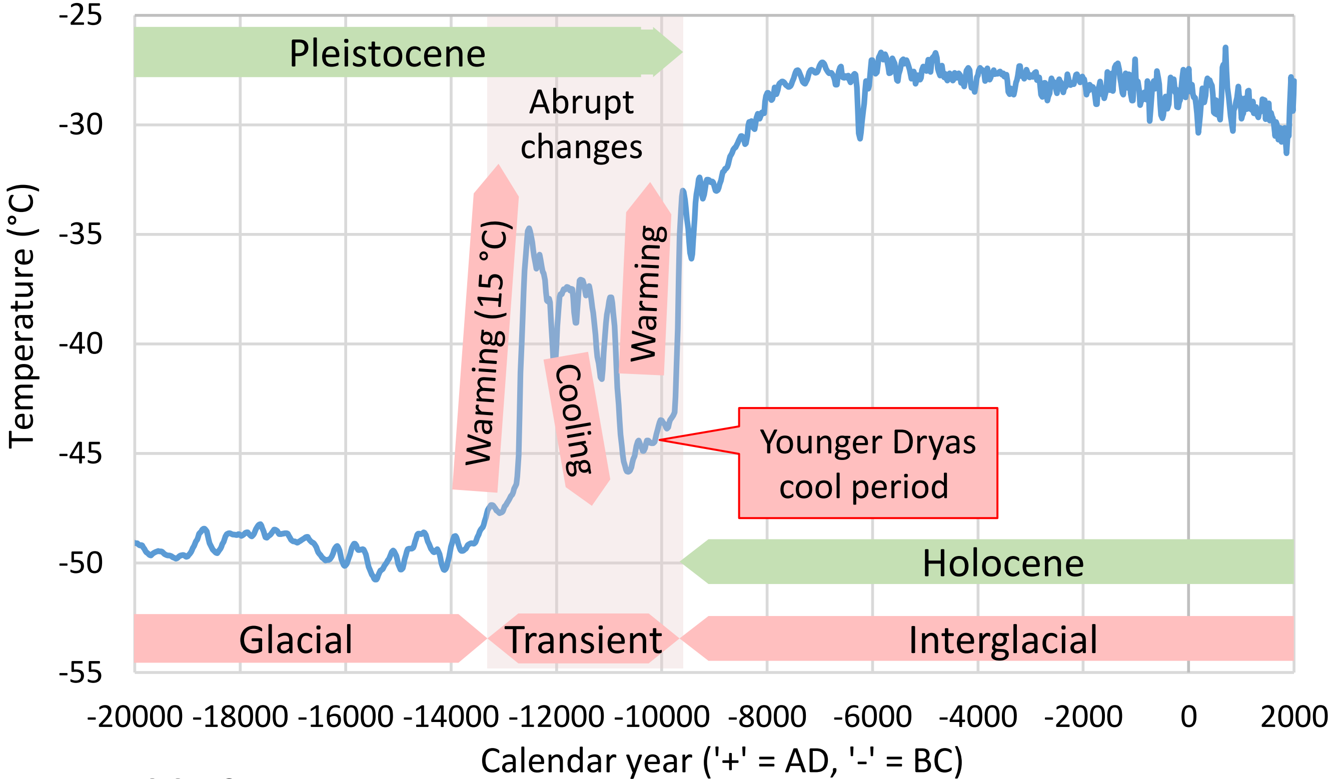


Temperature change in different time windows from observations and proxies

Markonis and Koutsoyiannis (2013)



Focus on the last deglaciation: temperature



Experimental drilling on the Greenland Ice Cap in 2005, https://earthobservatory.nasa.gov/features/Paleoclimatology_IceCores

Noticeable facts:

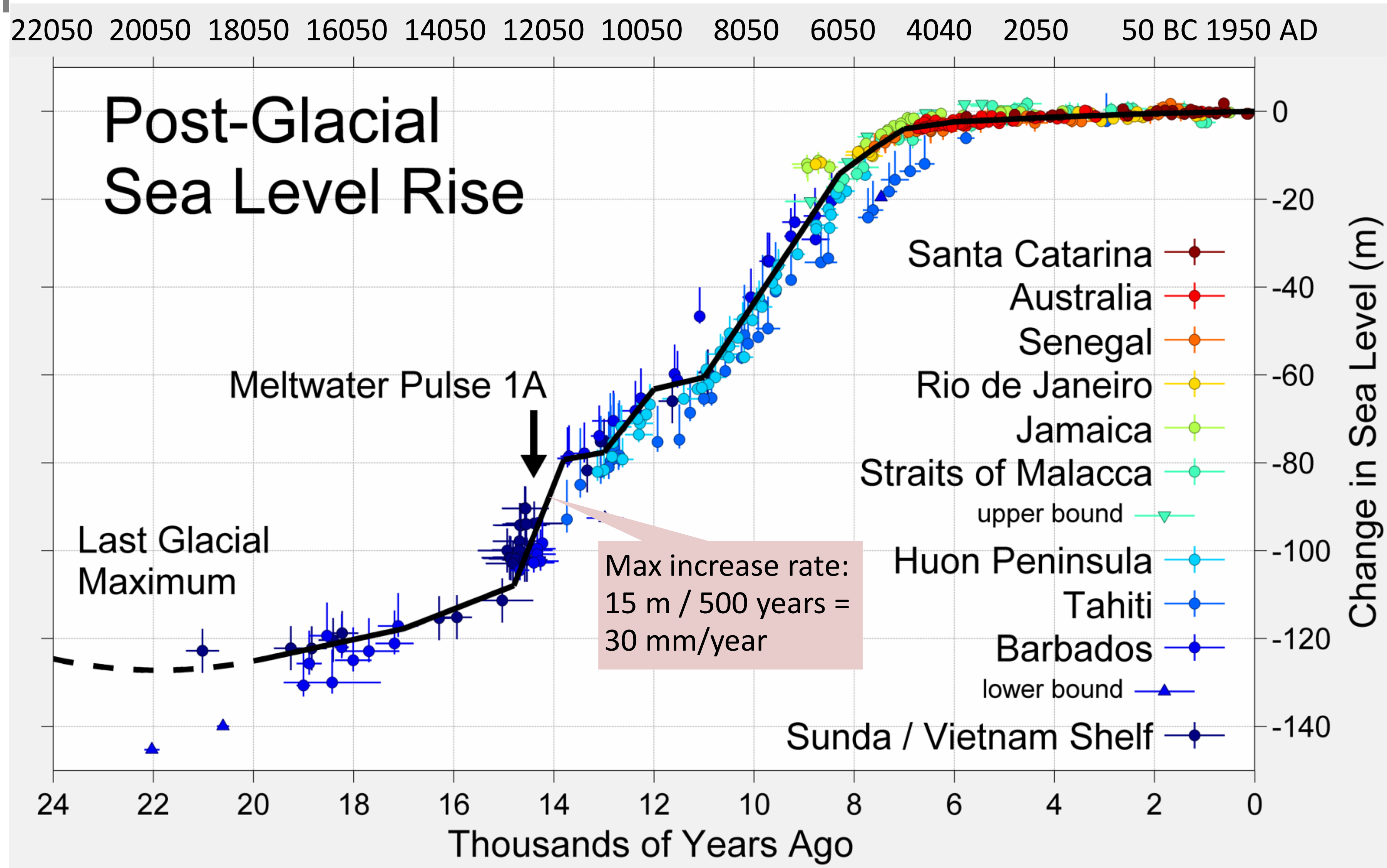
(1) The difference of the interglacial from glacial temperature is > 20 °C.

(2) In periods of temperature increase, the maximum rate of change has been 8.5 °C/century.

(3) In periods of decrease, the maximum rate has been -4.3 °C/century.

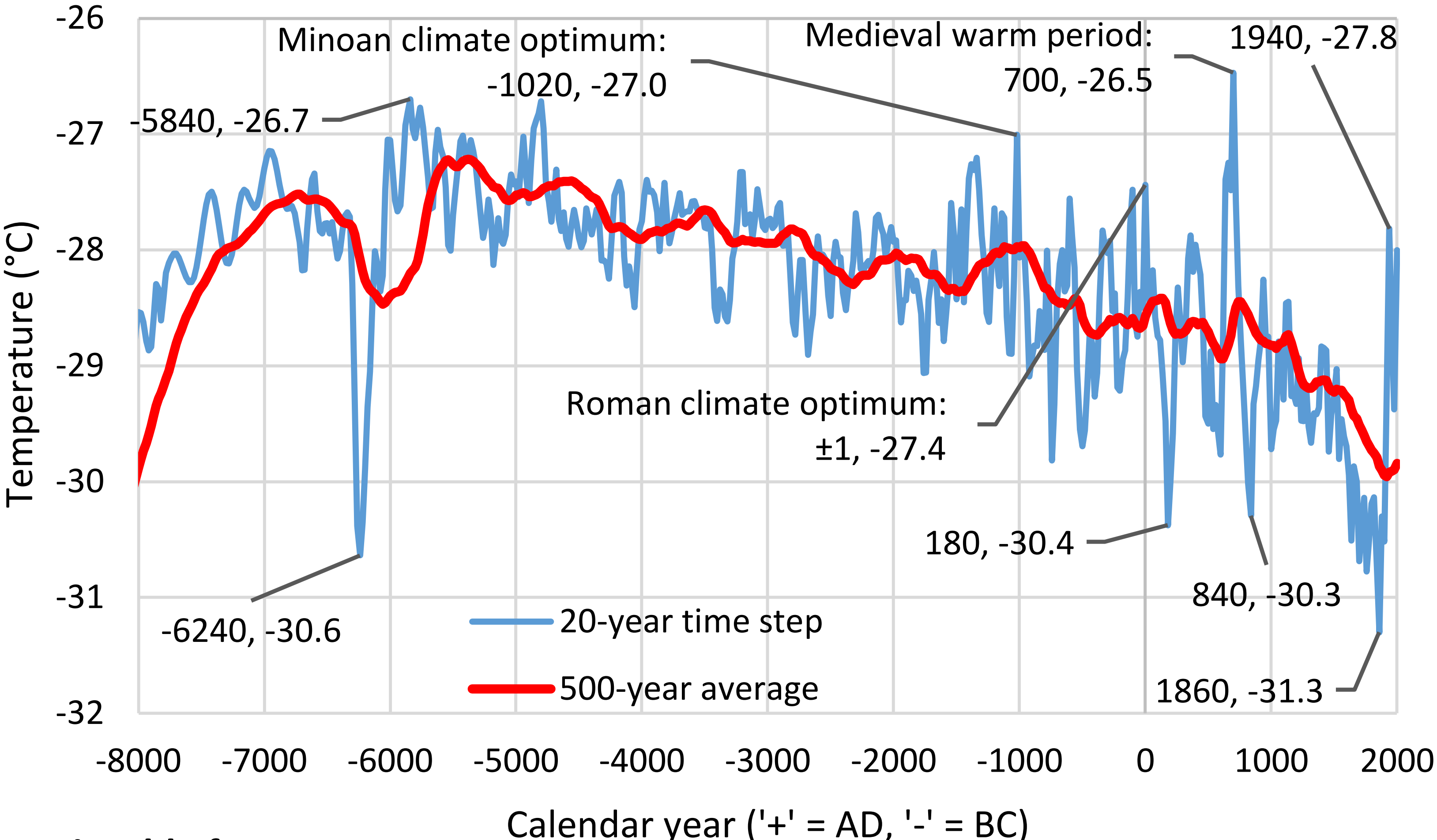
Data: Temperature reconstruction from Greenland ice cores; averages from GISP2, NGRIP and NEEM Ice Drilling locations as given by Buizert et al. (2018) for a 20-year time step (available from https://www.ncdc.noaa.gov/paleo-search/study/23430).

Focus on the last deglaciation: sea level



Source: https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png

Focus on the last 10 thousand years: temperature

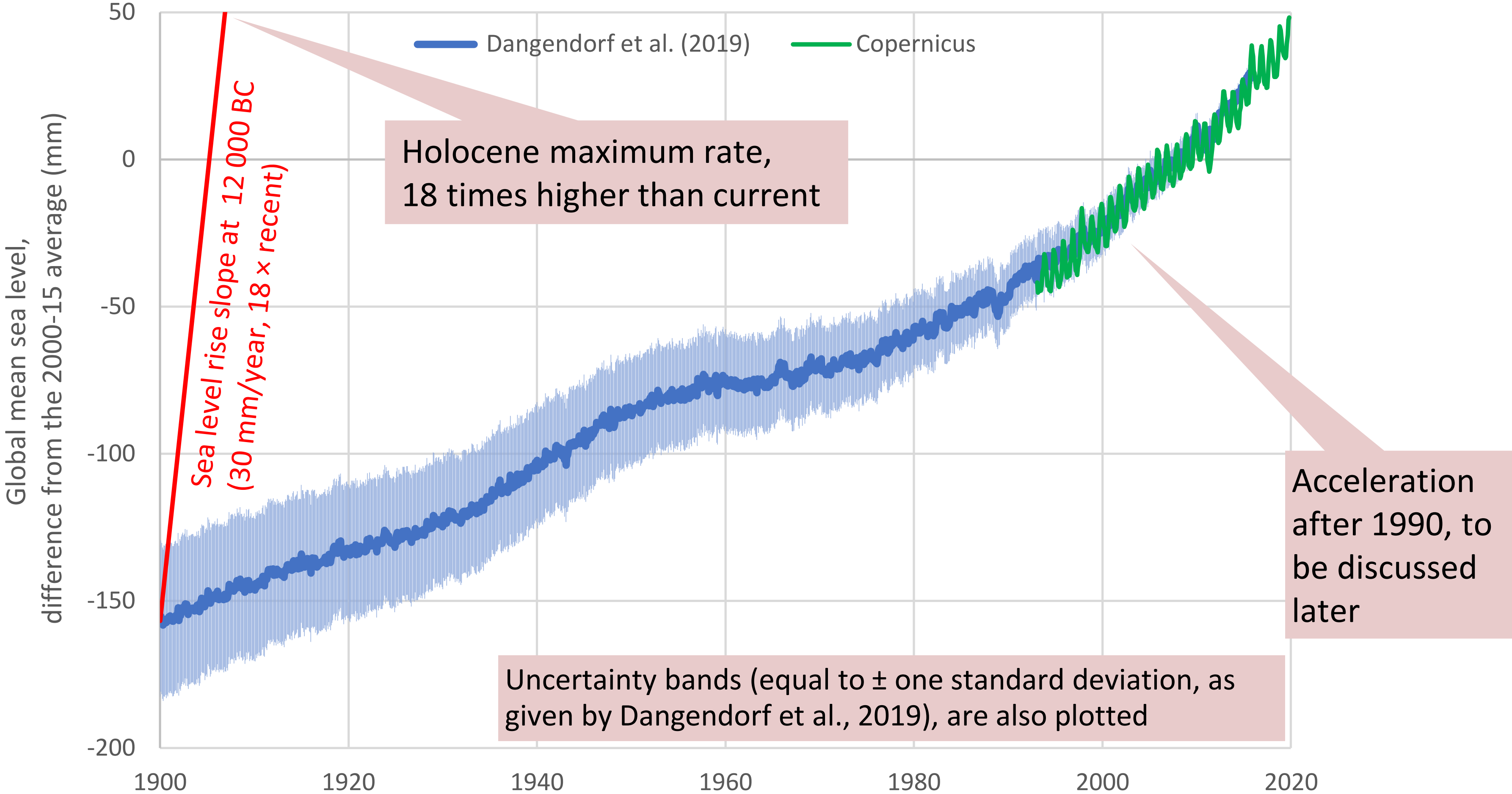


Noticeable facts:
(1) 1940 was warmer than present. (2) The warmest period was around 700 AD. (3) There has been a dominant cooling trend for more than 7000 years.

Data: Greenland ice cores as in a previous slide.

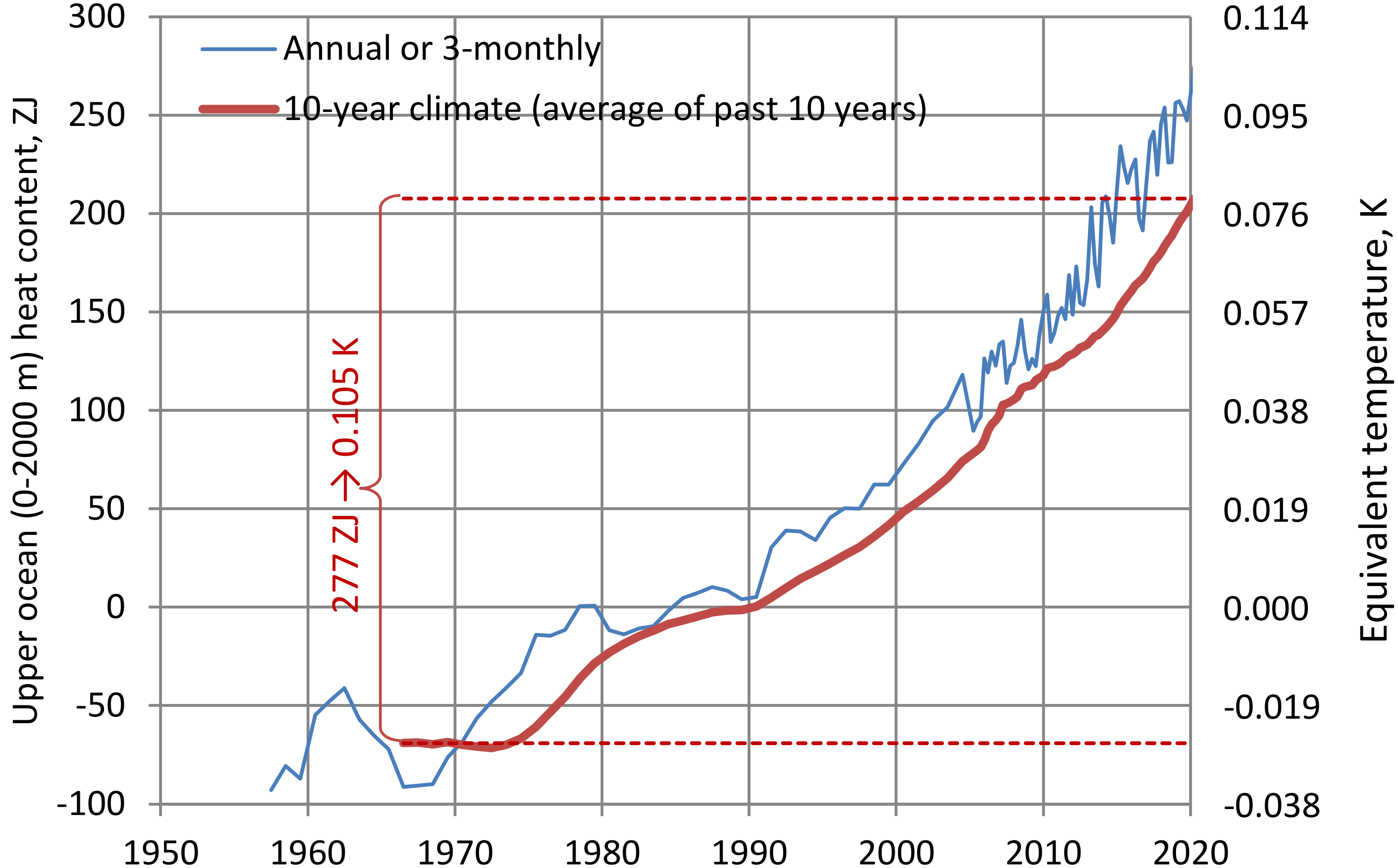
Part 4
Climate of the present

Recent global sea-level rise



Data:
(1) Dangendorf et al (2019): Synthesis of satellite altimetry with 479 tide-gauge records (https://static-content.springer.com/esm/art%3A10.1038%2Fs41558-019-0531-8/MediaObjects/41558_2019_531_MOESM2_ESM.txt)
(2) Copernicus: satellite altimetry for the global ocean from 1993 to present (http://climexp.climexp-knmi.surf-hosted.nl/getindices.cgi?WMO=CDSData/global_copernicus_sla&STATION=global_sla_C3S&TYPE=i&id=someone@somewhere)

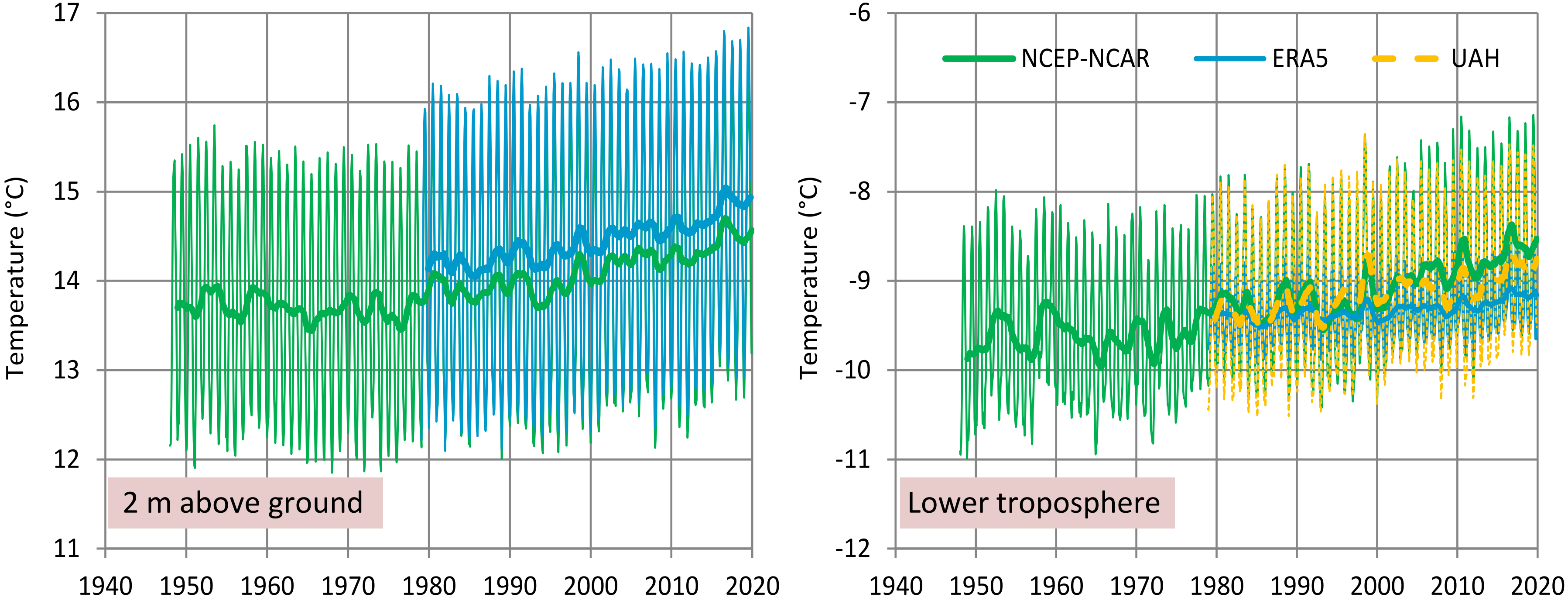
Ocean heat content



Noticeable fact: During the 54-year period 1966 -2020 the upper ocean heat content has increased by 277 ZJ, averaged globally at a 10-year climatic scale; this corresponds to a temperature increase of 0.105 K (average rate <2 hundredths of a °C per decade).

Data: NODC upper ocean (0-2000 m) heat content (from https://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/basin_data.html; conversion into equivalent temperature using data from http://climexp.knmi.nl/selectindex.cgi resulting in a conversion factor of 2640 ZJ/K).

Atmospheric temperature averaged over the globe



Noticeable fact: During the recent years, climatic temperature increases at a rate of:

- 0.19 °C/decade at the ground level, or
- 0.13 °C/decade at the lower troposphere.

Compare with the rate 0.85 °C/decade in the distant past.

Source of graph: Koutsoyiannis (2020a); data: (1) NCEP/NCAR R1 reanalysis; (2) ERA5 reanalysis by ECMWF; and (3) UAH satellite data for the lower troposphere gathered by advanced microwave sounding units on NOAA and NASA satellites (see Koutsoyiannis, 2020a for the data access sites).

Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Part 5
Basics of climate theory

Dominant theory: CO_2 and Svante Arrhenius

continuously. Conversations with my friend and colleague Professor Högbom, together with the discussions above referred to, led me to make a preliminary estimate of the probable effect of a variation of the atmospheric carbonic acid on the temperature of the earth. As this estimation led to the belief that one might in this way probably find an explanation for temperature variations of 5°–10° C., I worked out the calculation more in detail, and lay it now before the public and the critics.

