**CHALLENGE 1**

### ABSTRACT

Facing current climate and environmental crises needs long-term series of Earth Dynamics and anthropogenic pressures on the Planet. Numerous geological, chemical and biological natural archives capture large-scale, multi-temporal, abrupt, and often irreversible shifts in environmental and climate systems, providing an opportunity to better understand and therefore predict potential future impacts of the present anthropogenic warming and Humankind impact on the Planet. By providing robust, reliable, quantitative, detailed, high-resolution and long paleoclimate and paleoenvironmental data series, paleoclimatology and paleoenvironmental research place present climate variability and ecological crises in a long-term perspective to understand climate forcing mechanisms and environmental processes and responses. The success of science-based solutions to the global risks in the 21st century will strongly rely on our capacity to transfer this knowledge to politicians, managers, and society.

### KEYWORDS

anthropocene | paleodata | paleoclimate modelling | paleoarchives | past global changes

CHALLENGE 1

# PAST GLOBAL CHANGES: A CONTEXT TO THE ANTHROPOCENE

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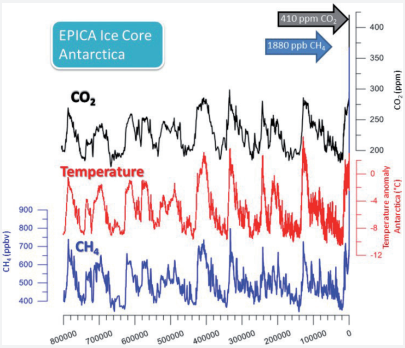
## 1. INTRODUCTION AND GENERAL DESCRIPTION

The Anthropocene is defined as the current period in Earth History in which the humankind appears as one of the main drivers in shaping the landscape, modifying main biogeochemical cycles, stressing the biodiversity and altering the atmosphere composition of our planet. In spite that formal definition and boundaries for this new geological Earth period are controversial and not yet agreed by the scientific community (Rull, 2018; Zalasiewicz et al., 2019), there are multiple evidences that indicate the unique nature of the last 50 years (otherwise defined as the Great Acceleration), as the rate of change of surface biogeochemical processes has increased, hand in hand with the increase in population and the growing demand of resources. The scientific community has been alerting about the dramatic trend in many drivers of global change (*stressors*) with consequences that can go beyond nowadays projections if some tipping points are reached (Rockström et al., 2009). Society demands progressively improved projections of future climate change that allow for designing more effective mitigation actions. In order to achieve them, a better knowledge of processes contributing to climate variability and change is needed. Undoubtedly, that knowledge roots on long-term observations of

**FIGURE 1**—Variations of temperature (red), atmospheric carbon dioxide (black) and methane (blue) over the past 800,000 years, from the EPICA Dome C ice core in Antarctica. Modern values (year 2019) of carbon dioxide and methane are indicated by arrows. Modified from http://www.iceandclimate.nbi. ku.dk




natural variability (Abram et al., 2016), performed on current ecological monitoring surveys (eg. LTER initiative) and climate, as well as on reconstructions provided by natural and documentary archives that allow to look further back in time than available observational data series which only record 150 years in the best cases. The use of state of the art Earth System Models (ESM) can provide mechanistic understanding of such processes in model-data comparison exercises.

Long-term and quantitative reconstructions of past Earth Dynamics at multiannual (or higher) time resolution should serve to look for analogues of present-day climate and environment, characterizing tipping points, understanding past climate and ecological feedbacks, and accurately describing and quantifying the anthropogenic effects on climate. Thus, by diving into paleoenvironmental/paleoclimate archives, we can determine if we are facing unprecedented changes compared to the natural baseline conditions defined by previous periods. Considering climate changes recorded by Antarctic ice cores, it is evident the unprecedented values in greenhouse gasses attained nowadays in the context of last 800,000 years (Figure 1). Importantly, many drivers of past global changes are similar to those stressors playing a key role today, but the rates of change and consequences are magnified. In fact, the velocity at which current global change is occurring is likely the main difference with previous periods of change. In addition, reconstructions of past interactions allow understanding the feedbacks that pushed the system into a different mode of operation. The "tipping points", when such abrupt changes occur, are notoriously hard to predict and paleoreconstructions aid to reduce the uncertainty in the current projections.

Numerical Earth System Models (ESM) experiments are designed, as in the case of laboratory experiments, to reveal potential cause-effect relationships. The main questions addressed by the most recent phases of the Coupled- and Paleo-Model Intercomparison Projects (CMIPs, PMIPs; Eyring et al., 2016; Taylor et al., 2012) target understanding how the Earth System responds to forcing, what are the origins and consequences of systematic model biases, and how can we assess future climate changes given internal climate variability, predictability and uncertainties in scenarios. In order to address these questions, current and future simulation efforts that span timescales much wider than the post-1850 historical period are needed. Past climate states can be very different from present climate, thus paleo model-data comparison provide stringent tests for state-of-the-art models and a way to assess whether their sensitivity to forcings is compatible with past climate observations.

The study of past global changes also helps to characterize the responsiveness of biomes and geographic regions to climate and environmental changes in the past and, thus, to identify which ones are more sensitive and endangered today (otherwise called hotspots). The polar regions, and specially the Arctic, are showing the most rapid rate of warming worldwide, with unprecedented sea-ice loss and ecological shifts with unknown consequences (e.g. ice-associated marine mammals and commercial fish stocks, and abrupt and dramatic collapse of the West Antarctic ice sheet). The Mediterranean area represents another key region both in terms of high biodiversity and long-term human occupation history. Its intrinsic features (summer droughts, periodical water shortages and relatively high human density population) make its terrestrial and marine ecosystems highly vulnerable to the current anthropogenic global warming and increasing human pressures. Furthermore, this key region is an ideal natural laboratory to characterize past society's resilience and adaptation to past climate/environmental fluctuations and tipping points. Previous examples of different scenarios and responses to climate and environmental abrupt changes including resilience, adaptation, and sometimes collapse of societies can be found in southern Iberia Peninsula: the Argaric culture collapse at around 4 millennia ago driven by both aridity crisis and strong anthropogenic impact including deforestations and fires (Carrión et al., 2007) is a good example. Besides, the migrations of hunter-gathered groups during the Early Holocene in the Ebro and neighbouring mountains reflect the contrasted and complex responses obtained from nearby areas (González-Sampériz et al., 2009). Positive feedbacks with great economic expansions and cultural success partially related with favourable climate conditions also occurred, e.g. the Egyptian culture associated to regular Nile floods or the Viking settlement in Greenland and Terranova regions when the Artic was navigable during the Medieval Climate Anomaly (10th -12th centuries).

In summary, robust and quantitative paleodata, as well as mechanistic understanding coming from modelling exercises, are urgently needed to provide the climatic and ecological framework to understand recent changes, slow down the impacts and improve adaptations to one of the most compelling challenges that humankind is presently facing.

## 2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

There is a scientific consensus that the current warming trend, particularly since the mid-20th century, is the result of human activities and the rates of change are unprecedented at least during the Holocene. As also stated in Thematics 13 and 14, one of the key scientific challenges for the 21st century is to understand the impacts of the present temperature rise in all Earth spheres and the underlying mechanisms and feedbacks responsible of the current situation, including anthropogenic pressures. The goals of this Chapter have been oriented following this basic science perspective. Many other research and consultant organizations such as the United Nations, with their Sustainable Development Goals (https://www.un.org/sustainabledevelopment/sustainable-development-goals) and the European Environment Agency (https://www.eea.europa.eu/), the Intergovernmental Panel on Climate Change (https://www.ipcc.ch), the United States Environmental Protection Agency (https://www.epa.gov), and Australia's national science research agency (https://www.climatechangeinaustralia.gov.au/en) are also aligned with the basic science perspective. These organizations are promoting the creation of indicators of climate and environmental change that are being used to understand the rapid changes that our planet is suffering and design friendly and sound mitigation strategies in the line of the Green Deal of the European Commission and the research program Horizon-Europe.

