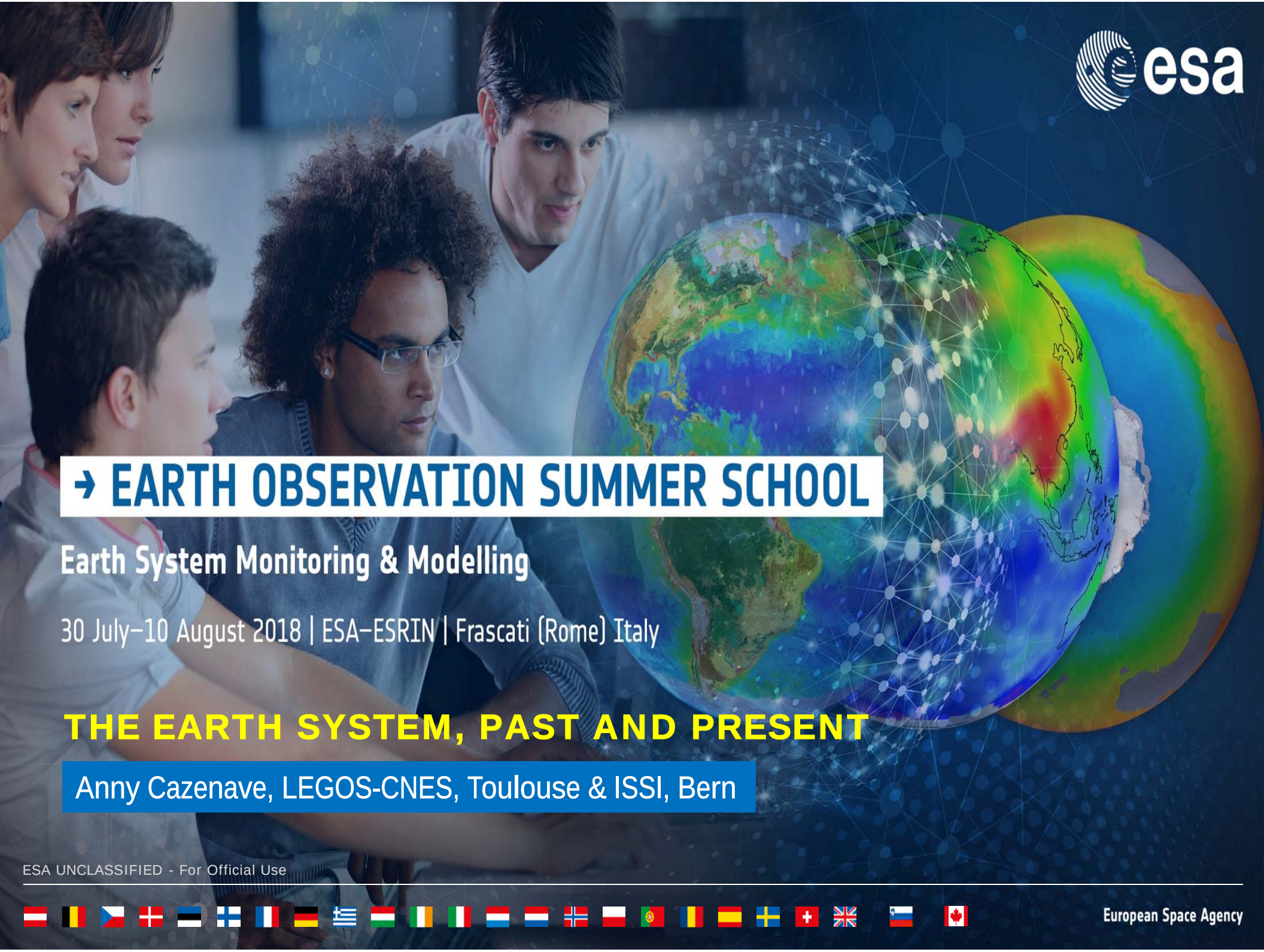


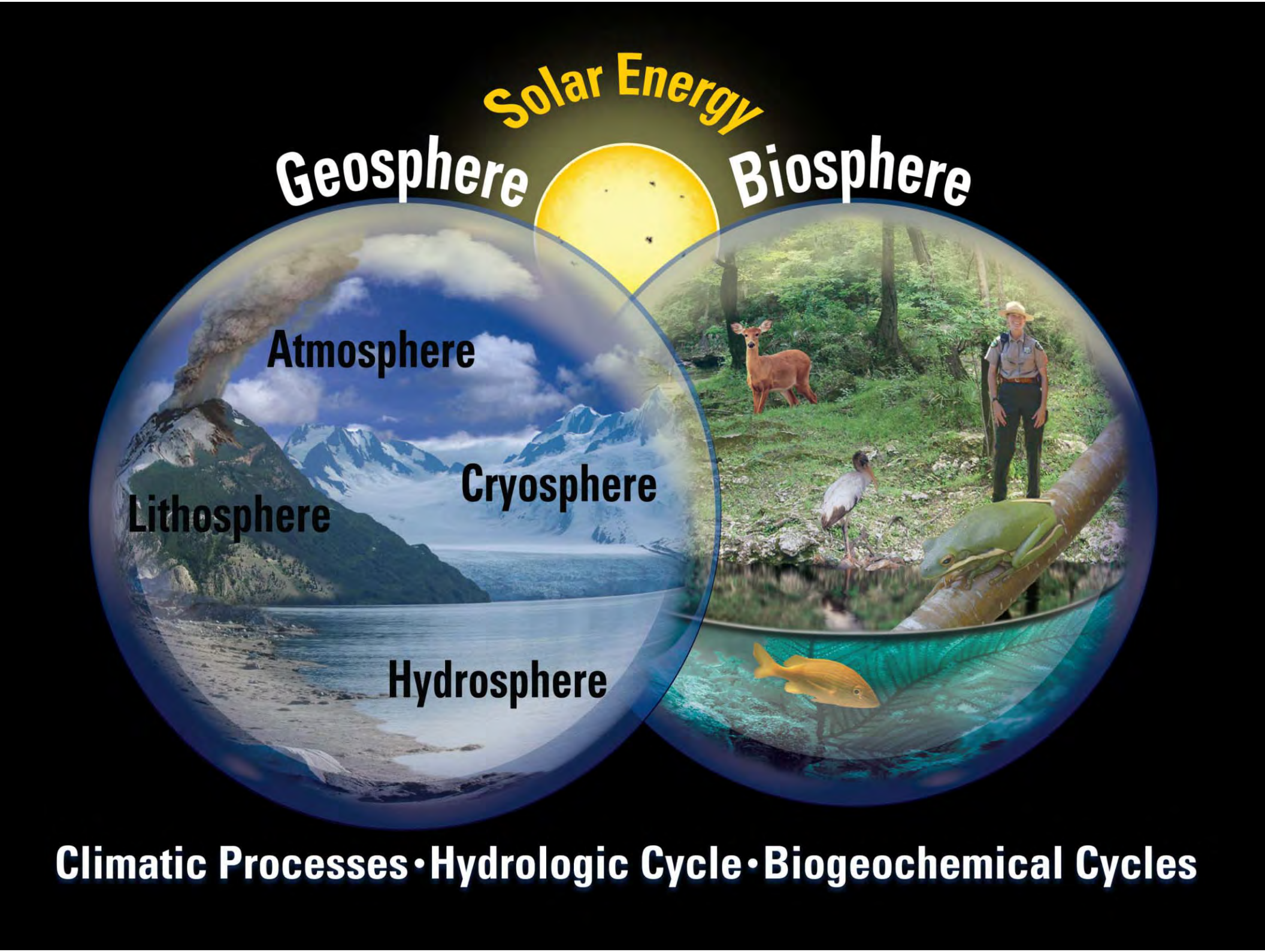
→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

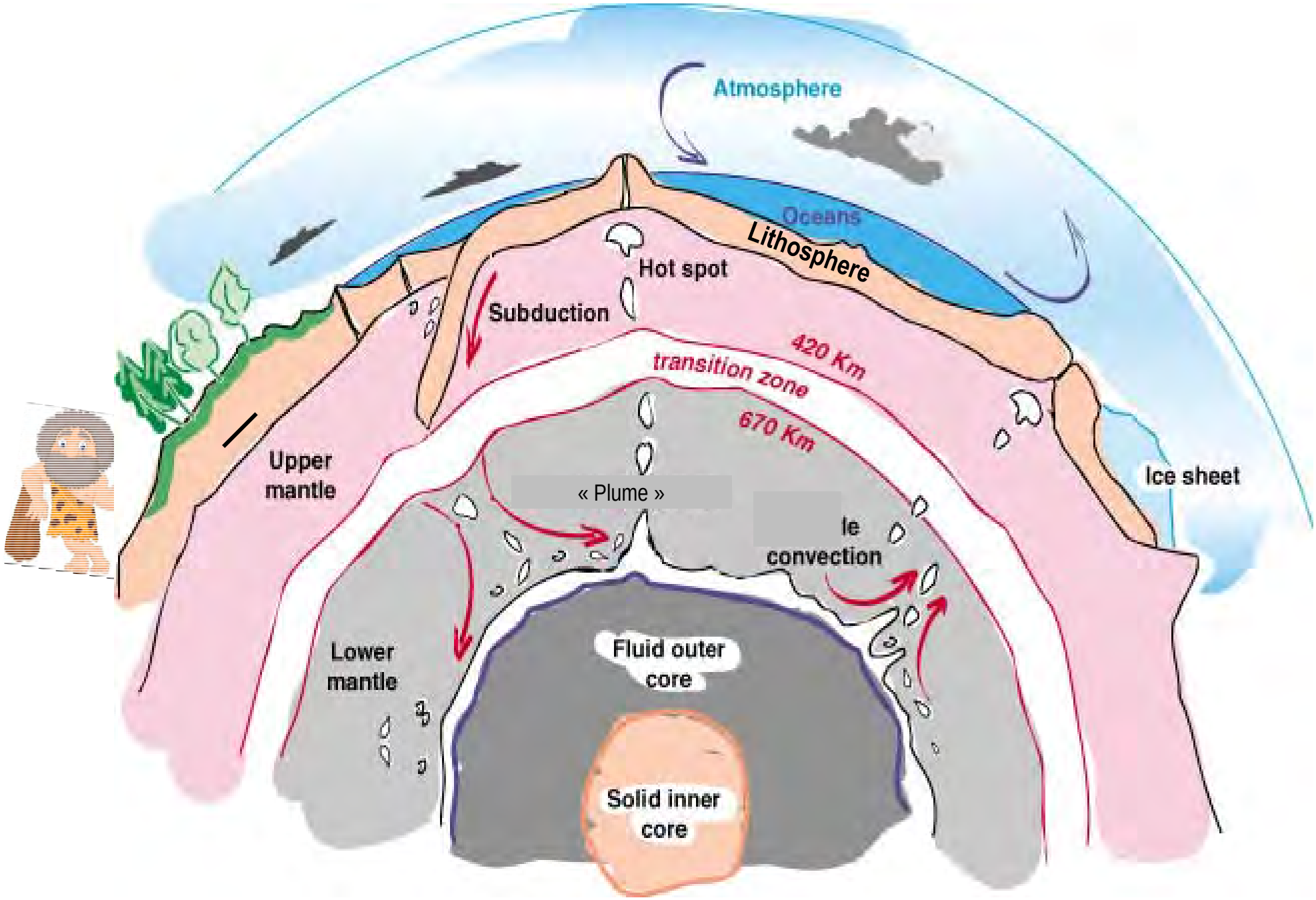
30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

THE EARTH SYSTEM, PAST AND PRESENT

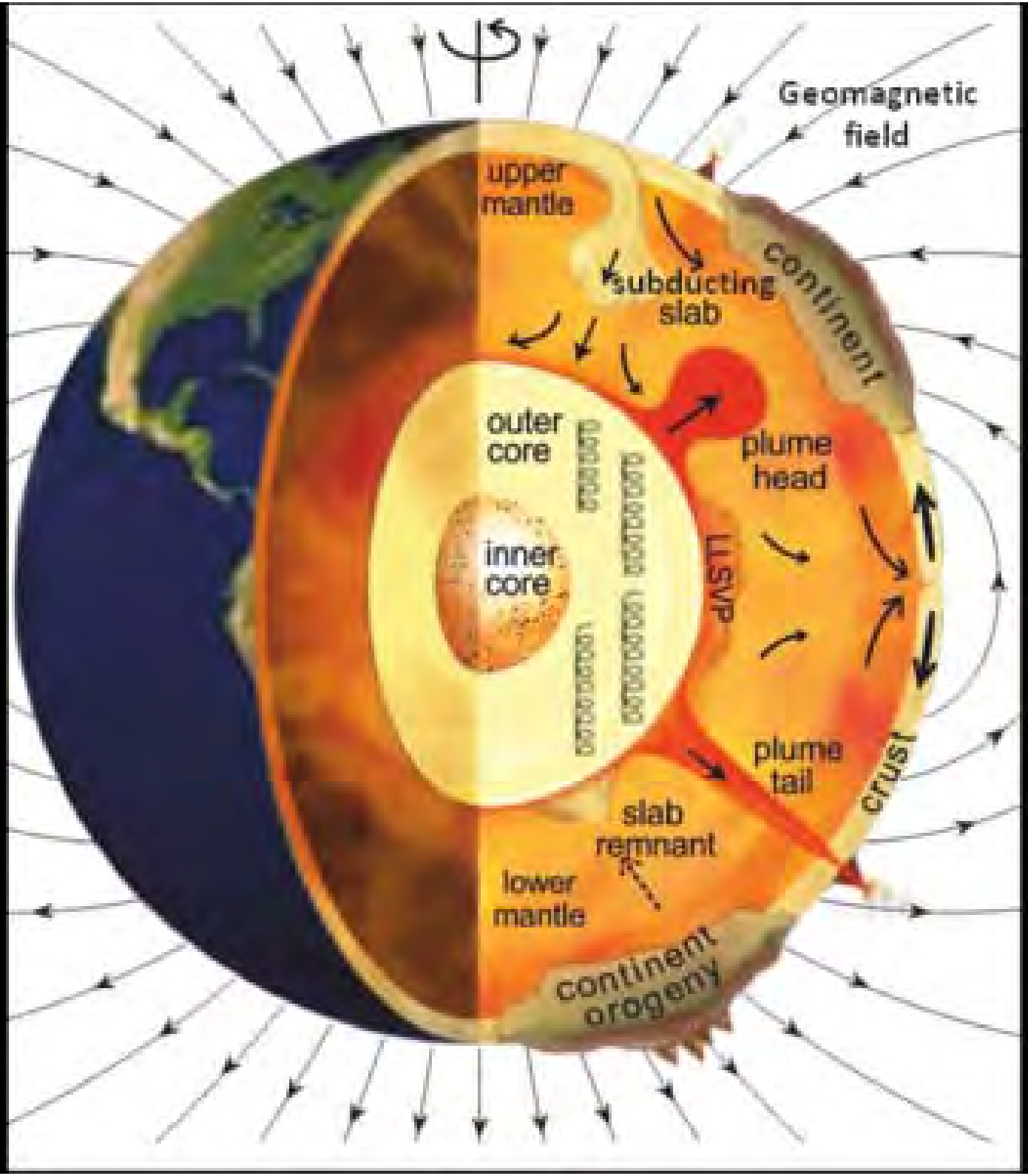
Anny Cazenave, LEGOS-CNES, Toulouse & ISSI, Bern