Arrhenius (1896)

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

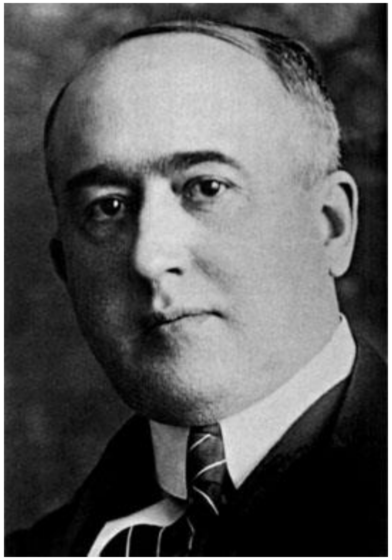
APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

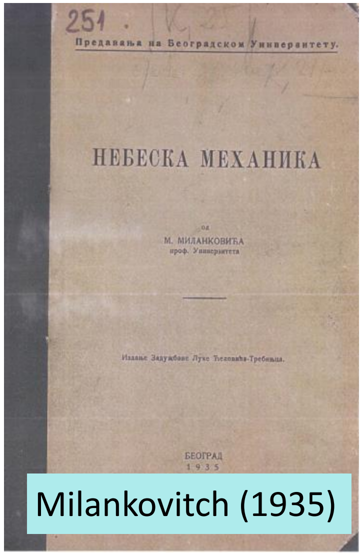
- Arrhenius regards CO_2 (which he calls carbonic acid) as the cause of temperature changes of the past.
- In his calculations, he underestimates by a factor of 7 the relative importance of atmospheric water (in fact, 4 times stronger than CO_2 in greenhouse effect).
- Following the Italian meteorologist De Marchi (1895), he rejects the orbital changes of the Earth as possible causes of the glacial periods.
- He does not explain what causes the changes in the CO_2 concentration in the atmosphere.

Astronomical theory and Milutin Milankovitch

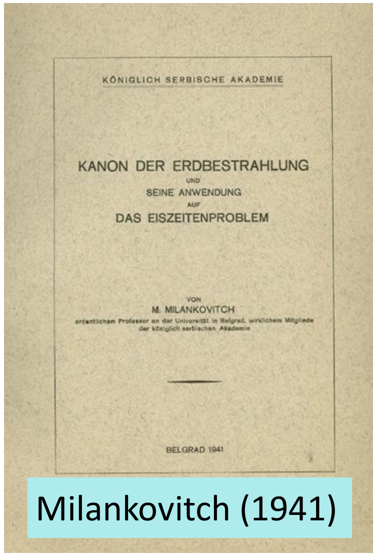
- Milutin Milankovitch (Милутин Миланковић; 1879 – 1958) was a Serbian civil engineer (by basic studies and PhD, as well as work in the design of dams, bridges, aqueducts and other reinforced concrete structures). He is also known as mathematician, astronomer, climatologist and geophysicist.
- He characterized the climates of all the planets of the Solar system.
- He provided an astronomical explanation of Earth's long-term climate changes caused by Earth's orbital changes.
- He proposed the Milankovitch calendar (revising the Julian calendar) in 1923, which in May 1923 was adopted by a congress of some Eastern Orthodox churches, including the Ecumenic Patriarchate of Constantinople and the Greek church. It is more accurate than the Gregorian (but the difference is small, now 0 to become +1 day in 2800).



Years AD (dates from 1 Mar to 28/29 Feb)	Milankovitch – Gregorian
1 –200	0
…	
1500 – 1600	−1
1600 – 2800	0
2800 – 2900	+1
…	
10 000 – 10 100	+3

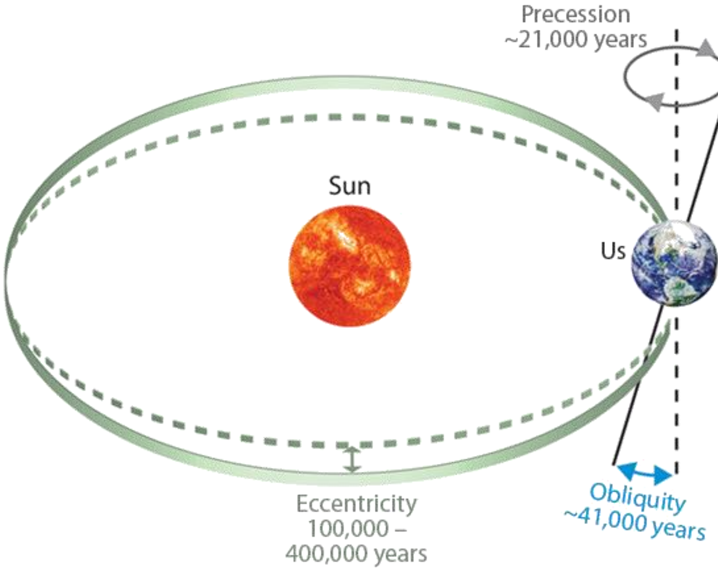


Milankovitch (1935)



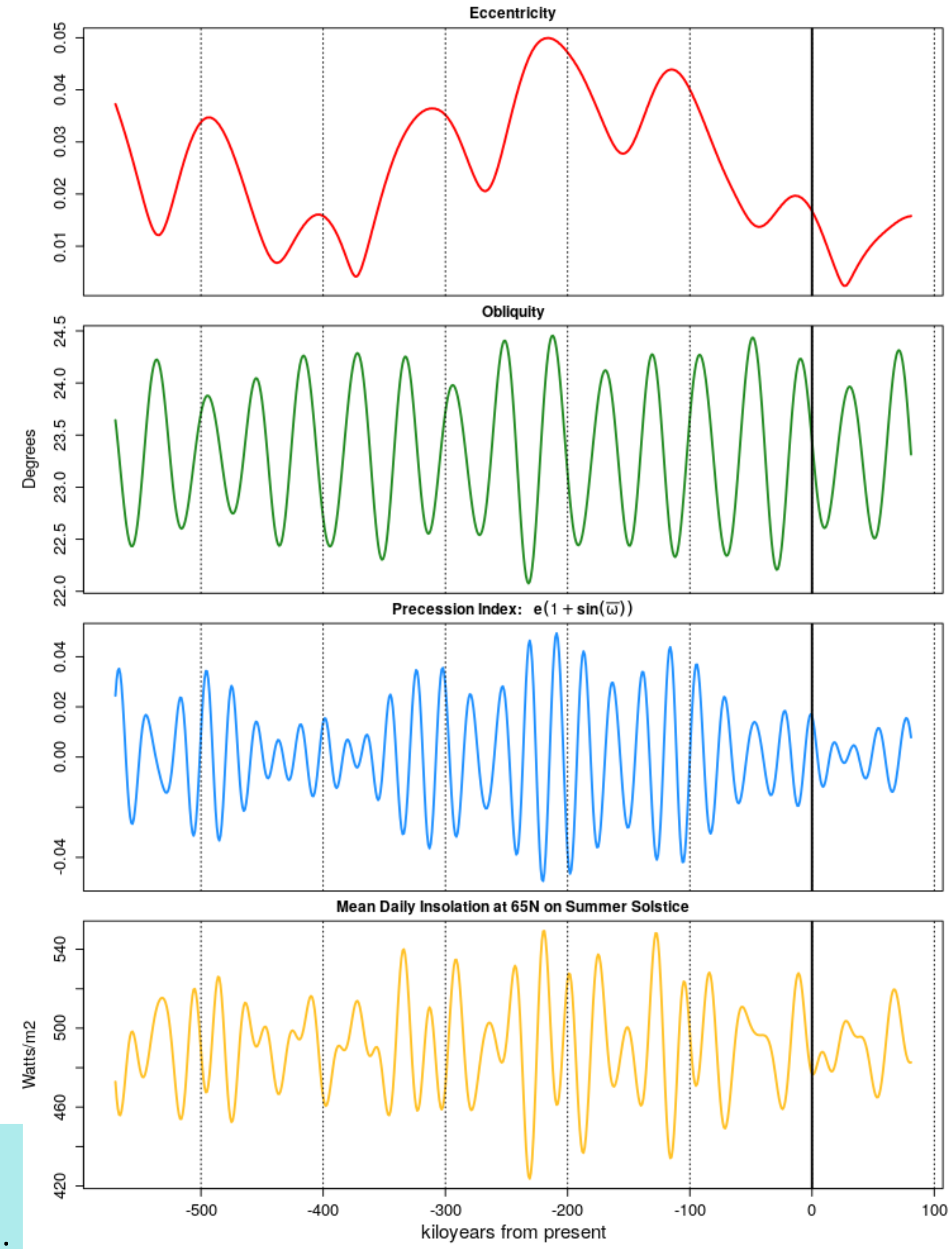
Milankovitch (1941)

Milankovitch cycles

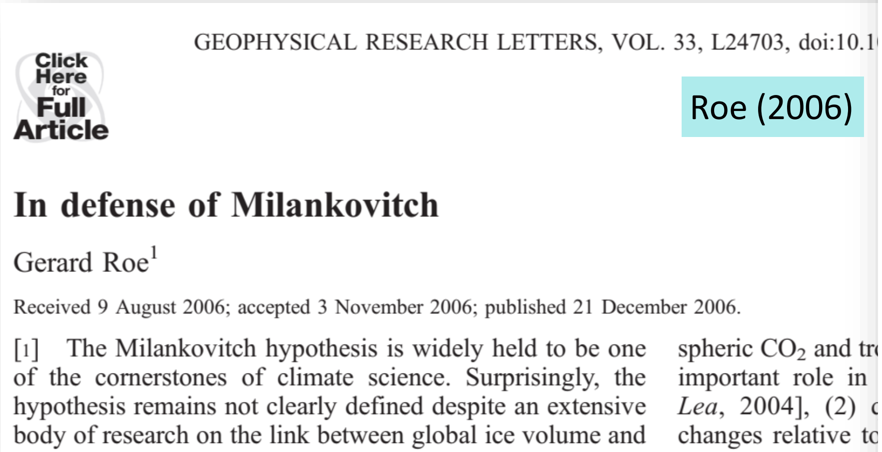


- Astronomical changes (already known):
  - Eccentricity (ἐκκεντρότης);
  - Obliquity (λόξωσις);
  - Precession (μετάπτωσις, first calculated by Hipparchus);
- Milankovitch calculated the insolation at latitude 65°N, which he regarded most sensitive to the change of thermal balance of Earth.

Source of figures and calculations:
https://biocycle.atmos.colostate.edu/shiny/Milankovitch/
based on the solutions of equations by Laskar et al. (2004).



Recent confirmation of Milankovitch theory


GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L24703, doi:10.1

Click Here for Full Article

Roe (2006)

In defense of Milankovitch

Gerard Roe[1]

Received 9 August 2006; accepted 3 November 2006; published 21 December 2006.

[1] The Milankovitch hypothesis is widely held to be one of the cornerstones of climate science. Surprisingly, the hypothesis remains not clearly defined despite an extensive body of research on the link between global ice volume and spheric CO_2 and tr important role in *Lea*, 2004], (2) c changes relative to

- Roe (2006) confirmed the Milankovitch theory by comparing the insolation at latitude 65°N with changes of global ice volume ($\mathrm{d}V/\mathrm{d}t$).
- He also observed that variations in ice melting precede variations in atmospheric CO_2, which implies a secondary role for CO_2.
- However, the Milankovitch theory does not explain every change, thus pointing at the need for a stochastic theory.

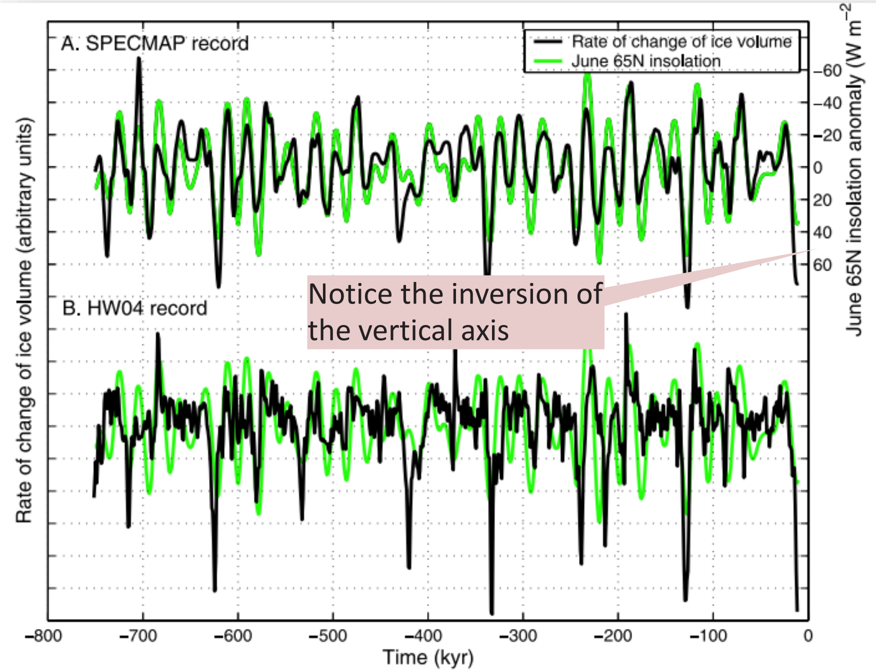


Figure 2. As for Figure 1, but comparing June 65N insolation anomaly with the time rate of change of global ice volume (*dV*/*dt*). The SPECMAP record has zero lag and HW04 record is lagged by only 1 kyr, in order to show the maximum lag correlation with the insolation time series of −0.8 and −0.4, respectively. Autocorrelation estimates suggest that the SPECMAP and HW04 time series of *dV*/*dt* have 106 and 123 degrees of freedom respectively. Therefore, in both cases the correlations are significant at well above the 99% confidence level. If the HW04 record is smoothed in the same manner as SPECMAP (using a nine-point Gaussian filter [*Imbrie et al.*, 1984]), the maximum lag correlation does not increase. Convention for units is as for Figure 1.

Climate stochastics: Kolmogorov, Hurst and the Nile

Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS
1940. Volume XXVI, № 2

Kolmogorov (1940)

MATHEMATIK

WIENERSCHE SPIRALEN UND EINIGE ANDERE INTERESSANTE KURVEN IM HILBERTSCHEN RAUM

Von A. N. KOLMOGOROFF, Mitglied der Akademie

Wir werden hier einige Sonderfälle von Kurven betrachten, denen meine vorhergehende Note «Kurven im Hilbertschen Raum, die gegenüber einer einparametrigen Gruppe von Bewegungen invariant sind» (1) gewidmet ist.

Unter einer Ähnlichkeitstransformation im Hil... Raum H werden ...

... und $y' \neq x'$ der Punkte, die auf derselben Kurve liegen, übergeht.

S a t z 6. *Die Funktion* $B_\xi(\tau_1, \tau_2)$, *die der Funktion* $\xi(t)$ *der Klasse* $\mathfrak{A}$ *entspricht, kann in der Form*

$$B_\xi(\tau_1, \tau_2) = c\,[\,|\tau_1|^\gamma + |\tau_2|^\gamma - |\tau_1 - \tau_2|^\gamma]$$

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AMERICAN SOCIETY OF CIVIL ENGINEERS
Founded November 5, 1852
TRANSACTIONS

Hurst (1951)

Paper No. 2447

LONG-TERM STORAGE CAPACITY OF RESERVOIRS

By H. E. Hurst[1]

With Discussion by Ven Te Chow, Henri Milleret, Louis M. Laushey, and H. E. Hurst.

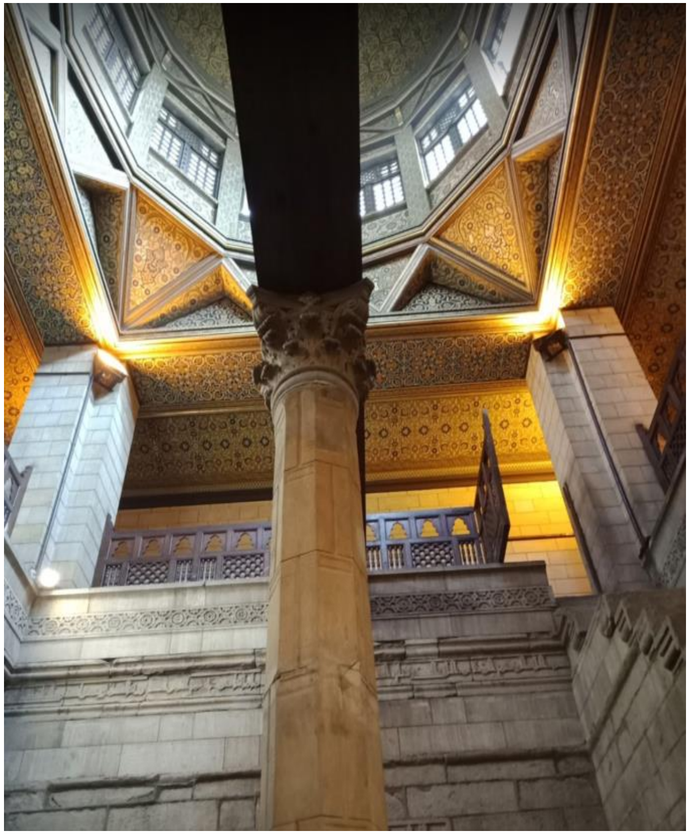
Synopsis

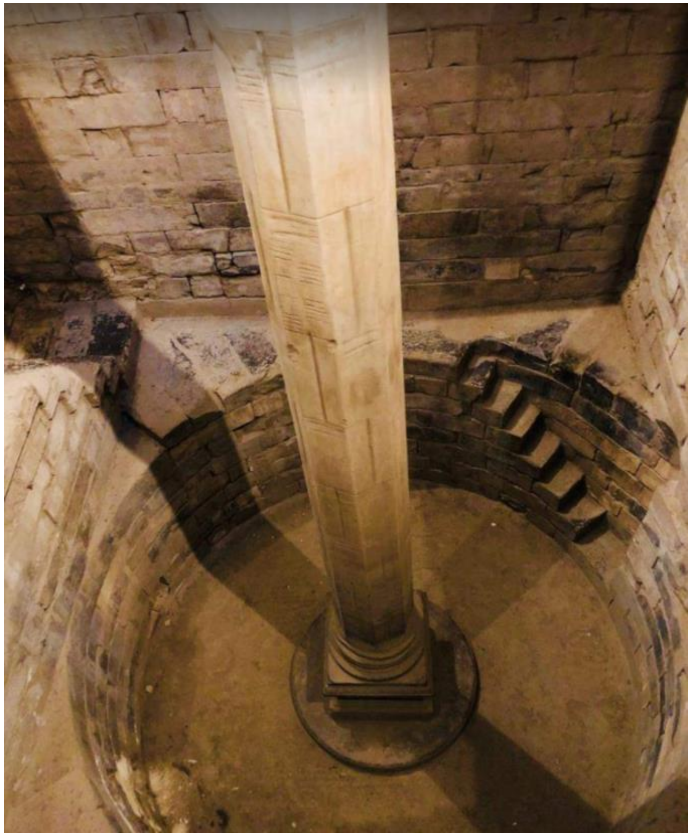
A solution of the problem of determining the reservoir storage required on a given stream, to guarantee a given draft, is presented in this paper. For example, if a long-time record of annual total discharges from the stream is available, the storage required to yield the average flow, each year, is obtained by ... of the departures of the annual totals from ... The range from the maximum to the mini... taken as the required storage.

Kolmogorov proposed a stochastic process that describes a behaviour unknown at that time. It was discovered a decade later in geophysics by Hurst.

"Although in random events groups of high or low values do occur, their tendency to occur in natural events is greater. This is the main difference between natural and random events."

The Roda Nilometer and the longest instrumental record on Earth



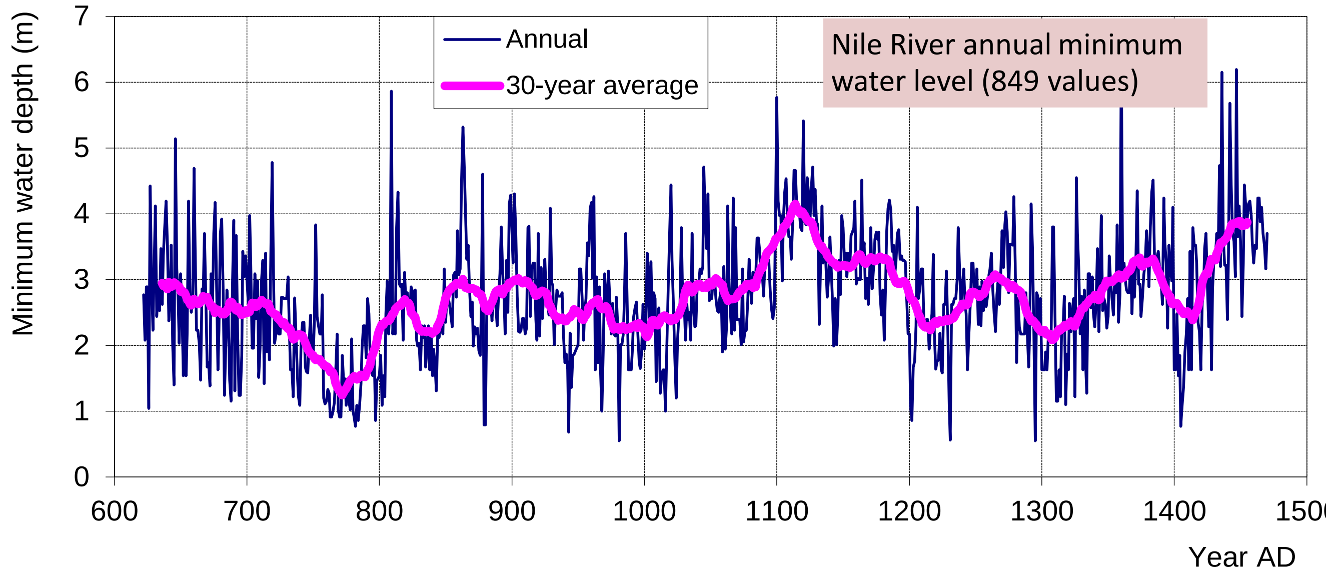


Photos by Loai Samen and Mohamd Mubarak; Google maps, https://goo.gl/maps/T8NUgoDAorK2 and https://goo.gl/maps/dsdJHJYVv572.

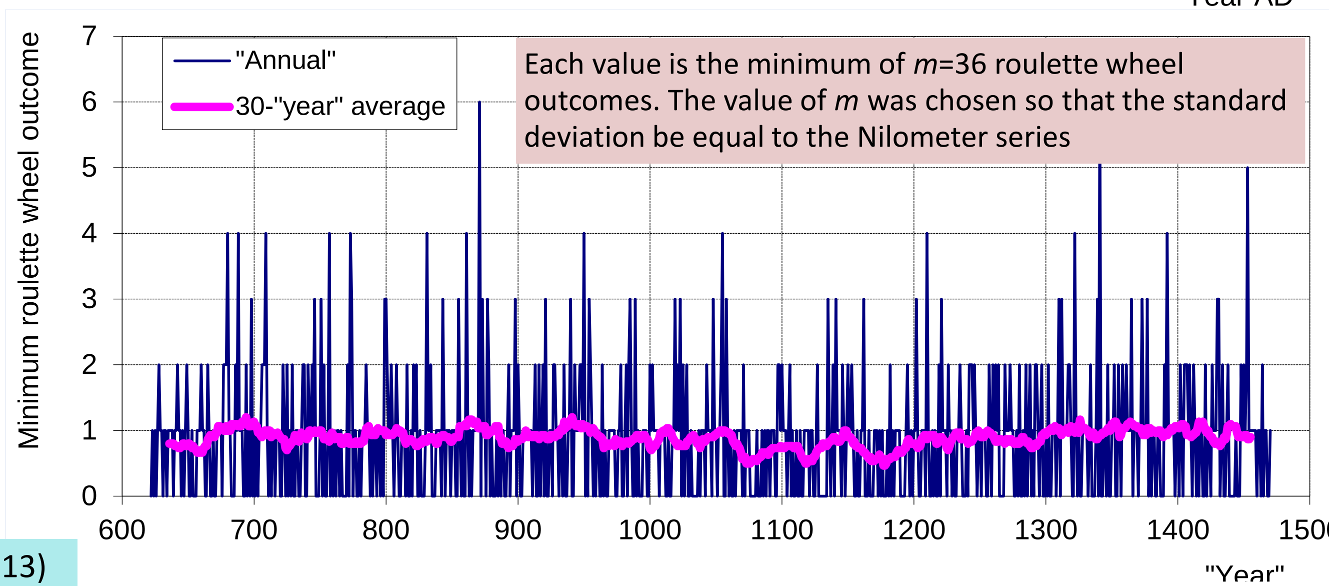
The Roda Nilometer, near Cairo. Water entered through three tunnels and filled the Nilometer chamber up to river level. The measurements were taken on the marble octagonal column (with a Corinthian crown) standing in the centre of the chamber; the column is graded and divided into 19 cubits (each slightly more than 0.5 m) and could measure floods up to about 9.2 m. A maximum level below the 16th mark could portend drought and famine and a level above the 19th mark meant catastrophic flood.