## 3. KEY CHALLENGING POINTS

To provide the necessary context to the Anthropocene first we need to improve our understanding of the **PROCESSES** controlling past global changes, focusing on those close to a tipping point or those that denote a gap of knowledge. One of the main challenges for the scientific community is to identify the dynamics involved in rapid and irreversible past environmental and climate changes and their impacts. To do that, we need to improve the **RECONSTRUCTION** of past global changes, with new and improved methods and proxies, with higher temporal and spatial resolution, with better quantification and calibration strategies and with a generalized use of statistical tools and databases resources. The third challenge is devoted to paleoclimate and paleoenvironmental **MODELLING**. Models need to span the simulations time intervals to the past, with improved and accurate representation of proxy-based forcing reconstructions and increasing computational resources. Modelling efforts should dedicate to incorporate all identified significant forcings (solar, volcanism, aerosol, anthropogenic), to ensure a meaningful advance in the understanding of processes and feedbacks while dedicating more efforts to model-data comparison.

### 3.1. Main processes involved in rapid climate and environmental changes

The goal is to identify and characterize the processes that cause past climate variability, discriminate their triggering mechanisms (drivers), understand feedbacks and thresholds and evaluate their impacts on different Earth systems in the past, considering the ecosystems resilience and the time needed to recover after an event. This research has to be directed to better understand processes of rapid climate and environmental change that are active and amplified (and or interacting with) anthropogenic impact on the planet.

#### *Oceans*

*The Ocean's meridional overturning circulation*

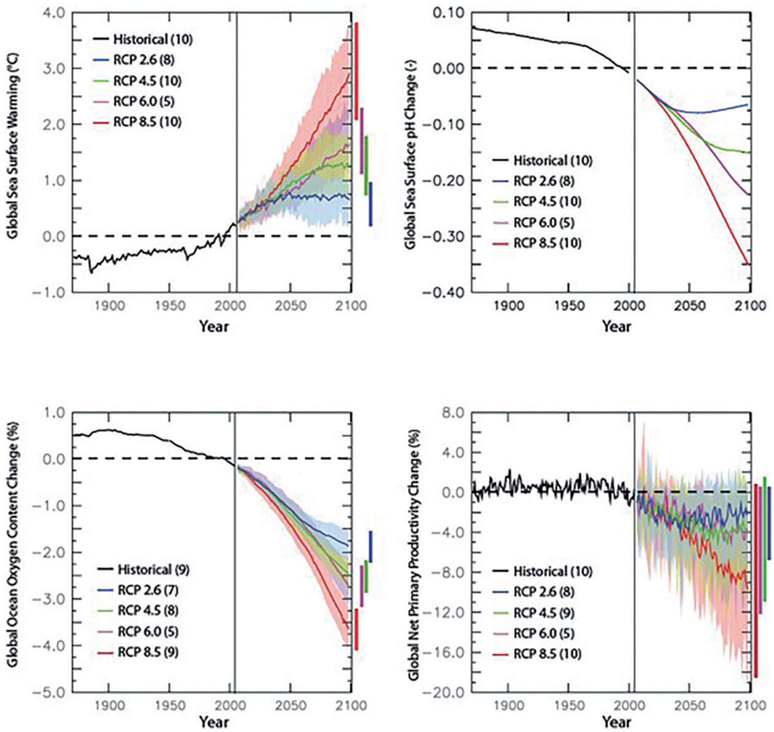
During the boreal winter months, sea winds and warm waters are directed towards the European margin from the subtropical regions to the pole. Cooling and sinking of surface waters at high North Atlantic latitudes play a vital role in the ventilation of the deep ocean and the modulation of regional climate, through the release of evaporative heat. The decrease or absence of deep water production in the North Atlantic (AMOC) caused strong cooling over Europe in the past: cold episodes taking place there when the predominance of deep-water formation changed from northern to southern sourced deep-waters, as traced by glacier ice and marine sediment cores (Martrat et al., 2007). Climate change scenarios point to a weakening of the transports (Heuzé et al., 2015); in fact, the Mediterranean has already experienced several intervals of circulation perturbations over the past five centuries (Incarbona et al., 2016). While in the absence of a strong AMOC reduction, for instance, the Arctic and Mediterranean regions are to warm two to three times the global annual average, an AMOC collapse could lead to a reduction in surface air temperatures of up to 10°C in the North Atlantic (Weijer et al., 2019). Key challenge goals to cover the gaps in our knowledge can be addressed by (i) studying the metrics that robustly show Atlantic and Southern Meridional (AMOC/SMOC) and Mediterranean circulations collapses with both data archives and among a wide range of models; (ii) distribution of a feasible long-term operational monitoring system and (iii) extrapolation by decadal prediction systems.

*Ocean stressors*

Oceans are being stressed as a result of human activities (marine pollution, overfishing, habitat destruction, eutrophication) with four major stressors (ocean warming, ocean acidification, ocean deoxygenation and changes in primary productivity) that impact on a global scale, threatening marine organisms, populations and ecosystems, and compromising the services that oceans provide to humanity (Figure 2). Their cumulative impact is expected to be amplified over the coming decades (Frölicher et al., 2016; Halpern et al., 2019), while different combinations may lead to synergistic impacts greater than the sum of their individual effects. There is an urgent need to explore and understand this new reality and to establish how to meet human needs in a sustainable and equitable way.

- **Ocean warming**: This is the global pressure that has concentrated most of the scientific attention since it is critically impacting a long list of ecosystems, being the tropical coral reefs the most iconic example, strongly damaged by the progressively intensified bleaching events. Ocean warming is heterogeneous and there is a need to further understand trends in the recent past, at high resolution, making use of sediment cores from high sedimentation rates regions and other archives such as corals.
- **Acidification:** Since the mid-2000s, research on this stressor has expanded exponentially, providing evidences on its detrimental effects over a wide range of marine organisms. The development of proxies for the reconstruction of past levels in pH, particularly boron isotopes and B/Ca ratios in calcifying organisms, allowed scientists to gain insight on short- and long-term variability of pH. The goal now is to exploit these proxies (i) in high resolution archives of the most recent past (deep sea

**FIGURE 2**–Ocean stressors (Bopp et al., 2013). Model-mean time series of global sea surface warming (ºC), surface pH change (pH unit), ocean $O_2$ content change (%),and global NPP change (%) over 1870–2100 using historical simulations as well as all RCP simulations. Shading indicates one inter-model standard deviation. All variables are plotted relative to 1990–1999.




sediments, tropical and cold water corals) to determine the modern acidification trend in the Anthropocene, and (ii) in older periods of time (i.e. glacial/interglacial timescales) to better constrain the changes in earth system processes accompanying the well-known variations in atmospheric $CO_2$.

- **Deoxygenation**: Ocean oxygen levels have been decreasing since 1950 Common Era (CE), impacting marine life and biogeochemical processes (Breitburg et al., 2018). Ocean deoxygenation is expanding the already vulnerable oxygen minimum zones and causing severe and adverse changes in marine ecosystems, both at global and local scale. In coastal areas and semi-enclosed seas, the delivery of nutrients from sewage, agriculture water discharges and airborne sources stimulate algal blooms which consume oxygen driving hypoxia. At the same time, climate warming intensifies the effects from eutrophication and reduces the air to sea oxygen flux and ventilation of the ocean interior. In order to further constrain the potential impact of the current deoxygenation, it is crucial to determine past changes in dissolved oxygen, for which quantitative proxies are still under development.