Solar Energy
Geosphere
Biosphere
Atmosphere
Cryosphere
Lithosphere
Hydrosphere
Climatic Processes • Hydrologic Cycle • Biogeochemical Cycles

The Earth System

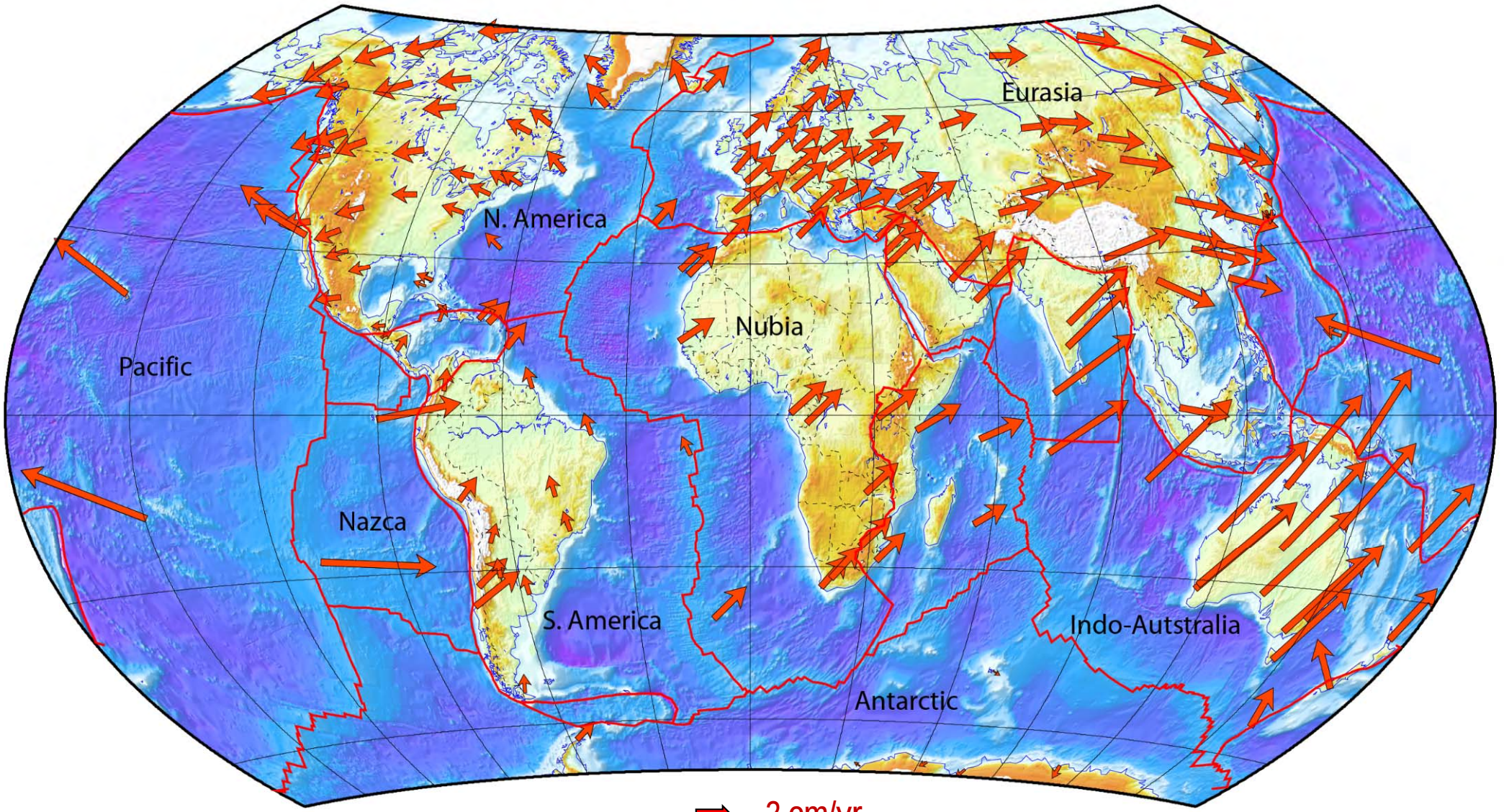


Source : LEGOS



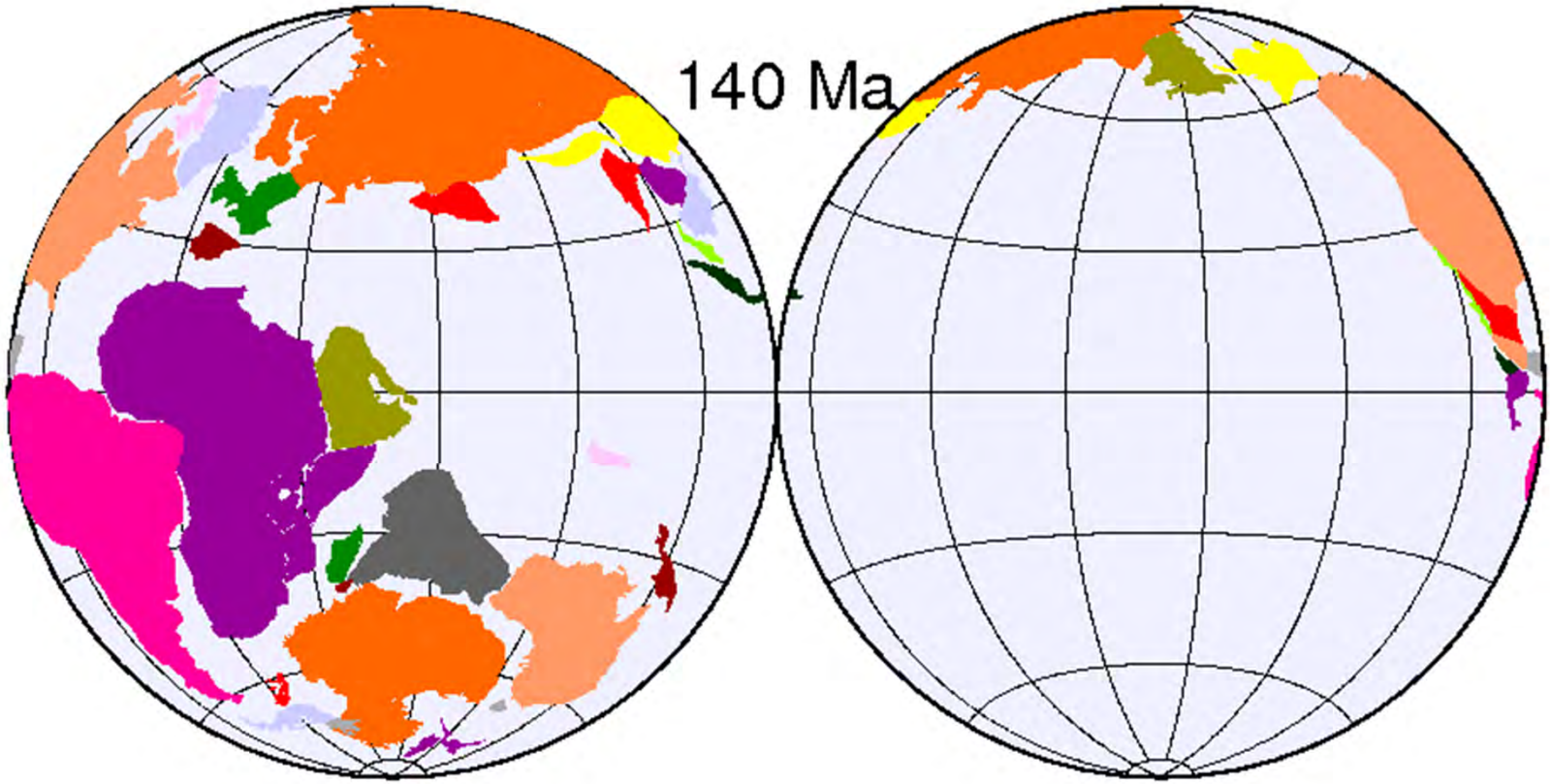
The internal structure of the Earth

Present-day tectonic place motions



Courtesy: Eric Calais

Tectonic plate motions over geological time scales (last 140 million years)