Hurst-Kolmogorov (HK) dynamics and the perpetual change of Earth's climate

A hydroclimatic process as seen in the longest instrumental record



A "roulette" process



Nilometer data: Koutsoyiannis (2013)

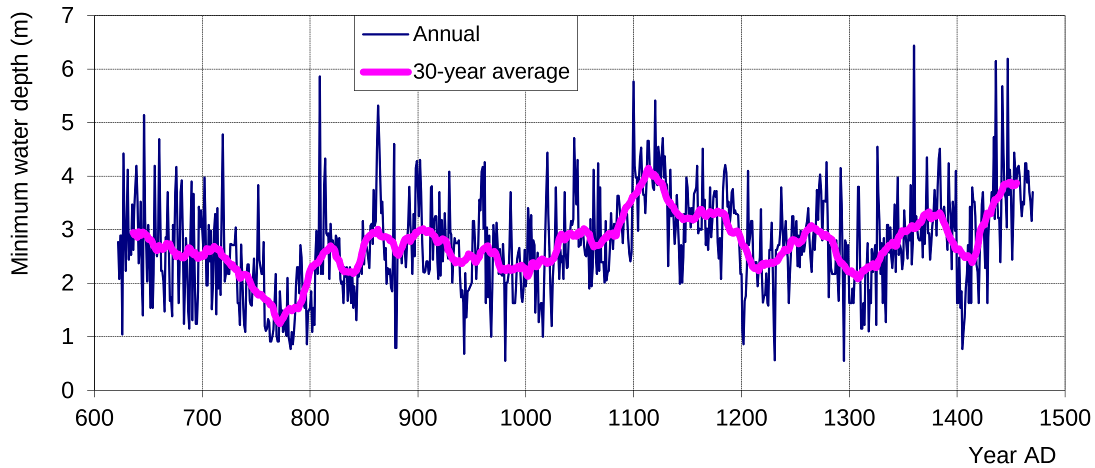
The climacogram: A simple statistical tool to quantify change across time scales

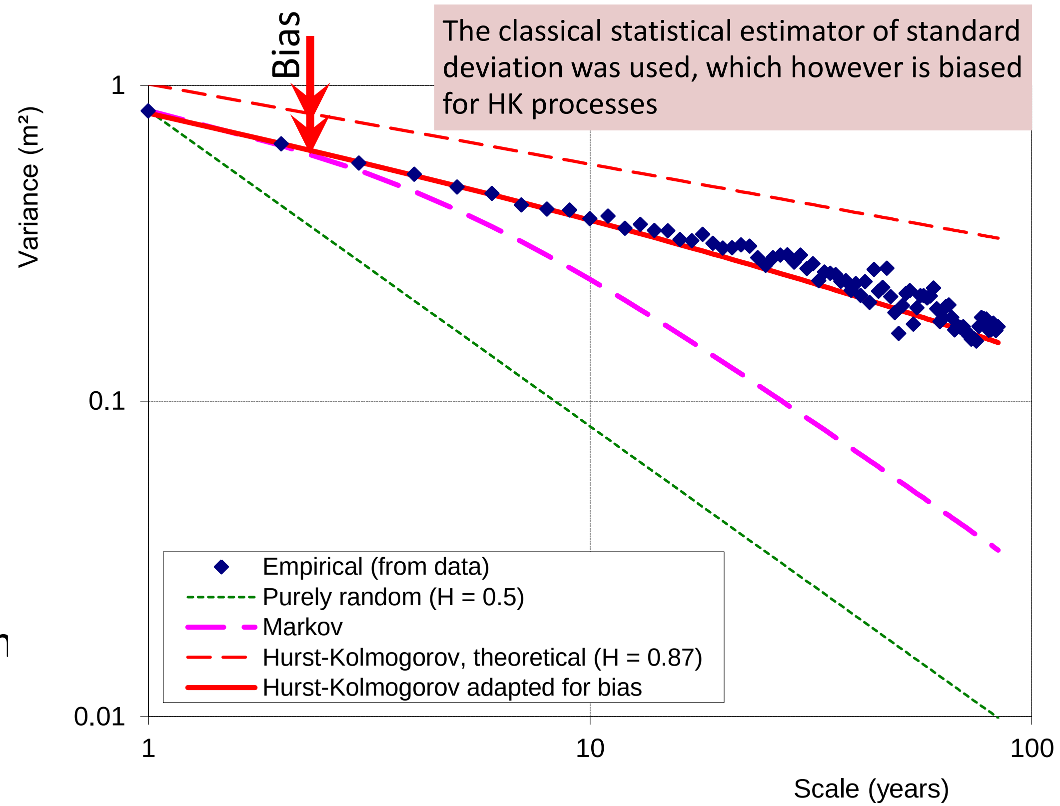
- Take the Nilometer time series, $x_1, x_2, \ldots, x_{849}$, and calculate the sample estimate of variance $\gamma(1)$, where the superscript (1) indicates time scale (1 year).
- Form a time series at time scale 2 (years):
  $x_1^{(2)} := (x_1 + x_2)/2, x_2^{(2)} := (x_3 + x_4)/2, \ldots, x_{424}^{(2)} := (x_{847} + x_{848})/2$
  and calculate the sample estimate of the variance $\gamma(2)$.
- Repeat the same procedure and form a time series at time scale 3, 4, … (years), up to scale 84 (1/10 of the record length) and calculate the variances $\gamma(3), \gamma(4), \ldots \gamma(84)$.
- The **climacogram** is a logarithmic plot of the variance $\gamma(\kappa)$ *vs*. scale κ.
- If the time series x_i represented a pure random process, the climacogram would be a straight line with slope -1 (the proof is very easy).
- In real world processes, the slope is different from -1, designated as $2H - 2$, where H is the so-called Hurst parameter ($0 < H < 1$).
- The scaling law $\gamma(\kappa) = \gamma(1) / \kappa^{2-2H}$ defines the **Hurst-Kolmogorov (HK) process**.
- High values of H (> 0.5) indicate **enhanced change** at large scales, else known as **long-term persistence**, or strong **clustering** (grouping) of similar values.

Koutsoyiannis (2010, 2013, 2016)

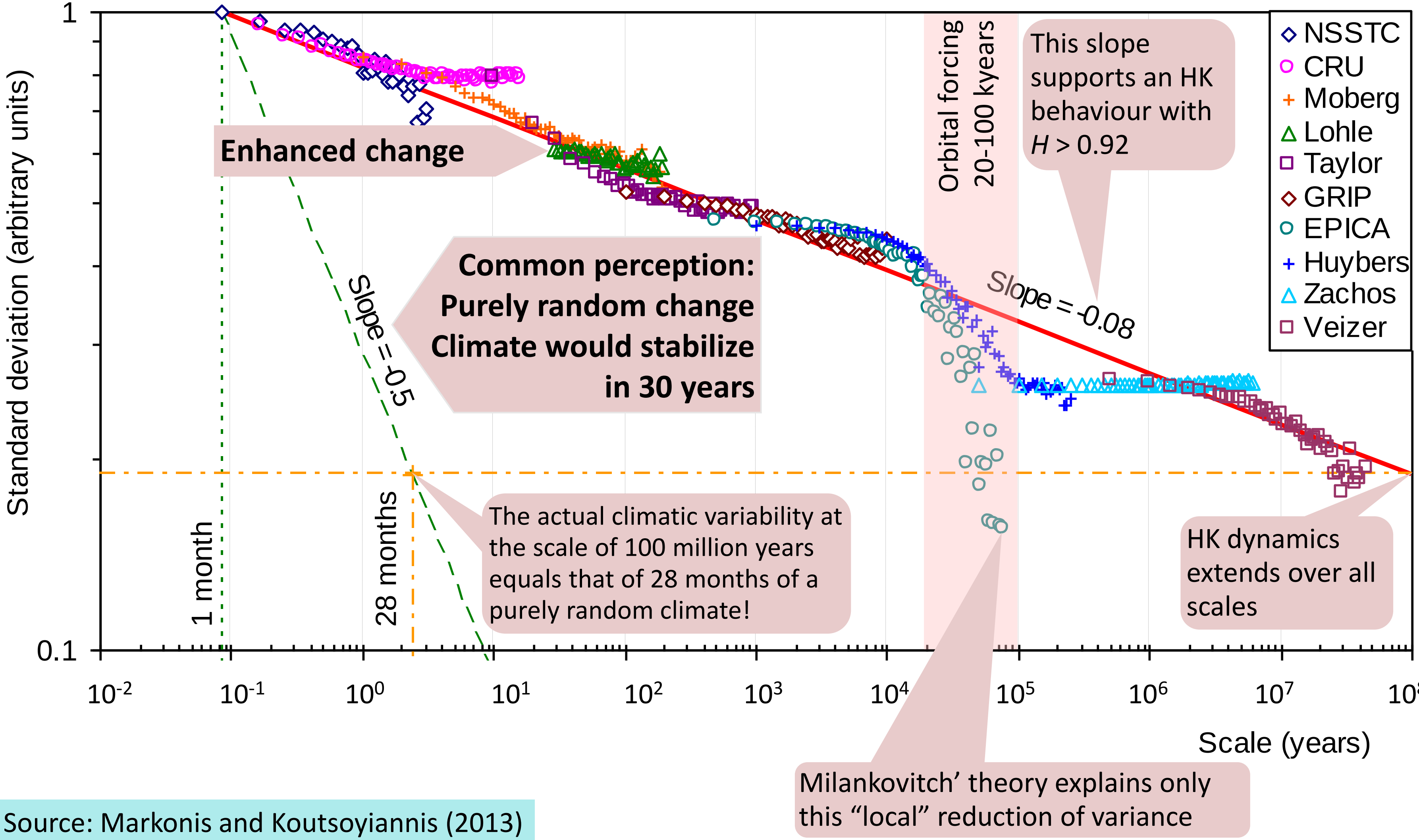
The climacogram of the Nilometer time series

- The Hurst-Kolmogorov process seems consistent with reality.
- The Hurst coefficient is H = 0.87. (Similar H values are estimated from the simultaneous record of maximum water levels and from the modern, 131-year, flow record of the Nile flows at Aswan).
- The Hurst-Kolmogorov behaviour, seen in the climacogram, indicates that:
  - (a) long-term changes are more frequent and intense than commonly perceived, and
  - (b) future states are much more uncertain and unpredictable on long time horizons than implied by pure randomness.





A combined climacogram of temperature observations and proxies (Hurst-Kolmogorov + Milankovitch)



Source: Markonis and Koutsoyiannis (2013)

Part 6
The energy cycle

Global energy flows and energy balance

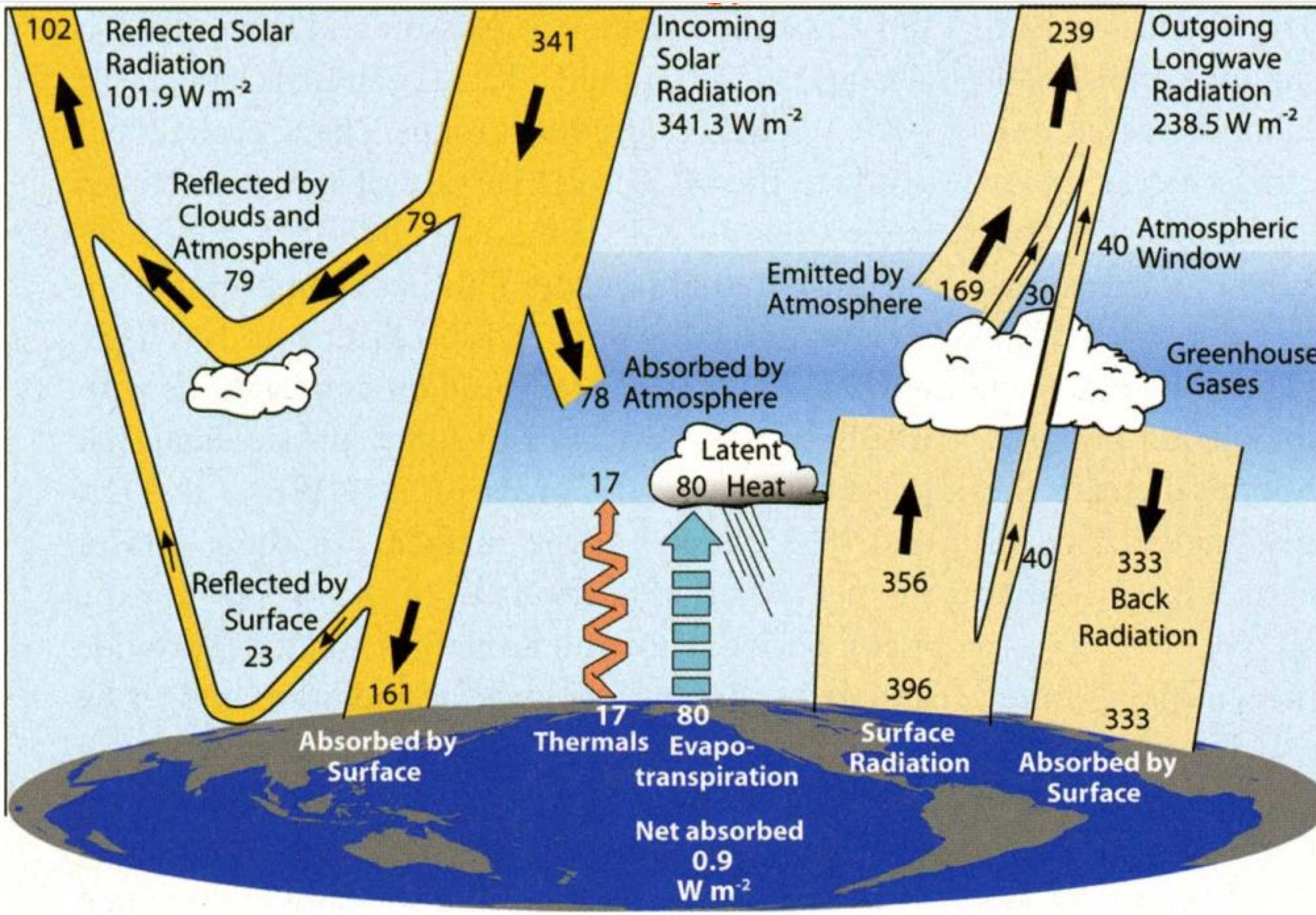


FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance.

Trenberth et al. (2009)

Comparison of human and natural locomotives (not to scale)

Image from http://4-designer.com/2014/03/Cartoon-steam-train-vector-material/

Human locomotive

All human energy production (2014):
170 000 TWh/year
= 0.612×10^{21} J/year
= 0.612 ZJ/year (Mamassis et al., 2020)

Natural locomotive

Power density (for evaporating water):
80 W/m^2

For earth's area
5.101×10^{14} m^2:

4.08×10^{16} W = 40.8 PW

Annual energy:
1.290×10^{24} J/year
= 1290 ZJ/year.

Koutsoyiannis (2020a)

Comparison of human and natural locomotives (to scale)

All human energy production

Human locomotive
0.612 ZJ/year

Natural locomotive
1290 ZJ/year
(2100 times higher than all human energy production)

Image from http://4-designer.com/2014/03/Cartoon-steam-train-vector-material/

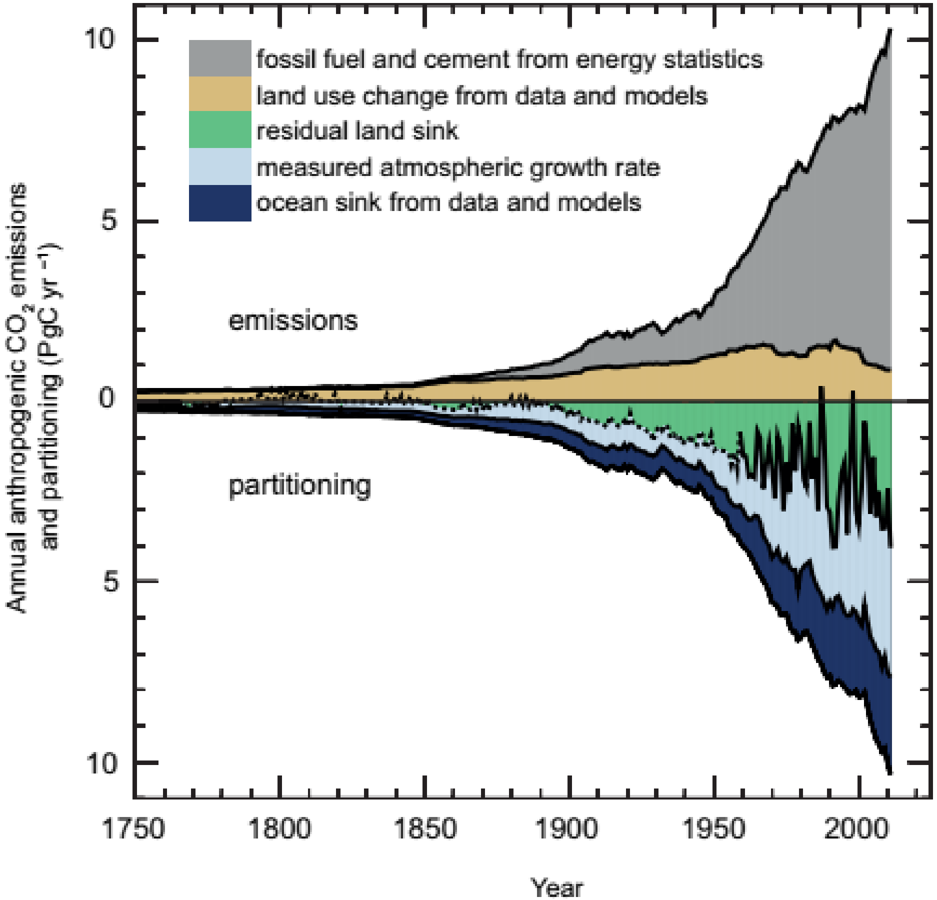
Koutsoyiannis (2020a)

Part 7
The carbon cycle

Anthropogenic changes in atmospheric carbon according to IPCC (2013)

Questions:

1. Does the measured atmospheric growth rate (cyan in the lower part of the figure) originate from anthropogenic emissions as implied by the figure?
2. What percentage of the total carbon flow to the atmosphere do anthropogenic emissions represent?
3. Is the net human effect on land use increasing the emissions, as implied by the figure?



From the original figure caption (IPCC, 2013)
Figure TS.4 | Annual anthropogenic CO_2 emissions and their partitioning among the atmosphere, land and ocean (Gt / year; 1 Gt = 1 Pg) from 1750 to 2011. […]. CO_2 emissions from net land use change, mainly deforestation, are based on land cover change data. […]

On question 3:
Is Earth browning or greening?

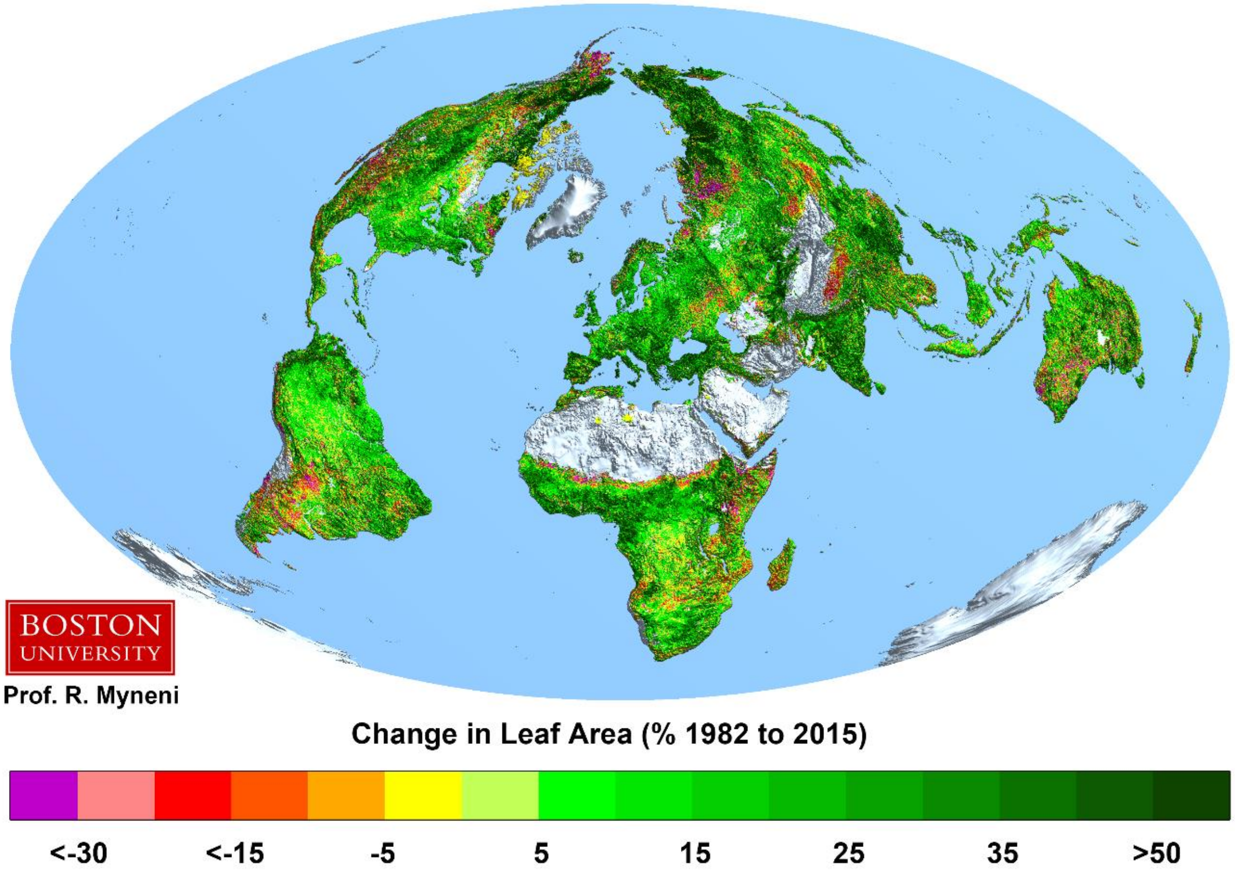


Image source: http://sites.bu.edu/cliveg/files/2016/04/LAI-Change.png

Quoting **Zhu et al. (2016)**:
"We show a persistent and widespread increase of growing season integrated LAI [Leaf Area Index] *(greening) over 25% to 50% of the global vegetated area, whereas less than 4% of the globe shows decreasing LAI (browning). Factorial simulations with multiple global ecosystem models suggest that CO_2 fertilization effects explain 70% of the observed greening trend, followed by nitrogen deposition (9%), climate change (8%) and land cover change (LCC) (4%). CO_2 fertilization effects explain most of the greening trends in the tropics* […]"

On question 3: Are human activities browning or greening the Earth?