- **Primary productivity**: The combined and synergistic effects of the aforementioned major ocean stressors have an impact on primary production, which is crucial to sustaining the future ocean and the global carbon cycle. Projections of future trends in marine productivity present high uncertainties but the general view is that it will decrease globally on average (Bopp et al., 2013). It is essential now to contextualize past changes in marine production, from the analyses of high resolution sediment cores in productive areas (e.g. upwelling regions), but also including the characterisation of past changes in nutrient chemistry (i.e. phosphate, nitrogen, silicon, iron) and vertical mixing.

***The polar cryosphere***

Antarctic and Arctic ice sheets are the main planetary freshwater reservoirs (99%). Their ice sheet dynamics has a global impact on sea level rise, ocean structure and circulation, marine productivity, and atmospheric $CO_2$ sequestration and circulation patterns, among others. Detailed reconstructions based on ocean and lake sediment records have yielded evidence for the strong impact that abrupt and rapid climate changes have on sea level, ecosystems and surface processes. For example, ice sheet calving, has been shown to be extremely sensitive to temperature changes and can occur remarkably fast and affect extensive areas. This melting, together with the thermal expansion of the seawater due to temperature rise, will largely affect coastal infrastructures around the globe with disastrous economic consequences. Since 1880 CE, the sea level measurements show that it has already risen 21 - 24 cm. To decipher the mechanisms associated with abrupt melting and rapid climate changes in polar regions, this challenge targets are: 1) understanding the timing and the patterns of environmental variability associated with past abrupt climate changes in polar regions; 2) exploring global connections in the climate system and 3) identifying ice sheet calving threshold. To address these will require:

1) identification and validation of new proxies for meltwater input and icebergs calving reconstruction, 2) recovering of high resolution proximal records in polar margins, which remain really scarce, especially in the southern high-latitudes, and 3) characterization of past and present climate conditions and feedbacks that have ruled these calving periods.

### *Atmospheric aerosols*

Limiting global warming to 2.0°C as stated in the Paris agreement at COP21 in 2015 requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Alongside, emissions of anthropogenic aerosols will decline as a result of their co-emission with GHG and the improvement of air quality. To date, the combined climate effect of GHG and aerosol emissions is poorly constrained (Samset et al., 2018), but it is evidenced that removing aerosols will heat global mean surface by 0.5–1.1°C, and cause more extreme weather events. Recent mitigation policies have been effective in the removal of "cooling" aerosols such as sulphates and nitrates but inadequate in the elimination of warming ones such as black carbon (BC). The continuation over time of this scenario may amplify current warming, with other related-effects on ecosystem fertilization by nitrogen deposition, which promotes $CO_2$ removal from the atmosphere, thereby buffering human effects on global radiative forcing (Tipping et al., 2017). Improved characterization of natural emissions and their radiative effects can therefore increase the accuracy of global climate model projections.

It is well-known that feedbacks between the global dust cycle and the climate system might have amplified past climate changes. Bearing in mind that the projected climate changes may boost mineral dust emissions to the atmosphere, the sensitivity to past climate changes raises the question of how the global dust cycle will respond and of whether the resulting dust–climate feedback will oppose or enhance those climate changes. Unfortunately, uncertainties in net climate forcing from aerosols are substantially limiting our understanding of the magnitude of the historical radiative forcing due to anthropogenic aerosol emissions (Hamilton et al., 2018). Improvements in historical reconstructions of natural and early anthropogenic emissions are thus a demand. Key aspects to reduce uncertainties in future predictions are (i) the exploitation of new/improved Earth system models, (ii) a better understanding and evaluation of the controlling processes, and (iii) the study of past aerosol records stored in ice or sediments.

### *Extreme temperature and hydroclimatic events*

Extreme climate events such as heat waves, avalanches, cold, snow, ice, large hail, frost, severe winds, storms, heavy rain, fluvial or coastal flooding, droughts and wildfires are a reason for concern given their important physical, economic, social and political implications (Masson-Delmotte, 2019). Understanding the links between extreme occurrence and climate variability is critical to anticipate impacts and vulnerability for planning adaptation. Paleoclimate analysis has demonstrated how shifts in climate produce changes in the magnitude and frequency of extremes. The study of long-term records of past climate extremes provides a realistic understanding of how the present climate differs from past periods, to simulate extreme events under global warming scenarios. The main goals on the characterization of extreme events in the past are:

- Produce regional multiproxy reconstructions for detection of periods with higher concentration of extreme events by using sedimentary and biological archives (fluvial and lake sediments, glacier ice, speleothems, trees, etc) and documentary evidence (extreme temperatures (Barriopedro et al., 2011); floods (Blöschl et al., 2020); droughts (Cook et al., 2015)).
- Inclusion of palaeorecords tracing aerosol, pollution dispersal and soil loss to help in deciphering their role on extreme events, which is linked to processes as yet to be explored. Current datasets are limited to experimental monitoring stations that barely span the last two decades.
- Identification of atmospheric and oceanic climate modes of variability leading to extremes and characterization of their variability in the past (changes in ENSO / monsoonal systems, extreme negative phases of NAO, etc).
- Work on data assimilation with particular emphasis on regional reconstructions of extreme events during past analogues of warming and transient climate periods.
- Development of statistical tools to detect non-stationarity break points in proxy series, and for including climate covariates in frequency analysis.

It is especially relevant the investigation of compound events, i.e. multiple hazards that combine to produce increased risks and impacts. For example, the occurrence of drought combined with extreme heat will increase the risk of wildfires and consequent losses. A changing climate may alter the interaction between hazards which in turn could exceed the adaptive capacity or resilience of the human and natural systems more quickly than individual events.

***Biogeochemical cycles***

Increasing concern about human manipulation of global biogeochemical cycles requires a long-term approach using data available in paleorecords to assess (1) the nutrient status of aquatic and terrestrial systems, (2) their baseline conditions, and (3) the long-term processes controlling elemental fluxes on decadal to millennial timescales.

- **Carbon cycle**: Studies of land–ocean–atmosphere integration should be strengthened to include and quantify the processes that connect land carbon, inland waters, coastal oceans and open oceans on different time scales. The Holocene, when significant changes in the carbon cycle and temperature were recorded, is an interesting period to explore the mechanisms responsible for $pCO_2$ increase (e.g. land carbon storage, the role of the ocean acting as a source or sink) and their links to climate (Brovkin et al., 2019).
- **N, P and O cycles**. Currently there is a progressive eutrophication of lacustrine systems and coastal areas as a result of the anthropogenic oversupply of nutrients causing a productivity increase and a consequent oxygen consumption leading to hypoxia and denitrification. The use of paleorecords can help to discern what factors influence nutrient cycling in natural settings over decadal to millennial time periods and establish their environmental consequences and feedbacks. That investigation should be prioritized to evaluate the possible consequences of future perturbations and the available alternatives to mitigate them (McLauchlan et al., 2013).
- **Metals (Pb, Hg)**. Enhanced input of metal pollutants in the atmosphere is affecting ecosystem function and biodiversity in profound ways. In this respect, mercury is an emission by-product of the extensive burning of coal and crude oil and its increasing accumulation constitutes an environmental deleterious impact. Those metals were delivered in large amounts in the past millennia (mining and smelting activities), allowing to explore the environmental consequences by using sedimentary records preserved in remote systems not overprinted by local anthropogenic processes (Catalan et al., 2013). The main goals are: (1) determining changes in anthropogenic trace metal concentrations

contextualizing current values with pre-industrial levels, (2) discerning site-specific processes that influence their enrichments, (3) evaluating the impact of past pollutants on the biological communities (function, diversity) and on the natural geochemical processes (coastal area, lake, peatbog).