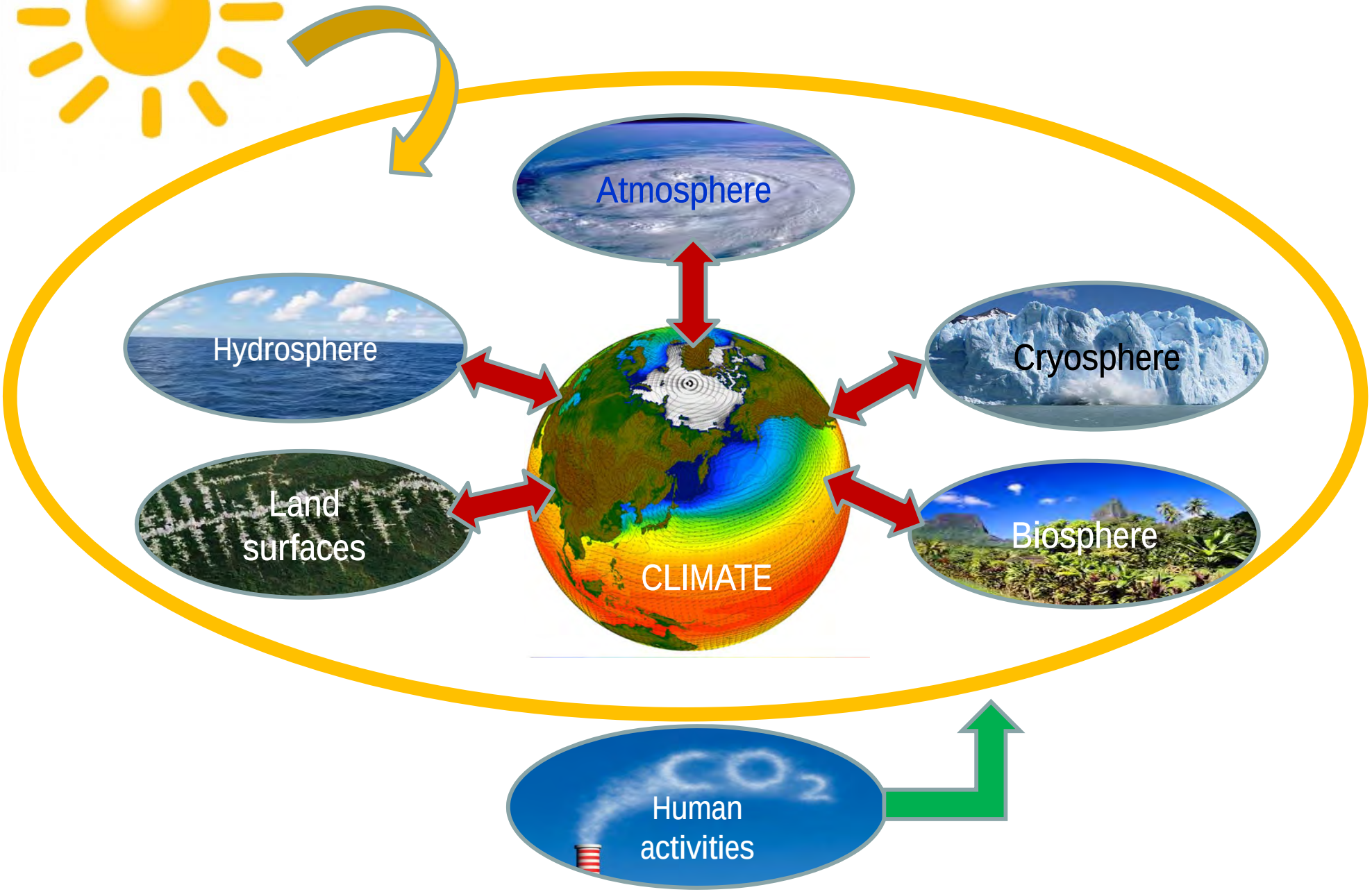


Alex Copley, Ashley Kennard, Jessica Kim, and Lindsey Stancliff

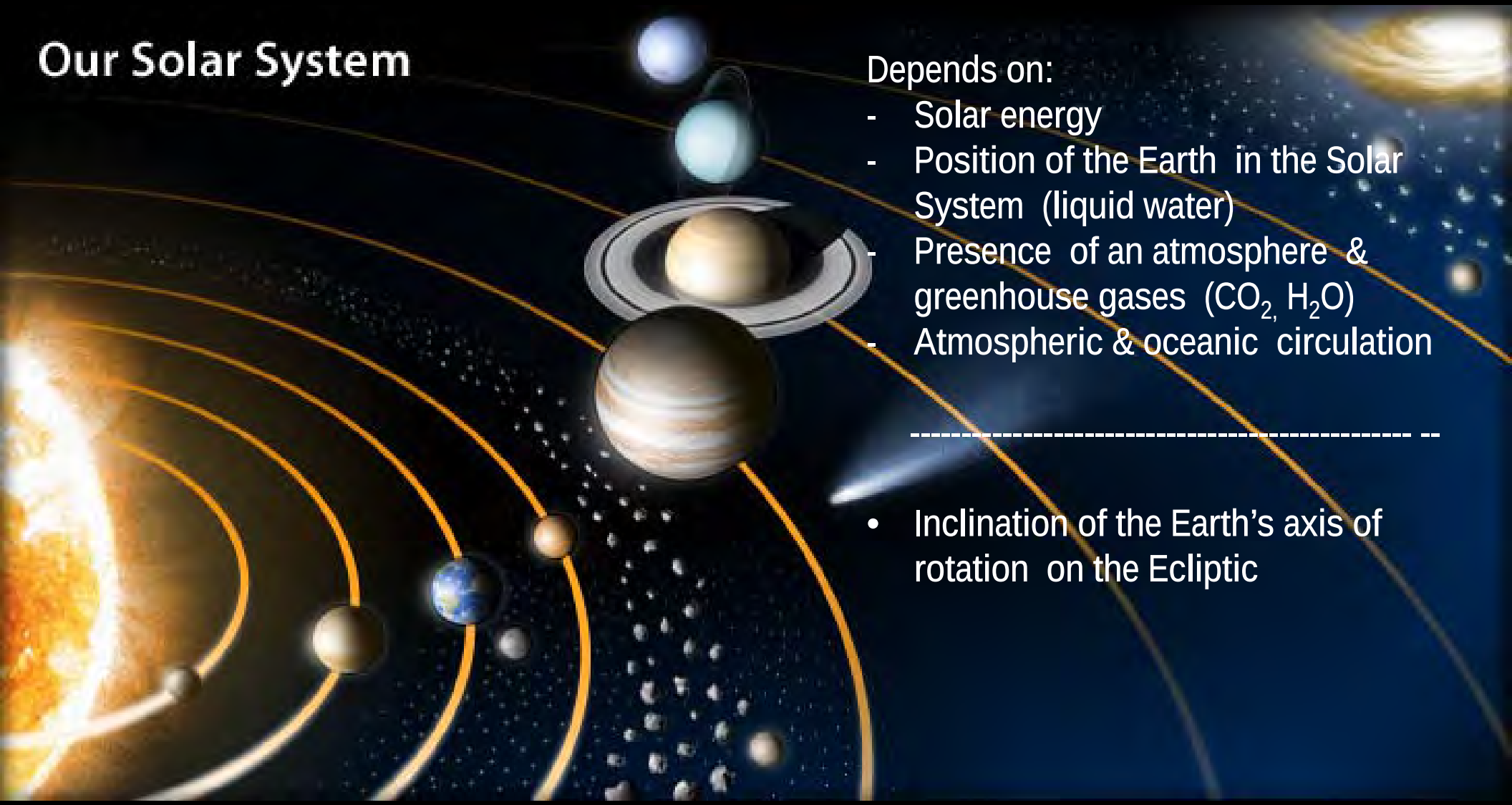
PANGEA

200 million years ago

The Climate System Today



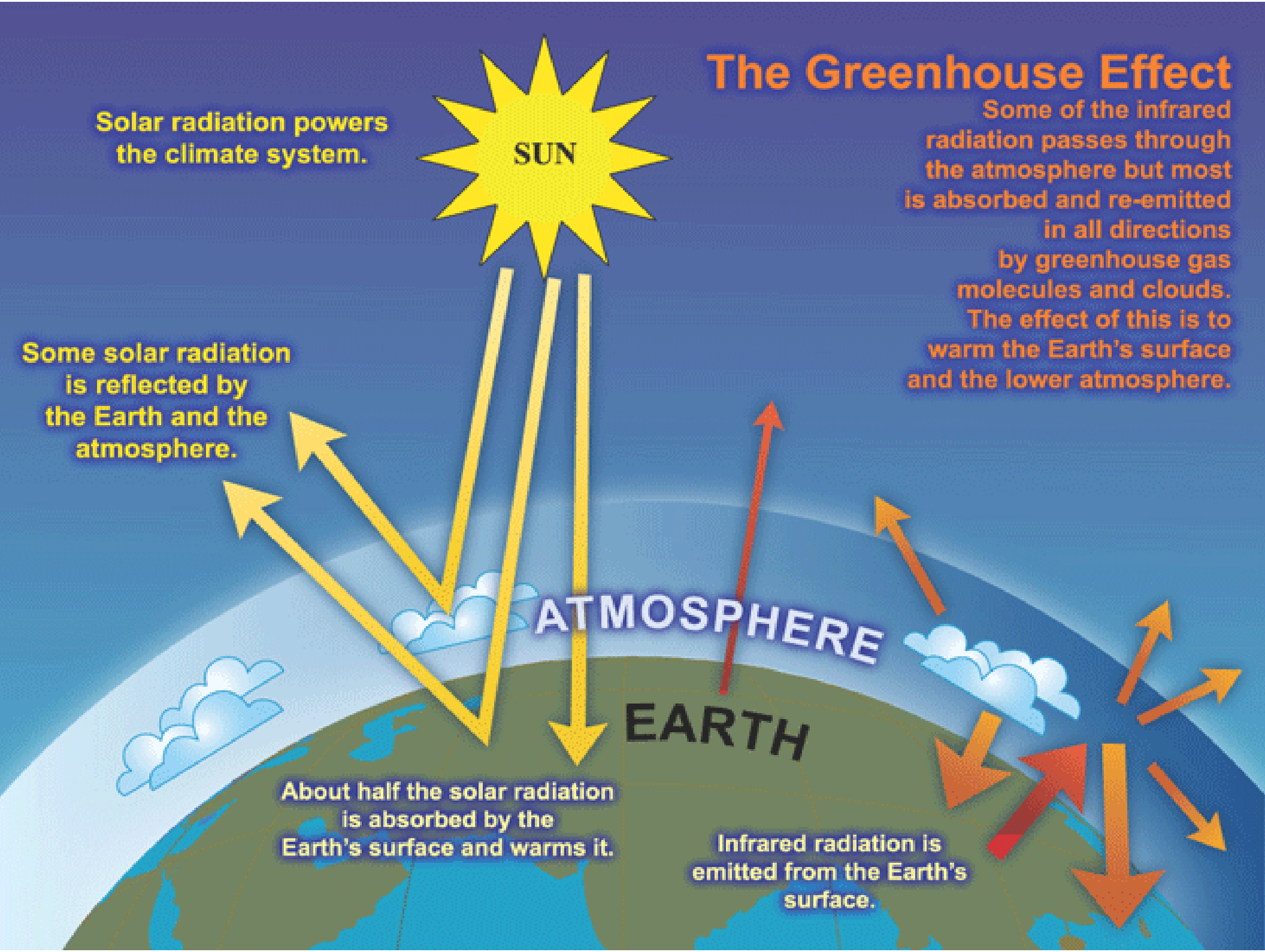
The Earth's climate



Depends on:

- Solar energy
- Position of the Earth in the Solar System (liquid water)
- Presence of an atmosphere & greenhouse gases (CO_2, H_2O)
- Atmospheric & oceanic circulation

- Inclination of the Earth's axis of rotation on the Ecliptic


The Greenhouse Effect
Solar radiation powers the climate system.
SUN
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Some solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

Mean Earth temperature : 15°C

If no ‘natural’ greenhouse effect (presence of water vapor H_20+ carbon dioxide CO_2)

→ mean Earth’s temperature would be -18°C

What is climate change?

Examples of natural forcings:

- Slow variation of orbital parameters
  → glacial-interglacial climates
- Internal processes (e.g. volcanism)
  → short to long-term variations of the mean climatic conditions

Climate Change involves :

- Climate forcing (or *radiative forcing*): an energy imbalance imposed on the climate system by different types of forcing factors (e.g., volcanism, human activities); ususally reported as a change in energy flux at the top of the atmosphere and expressed in units of watts per square meters (Wm^{-2})

  If Radiative Forcing >0 → warming; if Radiative Forcing <0 → cooling

- Climate response: Change in the climate system resulting from a climate forcing

- Climate feedback : Amplification or dampening of the climate response to a specific forcing; Caused by changes in the atmosphere, oceans, land or ice bodies

Brief overview of the Earth's climate through geological times

Key words:

- *Volcanism (internal activity of the Earth)*
- *Emission of CO_2*
- *Greenhouse effect*
- *Water cycle*
- *Acid rain*
- *Chemical erosion of silicate rocks*
- *Atmospheric CO_2 uptake*

Past climates (geological time scales)

Result from the internal activity of the solid Earth
+ interactions with the ocean/atmosphere system

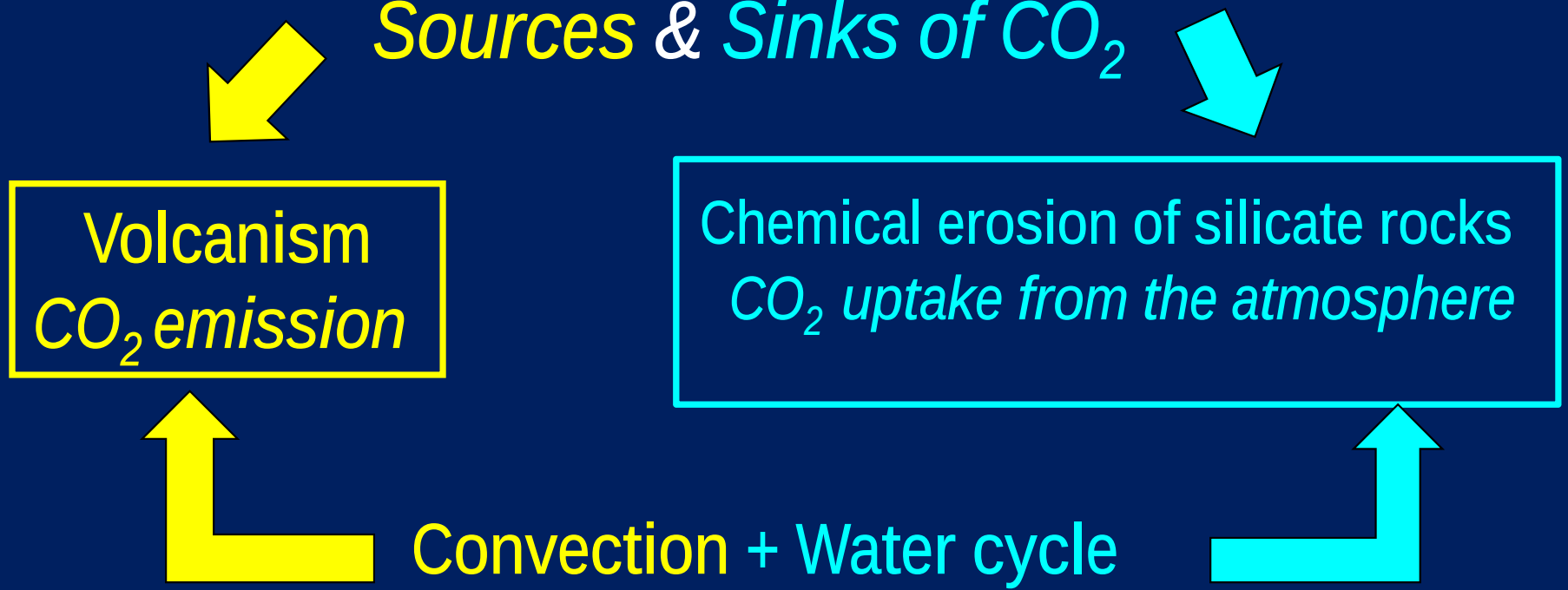
Driving mechanisms and processes:

- *Mantle convection → volcanism → CO_2 emission → T_{earth}* ↑
- *Mantle convection → ontinental break-up → strong water cycle + rich CO_2 atmosphere (acid rains) → chemical erosion of silicate rocks*
  → CO_2 uptake from the atmosphere → T_{earth} ↓

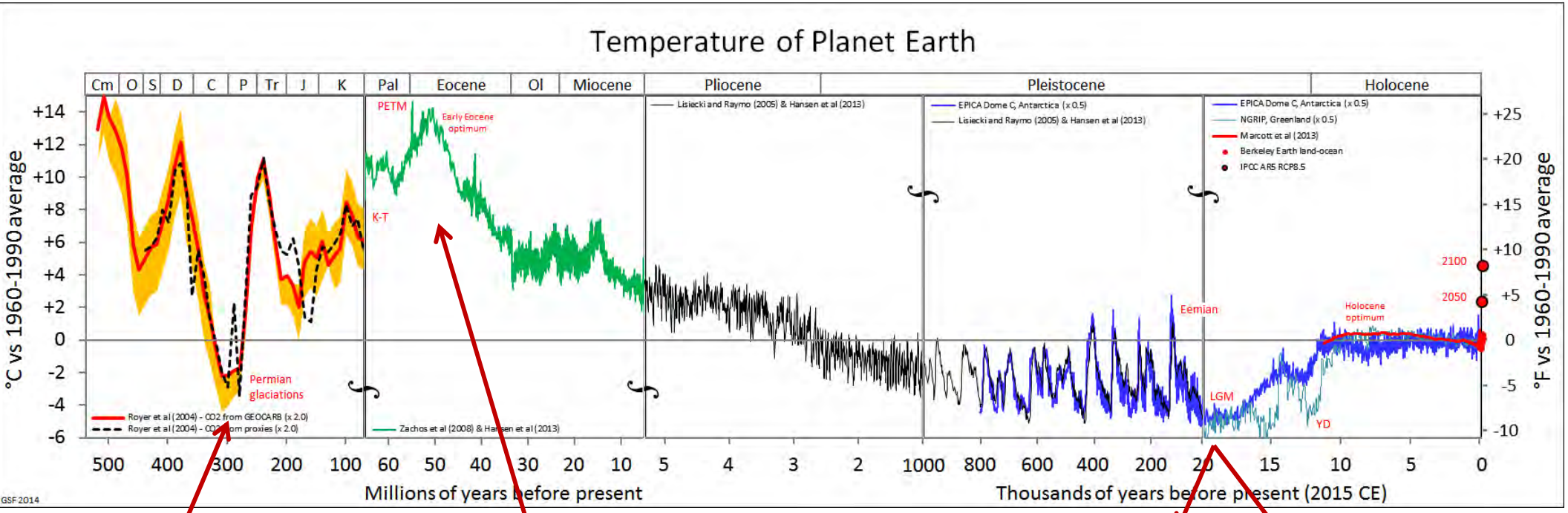
1.3 to 0.75 billion years ago → Super Continent Rodinia


SNOW BALL EARTH
Geological evidence of 4 major cold events
between 750 and 550 milllion years ago
© Stocktre

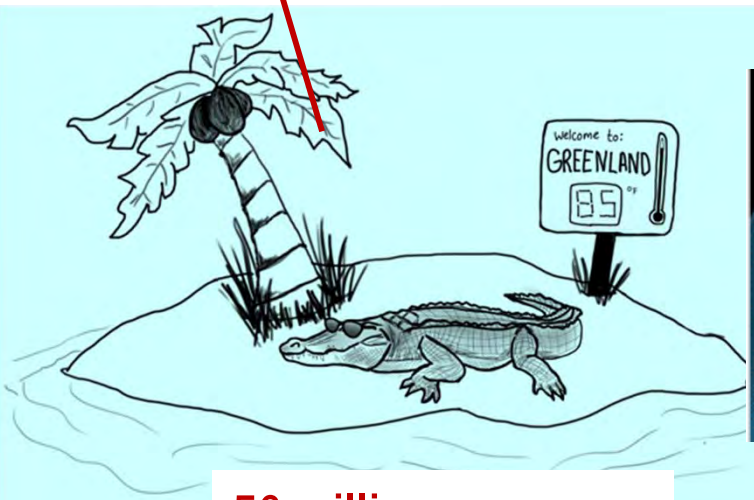
Past climates modulated by the CO_2 cycle and its greenhouse effect