Source: Chen et al. (2019)

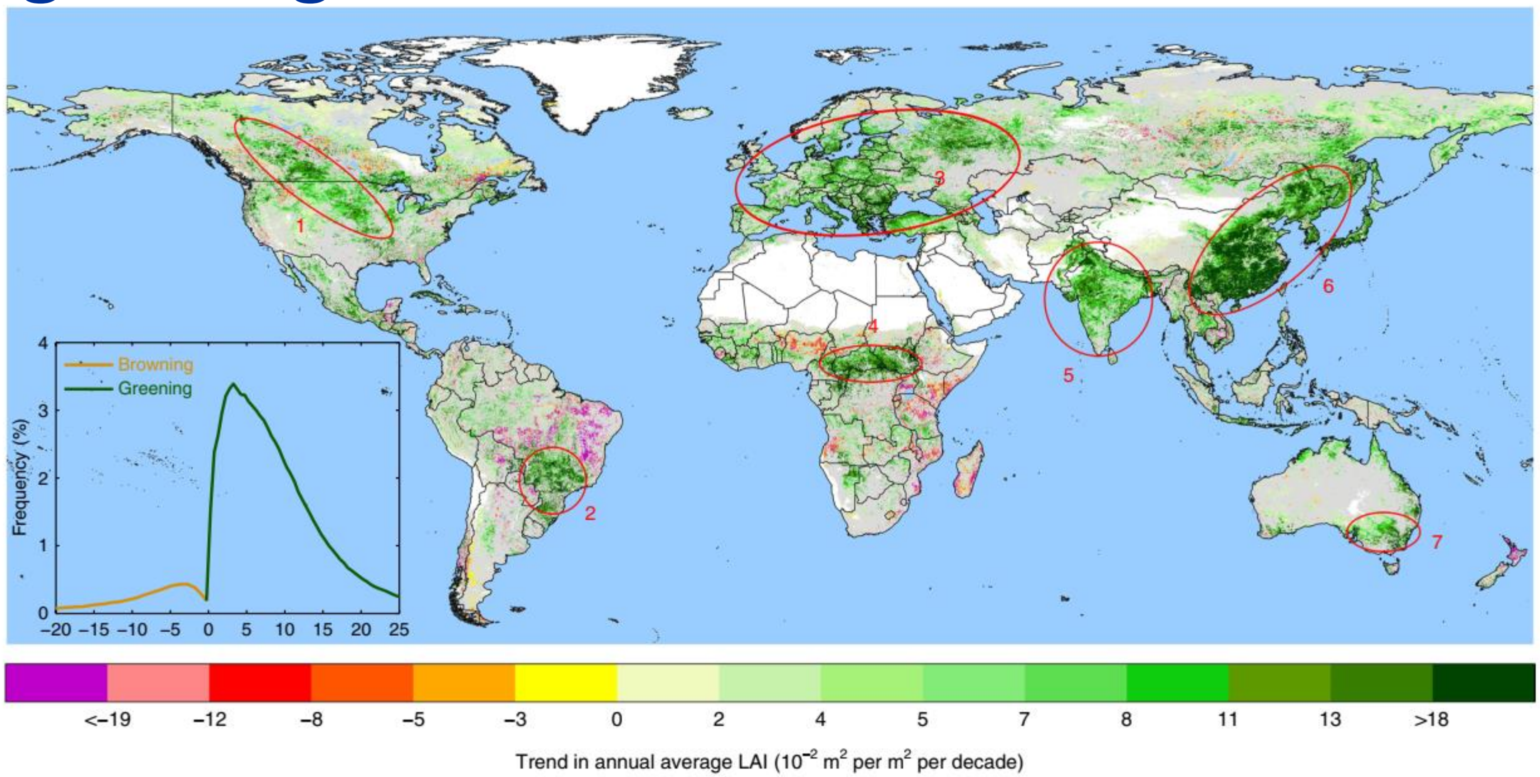
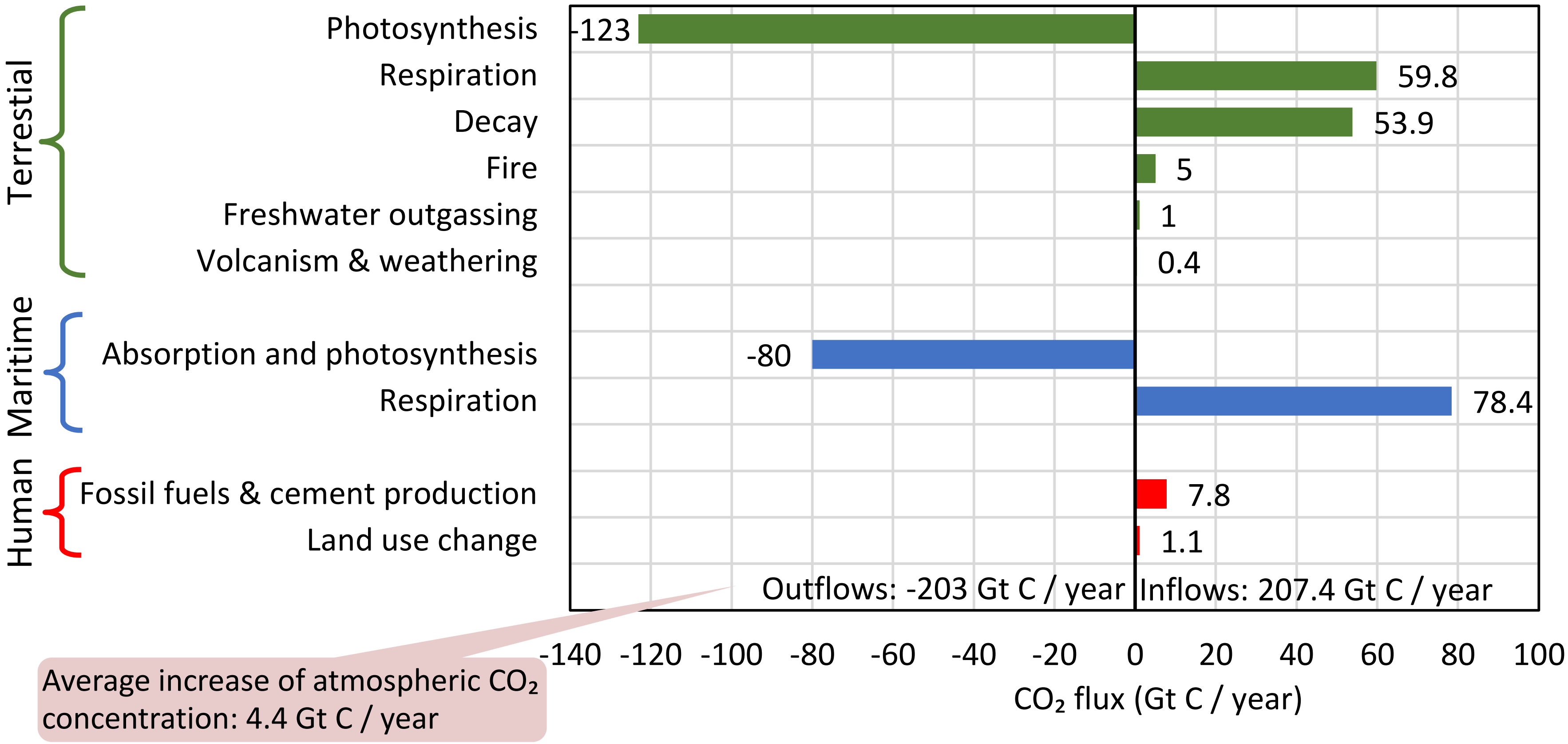


Fig. 1 | Map of trends in annual average MODIS LAI for 2000–2017. Statistically significant trends (Mann–Kendall test, $P \leq 0.1$) are colour-coded. Grey areas show vegetated land with statistically insignificant trends. White areas depict barren lands, permanent ice-covered areas, permanent wetlands and built-up areas. Blue areas represent water. The inset shows the frequency distribution of statistically significant trends. The highlighted greening areas in red circles mostly overlap with croplands, with the exception of circle number 4. Similar patterns are seen at $P \leq 0.05$ and the seven greening clusters are visible even at $P \leq 0.01$.

Quoting Chen et al. (2019): *"recent satellite data (2000–2017) reveal a greening pattern that is strikingly prominent in China and India and overlaps with croplands world-wide."*

On question 2: Synthesis of the atmospheric carbon balance



Totals according to IPCC (2013) and additional information from Green and Byrne (2004).

On question 2: Percentage of the anthropogenic emissions on total carbon flux to the atmosphere

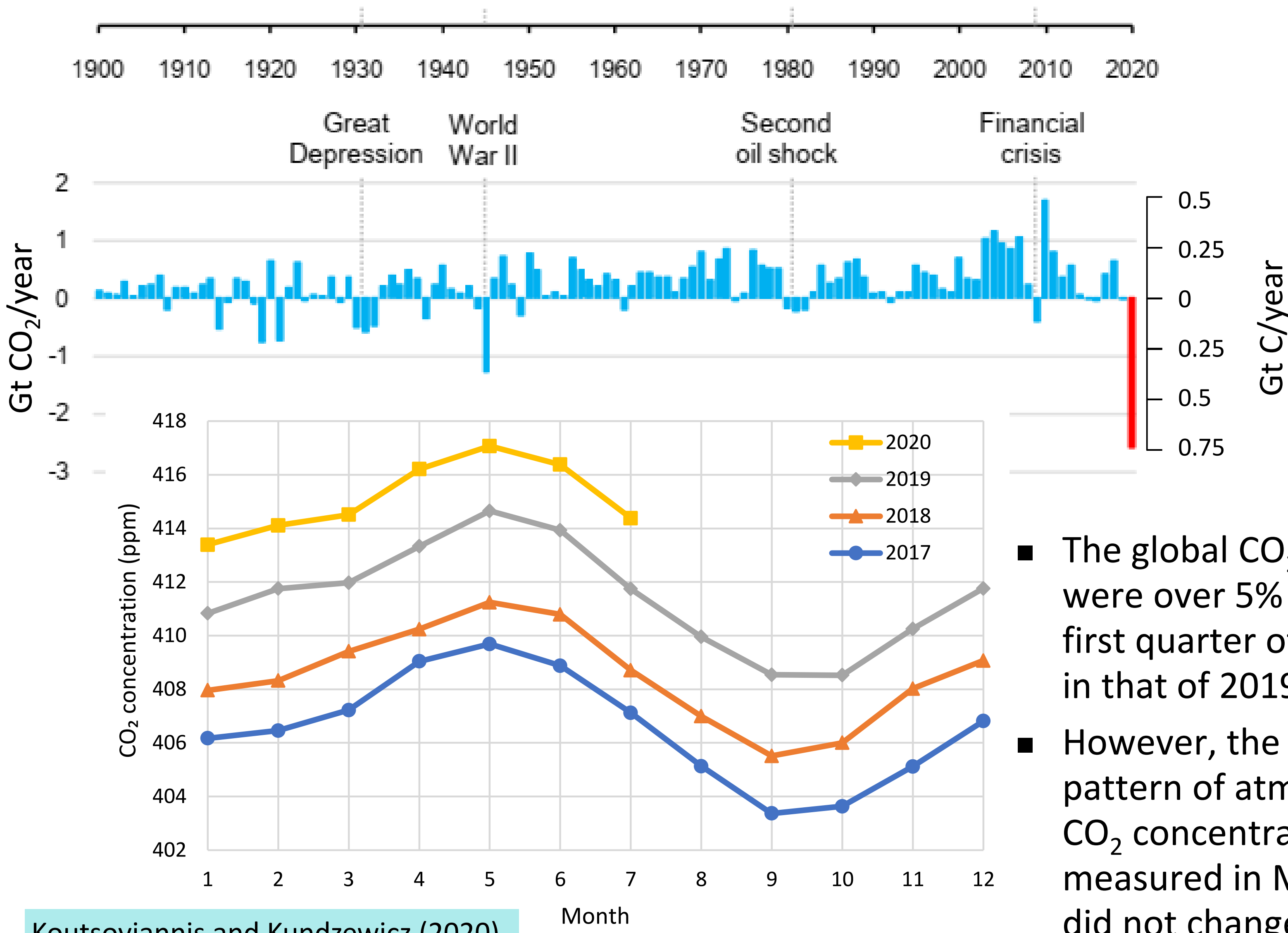
Human CO_2 emissions (fossil fuels and cement production): **3.8%**

Natural CO_2 emissions (respiration, decay, etc., in land and sea): **96.2%**

Areas plotted to scale

Images from: https://www.whitehorse.vic.gov.au/dust-smoke-fumes-and-odour-nuisance
https://www.wallpapers13.com/tropical-landscape-marine-animal-underwater-world-sea-dolphin-colorful-sea-fish-corals-land-coast-palm-trees-scarlet-birds-sunrise-art-wallpaper-hd-1920x1200/

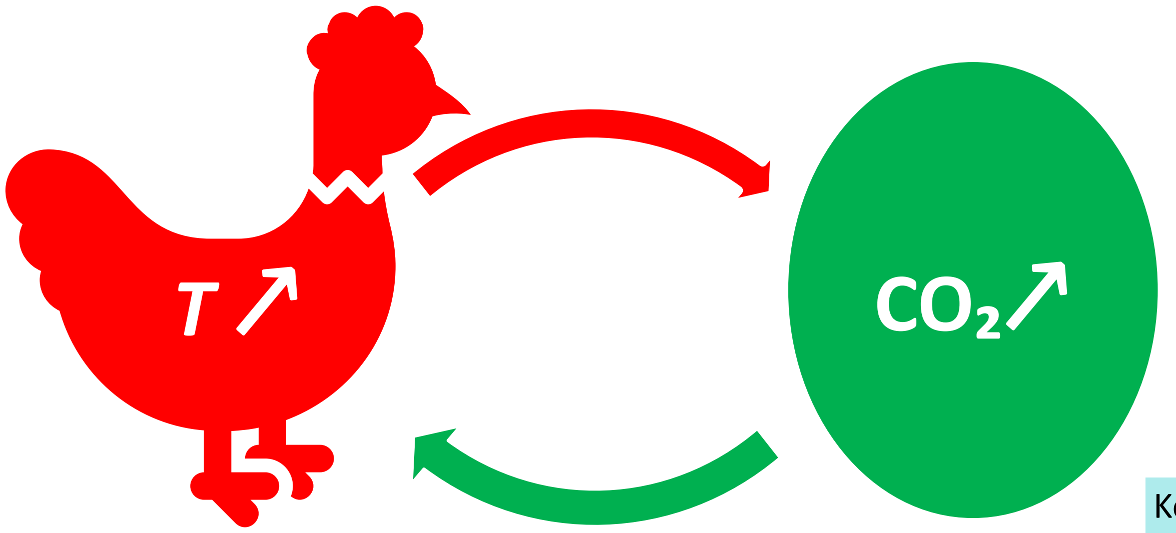
On Question 1: Covid-19 and an unfortunate experiment



Koutsoyiannis and Kundzewicz (2020)

- The global CO_2 emissions were over 5% lower in the first quarter of 2020 than in that of 2019 (IEA, 2020).
- However, the increasing pattern of atmospheric CO_2 concentration, as measured in Mauna Loa, did not change.

Causation between CO_2 and temperature: "ὄρνις ἢ ᾠὸν;" ("hen or egg?")[1]



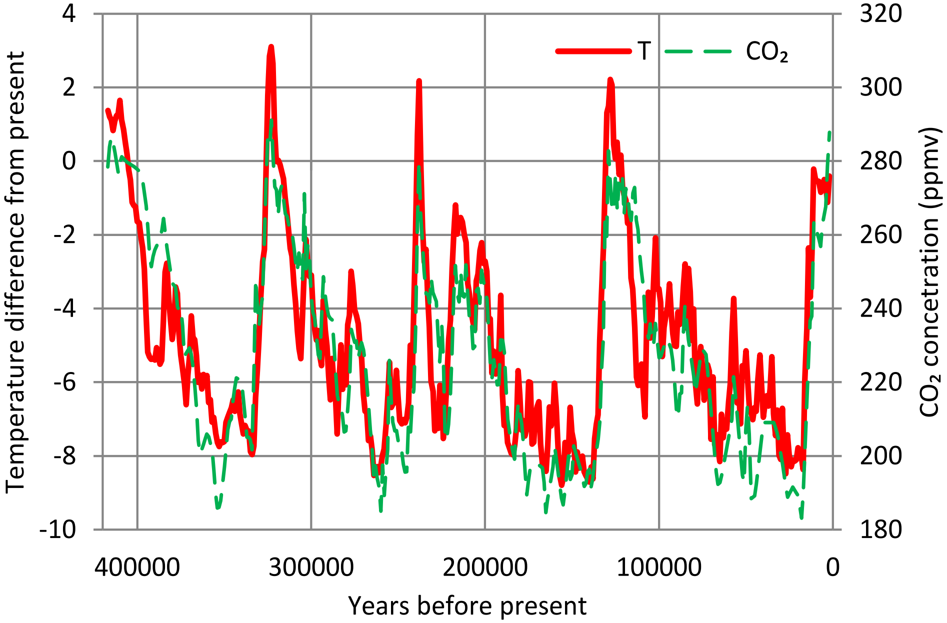
Koutsoyiannis and Kundzewicz (2020)

Koutsoyiannis and Kundzewicz (2020) postulate that the link between CO_2 and temperature classifies as a "hen-or-egg" causality problem, as it is not clear which of two is the cause and which the effect.

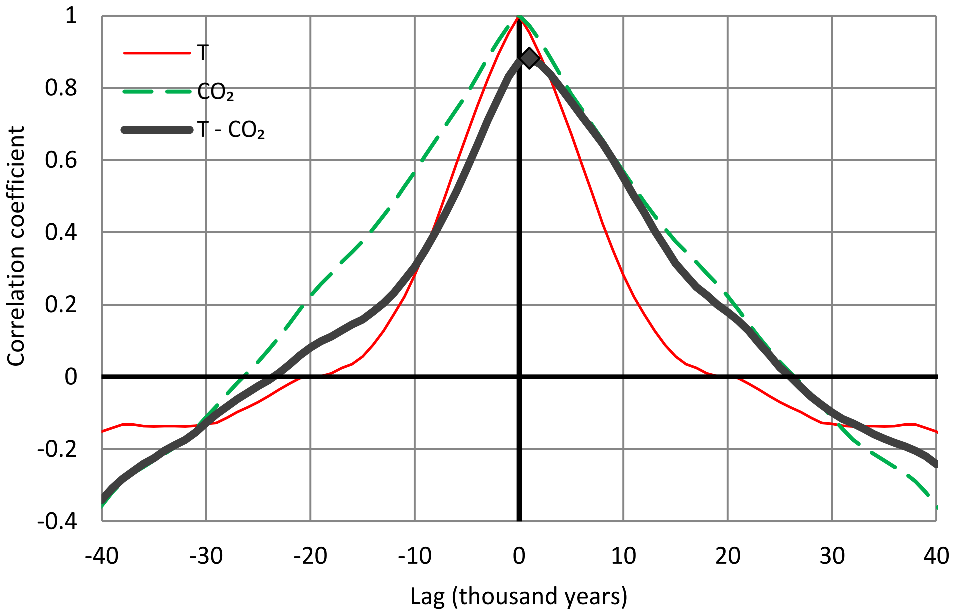
[1] Plutarch first posed this type of causality as a philosophical problem using the example of the hen and the egg: "*Πότερον ἡ ὄρνις πρότερον ἢ τὸ ᾠὸν ἐγένετο*" (Πλούταρχος, Ηθικά, Συμποσιακὰ Β, Πρόβλημα Γ) —Which of the two came first, the hen or the egg? (Plutarch, Moralia, Quaestiones convivales, B, Question III).

Palaeoclimatic data in search of causality

Time series of temperature and CO_2 concentration from the Vostok ice core, covering part of the Quaternary (420 000 years) with time step of 1000 years.



Auto- and cross-correlograms of the two time series. The maximum value of the cross-correlation coefficient is 0.88 and appears at lag 1 thousand years.

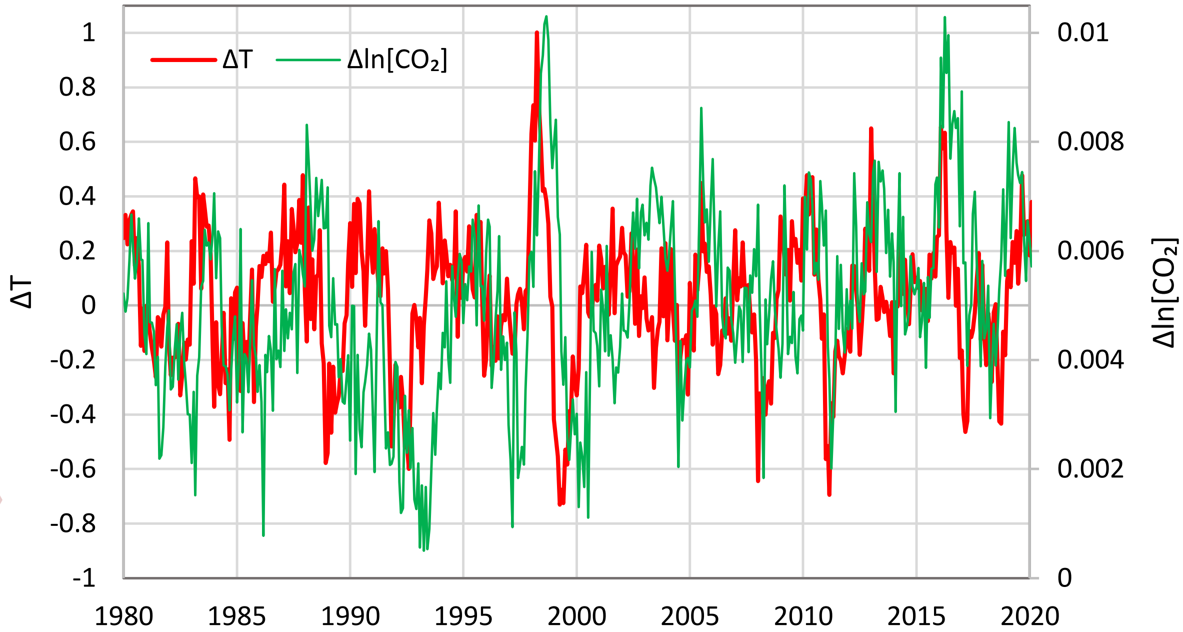


This suggests that the dominant causality direction is $T \rightarrow CO_2$ and that Milankovitch, rather than Arrhenius, is right.

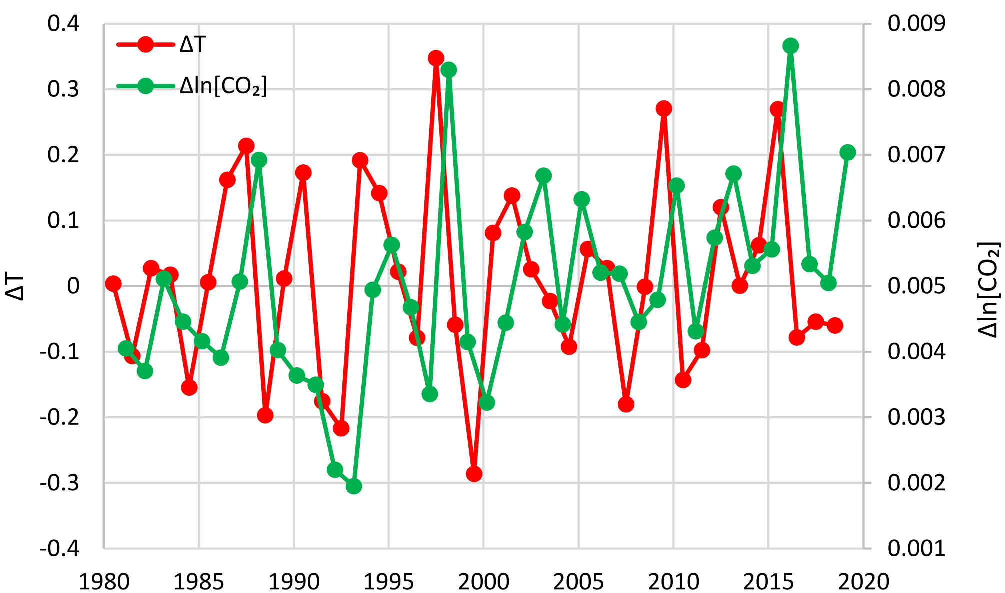
Adapted from Koutsoyiannis (2019)

Recent instrumental temperature and CO_2 data

Differenced monthly time series of global temperature (UAH) and logarithm of CO_2 concentration (Mauna Loa)



Annually averaged time series of differenced temperatures (UAH) and logarithm of CO_2 concentration (Mauna Loa). Each dot represents the average of a one-year duration ending at the time of its abscissa.