- **Organic contaminants**. Organic contaminants and wastes (eg. polycyclic aromatic hydrocarbons –PAH) are compounds primarily composed of carbon, hydrogen, and potentially other elements and are currently present in the soil, water, air, and sometimes food, resulting in harmful effects for human and environmental health (Pal et al., 2010). Paleoenvironmental records hold the potential to trace the presence of these compounds in the recent past and help to (1) establish the timing of contamination of previous pristine environments, (2) quantify the impact threshold above which there are harmful effects on the environment, and (3) understand the complexity of transport processes (e.g. volatile compounds) to finally contribute to future regulations.

***Interactions of past climate and human activities with vegetation***

Ecological and vegetation disturbance (overgrazing, agricultural pressure, deforestation, fire, expansion of invasive species, pests, diseases, deterioration caused by catastrophic storms, etc), mediated by both climate variability and human impact, is a major driver of ecosystem function, structure and composition. Vegetation changes take place over a long period and become evident gradually or abruptly, depending on the disturbance, and usually (not always) involve a reduction in biomass and changes in the structure and species composition (biodiversity). Some crises may also lead to an increase in biodiversity after the perturbation and during the adaptation to a new system. Ecosystems have been shaped by millennia of intense land use that makes difficult to distinguish the impacts of human disturbance and climatic change on past vegetation dynamics (Figure 3). Paleoecological reconstructions assess the natural dynamics of ecosystems and investigate how these systems respond to different drivers in different context. We outline here two of the main drivers affecting past vegetation changes:

- **Humankind**. Anthropogenic activities have been suggested as one of the major drivers of vegetation change in the Iberian Peninsula at least for the last 7500 years. In this sense, the improved linkage of archaeological and paleoecological records is essential to understand the timing and extent of alterations on natural vegetation during the past millennia.

**FIGURE 3–**Human-environment interactions in the past. Images corresponding to (A) fires, (B) agriculture (image of cattle herder from Egypt found in the Sennedjem tomb in Deir-el-Medina), (C) landscape of Roman mining (Las Médulas, León) and (D) rock painting of deer hunting in La Valltorta cave (Castellón).


- **Fire**. Fire acts both as a powerful filter of the species pool and as a strong driver of evolutionary selection. Most paleofire studies have reconstructed fire history and in certain cases fire regime. However, considering the regional variability on a spatial scale is necessary. The origin of fire is not always clear since it is both a natural element involved in Mediterranean regions and a process employed by ancient societies for agriculture and grazing maintenance systems.

Additionally, paleobotanical records provide abundant evidence for plant spread and migration together with indications for extinctions, exterminations and range shifts. The study of past forest change provides a necessary historical context for evaluating conservation policies. Analyses based on fossil and genetic data are necessary to advance our understanding of tree colonization, adaptation, and extinction, revealing cryptic refugia which potentially safeguard the persistence of biodiversity over centuries or millennia. The identification of those places should be a priority in restoration and conservation planning.

***Human societies and climate change interactions in the past.***
Climate change has been an important contributor to the development of human society throughout time. Because of current social development, it is very unlikely for climate change today to produce comparable impacts as those that occurred in the past. Nonetheless, tackling such historical cases can improve our understanding of the nature of human-climate-ecosystem interactions, as well as the vulnerability and sustainability of small-scale societies in the context of climate change, determining in some cases societal success or collapse.

However, causes and tempos of different social dynamics of change must be considered with caution. Models used to understand the collapse of state-level societies in tropical or arid environments, such as the Classic Maya or Akkadian states respectively, cannot be applied to terminal episodes in far less integrated societies in more temperate environments. Not only are regular cycles of socio-political changes and fragmentation intrinsic features in societies, but different ecosystems present varying degrees of vulnerability and different opportunities for adaptation and resilience of human populations. In fact, a complex landscape 'co-evolution' results for the interactions between climate, ecosystems and human activities through time, and there is clearly a need of collaboration between the historical-archaeological and the paleoenvironmental sciences to better understand these complex interactions (Figure 3) which, undoubtedly, also affect our current and future scenarios of global change.

## 3.2. Advances in proxies for past global changes

To understand and quantify processes in the past we need to advance on the methods and data processing, improving time resolution and space coverage of available records and developing new proxies able to detect rapid changes in the past environments. It is also crucial to dedicate more efforts to the creation and extended use of databases. Critical issues involving accuracy of the chronology, statistical treatment of the results and sensitivity and frequency in the proxy response to forcing mechanisms remain challenges for future investigations.

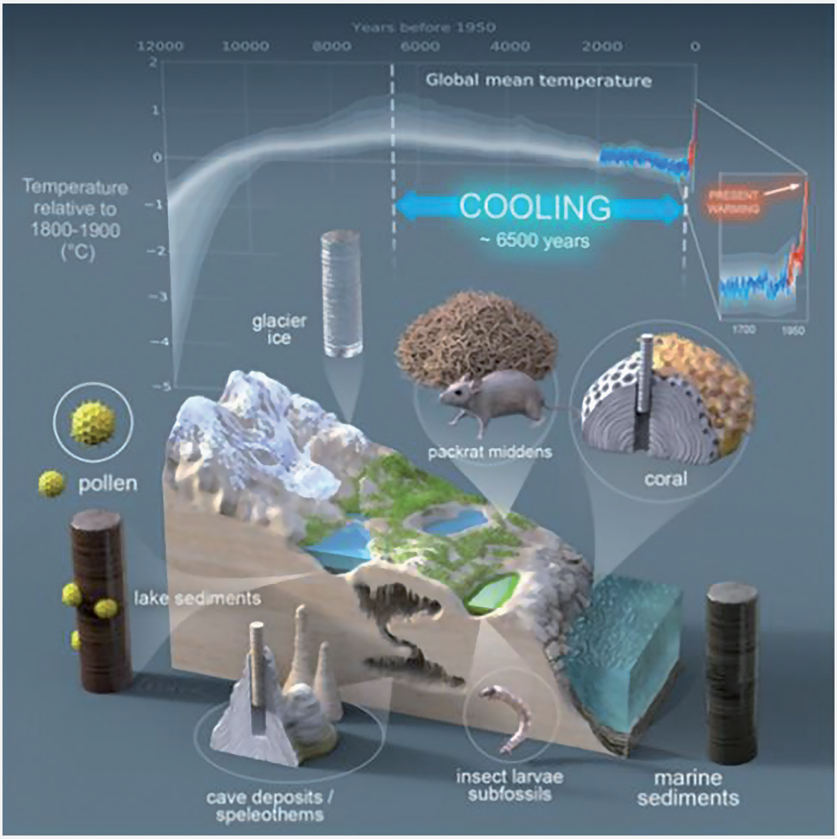
***Build and maintain open, up to date, interactive and modern metadatabases***
Database compilations help in understanding key climate variables and processes and are available for different paleoclimate archives (bivalve, borehole,

coral, documents, glacier ice, lake sediment, marine sediment, sclerosponge, speleothem, trees and many more) for global surface temperatures (PAGES2k Consortium et al., 2017), hydroclimate (Konecky et al., 2020) or modes of climate variability (Hernández et al., 2020). The increasingly amount of datasets needs synthesis efforts with clear pre-defined criteria to ensure quality control: (i) records have to be archived in a permanent publicly accessible data repository (examples in NOAA-WDS Paleoclimatology or PANGAEA); (ii) known relation between proxy value and climate or environmental parameter; (iii) minimum record duration over the time span of reference; (iv) quantifiable resolution, from seasonal to centennial; (v) chronological accuracy, i.e. number, position and uncertainties of control points. Open-data principles require to make all data used in modern paleoclimate databases **F**indable, **A**ccessible, **I**nteroperable and **R**eusable (**FAIR**; Wilkinson et al., 2016), whether referring to (1) data described in previous publications, including data-reanalysis products, and third-party unpublished data ("input data"), and/or (2) data generated as an outcome of the study ("output data"). In the Big Data age, analyzing large "paleo" data volumes critically hinges on clear standardized in format and terminology (Khider et al., 2019). This is one key challenge for natural (land, ocean) and documentary archives. Synthesis work and standards will allow researchers to curate and access datasets in online hubs while creating a common vocabulary for them, maximizing their reuse value, particularly for comparison to climate model simulations, a vital process to detect regional climate complexities.