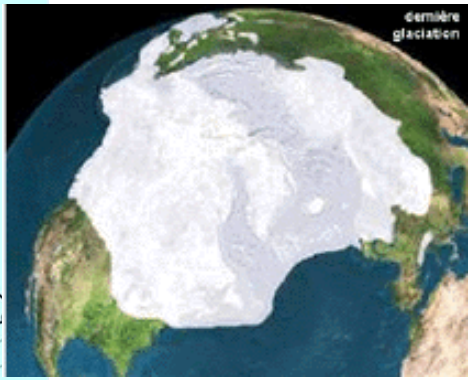
Mean Earth's temperature over the past 500 million years



« Snowball Earth »



56 million years ago



Quaternary glaciations

PRESENT-DAY CLIMATE

Driven by:

Sun & human activities (additional CO_2 greenhouse effect)

+ interactions ocean/atmosphere/ice/biosphere

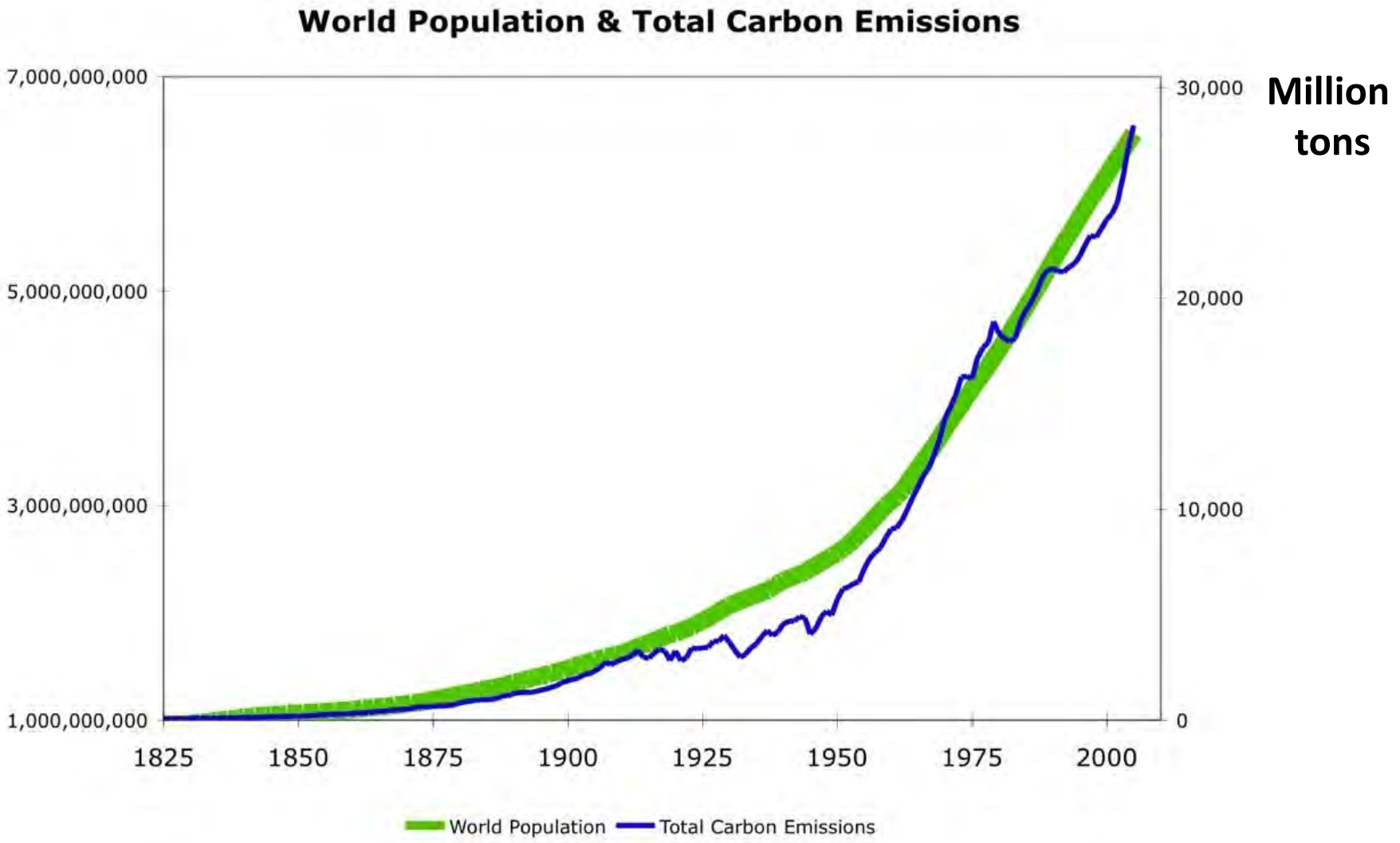
Key words:

Anthropogenic greenhouse gas (GHG) emissions

Carbon cycle & CO_2 concentration

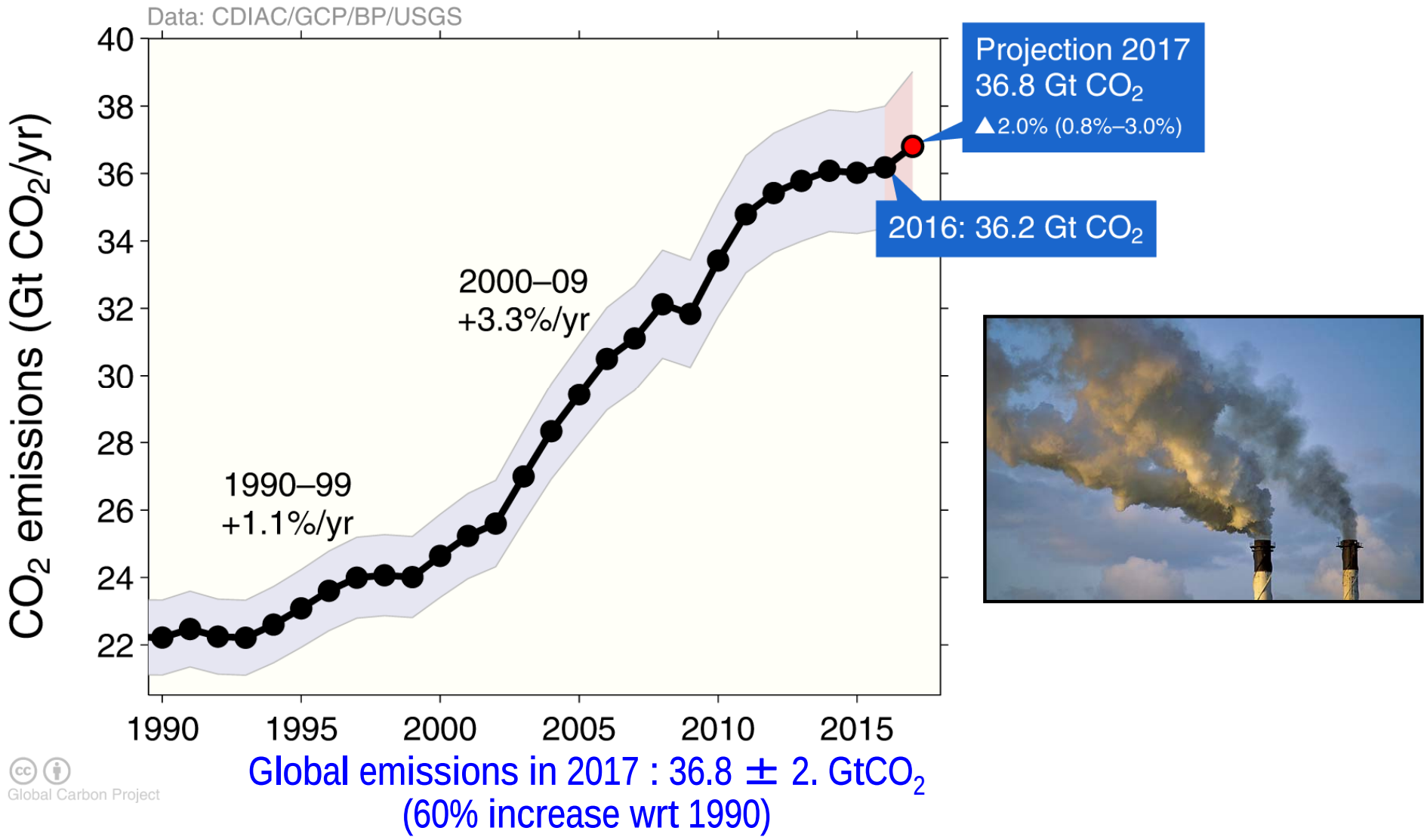
Ocean

Water cycle


World Population & Total Carbon Emissions
7,000,000,000
5,000,000,000
3,000,000,000
1,000,000,000
30,000
20,000
10,000
0
Million tons
1825
1850
1875
1900
1925
1950
1975
2000
World Population
Total Carbon Emissions

Human-induced greenhouse gas (CO_2) emissions

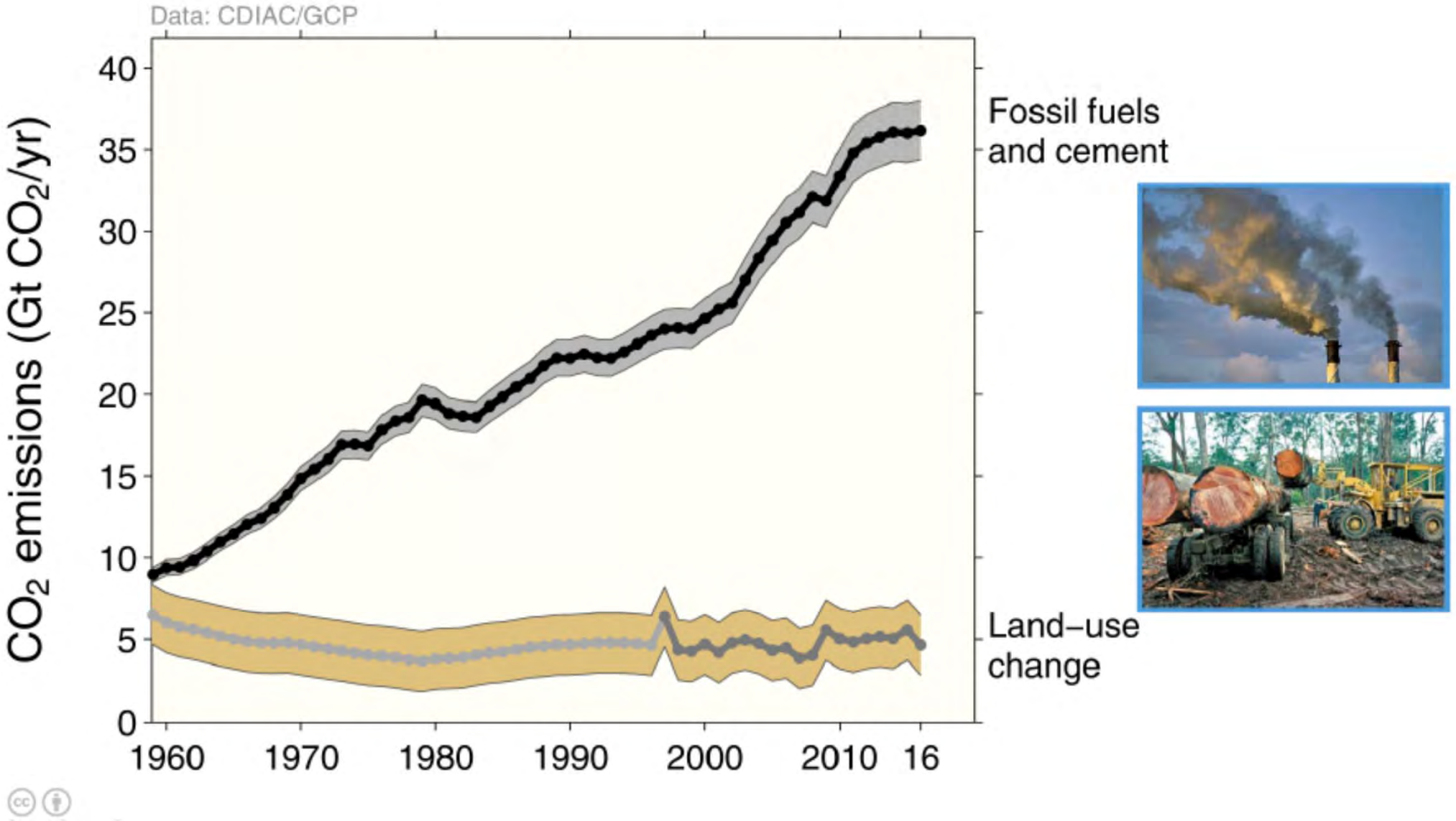
Total amount emissions since the begining of the industrial era: 2000 $GtCO_2$
(fossil fuel combustion: 1300 $GtCO_2$; deforestation: 700 $GtCO_2$)



Global emissions in 2017 : 36.8 ± 2. $GtCO_2$
(60% increase wrt 1990)

1Gt = 1 billion tons

Source: Global Carbon Project 2017; Le Quéré et al., 2017



Source: Global Carbon Project, 2017

Anthropogenic CO_2 emissions (2007-2016)