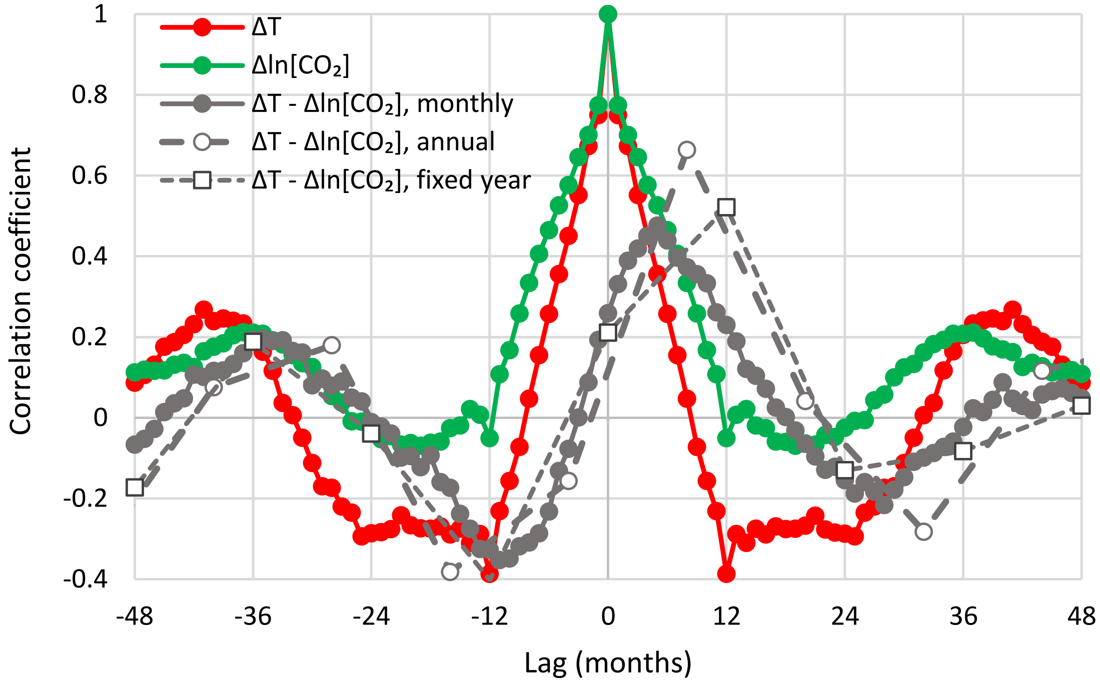
Which is the cause and which the effect?

Koutsoyiannis and Kundzewicz (2020); notice that logarithms of CO_2 concentration are used for linear equivalence with temperature.

Changes in CO_2 follow changes in global temperature

Auto- and cross-correlograms of the differenced time series of temperature (UAH) and logarithm of CO_2 concentration (Mauna Loa)

Which is the cause and which the effect?



Maximum cross-correlation coefficient (MCCC) and corresponding time lag in months

	Monthly time series		Annual time series – sliding annual window		Annual time series – fixed annual window	
Temperature - CO_2 series	MCCC	Lag	MCCC	Lag	MCCC	Lag
UAH – Mauna Loa	0.47	5	0.66	8	0.52	12
UAH – Barrow	0.31	11	0.70	14	0.59	12
UAH – South Pole	0.37	6	0.54	10	0.38	12
UAH – Global	0.47	6	0.60	11	0.60	12
CRUTEM4 – Mauna Loa	0.31	5	0.55	10	0.52	12
CRUTEM4 – Global	0.33	9	0.55	12	0.55	12

Koutsoyiannis and Kundzewicz (2020)

Towards a physical explanation for causality direction

- We start from the Arrhenius equation for the rate of chemical reactions (which should not be confused with the Arrhenius climate theory):

$$k = A \exp\left(-\frac{E}{RT}\right)$$

where *k* is the rate constant of the chemical reaction, *T* is the absolute temperature (in kelvins), *A* is a constant, *E* is the activation energy and *R* is the universal gas constant.

- Assuming $T = T_0 + \Delta T$ for some $T_0 > 0$ for which $k = k_0$ and for $\Delta T \ll T_0$, we can write:

$$\frac{k}{k_0} = \exp\left(-\frac{E}{R(T_0 + \Delta T)} + \frac{E}{RT_0}\right) = \exp\left(-\frac{E}{R(T_0 + \Delta T)} \frac{\Delta T}{T_0}\right) \approx \exp\left(-\frac{E}{RT_0} \frac{\Delta T}{T_0}\right)$$

- Hence:

$$k \approx k_0 \left(\frac{A}{k_0}\right)^{\frac{\Delta T}{T_0}} = k_0 B^{\Delta T}, \qquad \text{where} \quad B \coloneqq \left(\frac{A}{k_0}\right)^{\frac{1}{T_0}}$$

This is an exponential function of ΔT.

Physical explanation of the T → CO_2 causality

- The approximation of the Arrhenius equation for the rate of chemical reactions, i.e.:

$$k \approx k_0 B^{\Delta T}$$

remains valid for biochemical and biological processes (for typical temperature ranges).

- Thus, the graph on the right for the respiration rate R_s (emission of CO_2 from plants and microorganisms) of a coniferous forest can be modelled as:

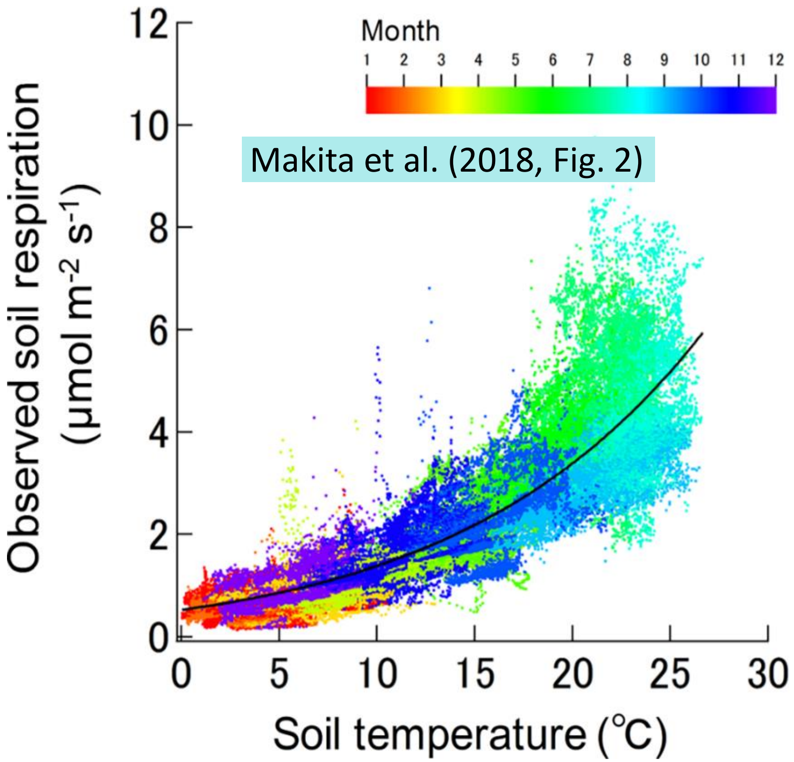
$$R_s = 2.18\,(1.09)^{T-15}$$

- This entails a 9% increase of respiration for an increase of temperature by 1 °C (= 1 K).
- Also, it has been known since 70 years ago (Pomeroy and Bowlus, 1946) that the metabolic rate (activity of microorganisms) in sewer networks follows similar dynamics, i.e.:

$$[\mathrm{EBOD}] = [\mathrm{BOD}]\,(1.07)^{T-20}$$

where BOD stands for biochemical oxygen demand and EBOD for effective BOD.

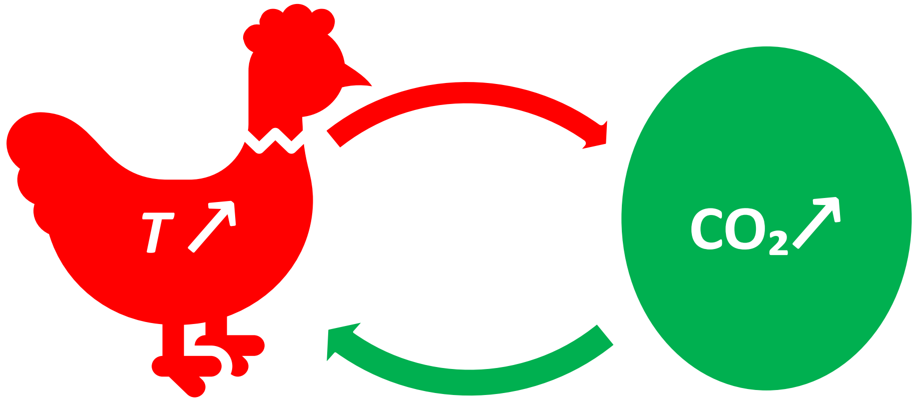
- The latter equation (routinely used in engineering design even today) suggests a 7% increase of metabolic rate for temperature increase of 1 °C.



Graph reproduced from Makita et al. (2018) showing the relationship between soil respiration and temperature during 2005-10 in a temperate evergreen coniferous forest area in Japan. The best-fit model is shown by the solid black line.

How does the natural increase of respiration compare to human emissions?

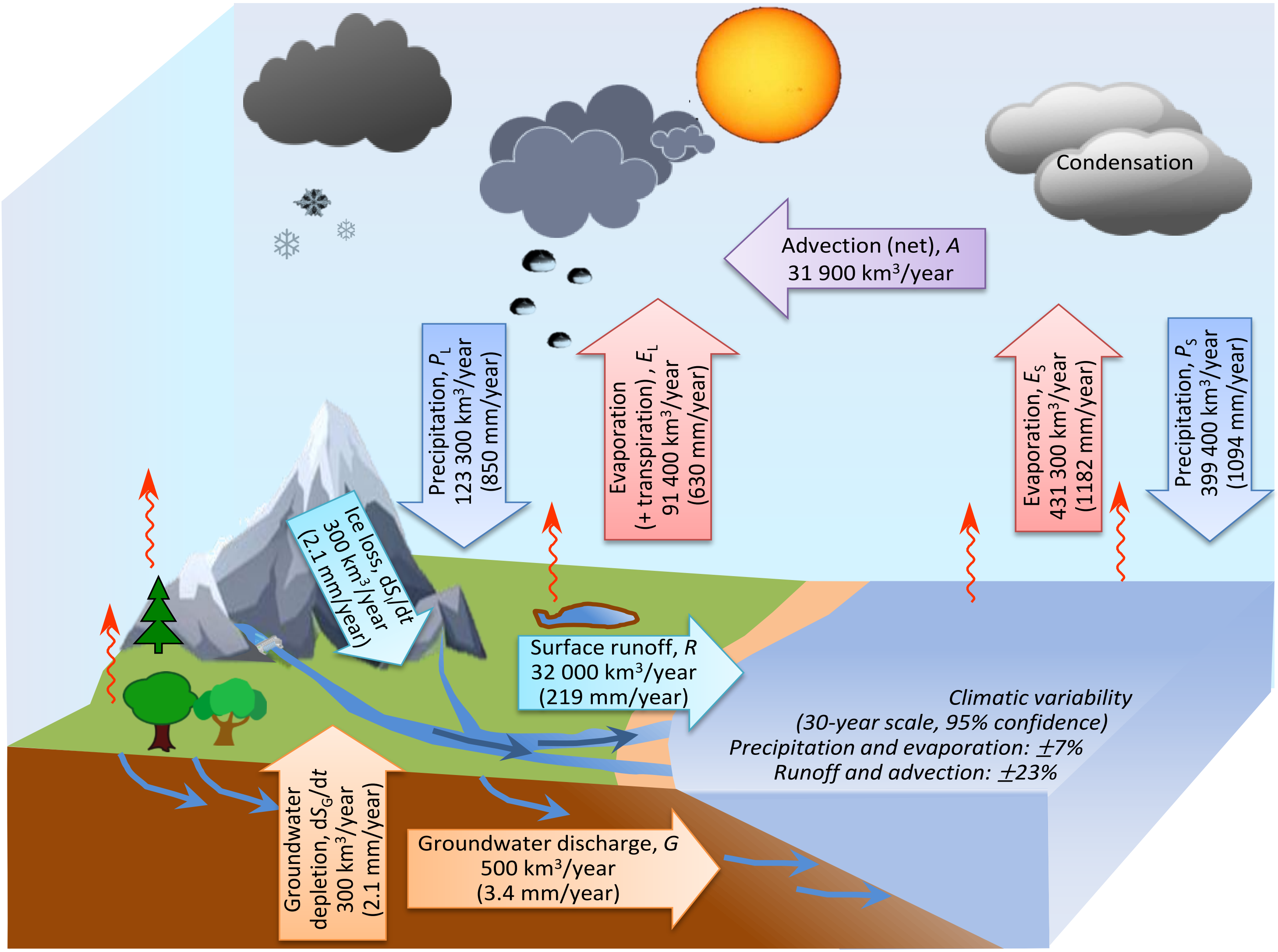
- The soil respiration, assumed to be the sum of respiration (plants) and decay (microbes) is 113.7 Gt C/year (see graph of atmospheric carbon balance).
- According to Koutsoyiannis (2020, Table 2), in the last 30 years the land temperature has been increasing by 0.29 °C/decade, corresponding to an increase in temperature over land of 1.16 °C for the 40-year period 1980 – 2020.
- This means that between 1980 and 2020 there was an increase of annual respiration and decay over land, amounting to 11% or 12 Gt C/year.
- This annual increase is by 50% higher than human emissions (7.8 Gt/year as shown in the graph of atmospheric carbon balance).
- We can expect that the sea respiration would have increased too, but at a lower rate as the sea temperature increase is much lower.



Part 8
The hydrological cycle
and its alleged intensification

The hydrological cycle: A recent quantification

Koutsoyiannis (2020a)



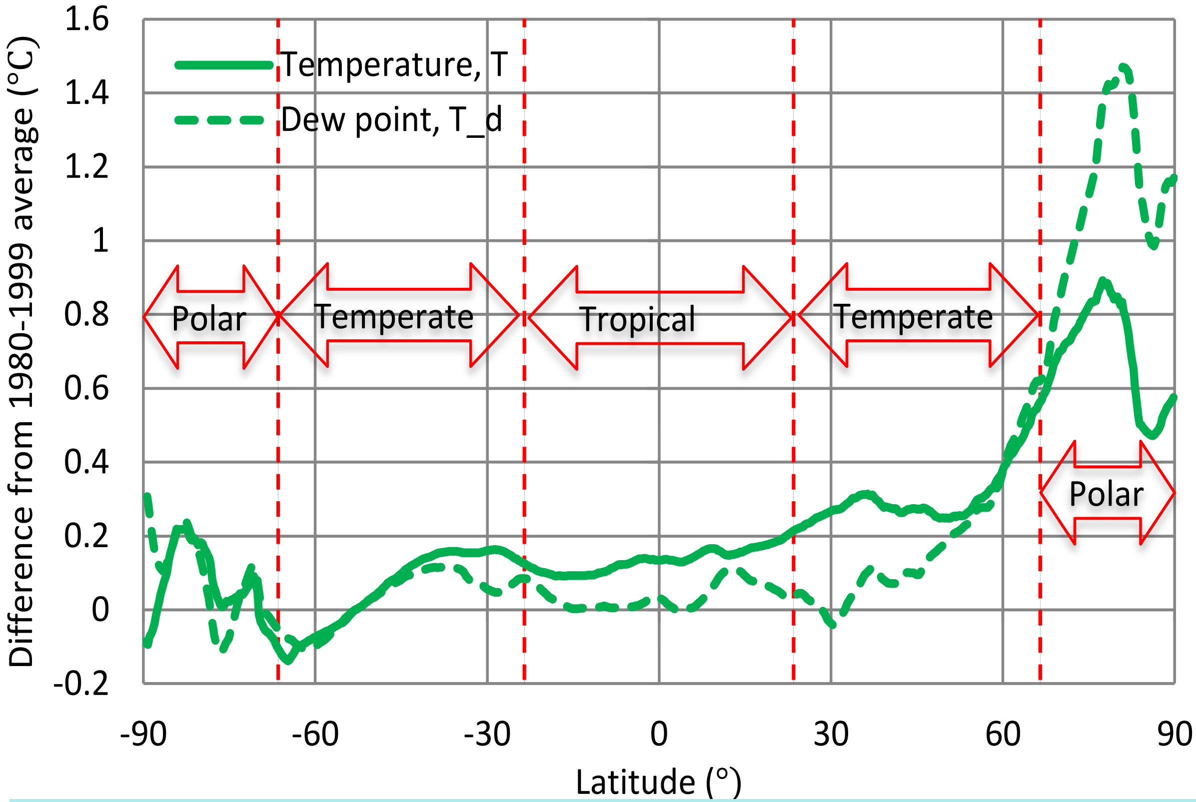
Notice the **groundwater depletion**, i.e., (unsustainable) over pumping beyond the rate of natural recharge.

This contributes 1/3 of the sea-level rise—the most significant anthropogenic effect on the hydrological cycle.

Another 1/3 is contributed by **ice loss** (not necessarily anthropogenic), while 1/3 is due to **thermal expansion**.

Dew point and its comparison to temperature

- The presence of water in the atmosphere (and hence hydrology) is affected more by the dew point, T_d, than the temperature, T.
- The dew point is defined as the temperature at which the air must be cooled to become saturated with water vapour; thus when the relative humidity is 100%, the dew point equals the temperature.



Zonal distribution of the difference of the earth temperature and dew point from their averages in the 20-year period 1980-99, from ERA5 **reanalysis data**. Note that the graph represents averages for the entire 40+ year period 1980-2019, rather than differences between two periods (the latter are about twice the former).

Notice the **zero change in the dew point in the tropics**, which are responsible for most part of evaporation.

Koutsoyiannis (2020a); Reanalysis data access and processing through http://climexp.knmi.nl

Saturation vapour pressure and humidity

- The **saturation vapour pressure**, e, increases almost exponentially with temperature, T:

$$e = e(T) = e_0 \exp\left(\frac{\alpha}{RT_0}\left(1-\frac{T_0}{T}\right)\right)\left(\frac{T_0}{T}\right)^{(c_\mathrm{L}-c_p)/R}$$
$$= e_0 \exp\left(24.921\left(1-\frac{T_0}{T}\right)\right)\left(\frac{T_0}{T}\right)^{5.06}$$

where (T_0, e_0) are the coordinates of the triple point of water, R is the specific gas constant of water vapour, c_p is the specific heat at constant pressure of the vapour and c_L is the specific heat of the liquid water.

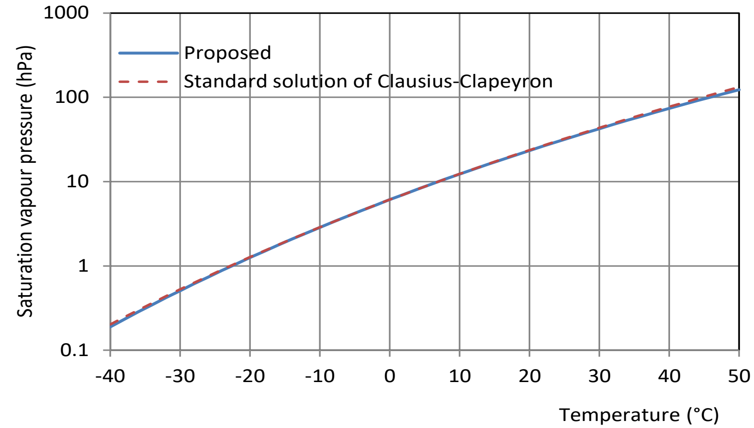
- The dew point is $T_d \coloneqq e^{-1}(e_\mathrm{A})$, where e_A is the actual vapour pressure, and the **relative humidity** is the ratio:

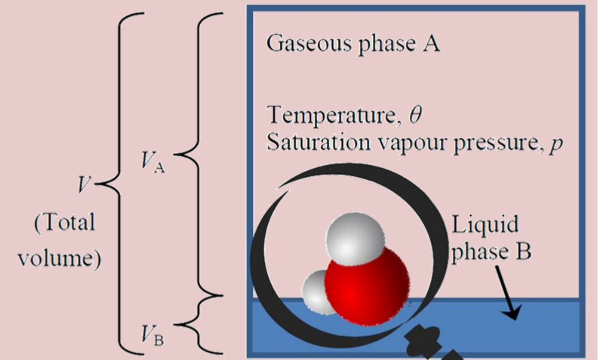
$$U \coloneqq \frac{e_\mathrm{A}}{e(T)} = \frac{e(T_\mathrm{d})}{e(T)}$$

- The **specific humidity** is the ratio of the density of vapour ρ_v to the density of air $\rho_\mathrm{v} + \rho_\mathrm{d}$, where ρ_d is the density of dry air, and is related to vapour pressure by:

$$q \coloneqq \frac{\rho_\mathrm{v}}{\rho_\mathrm{v}+\rho_\mathrm{d}} = \frac{\varepsilon e_\mathrm{A}}{p-(1-\varepsilon)e_\mathrm{A}}$$

where ε =0.622 is the ratio of the molecular mass of water to that of the mixture of gases in the dry air.





The law was derived by studying a single molecule and maximizing the combined uncertainty of its state, i.e.:

(a) its phase (whether gaseous or liquid);
(b) its position in space; and
(c) its kinetic state, i.e., its velocity and other coordinates corresponding to its degrees of freedom and making up its thermal energy.

Koutsoyiannis (2012, 2014a)

Basic assumptions of IPCC on hydrological cycle

- As a result of increasing temperature, the saturation vapour pressure is increasing by 6%–7% per °C of warming.
  - This is a fact resulting from the Clausius–Clapeyron relationship and does not need observations to confirm.
- In a warming climate, atmospheric moisture is changing in a manner that the **relative humidity remains constant**, but **specific humidity increases** according to the Clausius–Clapeyron relationship. As a result, the established view is that the global atmospheric water vapour should increase by about 6%–7% per °C of warming.
  - This is a conjecture that needs to be tested by data.
- This gives rise to what has been called **intensification of hydrological cycle**.
  - Because of the alleged intensification, the role of hydrology becomes thus important in the climate agenda from a sociological point of view: some of the most prominent predicted catastrophes are related to water shortage and extreme floods (Koutsoyiannis, 2014b).
- The rate of increase of precipitation, necessarily accompanied by an equal rate of increase of evaporation, estimated from climate model simulations, is conjectured to be smaller, 1% to 3% per °C, with a typical estimate of 2.2% per °C (Kleidon and Renner, 2013).
  - Even accepting this IPCC assertion and the celebrated target of 2 °C of global warming, which translates in 2-6% increase of rainfall, the change is negligible.

Decadal change as seen in a long daily precipitation record

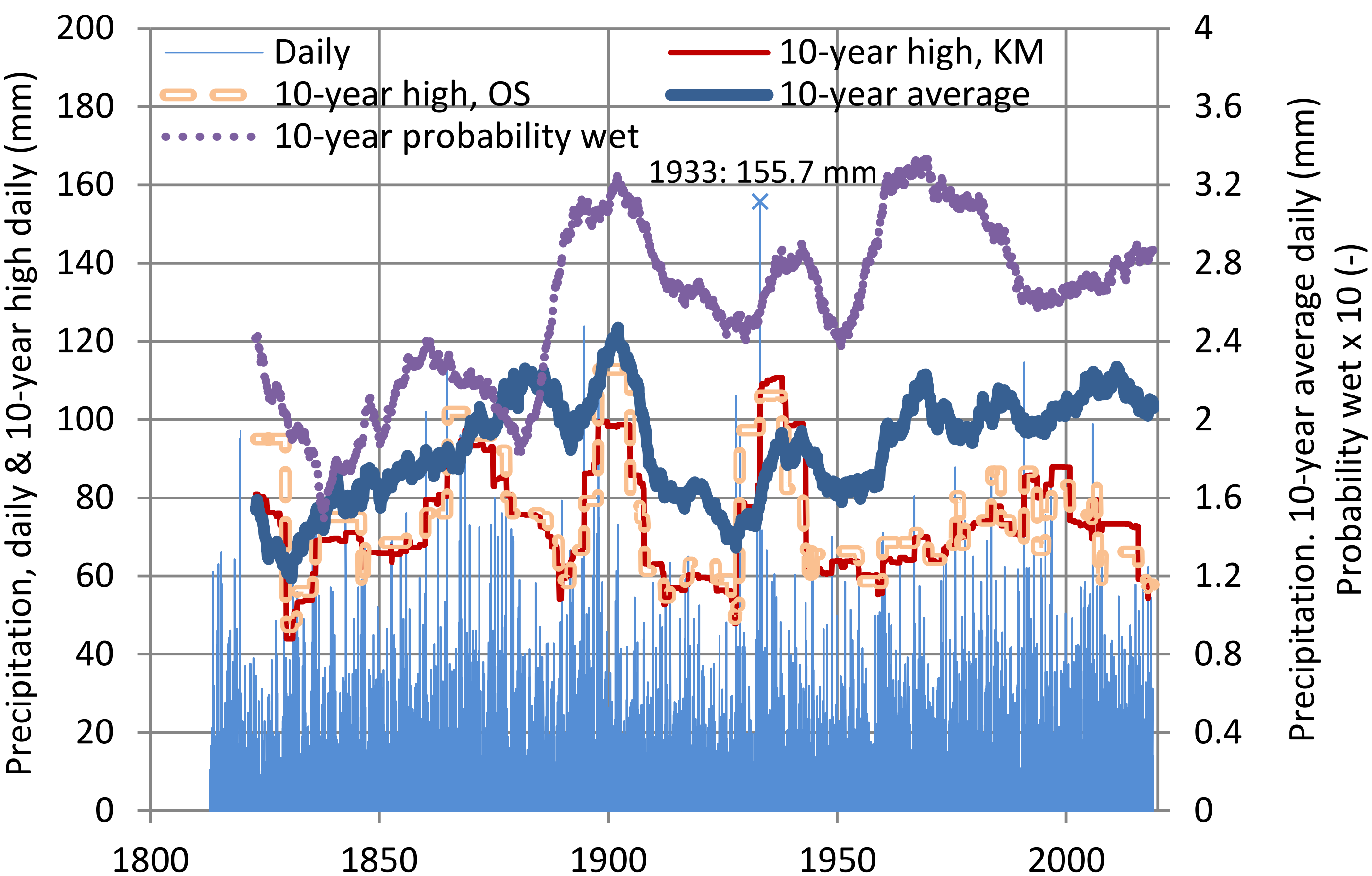
All 10-year **climatic indices** have varied substantially and irregularly:

The average by **100%** (from 1.2 to 2.4 mm).