### *Improving proxy resolution and spatial coverage*

Efforts to increase temporal and spatial resolution in paleorecords are necessary to encompass a better and robust understanding of processes, mechanisms, impacts and ecosystem to develop new scientific knowledge regarding current global climate. An important outcome of increasing time resolution in paleorecords is the ability to identify and characterize past extreme events (e.g. droughts, floods, heat waves, hurricanes, wildfires). Since extreme events have long periodicities, the instrumental period is too short to provide an adequate characterization and a robust risk assessment of their probability. High resolution paleoclimatology involves studies for past climate variations at a temporal scale that is comparable to that of instrumental data, which in practice, means annually resolved records. Some paleoarchives (Figure 4) store seasonal information *per se* (e. g. tree rings width as an indicator of summer temperatures) but usually a meticulous sampling is required to gain the full proxy potential and reach, in the best cases, annual signals.

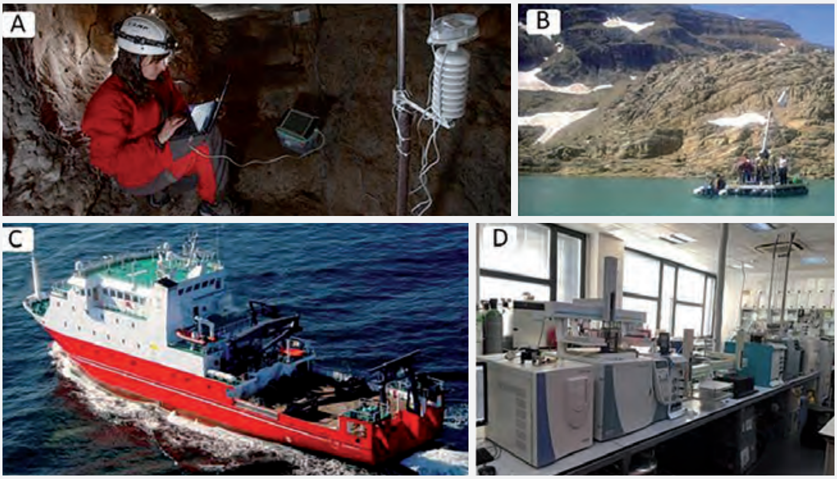
**FIGURE 4—**Past climate changes over the Holocene show that the Earth was warmest around 6500 years ago when global average temperature was likely about 0.7°C higher than during the 1800s. Global warming since then has reached about 1°C (Kaufman et al., 2020). This image also shows several archives of paleoclimate and paleoenvironmental information. Illustration by Victor O. Leshyk.




New analytical techniques (e.g. SIMS, LA-ICP-MS) offer many unexplored avenues of research in high resolution (e.g. continuous measurements, smaller sample amount requirements). The technological goal is to develop new methods to facilitate the continuous measurement of different variables obtaining robust and quantitative results.

The increasing recognition over the last few years of the necessity to understand the spatio-temporal evolution of climate trends, ecological impacts and extreme events has brought to light the still patchy coverage in available

**FIGURE 5—**Images of field and laboratory studies that we conduct in Paleoclimate and Paleoenvironmental sciences. (A) Cave monitoring in Las Güixas cave (Villanúa, Huesca); (B) coring Marbore Lake in the Pyrenees using a platform; (C) the oceanographic vessel Sarmiento de Gamboa (http://www.utm.csic.es) and (D) the stable isotope laboratory from the Instituto Andaluz de Ciencias de la Tierra (IACT-CSIC).




paleoreconstructions. Some remote regions remain less represented, such as large areas of the Pacific Ocean, Africa, the Amazon and Australia. Some of this poor representation is due to absence of sites (e.g. regions that have unsuitable climates to support ice sheets, trees, lakes or bogs), but at smaller scales there could be sampling biases related to the complex and expensive logistical infrastructure needed to properly sample these remote areas. One challenge to obtain complete representation of paleoclimate variations worldwide is to increase the spatial coverage focusing new studies in poorly represented regions.

***Development of new proxies and quality control of proxy reconstructions***

Reliable reconstructions of past climates require a well-suited battery of proxies capable of providing quantitative environmental information related to the physical, chemical and biological conditions of the past environment (Figure 5).

For a climate/environment proxy to be useful, we need to (i) improve the analytical measuring capabilities and (ii) understand the driving processes behind the analyzed proxy. The development in recent years of advanced and sophisticated analytical instruments with increased sensitivity and accuracy has opened up the possibility of measuring new and promising chemical tracers. On the other hand, the use of a multi-proxy approach (several tracers informing on the same variable) has proved to be very valuable to resolve discrepancies and/or inconsistencies among proxies, given that a single proxy is often affected by several processes or environmental conditions. The following goals have been identified:

- Explore the potential of new measurements now possible through the **development of techniques** capable of high accurate geochemical analyses, such as Multicollector-ICP-MS, and improve the precision capabilities of existing analytical methodologies that are now hampered by the relatively large amount of sample needed (e.g. boron and neodymium isotopes on marine sediments or carbonate clumped isotope thermometry on speleothems). Also, in the marine realm, several trace metal isotopes (e.g.: Fe, Zn, Cd, Mo, Ba…) are being tested as potential marine paleoproductivity and/or redox conditions proxies. The recently developed GC-MS Q Exactive Orbitrap systems provide high sensitivity and selectivity which greatly enhances the identification and quantification of sedimentary organic molecules in marine and freshwater ecosystems.
- Develop, and improve existing, **proxy-to-environment calibrations** in order to obtain meaningful and quantitative reconstructions of past climates. In this regard, some of the proxies where special effort is needed given the relevance of the reconstructed variable include: (i) Specific organic biomarkers preserved in speleothems and marine sediments as proxies for surrounding vegetation types, storms, desertification and bacterial activity, (ii) carbon isotopes and trace elements (I/Ca and U/Ca) in foraminifera, organic biomarkers and trace metal isotopes from marine sediments as proxies for dissolved oxygen and deep water ventilation, and (iii) proxies of marine export production, which include tracers of redox conditions, particle fluxes (barite and molecular biomarkers) and nutrient tracers.
- Adapt and develop new **statistical tools** to ensure the robust and quantitative reconstruction of climate variables from high-resolution and multi-proxy characterization of natural archives, encouraging a close collaboration between statisticians and paleoclimatologists. This challenge should focus on (i) developing new calibration methodologies by employing cutting-edge statistical tools such as machine learning and bayesian approaches, (ii) calculating and incorporating to the paleodata

all uncertainties associated to chronological models, and (iii) developing statistical tools to correctly assess the frequency behavior of unevenly-spaced temporal series.

### 3.3. Advances in modelling and model-data integration at different timescales

Earth System Models (ESM) represent the highest level in the hierarchy of complexity of coupled general circulation models (GCMs) (McGuffie and Henderson-Sellers, 2014). The last generations ESMs have evolved to represent realistically many of the climate processes to analyze sensitivity to changes and interactions between climate subsystems, ultimately being the key tool to estimate future climate (Masson-Delmotte, 2019). The complexity of ESMs has increased with the inclusion of a progressively larger number of GCM components and processes and with an increasing level of realism in representing them. This evolution and the needs for intensive simulation of the climate system at different timescales relies on the progressive increase in computing resources, better physical understanding of climate subsystems and their interactions and model-data comparison, thereby improving quantification of uncertainties and detecting unresolved processes or model biases.