Sources = **Sinks**

34.3 $GtCO_2/yr$

88%

12%

4.9 $GtCO_2/yr$

17.3 $GtCO_2/yr$

47%

30%

11.2 $GtCO_2/yr$

23%

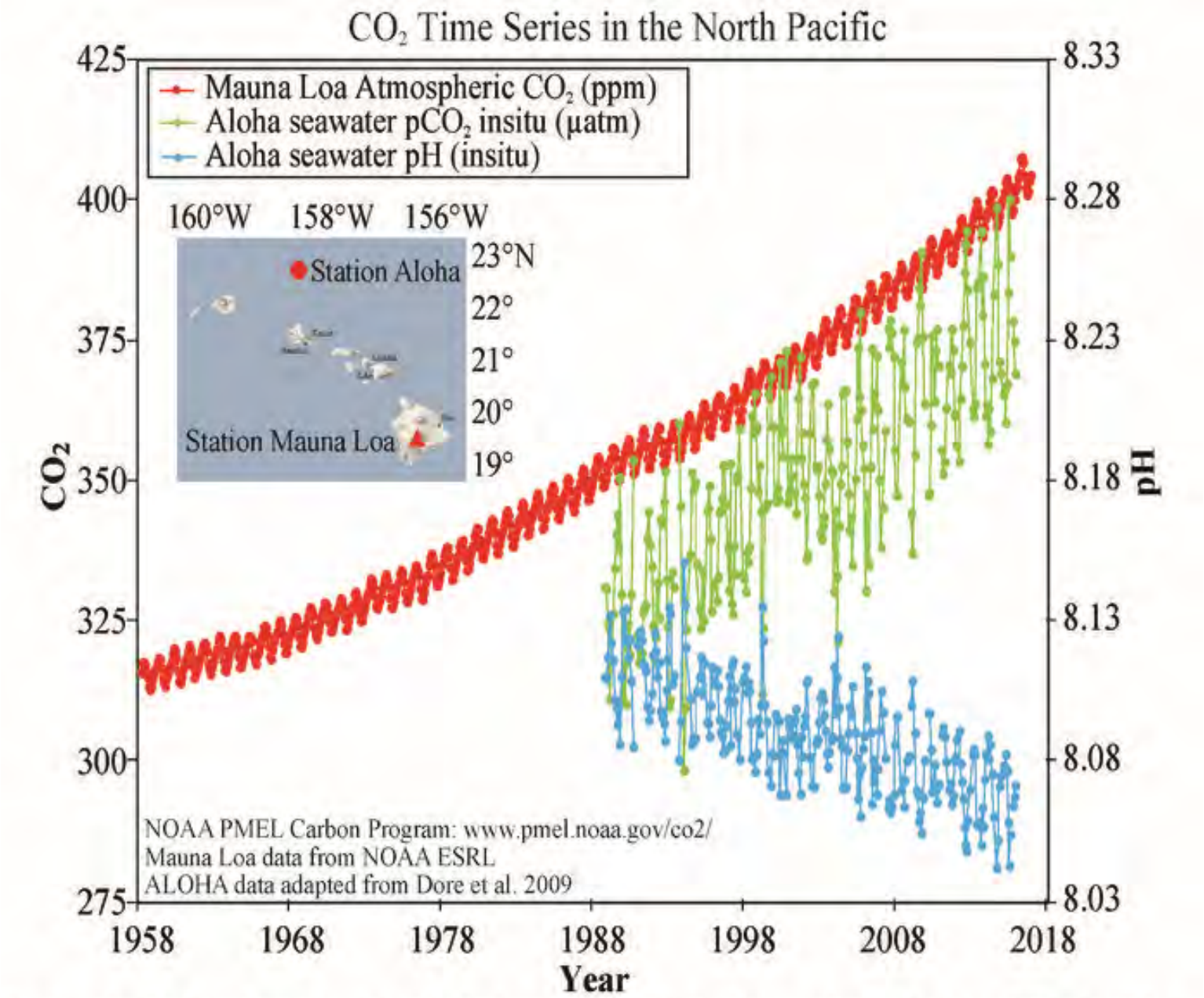
8.7 $GtCO_2/yr$

Budget Imbalance:
(the difference between estimated sources & sinks)

6%
2.1 $GtCO_2/yr$

Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Le Quéré et al 2017; Global Carbon Budget 2017

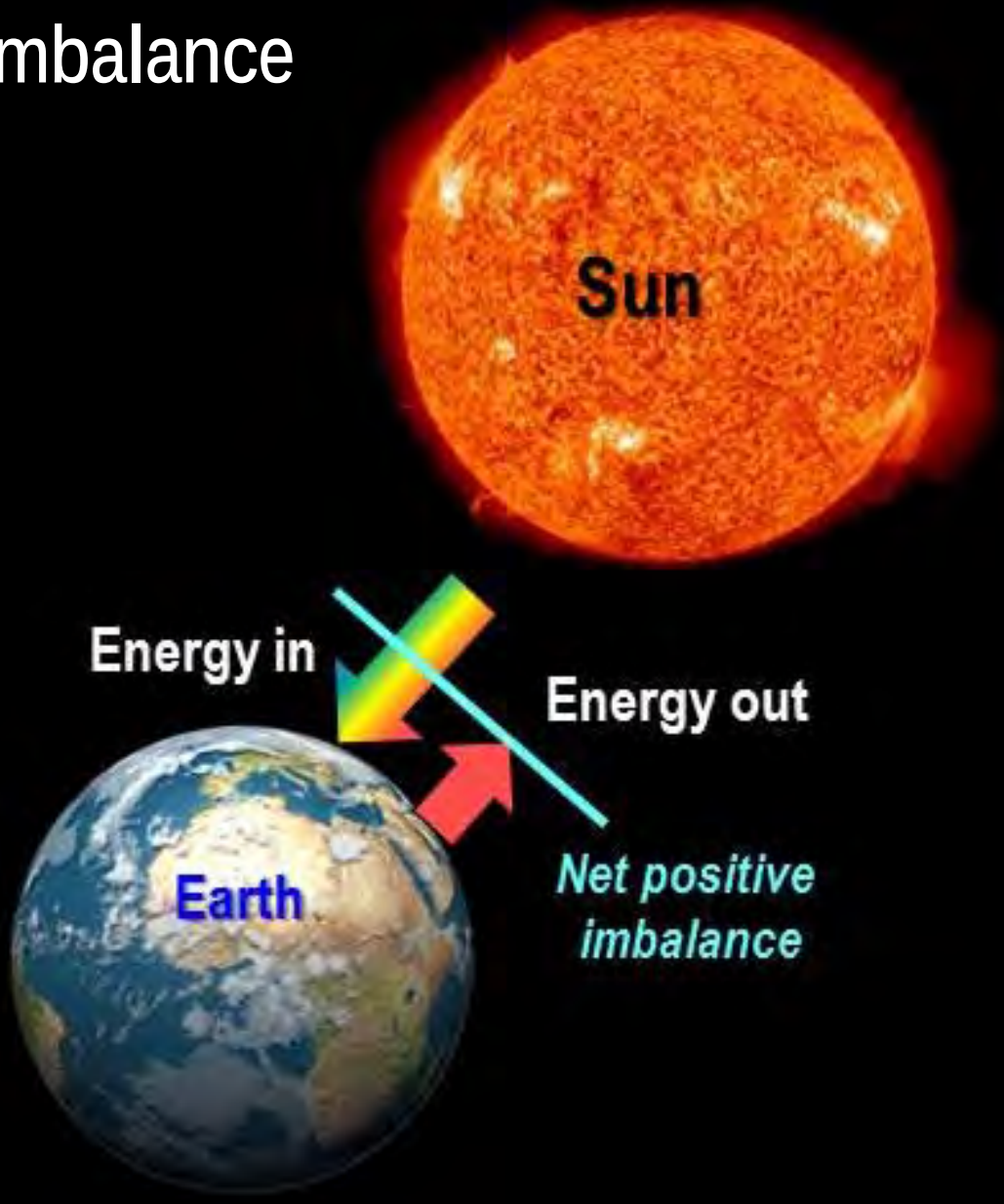
Ocean acidification



Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2.txt)
Ref: J.E. Dore et al, 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc Natl Acad Sci USA* **106**:12235-12240.

Source: NOAA

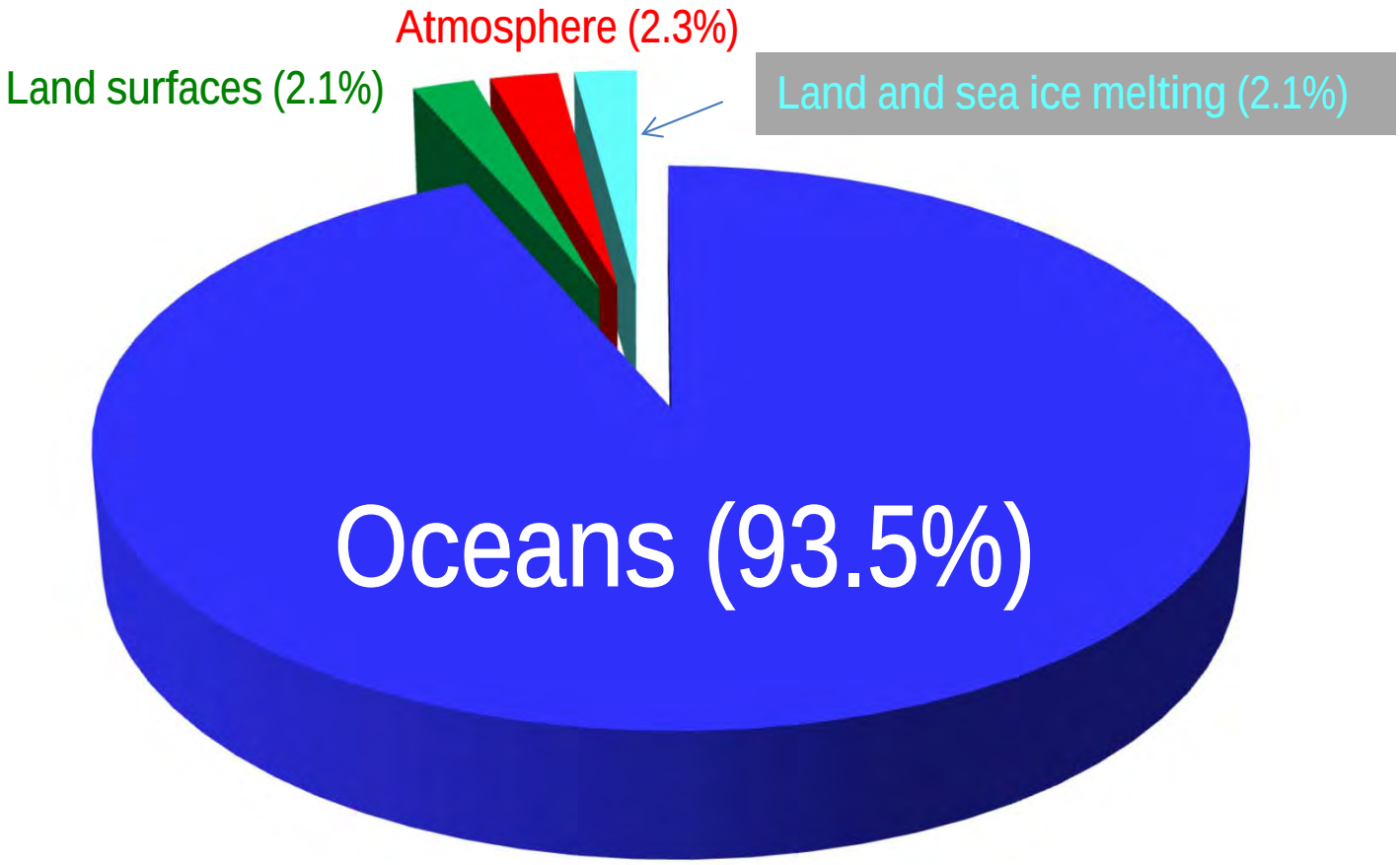
Earth's Energy Imbalance



Today → Energy imbalance
→ 0.5 -1 Wm^{-2}

Heat excess in the climate system:

Percentage of heat accumulated in the different reservoirs over the last 50 years



Von Schuckmann et al., 2016

Thermal inertia of the ocean

- Ocean mass = 300 times that of the atmosphere
- Heat capacity of water = 4 times that of air
- Heat storage capability = 1200 times higher than that of atmosphere

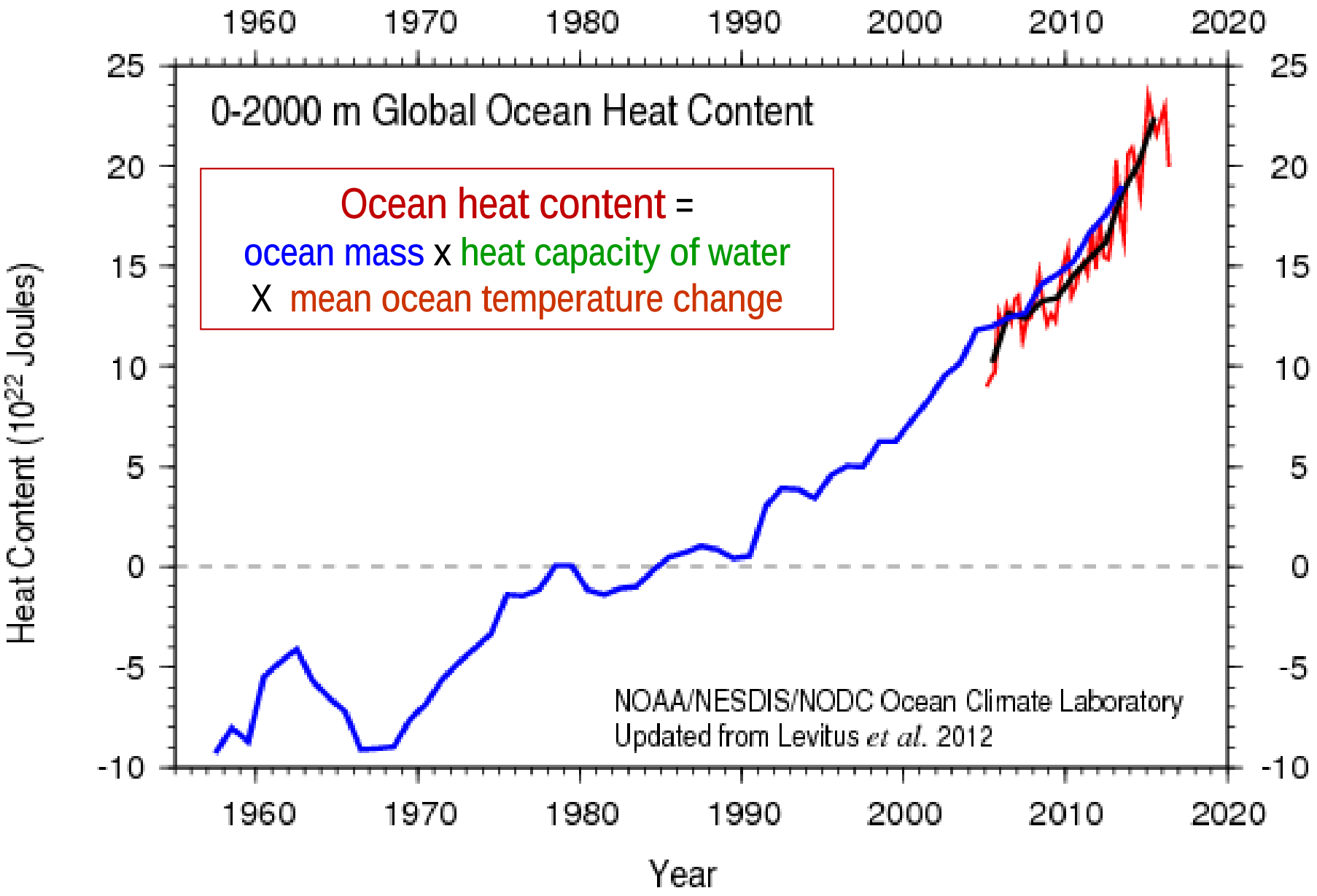
Ocean and climate

- *Main reservoir of heat in the climate system*
- *Transports and re distributes heat over time scales much longer than the atmosphere*