The probability wet by **120%** (from 0.15 to 0.33).

The high daily precipitation by **150%** (from 44 to 110 mm/d).

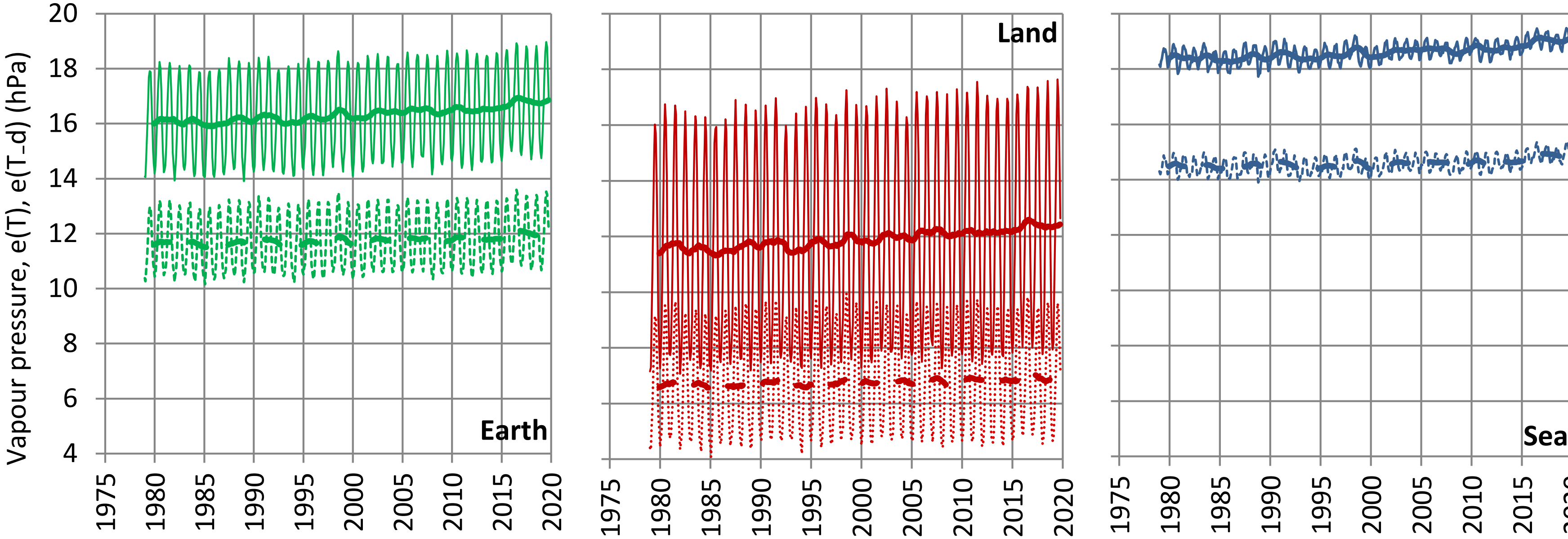
Why hydrologists have given so much energy in studying impacts a priori framed within **2-6%**?



Bologna, Italy (44.50°N, 11.35°E, +53.0 m). Available from the Global Historical Climatology Network (GHCN) – Daily (https://climexp.knmi.nl/gdcnprcp.cgi?WMO=ITE00100550). Uninterrupted for the period 1813-2007: 195 years. For the period 2008-2018, daily data are provided by the repository Dext3r of ARPA Emilia Romagna. **Total length: 206 years.**

Saturation vs. actual water vapour pressure

- The graph shows the variation of the water vapour pressure, saturation, $e(T)$, (continuous lines) and actual, $e(T_\mathrm{d})$, (dashed lines) for the average temperature T and dew point T_d.
- Clearly, the increase in $e(T_\mathrm{d})$ is smaller than that in $e(T_\mathrm{d})$, thus falsifying the constant relative humidity conjecture of IPCC.
- In particular, in land, where hydrological processes mostly occur, there is no increase in $e(T_\mathrm{d})$, while there is in $e(T)$.

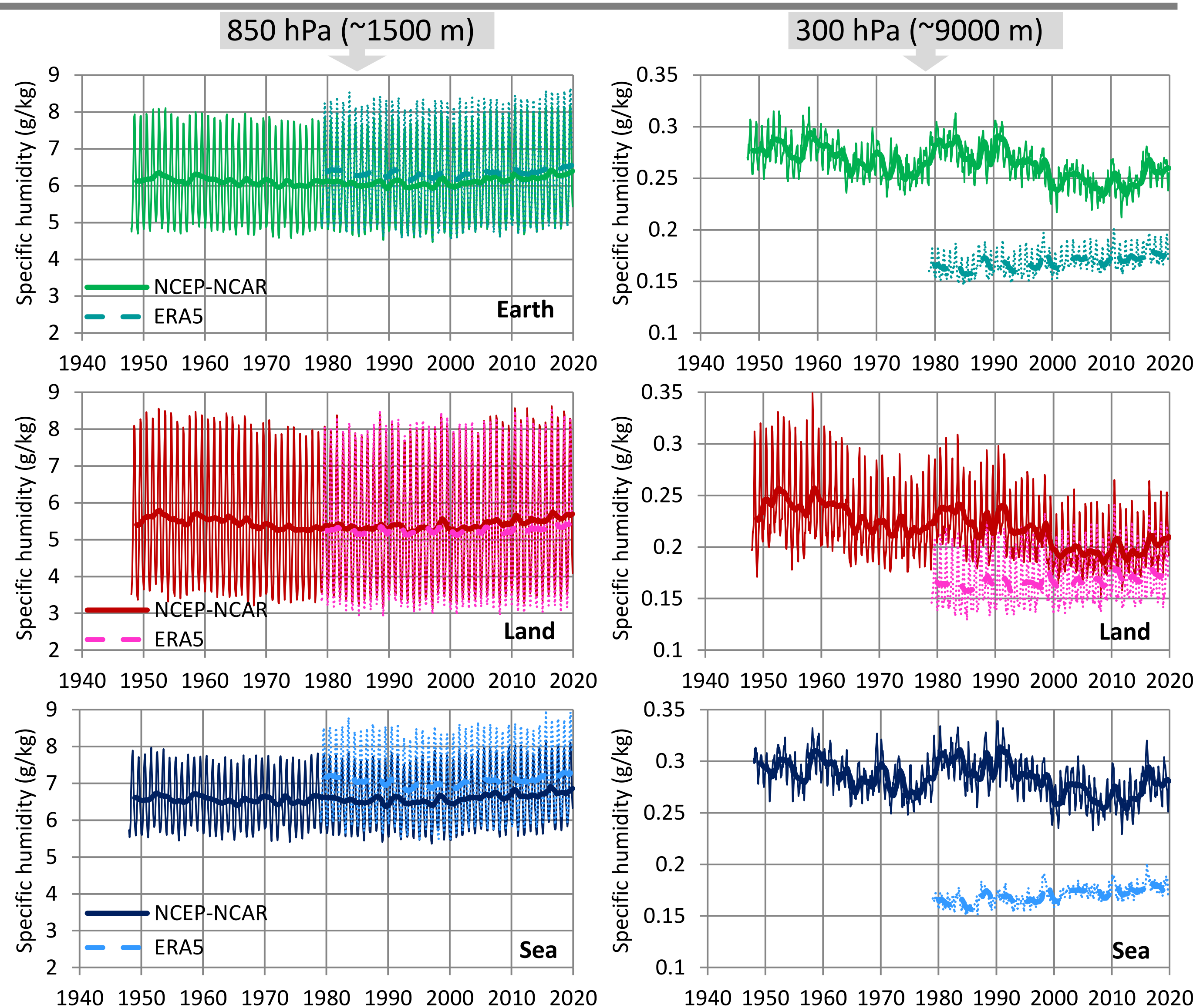


Source of graph: Koutsoyiannis (2020a); source of data: ERA5 reanalysis, http://climexp.knmi.nl

Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Specific humidity: Does it increase?

- The specific humidity is fluctuating—not increasing monotonically.
- Hence, the IPCC conjecture is falsified.
- Interestingly, in the NCEP-NCAR reanalysis at the 300 hPa, the specific humidity is decreasing.



Source of graph: Koutsoyiannis (2020a); data: NCEP-NCAR & ERA5 reanalysis, http://climexp.knmi.nl

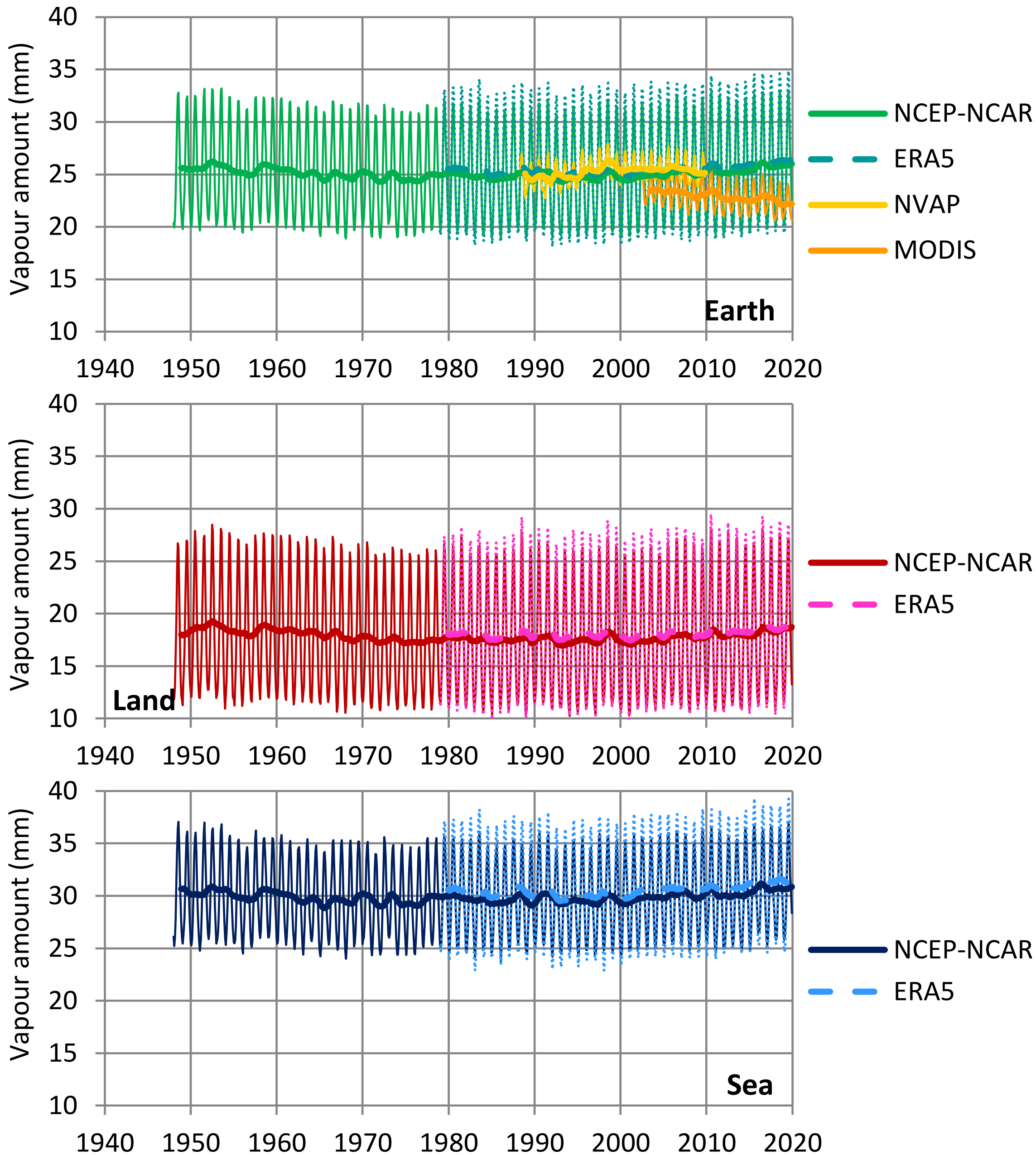
Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Water vapour amount: Does it increase?

- The water vapour amount in the atmosphere (most often misnamed as *precipitable water*) is fluctuating—not increasing monotonically.
- Hence, the IPCC conjecture is falsified.
- Interestingly, the satellite data (mostly MODIS) show a decreasing vapour amount.

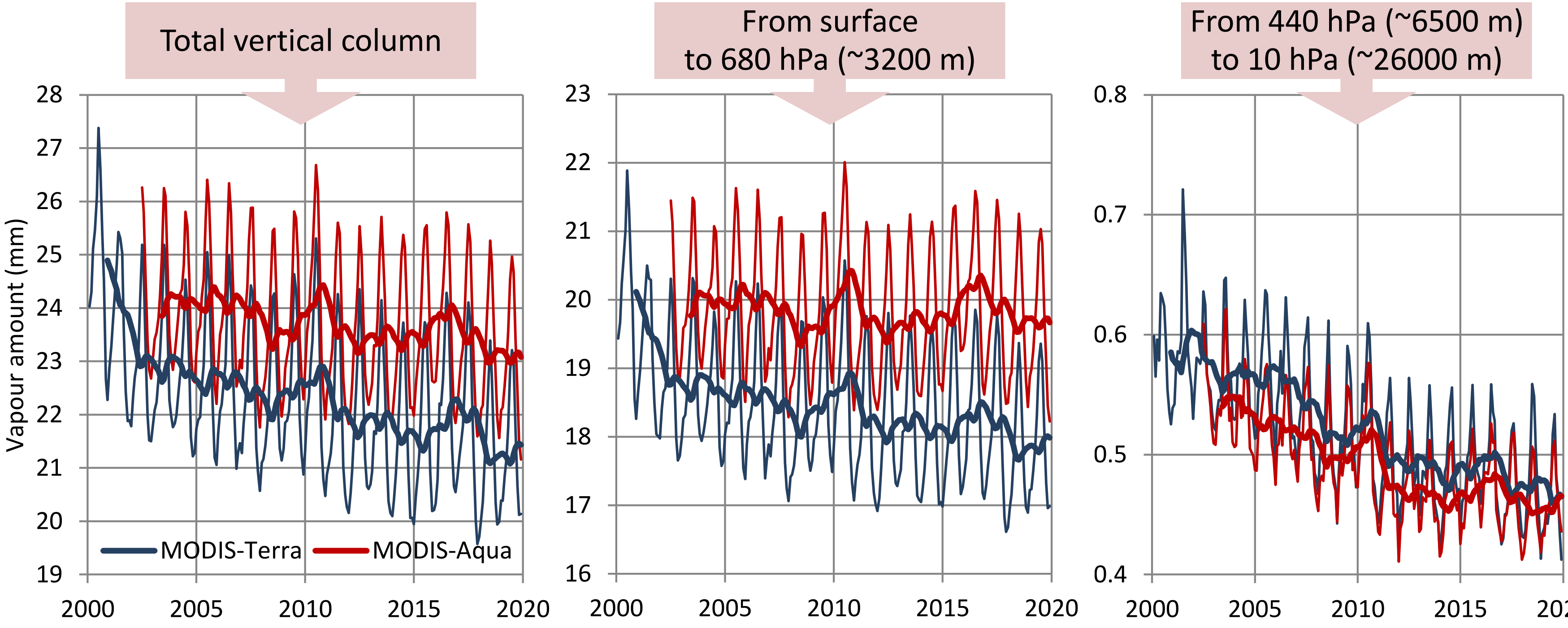
Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Source of graph: Koutsoyiannis (2020a); reanalysis data (NCEP-NCAR & ERA5): http://climexp.knmi.nl; satellite data, NVAP: Vonder Haar et al. (2012) (Figure 4c, after digitization); satellite data, MODIS: https://giovanni.gsfc.nasa.gov/giovanni/; averages from Terra and Aqua platforms.



Satellite data of the 21st century for water vapour amount: Is there an increasing trend?

- Both Terra and Aqua satellite platforms for all atmospheric levels suggest decreasing trends.
- Hence, the data are opposite to the IPCC conjecture.

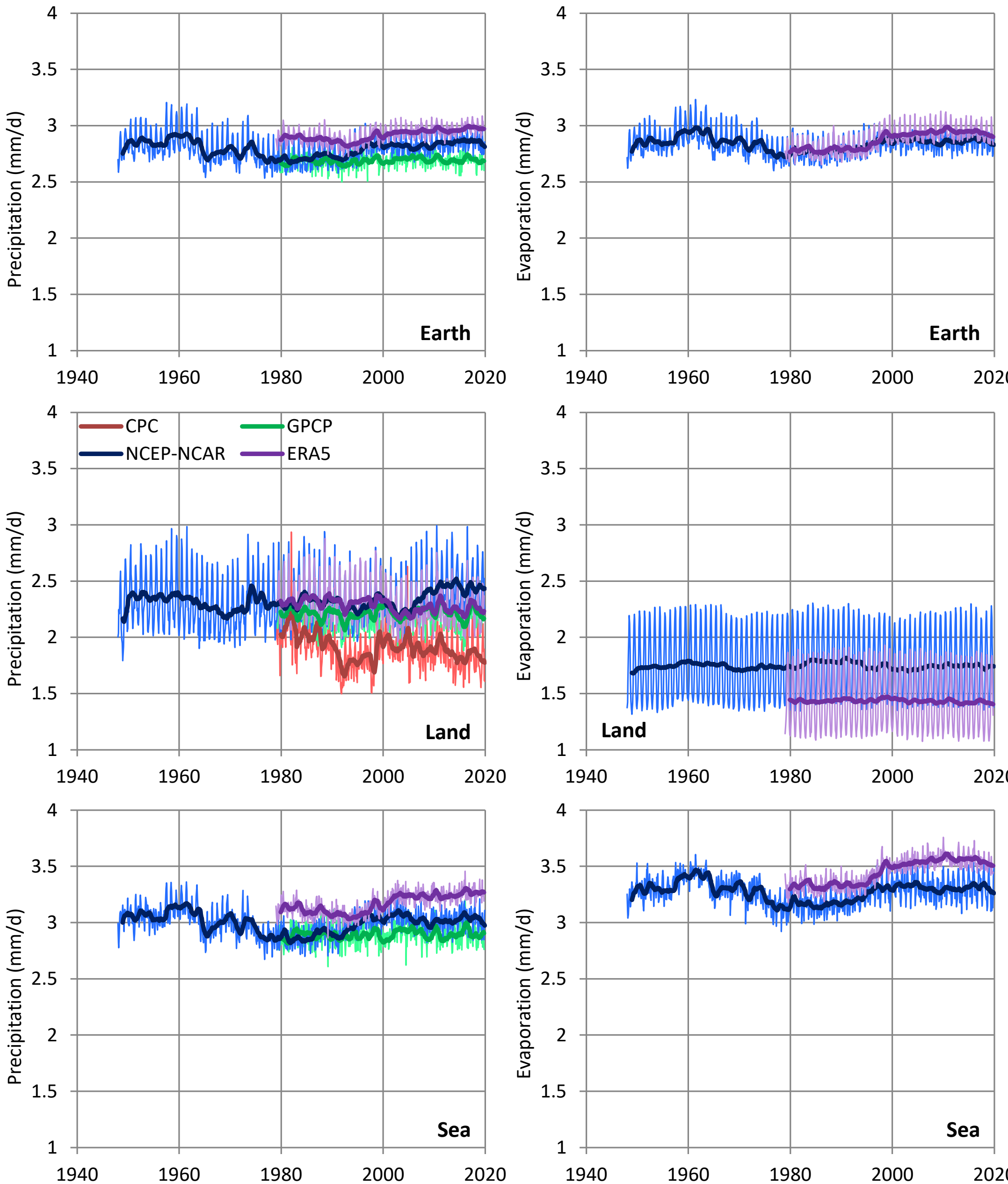


Source of graph: Koutsoyiannis (2020a); MODIS data: https://giovanni.gsfc.nasa.gov/giovanni/

Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Precipitation and evaporation: Do they increase?

- Both precipitation and evaporation are fluctuating—not increasing monotonically.
- Hence, the IPCC conjecture is falsified.

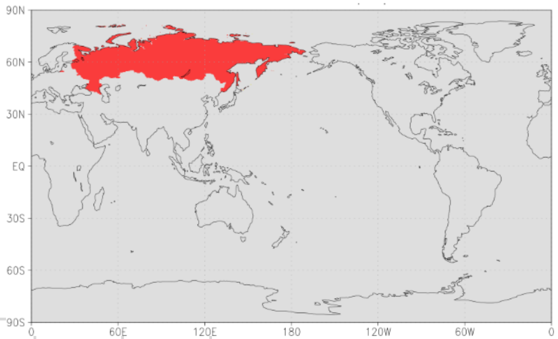


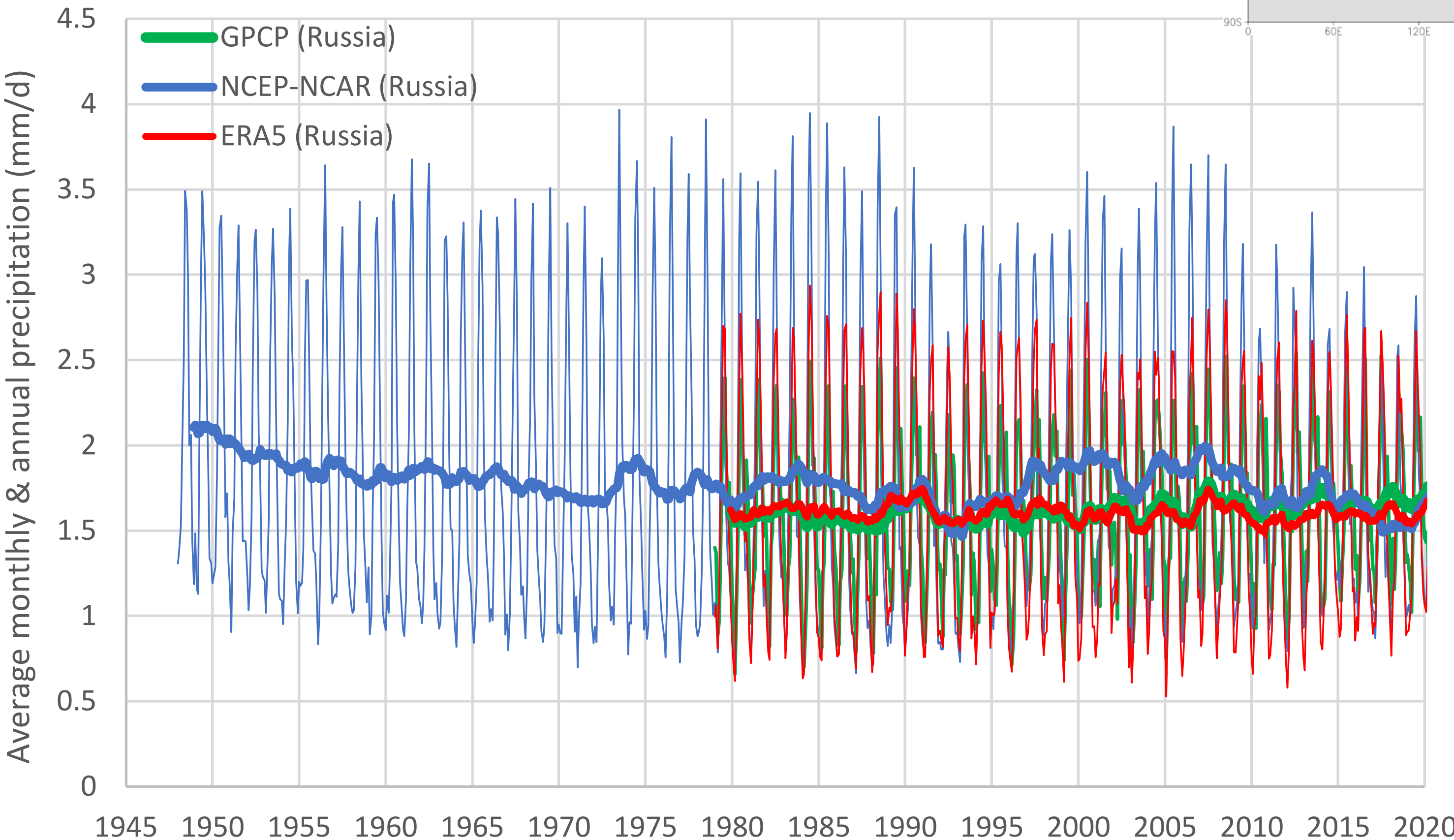
Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Source of graph: Koutsoyiannis (2020a); reanalysis data (NCEP-NCAR & ERA5), gauge-based precipitation data gridded over land (CPC), and combined gauge and satellite precipitation data over a global grid (GPCP): http://climexp.knmi.nl

Is there precipitation intensification in Russia?