***Model simulation of different time intervals in the past***

Extending the time interval of simulations to the past well beyond the instrumental period helps to analyze the response to major drivers and feedbacks for past climates outside the range of recent variability, thereby assessing the credibility of climate models used for future climate projections. Ultimately, it helps in disentangling long-term natural variability such as solar or volcanic, from anthropogenic influences i.e. greenhouse gases, land-use-land-cover and associated aerosols, among others. This implies a continuous need for extending the representation of proxy-based external forcing reconstructions as far back as possible (Jungclaus et al., 2017).

- The pre-industrial millennium (*past1000* transient simulations), from 850 CE to 1849 CE is used to investigate the response to (mainly) natural forcing under background conditions not too different from today, and to discriminate between forced and internally generated variability at interannual to centennial timescales. The most complete version of these simulations in terms of the mechanisms considered are the *all-forcing* simulations, incorporating an exhaustive set of natural and anthropogenic processes. Additionally, single forcing simulations are also considered to address the sensitivity to individual radiative forcing factors. Few models have produced a comprehensive set of experiments for both types of *all-* and *single-*forcing ensembles (e.g. and future simulation efforts expand on this line as computing capabilities increase) (Otto-Bliesner et al., 2015).

- Additionally, three more periods are currently targeted that are particularly relevant to provide a context for early human influences (the mid-Holocene, 6,000 years ago; the Last Glacial Maximum, 21,000 years ago and the Last Interglacial, 127,000 years ago). All these periods are considered in equilibrium simulations, keeping forcing values constant and representative of average conditions within the time interval considered. Future challenges will likely incorporate the production of long continuous ESM simulations within them (transient simulations; Otto-Bliesner et al., 2015) and eventually glacial-interglacial transitions, once computational resources and improved forcing representations allow for it.

***Advances in model physics***

Future simulation efforts will continue to allow for testing our understanding of the interplay between radiative forcing and atmospheric circulation as well as the connections among large-scale and regional climate changes giving rise to phenomena such as polar amplification or monsoon responses. Paleoclimate Modelling Intercomparison Project (PMIP) ESM experiments will be more and more complemented by sensitivity experiments that allow for improving our understanding and quantification of the strength of atmosphere, ocean, cryosphere, and land-surface feedbacks, thus highlighting the role of specific PMIP efforts dealing with model physics and forcing changes, like the Ice Sheet, Couple Climate and Carbon Cycle, or the Aerosol and Chemistry MIPs (Eyring et al., 2016):

- Dynamic vegetation and biogeochemical cycle modelling. Models will have to account for the biogeophysical and chemical influences of land-use and land-cover changes, including more realistic subsurface thermodynamics as well as interactions between subsurface thermodynamics and hydrology of relevance for permafrost and carbon pools (Bonan and Doney, 2018; Melo-Aguilar et al., 2018).

- Understanding aerosol-cloud feedbacks. The current generation of models have to deal with uncertainties in the simulation of the aerosol direct and indirect effects, which produce diverse impacts on the spread of climate sensitivity (Meehl et al., 2020) by modulating the radiative transfer of energy, distributing precipitation and influencing tropical and extratropical circulations. Future model challenges include better knowledge of the role of convection and convective aggregation in cloud feedback, together with sources for the variability of storm tracks and tropical rain belts (Bony et al., 2015).
- Troposphere-stratosphere two-way coupling: Interactions between atmospheric variability, dynamics and climate change represent challenges (Gerber and Manzini, 2016) that address (i) how dynamics contribute to model biases in atmospheric mean state and variability, (ii) what the role of dynamics and the transport of momentum and energy in shaping the climate response to anthropogenic drivers and related uncertainties is, and (iii) how does the stratosphere affect climate variability at intra-seasonal, inter-annual and decadal timescales.

Other issues include a better understanding of the rate of deep ocean energy storage and the connections with modes of internal climate variabilities or the accurate simulation of storm track climatology and variability. Ultimately, future large increments in High Performance Computing resources will allow for boosting model resolution reaching explicit representation of essential processes, avoiding parameterizations of convection and cloud formation and leading to reduction of regional biases (Palmer and Stevens, 2019).

***Advances in model-data integration and comparison***

Paleoclimate model-data comparison offers powerful tools to test hypotheses about past climates, quantify the limits of knowledge, and design the next generation of modelling and reconstruction efforts (Braconnot et al., 2012). Techniques for comparing and combining numerical models and data (including data assimilation) include metrics for comparison and uncertainty quantification of both climate reconstructions and simulations. Analyses focus on key paleoenvironmental questions including but not limited to assessing climate sensitivity and characterizing internal climate variability, large-scale dynamics and extremes (Fernández-Donado et al., 2013; Luterbacher et al., 2016; PAGES2k Consortium et al., 2017). Analyses span a wide range of proxy systems and time scales and are burdened by uncertainties in both sources of information and the fact that both approaches target conceptually different representation of reality: while climate reconstructions aim to capture the precise evolution of a climate variable in the past, simulations provide estimates that are consistent with the physical equations and with the imposed initial and boundary (forcing) conditions. Therefore comparison approaches must adapt to the specific climate parameter considered and the nature of the proxy information used as observational information. Model-data comparison will benefit from the availability of wider simulation ensembles of a larger time span as discussed in 3.1, as well as from improvements in reconstruction techniques and in their quantification of uncertainties. This will lead to more detection-attribution exercises through which external forcing and specifically human-induced changes can be discerned from natural variability (Hegerl et al., 2011), as well as improved understanding on the role of internal variability and natural forcing on extreme periods that had an impact on society and the demise of civilizations in the past (Steiger et al., 2019). Also, expected progress in the near future incorporates more data-assimilation exercises blending proxy data and model work to nudge model simulations to the observed evolution in proxy data, thus addressing an accurate representation of past internal variability in the targeted parameters and timescales (Bothe and Zorita, 2020).

A complementary approach to model-data comparison is the generation of simulated surrogates for proxy data using forward models applied to climate model output, thus simulating directly proxy variables suitable for comparison instead of climate variables. The development of such specific modelling using offline forward models can produce a more accurate characterization of the evolution of specific subsystems in the past, with applications also in future climate change scenario simulations. Some examples are ice sheet modelling, tree growth, water isotope-based proxies or subsurface temperatures (Melo-Aguilar et al., 2020).

## CHALLENGE 1 REFERENCES

**Abram, N.J., McGregor, H.V., Tierney, J.E., et al. (2016).** Early onset of industrial-era warming across the oceans and continents. Nature 536: 411–418. https://doi.org/10.1038/nature19082

**Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M., García-Herrera, R. (2011).** The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. Science 332: 220– 224. https://doi.org/10.1126/science.1201224

**Blöschl, G., Kiss, A., Viglione, A., et al. (2020).** Current European flood-rich period exceptional compared with past 500 years. Nature 583: 560–566. https://doi.org/10.1038/s41586-020-2478-3

**Bonan, G.B., Doney, S.C. (2018).** Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. Science 359. https://doi.org/10.1126/science.aam8328

**Bony, S., Stevens, B., Frierson, D.M.W., et al. (2015).** Clouds, circulation and climate sensitivity. Nature Geoscience 8: 261–268. https://doi.org/10.1038/ngeo2398

**Bopp, L., Resplandy, L., Orr, J.C. et al (2013).** Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10: 6225–6245. https://doi.org/10.5194/bg-10-6225-2013

**Bothe, O., Zorita, E. (2020).** Technical Note: The analogue method for millennial-scale, spatiotemporal climate reconstructions. Climate of the Past Discussions: 1–45. https://doi.org/10.5194/cp-2019-170

**Braconnot, P., Harrison, S.P., Kageyama, et al. (2012).** Evaluation of climate models using palaeoclimatic data. Nature Climate Change 2: 417–424. https://doi.org/10.1038/nclimate1456

**Breitburg, D., Levin, L.A., Oschlies, A. et al (2018).** Declining oxygen in the global ocean and coastal waters. Science 359. https://doi.org/10.1126/science.aam7240

**Brovkin, V., Lorenz, S., Raddatz, T. et al. (2019).** What was the source of the atmospheric $CO_2$ increase during the Holocene? Biogeosciences 16: 2543–2555. https://doi.org/10.5194/bg-16-2543-2019

**Carrión, J.S., Fuentes, N., González-Sampériz, P. et al. (2007).** Holocene environmental change in a montane region of southern Europe with a long history of human settlement. Quaternary Science Reviews 26: 1455–1475.