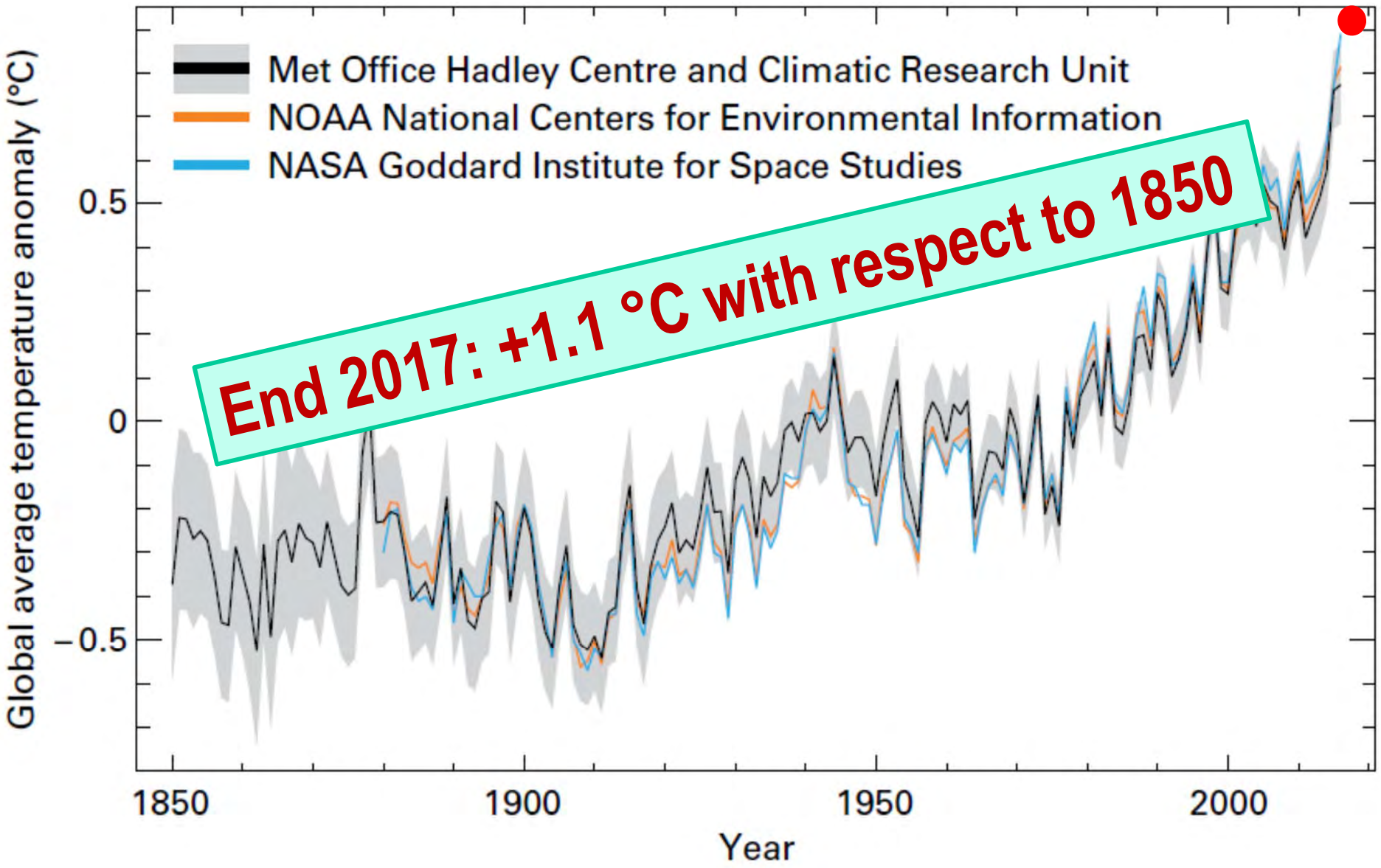
→ *« long-term memory » of the climate system*

Heat capacity : quantity of heat needed to raise the temperature of 1g water by 1°K

The ocean heat content is increasing

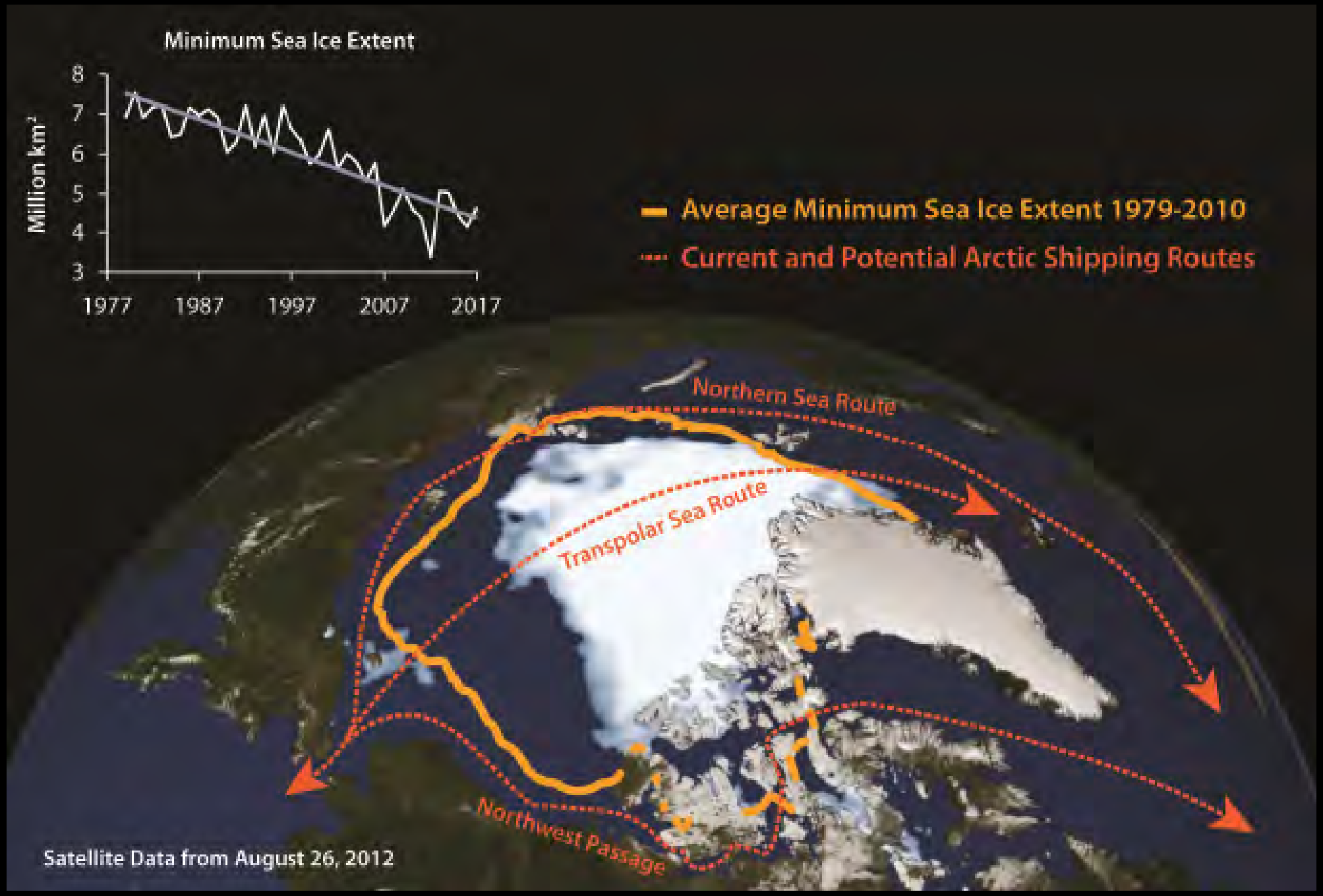


Evolution of the Earth's mean temperature since 1850

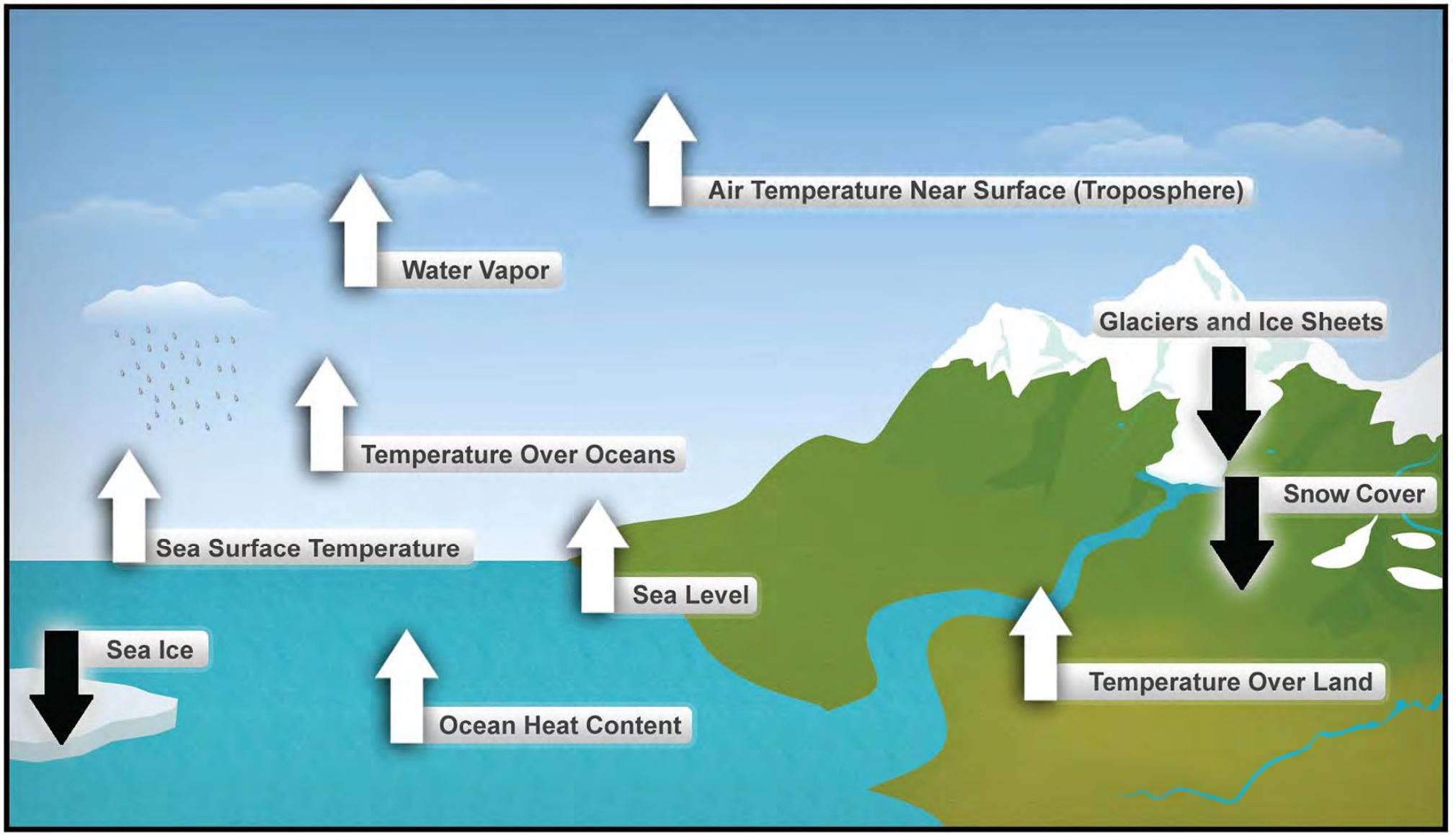


Source: WMO State of Climate 2016

Arctic sea ice decline (extent in August 2012)



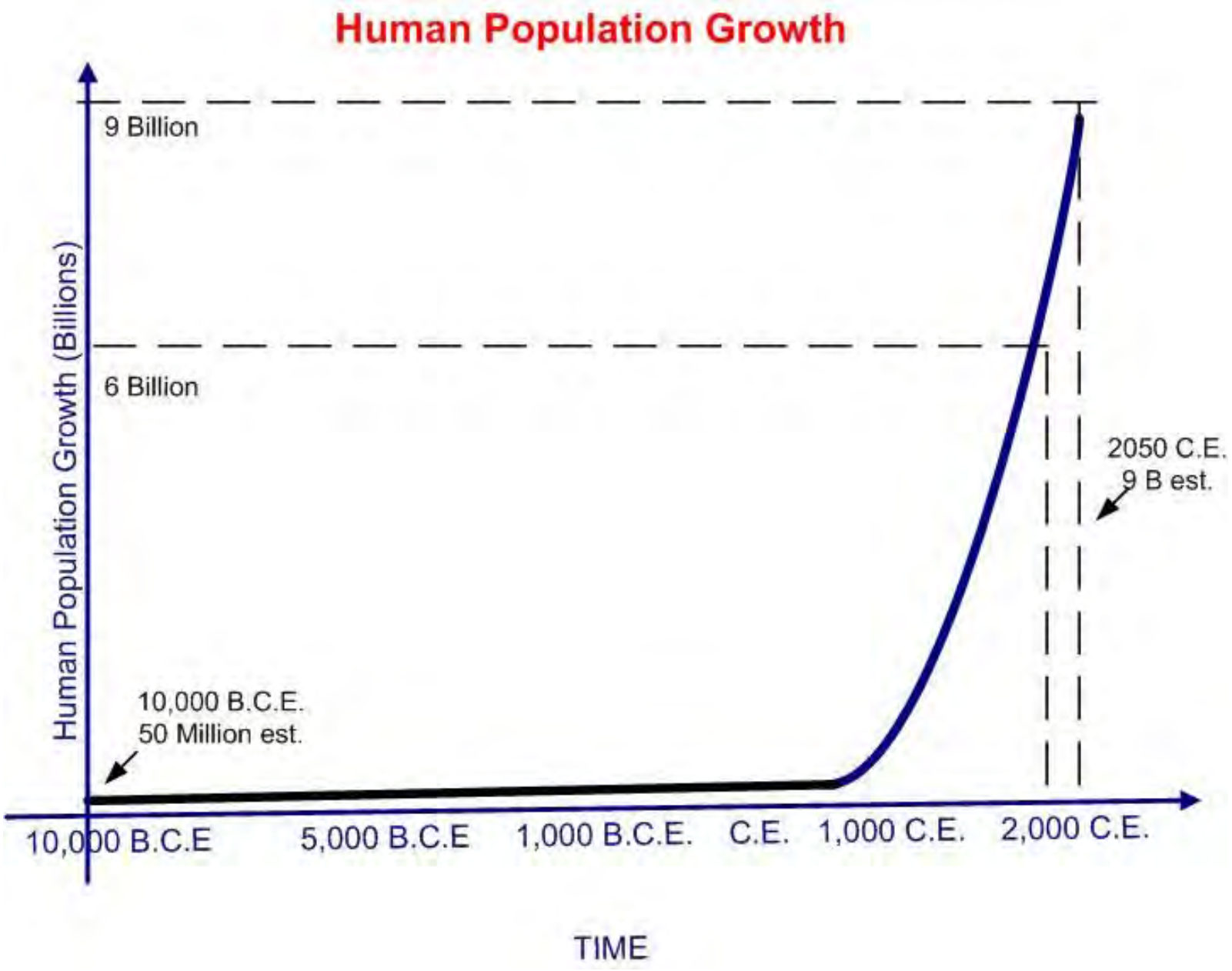
Ten Indicators of a Warming World



OTHER GLOBAL ENVIRONMENTAL CHANGES DUE TO HUMAN ACTIVITIES

- Deforestation
- Change in land use
- Urbanization
- Modification of coastal areas
- Air and sea pollution
- Decline of biodiversity
- Surexploitation of natural resources (including water)
- Modification of the water cycle
- ……

Evolution of the world population since 10 000 years



HOW RESPOND?