- Short reply: **No.**
- Long reply: There are fluctuations, as always and everywhere.



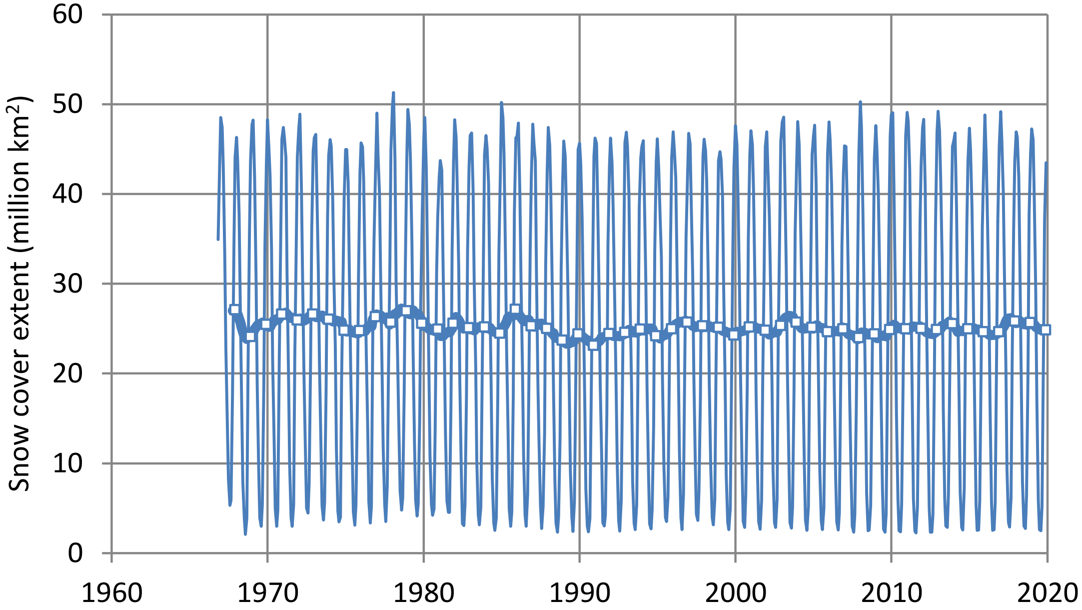


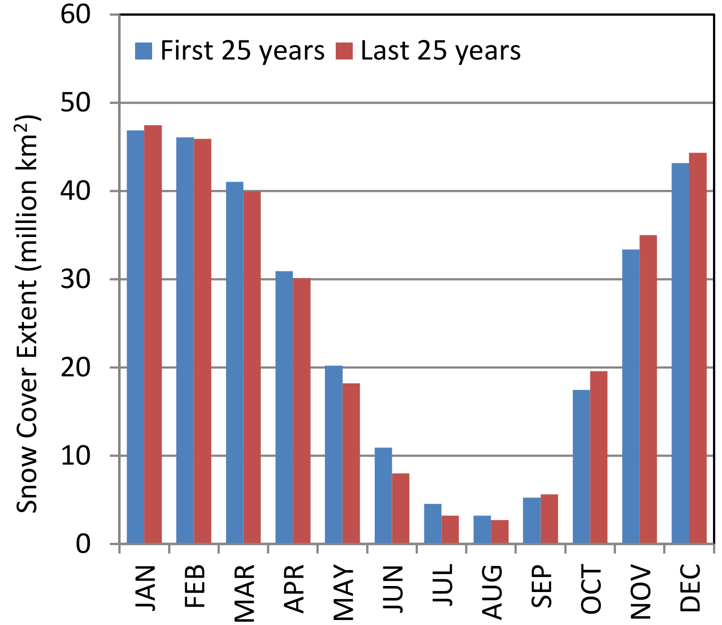
Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Reanalysis data (NCEP-NCAR & ERA5) and combined gauge and satellite precipitation data over a global grid (GPCP): http://climexp.knmi.nl

Snow: Does it tend to disappear?

- The snow part of precipitation is interesting to examine, as snow is more directly related to temperature and also affects Earth's albedo.
- Systematic satellite observations of snow cover extent exist only for the northern hemisphere.
- Despite temperature increase, no noticeable change appears on the annual basis.
- However, there are perceptible changes in the seasonal variation (right panel): in the most recent period the snow cover has decreased during the summer months and increased during the autumn and winter months.





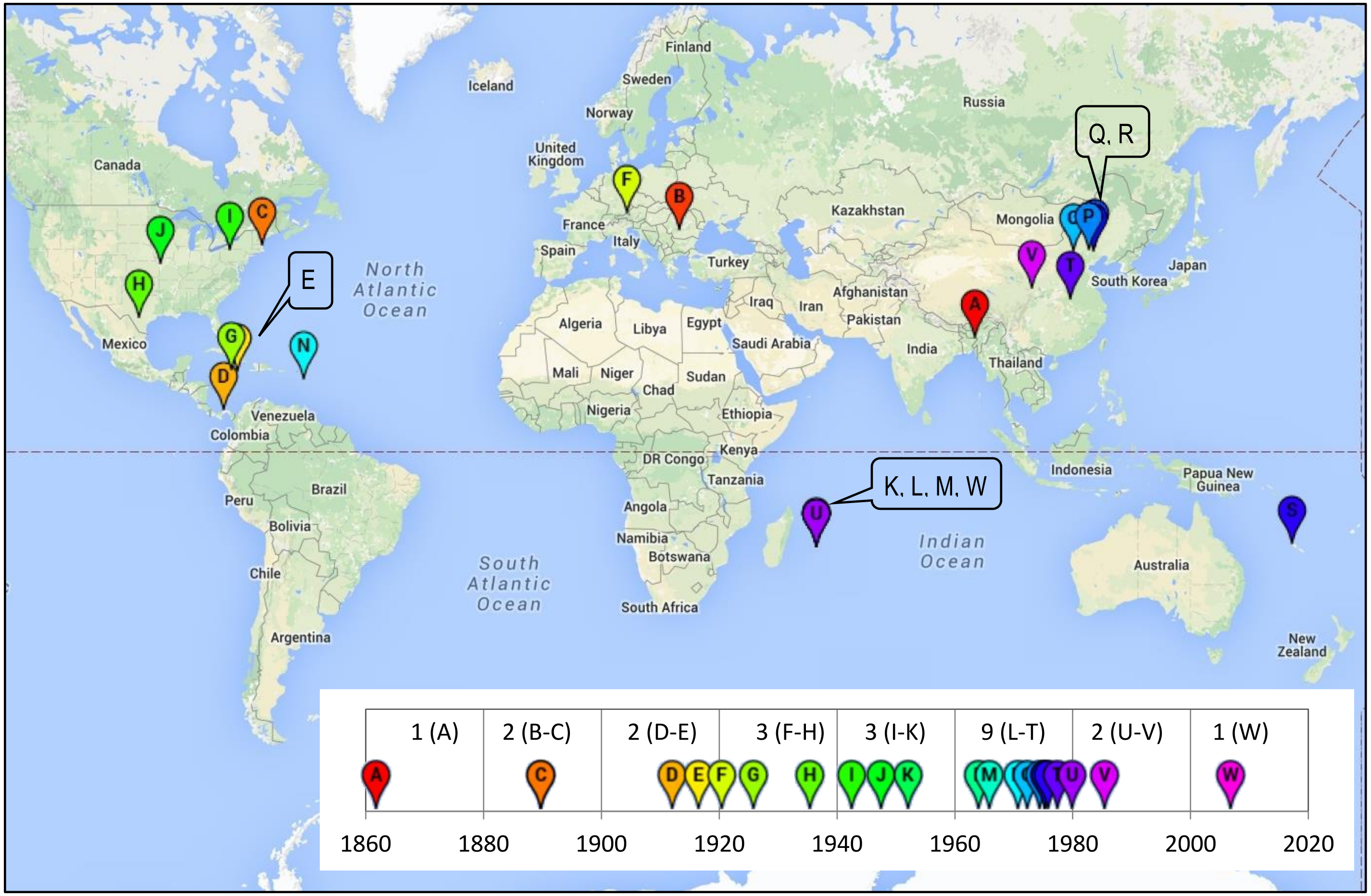
Source of graph: Koutsoyiannis (2020a); source of snow cover data: Global Snow Laboratory (GSL), https://climate.rutgers.edu/snowcover/table_area.php

Thin and thick lines represent monthly values and running annual averages (right aligned), respectively. Squares are annual averages aligned at December of each year.

Part 9
The alleged intensification of the hydrological extremes

Point rainfall data: When did world records in rainfall occur?

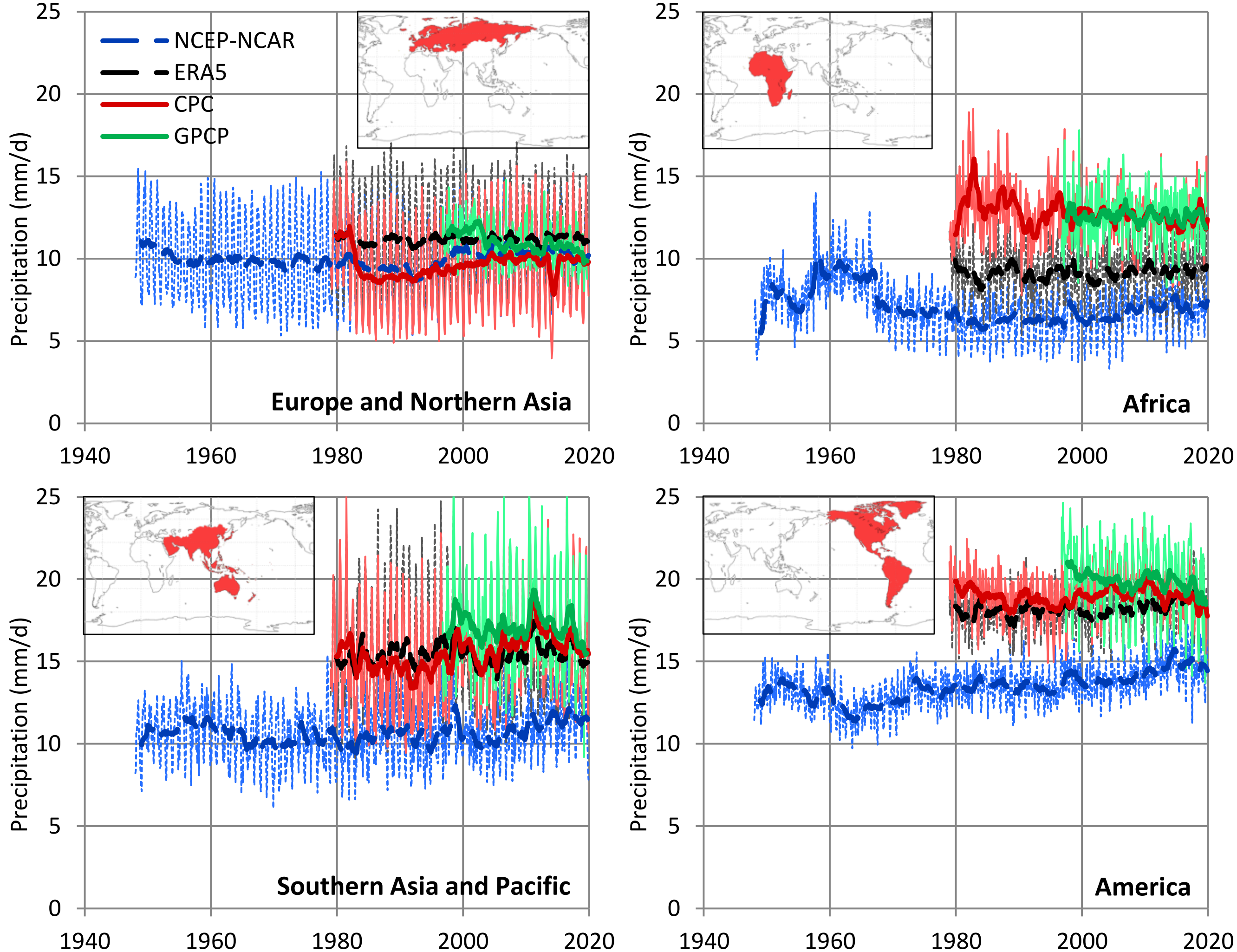
Data: World record point precipitation measurements for time scales ranging from 1 min to 2 years, compiled in Koutsoyiannis and Papalexiou (2017).



- The graph shows the locations and time stamps of the events producing record rainfall for various time scales ranging from 1 min to 2 years.
- The highest frequency of record rainfall events occurred in the period 1960-80; later the frequency was decreased substantially.

Monthly maximum daily precipitation: Is it increasing?

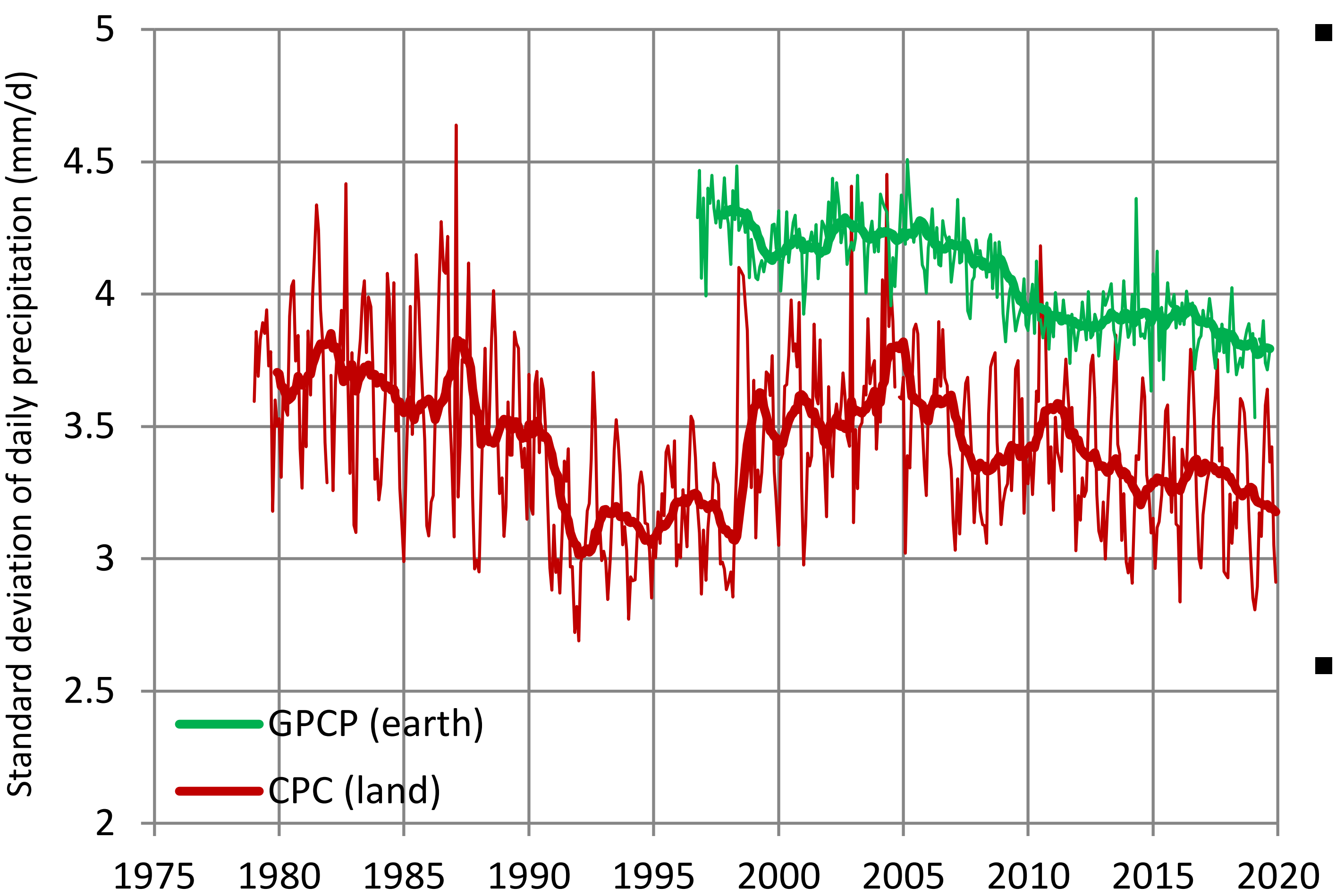
- The graphs show the variation of the monthly maximum daily precipitation areally averaged over the continents.
- In all continents, the monthly maximum daily precipitation is fluctuating—not increasing monotonically.
- In particular, the satellite observations show decreasing, rather than increasing trends in the 21st century.



Source of graph: Koutsoyiannis (2020a); reanalysis data (NCEP-NCAR & ERA5), gauge-based precipitation data gridded over land (CPC), and combined gauge and satellite precipitation data over a global grid (GPCP): http://climexp.knmi.nl

Thin and thick lines represent monthly values and running annual averages (right aligned).

Daily precipitation variability: Is it increasing?



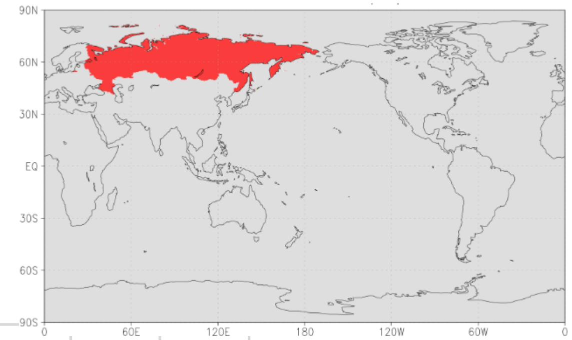
- The standard deviation of daily rainfall, areally averaged, as seen both from CPC and GPCP observational data, decreases, thus signifying deintensification of extremes in the 21st century.
- Again, it will be more prudent to speak about fluctuations rather than deintensification.

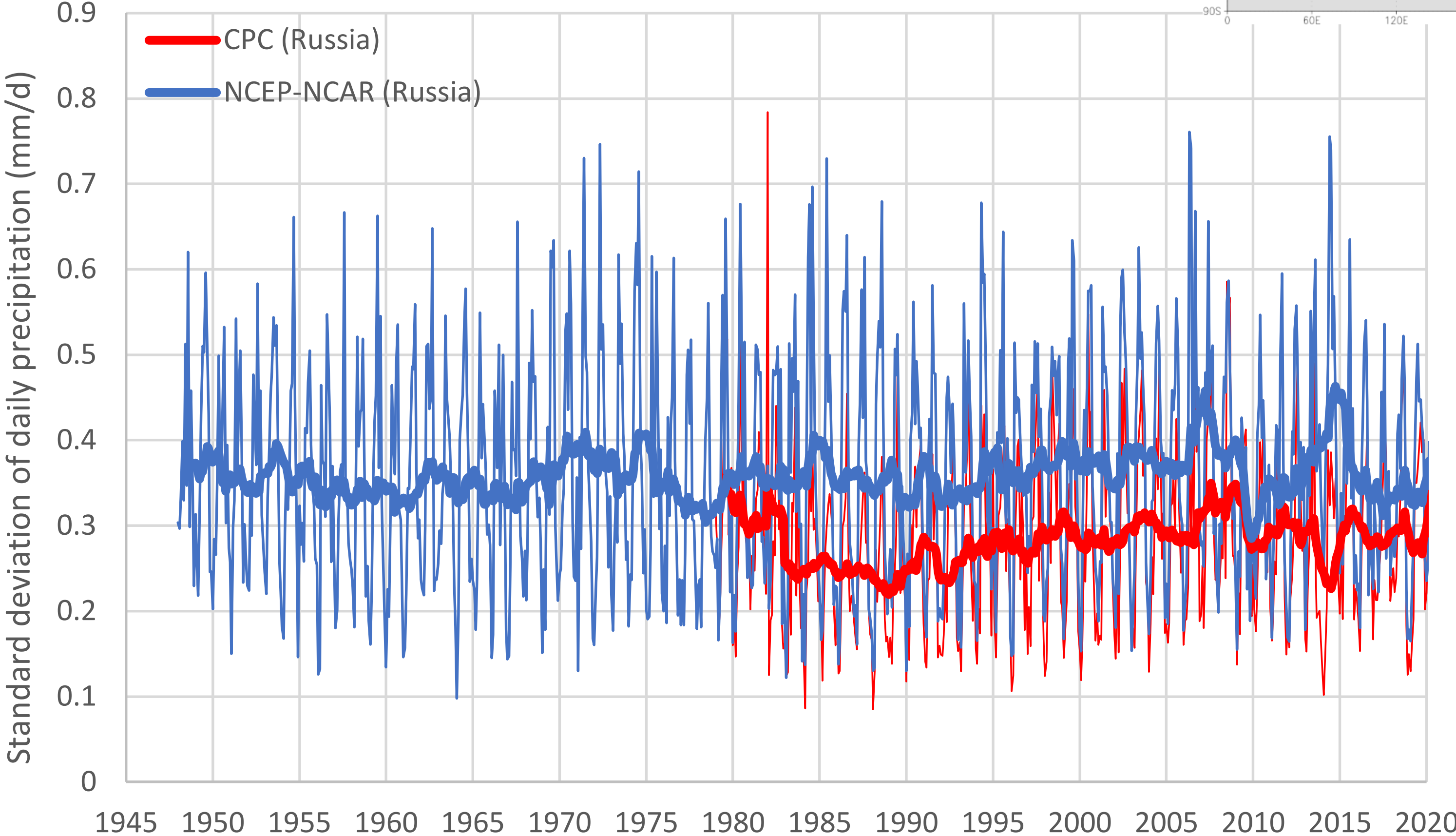
Source of graph: Koutsoyiannis (2020a); gauge-based precipitation data gridded over land (CPC), and combined gauge and satellite precipitation data over the entire Earth (GPCP): http://climexp.knmi.nl

Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Is daily precipitation variability in Russia increasing?

- Short reply: **No.**
- Long reply: There are fluctuations, as always and everywhere.





Thin and thick lines of the same colour represent monthly values and running annual averages (right aligned), respectively.

Reanalysis data (NCEP-NCAR) and gauge-based precipitation data gridded over land (CPC): http://climexp.knmi.nl

Do background conditions favour enhancement of precipitation extremes?

Possible background conditions affecting precipitation extremes:

1. Atmospheric moisture.

   As we have seen this is fluctuating – not increasing monotonically.