**Catalan, J., Pla-Rabés, S., Wolfe, A.P. et al. (2013).** Global change revealed by palaeolimnological records from remote lakes: a review. J Paleolimnol 49: 513–535. https://doi.org/10.1007/s10933-013-9681-2

**Cook, E.R., Seager, R., Kushnir, Y. et al. (2015).** Old World megadroughts and pluvials during the Common Era. Science Advances 1: e1500561. https://doi.org/10.1126/sciadv.1500561

**Eyring, V., Bony, S., Meehl, G.A. et al. (2016).** Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development 9: 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

**Fernández-Donado, L., González-Rouco, J.F., Raible, C.C. et al. (2013).** Large-scale temperature response to external forcing in simulations and reconstructions of the last millennium. Climate of the Past 9: 393–421. https://doi.org/10.5194/cp-9-393- 2013

**Frölicher, T.L., Rodgers, K.B., Stock, C.A., Cheung, W.W.L. (2016).** Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. Global Biogeochemical Cycles 30, 1224–1243. https://doi.org/10.1002/2015GB005338

**Gerber, E.P., Manzini, E. (2016).** The Dynamics and Variability Model Intercomparison Project (DynVarMIP) for CMIP6: assessing the stratosphere–troposphere system. Geoscientific Model Development 9: 3413–3425. https://doi.org/10.5194/gmd-9-3413-2016

**González-Sampériz, P., Utrilla, P., Mazo, C. et al. (2009).** Patterns of human occupation during the Early Holocene in the Central Ebro Basin (NE Spain) in response to the 8.2 ka climatic event. Quaternary Research 71: 121–132.

**Halpern, B.S., Frazier, M., Afflerbach, J. et al. (2019).** Recent pace of change in human impact on the world's ocean. Scientific Reports 9: 11609. https://doi.org/10.1038/s41598-019-47201-9

**Hamilton, D.S., Hantson, S., Scott, C.E. et al. (2018).** Reassessment of pre-industrial fire emissions strongly affects anthropogenic aerosol forcing. Nature Communications 9: 3182. https://doi.org/10.1038/s41467-018-05592-9

**Hegerl, G., Luterbacher, J., González-Rouco, F. et al. (2011).** Influence of human and natural forcing on European seasonal temperatures. Nature Geoscience 4: 99–103. https://doi.org/10.1038/ngeo1057

**Hernández, A., Martin-Puertas, C., Moffa-Sánchez, P. et al. (2020).** Modes of climate variability: Synthesis and review of proxy-based reconstructions through the Holocene. Earth-Science Reviews 103286. https://doi.org/10.1016/j.earscirev.2020.103286

**Heuzé, C., Heywood, K.J., Stevens, D.P., Ridley, J.K. (2015).** Changes in Global Ocean Bottom Properties and Volume Transports in CMIP5 Models under Climate Change Scenarios. J. Climate 28: 2917–2944. https://doi.org/10.1175/JCLI-D-14-00381.1

**Incarbona, A., Martrat, B., Mortyn, P.G. et al. (2016).** Mediterranean circulation perturbations over the last five centuries: Relevance to past Eastern Mediterranean Transient-type events. Sci Rep 6. https://doi.org/10.1038/srep29623

**Jungclaus, J.H., Bard, E., Baroni, M. et al. (2017).** The PMIP4 contribution to CMIP6 – Part 3: The last millennium, scientific objective, and experimental design for the PMIP4 *past1000* simulations. Geoscientific Model Development 10: 4005–4033. https://doi.org/10.5194/gmd-10-4005-2017

**Kaufman, D., McKay, N., Routson, C. et al. (2020).** A global database of Holocene paleotemperature records. Scientific Data 7: 115. https://doi.org/10.1038/s41597-020- 0445-3

**Khider, D., Emile-Geay, J., McKay, N.P. et al. (2019).** PaCTS 1.0: A Crowdsourced Reporting Standard for Paleoclimate Data. Paleoceanography and Paleoclimatology 34: 1570–1596. https://doi.org/10.1029/2019PA003632

**Konecky, B.L., McKay, N.P., Churakova (Sidorova), O.V., et al. (2020).** The Iso2k Database: A global compilation of paleo-δ18O and δ2H records to aid understanding of Common Era climate. Earth System Science Data Discussions: 1–49. https://doi.org/10.5194/essd-2020-5

**Luterbacher, J., Werner, J.P., Smerdon, J.E. et al. (2016).** European summer temperatures since Roman times. Environ. Res. Lett. 11: 024001. https://doi.org/10.1088/1748-9326/11/2/024001

**Martrat, B., Grimalt, J.O., Shackleton, N.J. (2007).** Four Climate Cycles of Recurring Deep and Surface Water Destabilizations on the Iberian Margin. Science 317: 502–507. https://doi.org/10.1126/science.1139994

**Masson-Delmotte, V. (2019).** Global Warming of 1.5°C. IPCC.

**McGuffie, K., Henderson-Sellers, A. (2014).** The Climate Modelling Primer. John Wiley & Sons.

**McLauchlan, K.K., Williams, J.J., Craine, J.M., Jeffers, E.S. (2013).** Changes in global nitrogen cycling during the Holocene epoch. Nature 495: 352–355. https://doi.org/10.1038/nature11916

**Meehl, G.A., Senior, C.A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R.J., Taylor, K.E., Schlund, M. (2020).** Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. Science Advances 6, eaba1981. https://doi.org/10.1126/sciadv.aba1981

**Melo-Aguilar, C., González-Rouco, J.F., García-Bustamante, E., Navarro-Montesinos, J., Steinert, N. (2018).** Influence of radiative forcing factors on ground–air temperature coupling during the last millennium: implications for borehole climatology. Climate of the Past 14: 1583–1606. https://doi.org/10.5194/cp-14-1583-2018

**Melo-Aguilar, C., González-Rouco, J.F., García-Bustamante, E., Steinert, N., Jungclaus, J.H., Navarro, J., Roldán-Gómez, P.J. (2020).** Methodological and physical biases in global to subcontinental borehole temperature reconstructions: an assessment from a pseudo-proxy perspective. Climate of the Past 16, 453–474. https://doi.org/10.5194/cp-16-453-2020

**Otto-Bliesner, B.L., Brady, E.C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., Rosenbloom, N., Mai, A., Strand, G. (2015).** Climate Variability and Change since 850 CE: An Ensemble Approach with the Community Earth System Model. Bull. Amer. Meteor. Soc. 97: 735–754. https://doi.org/10.1175/BAMS-D-14-00233.1