- Observation →
  detection of changes, process understanding

+

- Modelling →
  predictability and projection of future changes

GLOBAL CLIMATE OBSERVING SYSTEM

GCOS

GLOBAL CLIMATE OBSERVING SYSTEM

GCOS was established in 1992 to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users

WMO

UN environment

GLOBAL CLIMATE OBSERVING SYSTEM (GCOS)

Implementation plan 2016

4 long-term, overarching targets:

(a) Closing the carbon budget

(b) Closing the global water cycle

(c) Closing the global energy balance

(d) Explaining changing conditions to the biosphere

ESSENTIAL CLIMATE VARIABLES (ECVs) defined by GCOS

Measurement domain	Essential Climate Variables (ECVs)
Atmospheric	Surface: air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget Upper-air: temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget, lightning Composition: carbon dioxide (CO_2), methane (CH_4), other long-lived greenhouse gases, ozone, aerosol, precursors for aerosol and ozone
Oceanic	Physics: temperature: sea surface and subsurface; salinity: sea surface and subsurface; currents, surface currents, sea level, sea state, sea ice, ocean surface stress, ocean surface heat flux Biogeochemistry: inorganic carbon, oxygen, nutrients, transient tracers, nitrous oxide (N_2O), ocean colour Biology/ecosystems: plankton, marine habitat properties
Terrestrial	Hydrology: river discharge, groundwater, lakes, soil moisture Cryosphere: snow, glaciers, Ice sheets and Ice shelves, permafrost Biosphere: albedo, land cover, fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire, land surface temperature Human use of natural resources: water use, greenhouse gas fluxes

World Climate Research Programme (WCRP)

an international programme established in 1980 to coordinate global climate research

Sponsored by WMO, IOC/UNESCO & ISC

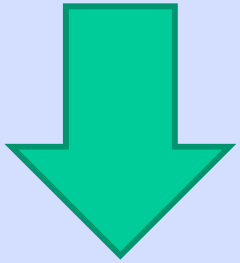
Mission: facilitate the analysis and prediction of Earth system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society

2 overarching objectives:

- Determine the predictability of climate
- Determine the effect of human activities on climate

«Grand Challenges » in climate research

defined by the World Climate Research Programme



1. Clouds, atmospheric circulation and climate sensitivity
2. Melting ice and global consequences
3. Weather and climate extremes
4. Sea level rise and coastal impacts
5. Water for the food baskets of the world
6. Near-term climate prediction
7. Carbon feedbacks in the climate system

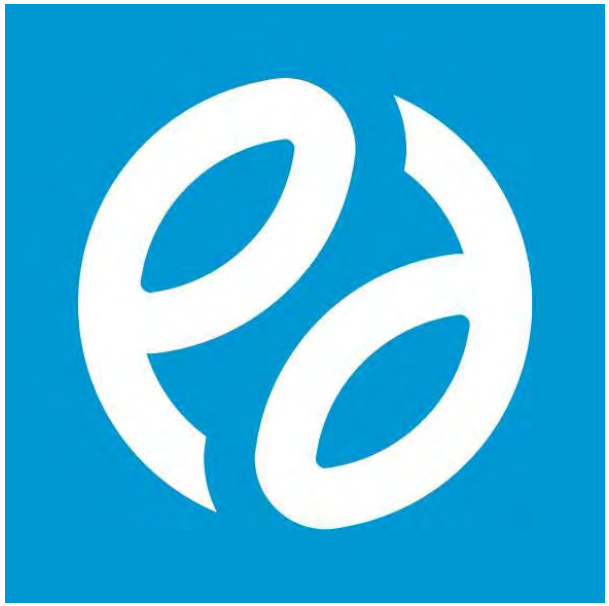
WCRP Coupled Model Intercomparison Project (CMIP)

- The objective of the Coupled Model Intercomparison Project (CMIP) is to better understand past, present and future climate changes arising from natural, unforced variability and in response to changes in radiative forcing in a multi-model context.
- CMIP provides a standard protocol to study the outputs of coupled atmosphere-ocean general circulation models (AOGCMs) (now Earth System Models/ESMs)
- This includes assessments of model performance during the historical period and quantifications of the causes of the spread in future projections.
- Numerical experiments are also performed to investigate the predictability of the climate system on various time and space scales
- Since 1995, several CMIPs exercices (ongoing →CMIP6)

CMIP feeds the IPCC (Intergovernmental Panel on Climate Change) assessments (IPCC AR6 ongoing)

Intergovernmental Panel on Climate Change (IPCC)

- Created in 1988 (WMO, UNEP)
- Role: assess the best available scientific, technical and socio-economic information on climate change from around the world
- The assessments are based on information contained in peer-reviewed literature
- 5 assessment reports published; 6th assessment (AR6) in progress



FUTURE EARTH

- An international, interdisciplinary research programme to produce knowledge about the environmental and human aspects of GLOBALCHANGE and to find solutions for sustainable development

- Global Research Projects & Knowledge-Action Networks

- ❑ Create interdisciplinary science relevant to major global sustainability challenges
- ❑ Deliver products and services that society needs, in order to meet these challenges
- ❑ Co-design and co-produce solutions-oriented science, knowledge and innovation for global sustainable development

Copernicus
Europe's eyes on Earth

COPERNICUS:
A European system for monitoring the Earth

Earth Observation from Space

Space-based observations provide a global perspective that contribute to improved understanding of the Earth system

- →Dynamical interactions between atmosphere, ocean, land, ice and human society

- → Societal applications

ESA-DEVELOPED EARTH OBSERVATION MISSIONS

2010

Proba-1
SMOS
GOCE
CryoSat
Proba-V
Swarm
Meteosat 10 (MSG)
MetOp-B
Sentinel-1A
Sentinel-2A
Sentinel-1B
Sentinel-2B
Sentinel-3A
Sentinel-3B
Sentinel-5p
Aeolus
Seosat
EarthCARE
Biomass
FLEX

2015

Meteosat 11 (MSG)
Sentinel-6A
Sentinel-2C
Sentinel-1C
Sentinel-3C
Sentinel-1D
Sentinel-2D
Sentinel-3D
Sentinel-6B

2020

MetOp-C
Sentinel-5A MetOp-SG-A1
MetOp-SG-B1
MTG-I
Sentinel-4A MTG-S1

2025

MTG-I2
Sentinel-5B MetOp-SG-A2
MTG-I3
MetOp-SG-B2

2030

Sentinel-4B MTG-S2

Science | **Copernicus** | **Meteorology**

European Space Agency

The Sentinel missions

- Sentinel-1 provides all-weather, day and night radar imagery for land and ocean services
- Sentinel-2 provides high-resolution optical imagery for land services
- Sentinel-3 provides high-accuracy optical, radar and altimetry data for marine and land services
- Sentinel-4 and Sentinel-5 will provide data for atmospheric composition monitoring from geostationary orbit and polar orbit, respectively
- Sentinel-5 Precursor will bridge the gap between Envisat (Sciamachy data in particular) and Sentinel-5
- Sentinel-6 will provide radar altimetry to measure global sea-surface height, primarily for operational oceanography and for climate studies


opernicus
CLIMATE CHANGE
MARINE MONITORING
ATMOSPHERE MONITORING
LAND MONITORING
SECURITY
EMERGENCY MANAGEMENT

Copernicus Services

CLMS (Copernicus Land Monitoring Service)

CAMS (Copernicus Atmosphere Monitoring Service)

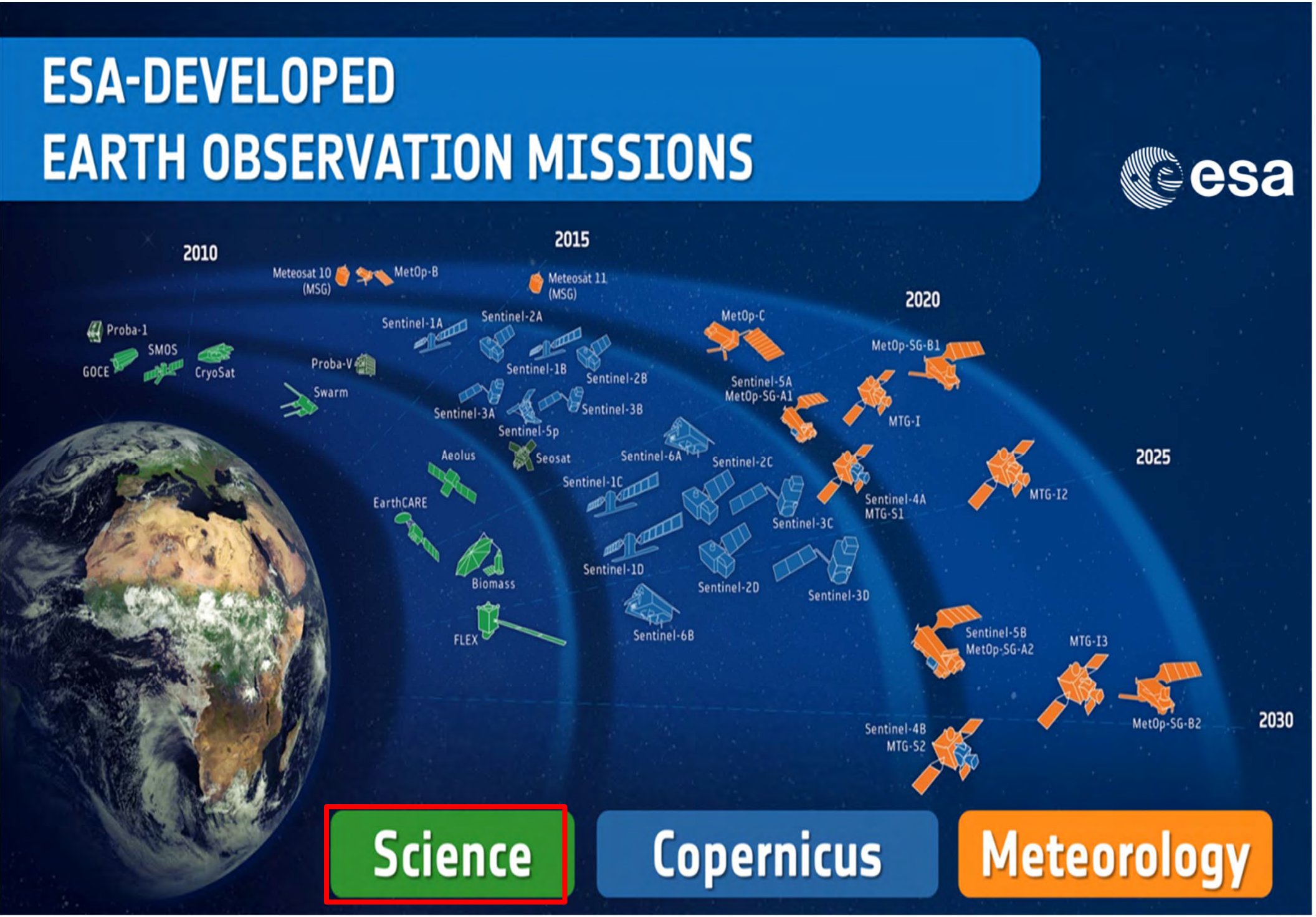
CMENS (Copernicus Marine Environment Monitoring Service)

EMS (Emergency Management Service) (natural and man-made hazards)

C3S (Copernicus Climate Change Service)

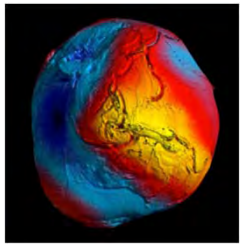
Security.