2. Wind.

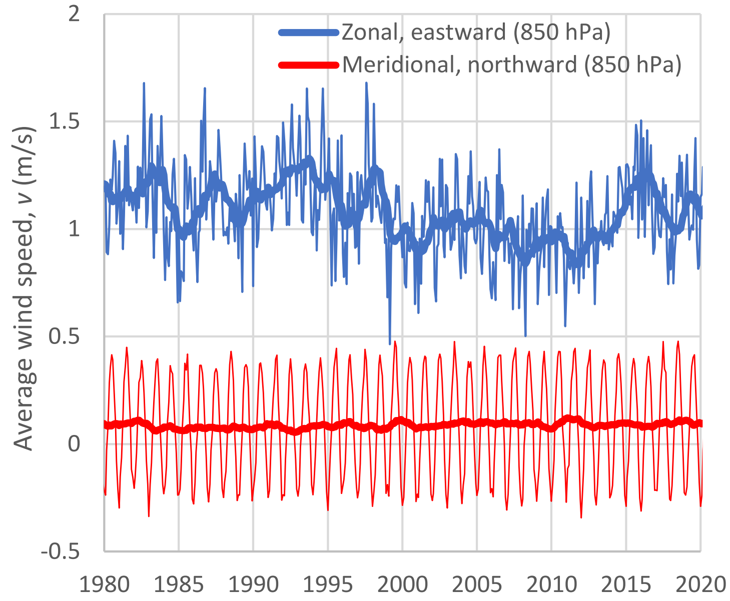
   Is it increasing?

3. Aerosols.

   Are they changing and how?

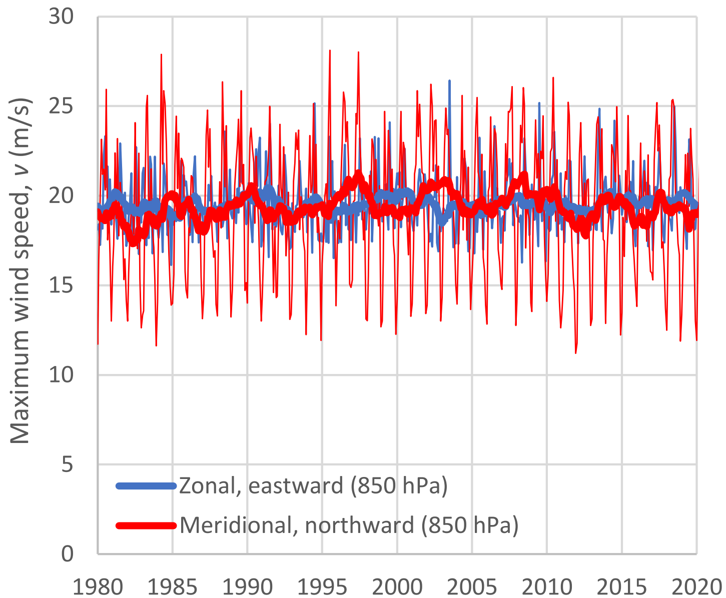
Is the wind regime changing?

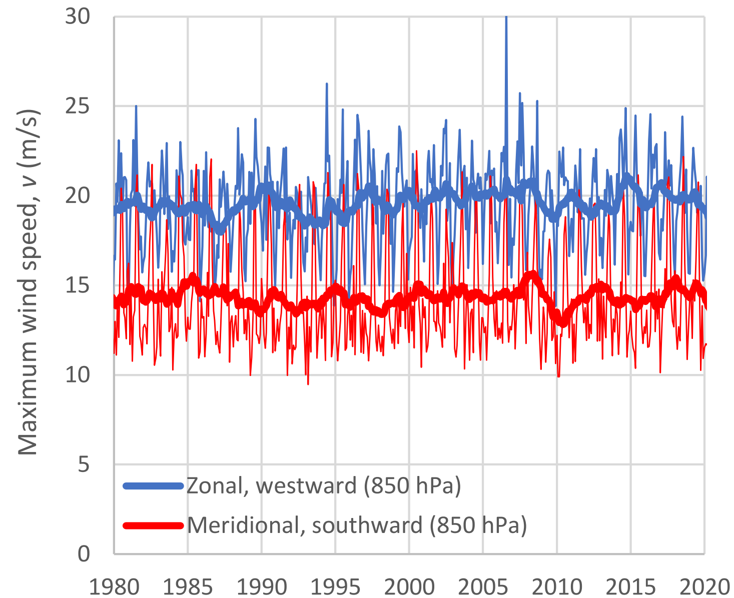
- Both global average and global maximum wind speed, zonal and meridional, do not show any noteworthy change (trend). Only slight fluctuations appear.
- Thus, the wind regime does not justify intensification of precipitation extremes.



Thin and thick lines represent monthly values and running annual averages (right aligned).

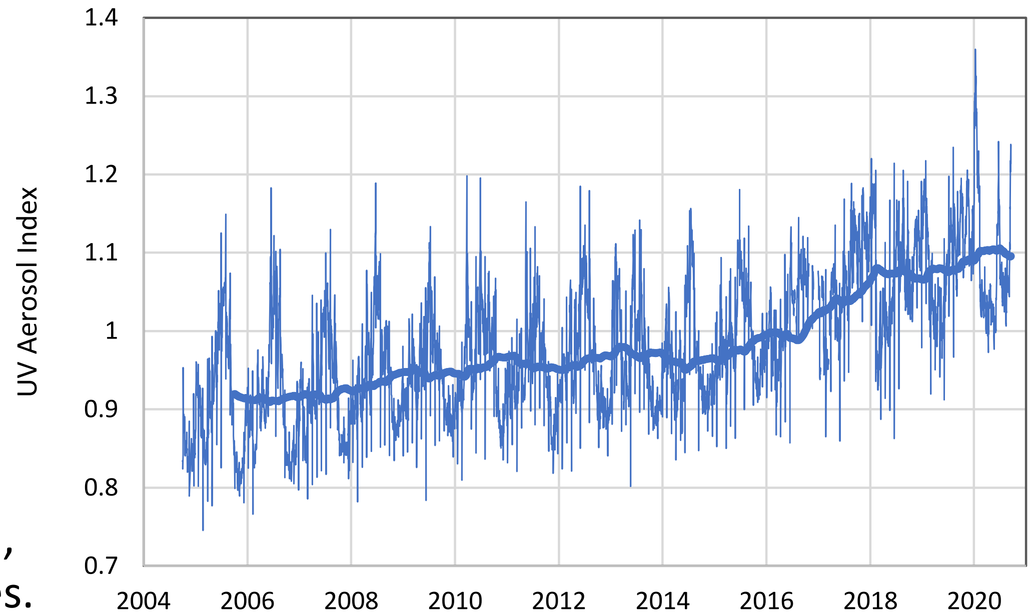
Reanalysis data (ERA5): http://climexp.knmi.nl





Effect of aerosols

- The data on the graph show increasing Aerosol Index.
- Positive values of the Aerosol Index generally represent absorbing aerosols (dust and smoke) while small or negative values represent non-absorbing aerosols and clouds.
- The aerosols have an effect on precipitation, mostly suppressing its formation, but there are competing effects of different types of aerosols (L'Ecuyer et al. 2009; Wu et al., 2013).
- The increasing Aerosol Index is generally consistent with the deintensification of precipitation in the 21st century.
- It may be conjectured that the increased Aerosol Index is an anthropogenic effect, competing with increased temperature.
- This issue deserves further research, particularly on its effect on extremes.



Data: Globally averaged Aerosol Index (OMTO3d; produced by NASA by gridding and averaging good quality level-2 total column ozone orbital swath data), https://giovanni.gsfc.nasa.gov/giovanni/; see also: https://disc.gsfc.nasa.gov/information/glossary?keywords=giovanni%20measurements&title=Giovanni%20Measurement%20Definitions:%20Aerosol%20Index

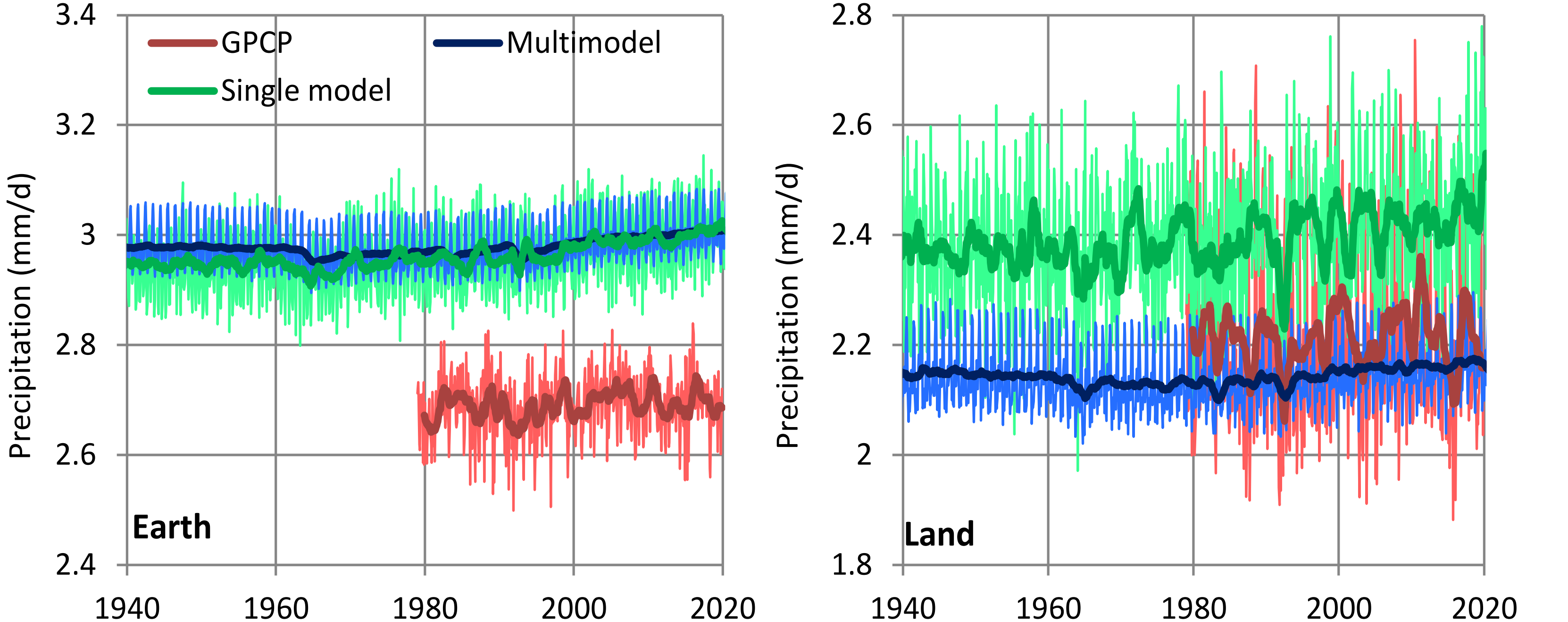
Thin and thick lines represent daily values and running annual averages (right aligned), respectively.

Part 10
Dealing with the future of climate and water

Do climate models provide guidance for the future?

Short answer: **No**.

Long answer: They have not provided skill for the past. Notice: (1) the large error of the "Multimodel" ensemble in terms of the mean; (2) the increasing trend of climate model outputs after 1980, which did not appear in reality.

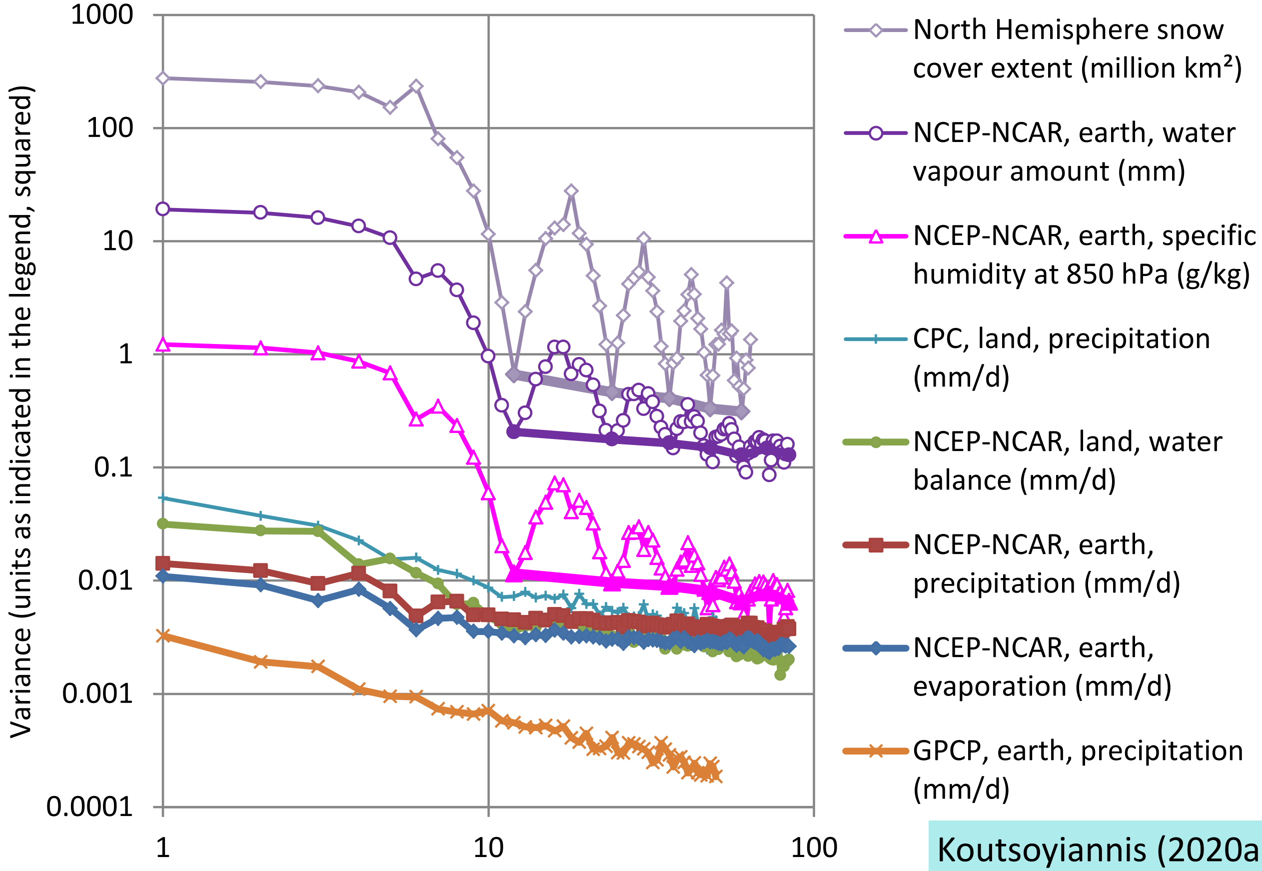


Source of graph: Koutsoyiannis (2020a); observations come from the combined gauge and satellite precipitation data over a global grid (GPCP); climate model outputs are for the scenario "RCP8.5" (frequently referred to as "business as usual"); "Multimodel" refers to CMIP5 scenario runs (entries: CMIP5 mean – rcp85) and "Single model" refers to CCSM4 – rcp85 (ensemble member 0), where CCSM4 stands for Community Climate System Model version 4, released by NCAR. Data and model outputs are accessed through http://climexp.knmi.nl

Thin and thick lines represent monthly values and running annual averages (right aligned).

What is the scientific approach to deal with the future?

- Only stochastic approaches can provide means to deal with the future of non-trivial complex systems.
- Stochastics cannot make accurate predictions but can quantify uncertainty.
- Uncertainty is amplified because of the long-term fluctuations apparent in all processes.
- These can be modelled as Hurst-Kolmogorov dynamics.

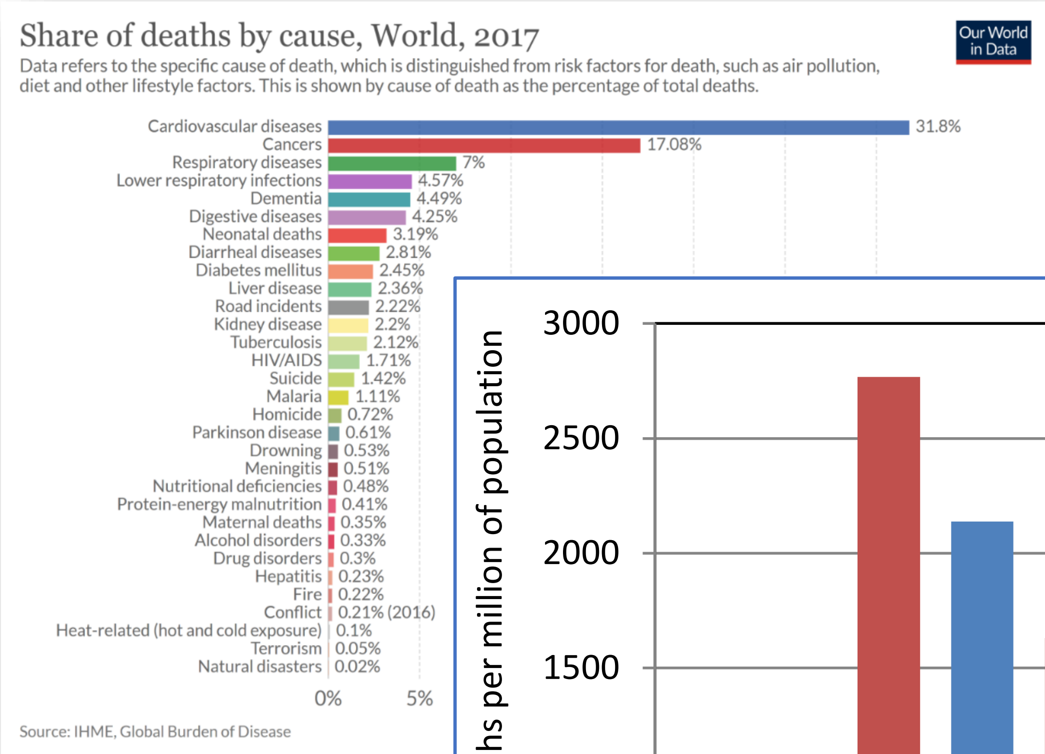


Koutsoyiannis (2020a)

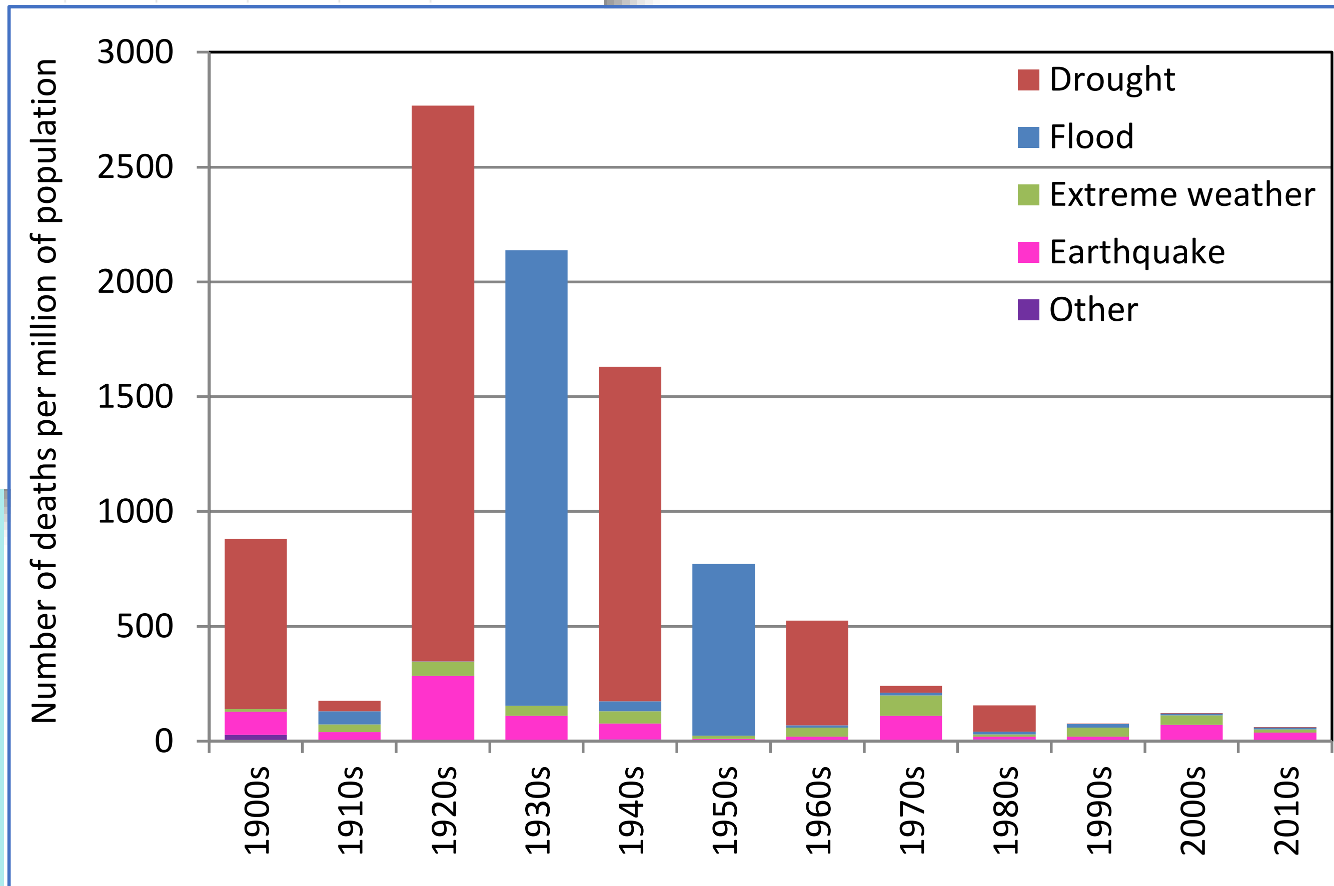
Climacograms of the indicated processes are calculated from monthly time series; for some series with prominent seasonality the climacograms from annual time series are also plotted with thicker lines of same colour. For time scales larger than annual, all slopes in the double logarithmic plots are close to –0.2, suggesting a Hurst parameter 0.90 or larger. Exceptions are the NH snow cover extent with a slope of –0.47, suggesting a Hurst parameter 0.76 and the GPCP precipitation series with a slope of –0.72, suggesting a Hurst parameter 0.64.

Epilogue: Is our future dark?

Engineers' epinicion on actual risk reduction



Instead of casting pessimistic prophesies about the future, engineers improved hydro-technology, water management, and risk assessment and reduction.



Upper graph: https://ourworldindata.org/grapher/share-of-deaths-by-cause?time=latest
Lower graph: Koutsoyiannis (2020a); data from https://ourworldindata.org/world-population-growth; https://ourworldindata.org/ofdacred-international-disaster-data

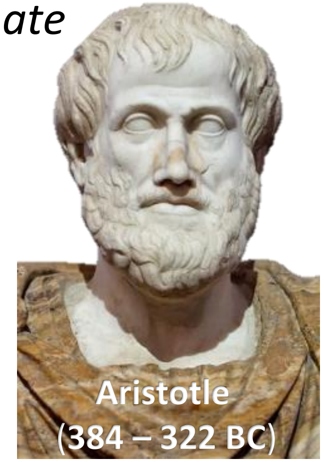
Concluding remarks

- Science and technology have helped to solve real problems and reduce risks in the past.
- They could also help for a bright future.
- A scientific approach to climate can only be based on stochastics as climate is properly defined within stochastics.
- Climate has perpetually changed in the past, is changing at present and will be changing in the future.
- Hydrology and climate are tightly connected.
- Neither climate not hydrology of the future can be known in deterministic terms, by using deterministic climate models.
- The science dealing with climate has been known for about 200 years as *climatology*.
- However, climate models and their predictions (or projections, or prophecies) designate what has been known as *climate science*, connected to the political *Climate Change Agenda* and, thus, more accurately named *climate sophistry*.

ἔστι γὰρ ἡ σοφιστικὴ φαινομένη σοφία οὖσα δ᾽ οὔ, καὶ ὁ σοφιστὴς χρηματιστὴς ἀπὸ φαινομένης σοφίας ἀλλ᾽ οὐκ οὔσης.

Sophistry is the semblance of wisdom without the reality, and the sophist is one who makes money from apparent but unreal wisdom.

(Aristotle, On Sophistical Refutations, 165a21)



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