**PAGES2k Consortium, Emile-Geay, J., McKay, N.P., Kaufman, D.S., Gunten, L. von, Wang, J., Anchukaitis, K.J., Abram, N.J., Addison, J.A., Curran, M.A.J., Evans, M.N., Henley,B.J., Hao, Z., Martrat, B., McGregor, H.V., Neukom, R., Pederson, G.T., Stenni, B.,Thirumalai, K., Werner, J.P., Xu, C., Divine, D.V., Dixon, B.C., Gergis, J., Mundo, I.A.,Nakatsuka, T., Phipps, S.J., Routson, C.C., Steig, E.J., Tierney, J.E., Tyler, J.J., Allen,K.J., Bertler, N.A.N., Björklund, J., Chase, B.M., Chen, M.-T., Cook, E., Jong, R. de,DeLong, K.L., Dixon, D.A., Ekaykin, A.A., Ersek, V., Filipsson, H.L., Francus, P., Freund, M.B., Frezzotti, M., Gaire, N.P., Gajewski, K., Ge, Q., Goosse, H., Gornostaeva, A., Grosjean, M., Horiuchi, K., Hormes, A., Husum, K., Isaksson, E., Kandasamy, S., Kawamura, K., Kilbourne, K.H., Koç, N., Leduc, G., Linderholm, H.W., Lorrey, A.M., Mikhalenko, V., Mortyn, P.G., Motoyama, H., Moy, A.D., Mulvaney, R., Munz, P.M.,Nash, D.J., Oerter, H., Opel, T., Orsi, A.J., Ovchinnikov, D.V., Porter, T.J., Roop, H.A., Saenger, C., Sano, M., Sauchyn, D., Saunders, K.M., Seidenkrantz, M.-S., Severi, M., Shao, X., Sicre, M.-A., Sigl, M., Sinclair, K., George, S.S., Jacques, J.-M.S., Thamban,M., Thapa, U.K., Thomas, E.R., Turney, C., Uemura, R., Viau, A.E., Vladimirova, D.O., Wahl, E.R., White, J.W.C., Yu, Z., Zinke, J. (2017).** A global multiproxy database for temperature reconstructions of the Common Era. Scientific Data 4, sdata201788. https://doi.org/10.1038/sdata.2017.88

**Pal, A., Gin, K.Y.-H., Lin, A.Y.-C., Reinhard, M. (2010).** Impacts of emerging organic contaminants on freshwater resources: Review of recent occurrences, sources, fate and effects. Science of The Total Environment 408: 6062–6069. https://doi.org/10.1016/j.scitotenv.2010.09.026

**Palmer, T., Stevens, B. (2019).** The scientific challenge of understanding and estimating climate change. PNAS 116: 24390–24395. https://doi.org/10.1073/pnas.1906691116

**Rockström, J., Steffen, W., Noone, K., Persson, \AA., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., et al. (2009).** A safe operating space for humanity. Nature 461: 472–475.

**Rull, V. (2018).** El Antropoceno, ¿Qué sabemos de...? CSIC, Madrid.

**Samset, B.H., Sand, M., Smith, C.J., Bauer, S.E., Forster, P.M., Fuglestvedt, J.S., Osprey, S., Schleussner, C.-F. (2018).** Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. Geophysical Research Letters 45, 1020–1029. https://doi.org/10.1002/2017GL076079

**Steiger, N.J., Smerdon, J.E., Cook, B.I., Seager, R., Williams, A.P., Cook, E.R. (2019).** Oceanic and radiative forcing of medieval megadroughts in the American Southwest. Science Advances 5, eaax0087. https://doi.org/10.1126/sciadv.aax0087

**Taylor, K.E., Stouffer, R.J., Meehl, G.A. (2012).** An Overview of CMIP5 and the Experiment Design. Bull. Amer. Meteor. Soc. 93: 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

**Tipping, E., Davies, J. a. C., Henrys, P.A., Kirk, G.J.D., Lilly, A., Dragosits, U., Carnell, E.J., Dore, A.J., Sutton, M.A., Tomlinson, S.J. (2017).** Long-term increases in soil carbon due to ecosystem fertilization by atmospheric nitrogen deposition demonstrated by regional-scale modelling and observations. Scientific Reports 7: 1890. https://doi.org/10.1038/s41598-017-02002-w

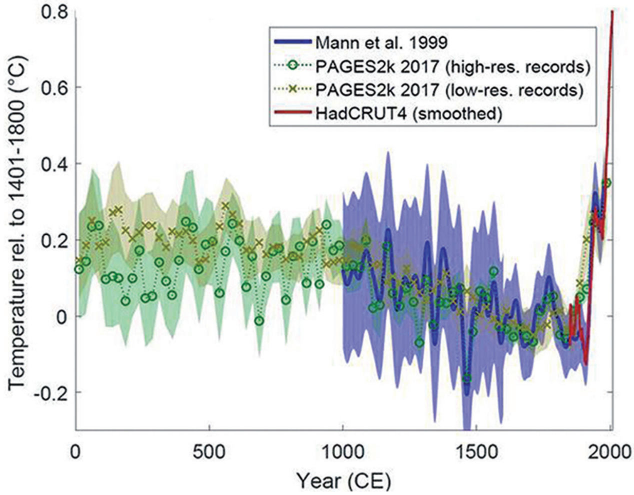
**Weijer, W., Cheng, W., Drijfhout, S.S., Fedorov, A.V., Hu, A., Jackson, L.C., Liu, W., McDonagh, E.L., Mecking, J.V., Zhang, J. (2019).** Stability of the Atlantic Meridional Overturning Circulation: A Review and Synthesis. Journal of Geophysical Research: Oceans 124, 5336–5375. https://doi.org/10.1029/2019JC015083

**Wilkinson, M.D., Dumontier, M., Aalbersberg, Ij.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R.,Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 'tHoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B. (2016).** The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3: 160018. https://doi.org/10.1038/sdata.2016.18

**Zalasiewicz, J., Waters, C.N., Head, M.J., Poirier, C., Summerhayes, C.P., Leinfelder, R., Grinevald, J., Steffen, W., Syvitski, J., Haff, P., McNeill, J.R., Wagreich, M., Fairchild, I.J., Richter, D.D., Vidas, D., Williams, M., Barnosky, A.D., Cearreta, A. (2019).** A formal Anthropocene is compatible with but distinct from its diachronous anthropogenic counterparts: a response to W.F. Ruddiman's 'three flaws in defining a formal Anthropocene': Progress in Physical Geography: Earth and Environment. https://doi.org/10.1177/0309133319832607

## ACADEMIC SLIDE

### Past Global Changes: a context to the Anthropocene

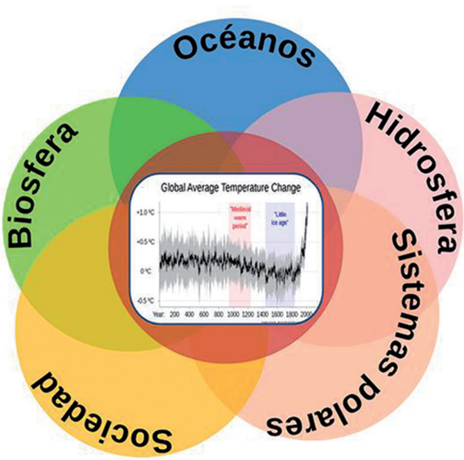



Reconstruction of past temperature variations for last 2000 years based on different natural archives such as ice cores, lake and marine sediments, speleothems, corals, tree-rings and pollen records

Emile-Geay et al., (2017)

## DISSEMINATION SLIDE

### Cambios Globales Pasados: un contexto para el Antropoceno




- Los cambios globales de los últimos 2000 se han debido a la interacción entre forzamientos naturales y antrópicos.
- Caracterizar los cambios globales de los últimos 2000 años.
- Definir sus impactos en la sociedad, hidrología, océanos, sistemas polares y biosfera.
- Modelizar los cambios globales del pasado para separar los mecanismos de forzamiento.