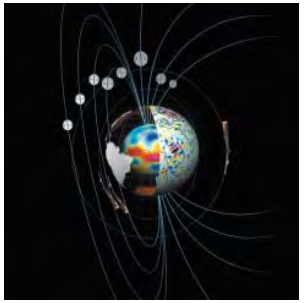
ESA-DEVELOPED EARTH OBSERVATION MISSIONS



Earth Explorer Missions

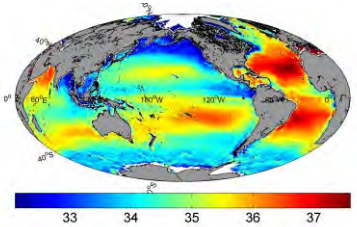
GOCE (2009-2013) → Earth gravity field





SWARM (2013-) → Earth magnetic field

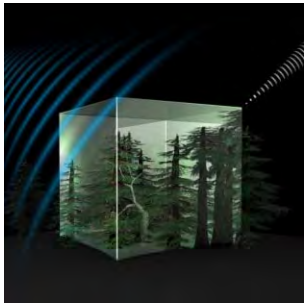
SMOS (2009-) → Soil moisture and ocean salinity



Cryosat (2010-) → Sea & land ice

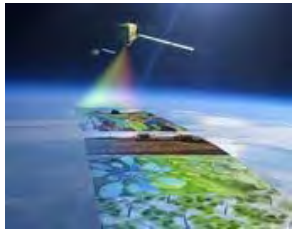
Aeolus (2018) → Atmospheric winds

BIOMASS (2020) → Forest biomass and carbon



EarthCARE (2021) → Clouds and aerosols

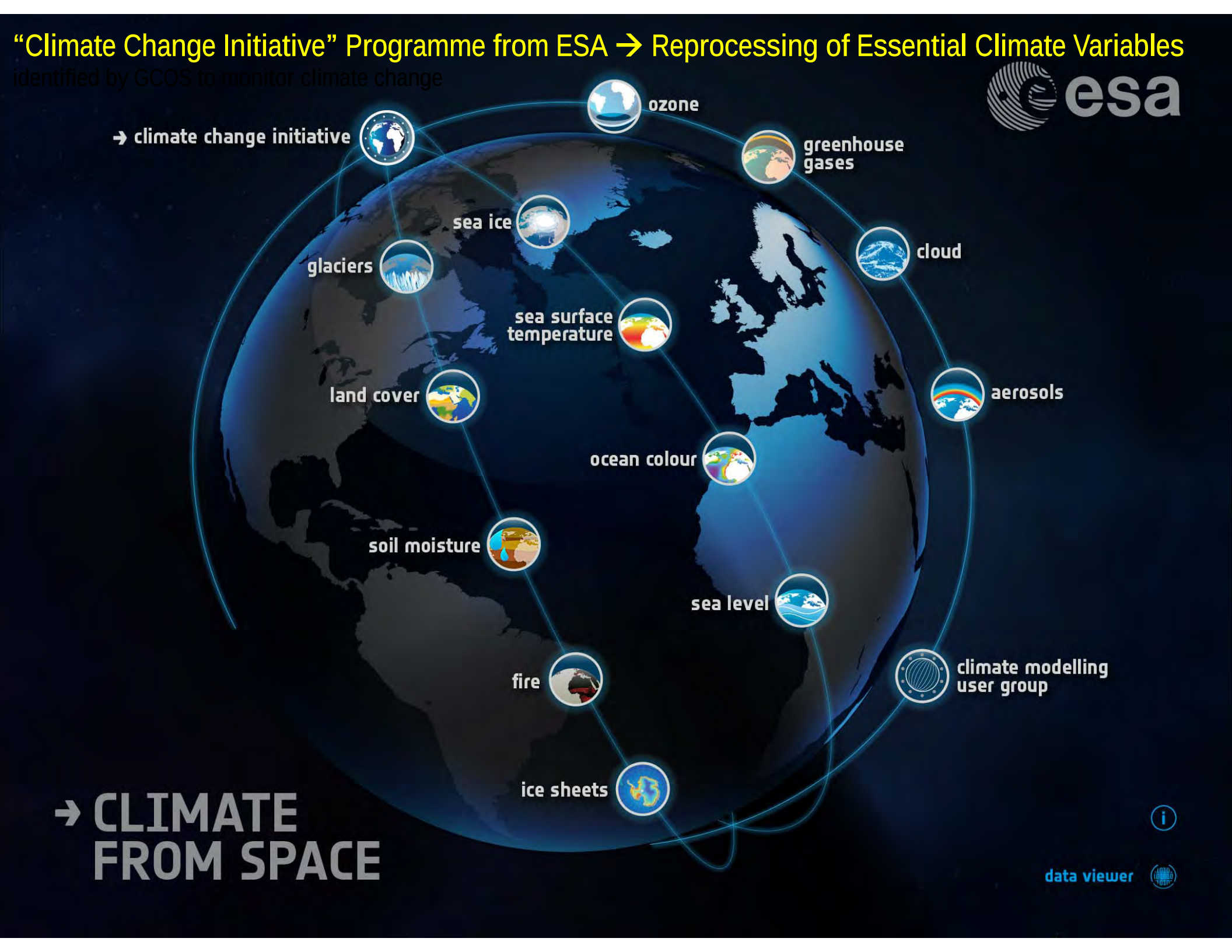
FLEX (2022) → Photosynthetic activity of vegetation



DATA REPROCESSING OF OLD & EXISTING MISSIONS

“Climate Change Initiative” Programme from ESA → Reprocessing of Essential Climate Variables

identified by GCOS to monitor climate change



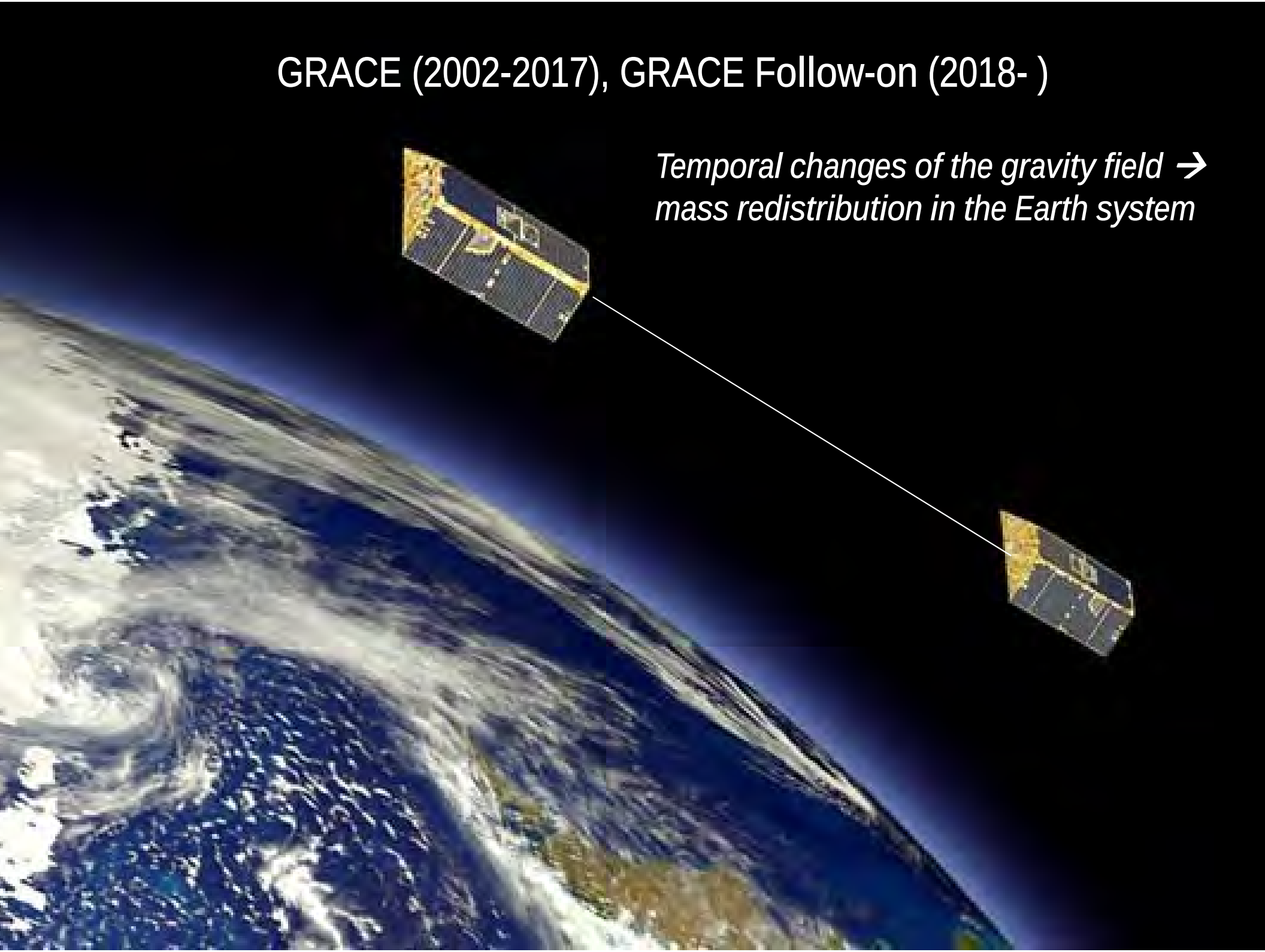
NASA EARTH OBSERVATORIES

Earth Science Missions

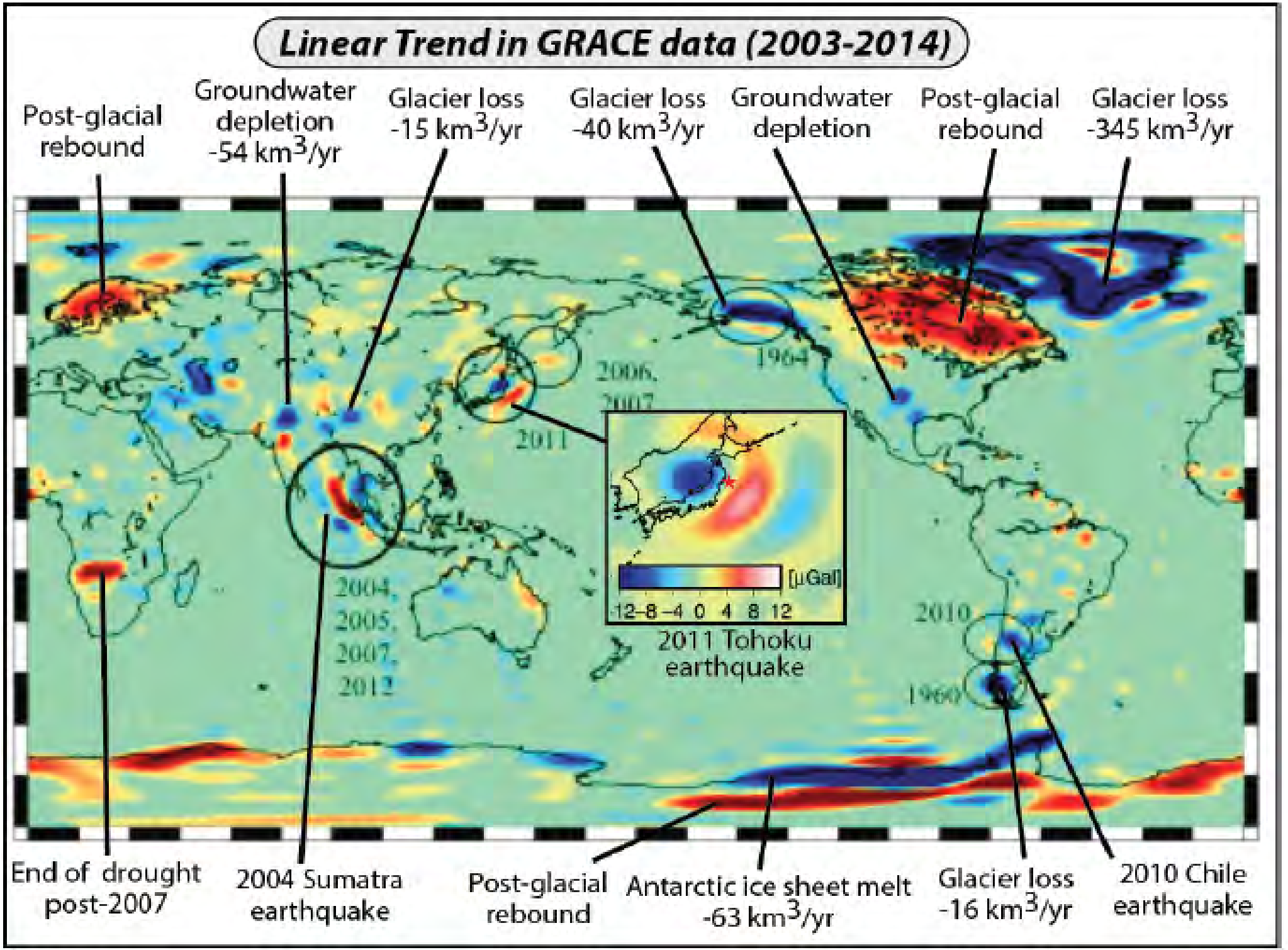
NASA « A-Train »

clouds, aerosols, atmospheric chemistry

GRACE (2002-2017), GRACE Follow-on (2018-)



Temporal changes of the gravity field → mass redistribution in the Earth system



Han et al., 2015

USA → A Decadal Strategy for Earth Observation from Space DECADAL SURVEY

THE 2017-2027 DECADAL SURVEY FOR EARTH SCIENCE AND APPLICATION FROM SPACE

Carried out by the US National Academies of Sciences, Engineering and Medecine

Document available online, 700 pages, published 2018

Objectives:

- **Assess past decade progress**
- **Establish a vision strategy for the future decade**
- **Provide guidance on implementation of the plan by NASA, NOAA & USGS**

Specificity

- ***Focus on science, applications and observations (rather than on instruments & missions) → prioritized strategic "science targets"***
- ***(i.e., sciences objectives related to a common space-based observable)***

USA →A Decadal Strategy for Earth Observation from Space (2017-2027) DECADAL SURVEY

MOST IMPORTANT PRIORITIES FOR THE DECADE 2017-2027

1. Coupling of the Water and Energy Cycles (How is the water cycle changing? What are the magnitude and frequency of extremes?....)

2. Ecosystem Changes (What are the structure, function and biodiversity of Earth's ecosystems? How are they changing in space and time? What are the fluxes of carbon, water, nutrients and energy between ecosystems?)

3. Weather and Air Quality forecasts (How improve forecasts of weather and air quality? What processes determine the spatio-temporal structure of air pollutants?)

4. Reducing Climate Uncertainty and Informing Societal Response (How can we reduce the uncertainty of the amount of future warming as a function of fossil fuel emissions?)

5. Sea Level Rise (How much will sea level rise globally and regionally? What are the role of ice sheets and ocean heat storage? How will local sea level change locally along coastlines?)

6. Geological Hazards and Disasters (Can we forecast geological hazards in a socially relevant timeframe? How do they impact society?)

THANKS FOR YOUR ATTENTION

THE SENTINELS

FULL, FREE AND OPEN

Space Component

Sentinel Mission and Status		Key Features
 SENTINEL-1: 9-40m resolution, 6 days revisit at equator	*S1-A and B in orbit*	Polar-orbiting, all-weather, day-and-night radar imaging
 SENTINEL-2: 10-60m resolution, 5 days revisit time	*S2-A in Orbit S2-B Launch Q1 2017*	Polar-orbiting, multispectral optical, high-res imaging
 SENTINEL-3: 300-1200m resolution, <2 days revisit	*S3-A in Orbit S3-B Launch Q4 2017*	Optical and altimeter mission monitoring sea and land parameters
 SENTINEL-4: 8km resolution, 60 min revisit time	*1st Launch Q4 2022*	Payload for atmosphere chemistry monitoring on MTG-S
 SENTINEL-5p: 7-68km resolution, 1 day revisit	*Launch in Q2 2017*	Mission to reduce data gaps between Envisat, and S-5
 SENTINEL-5: 7.5-50km resolution, 1 day revisit	*1st Launch in 2021*	Payload for atmosphere chemistry monitoring on MetOp 2nd Gen
 SENTINEL-6: 10 days revisit time	*July 2020*	Radar altimeter to measure sea-surface height globally

European Commission | Copernicus