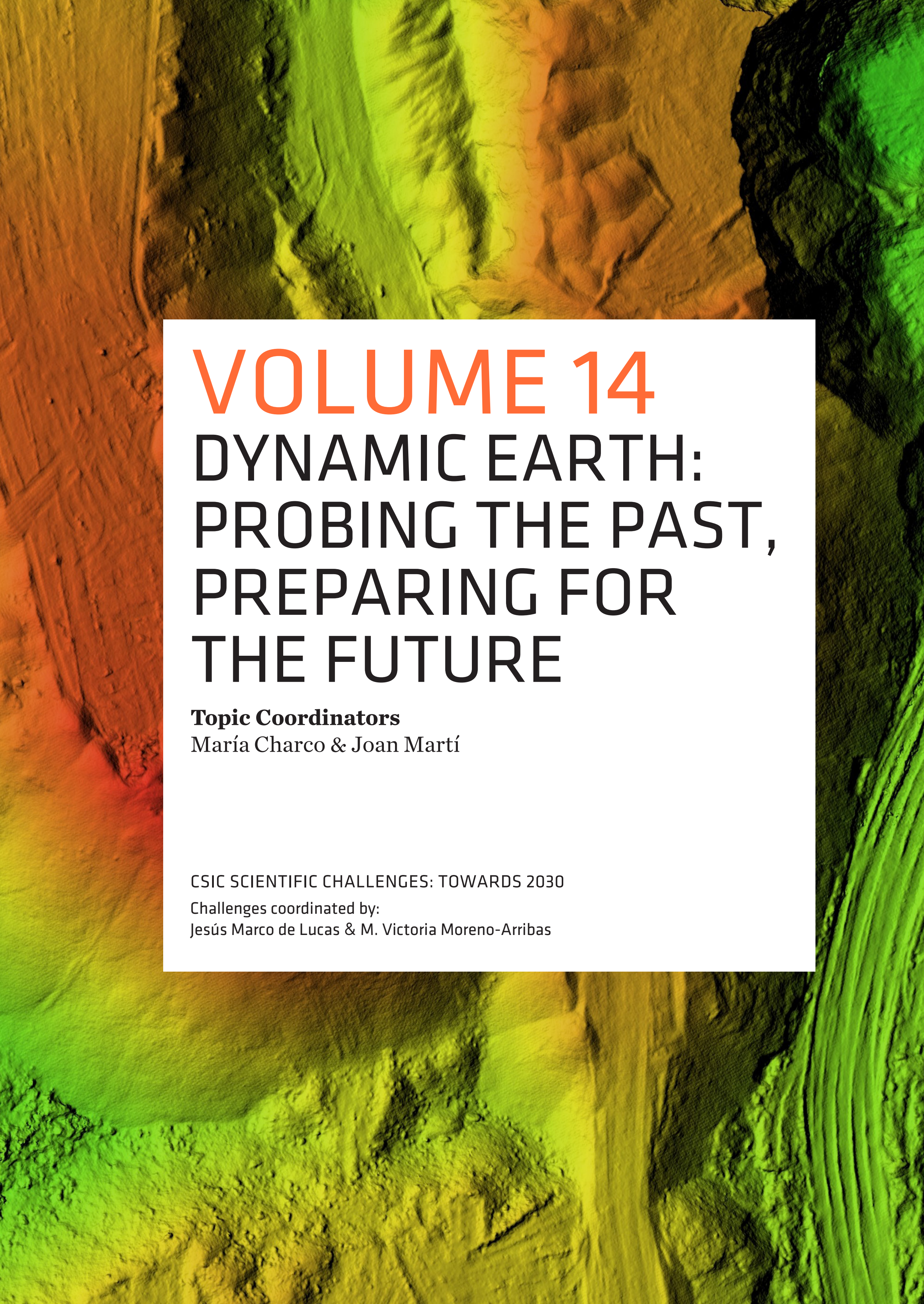


VOLUME 14

DYNAMIC EARTH: PROBING THE PAST, PREPARING FOR THE FUTURE

Topic Coordinators
María Charco & Joan Martí

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

VOLUME 14

DYNAMIC EARTH: PROBING THE PAST, PREPARING FOR THE FUTURE

Reservados todos los derechos por la legislación en materia de propiedad intelectual. Ni la totalidad ni parte de este libro, incluido el diseño de la cubierta, puede reproducirse, almacenarse o transmitirse en manera alguna por medio ya sea electrónico, químico, óptico, informático, de grabación o de fotocopia, sin permiso previo por escrito de la editorial.

Las noticias, los asertos y las opiniones contenidos en esta obra son de la exclusiva responsabilidad del autor o autores. La editorial, por su parte, solo se hace responsable del interés científico de sus publicaciones.

Catálogo de publicaciones de la Administración General del Estado:
https://cpage.mpr.gob.es

Editorial CSIC:
http://editorial.csic.es (correo: *publ@csic.es*)

GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA E INNOVACIÓN · CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS · EDITORIAL CSIC

© CSIC
© de cada texto, sus autores
© de las ilustraciones, las fuentes mencionadas

ISBN Vol. 14: 978-84-00-10764-2
ISBN O.C.: 978-84-00-10736-9
e-ISBN Vol. 14: 978-84-00-10765-9
e-ISBN O.C.: 978-84-00-10734-5
NIPO: 833-21-165-6
e-NIPO: 833-21-166-1
DL: M-2426-2021

Diseño y maquetación: gráfica futura

VOLUME 14
DYNAMIC EARTH: PROBING THE PAST, PREPARING FOR THE FUTURE

Topic Coordinators
María Charco & Joan Martí

Copia gratuita / Personal free copy http://libros.csic.es

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

What are the major scientific challenges of the first half of the 21st century? Can we establish the priorities for the future? How should the scientific community tackle them?

This book presents the reflections of the Spanish National Research Council (CSIC) on 14 strategic themes established on the basis of their scientific impact and social importance.

Fundamental questions are addressed, including the origin of life, the exploration of the universe, artificial intelligence, the development of clean, safe and efficient energy or the understanding of brain function. The document identifies complex challenges in areas such as health and social sciences and the selected strategic themes cover both basic issues and potential applications of knowledge. Nearly 1,100 researchers from more than 100 CSIC centres and other institutions (public research organisations, universities, etc.) have participated in this analysis. All agree on the need for a multidisciplinary approach and the promotion of collaborative research to enable the implementation of ambitious projects focused on specific topics.

These 14 "White Papers", designed to serve as a frame of reference for the development of the institution's scientific strategy, will provide an insight into the research currently being accomplished at the CSIC, and at the same time, build a global vision of what will be the key scientific challenges over the next decade.

VOLUMES THAT MAKE UP THE WORK

1. *New Foundations for a Sustainable Global Society*
2. *Origins, (Co)Evolution, Diversity and Synthesis of Life*
3. *Genome & Epigenetics*
4. *Challenges in Biomedicine and Health*
5. *Brain, Mind & Behaviour*
6. *Sustainable Primary Production*
7. *Global Change Impacts*
8. *Clean, Safe and Efficient Energy*
9. *Understanding the Basic Components of the Universe, its Structure and Evolution*
10. *Digital and Complex Information*
11. *Artificial Intelligence, Robotics and Data Science*
12. *Our Future? Space, Colonization and Exploration*
13. *Ocean Science Challenges for 2030*
14. *Dynamic Earth: Probing the Past, Preparing for the Future*

© CSIC © del autor o autores / Todos los derechos reservados

CSIC scientific challenges: towards 2030
Challenges coordinated by:
Jesus Marco de Lucas & M. Victoria Moreno-Arribas

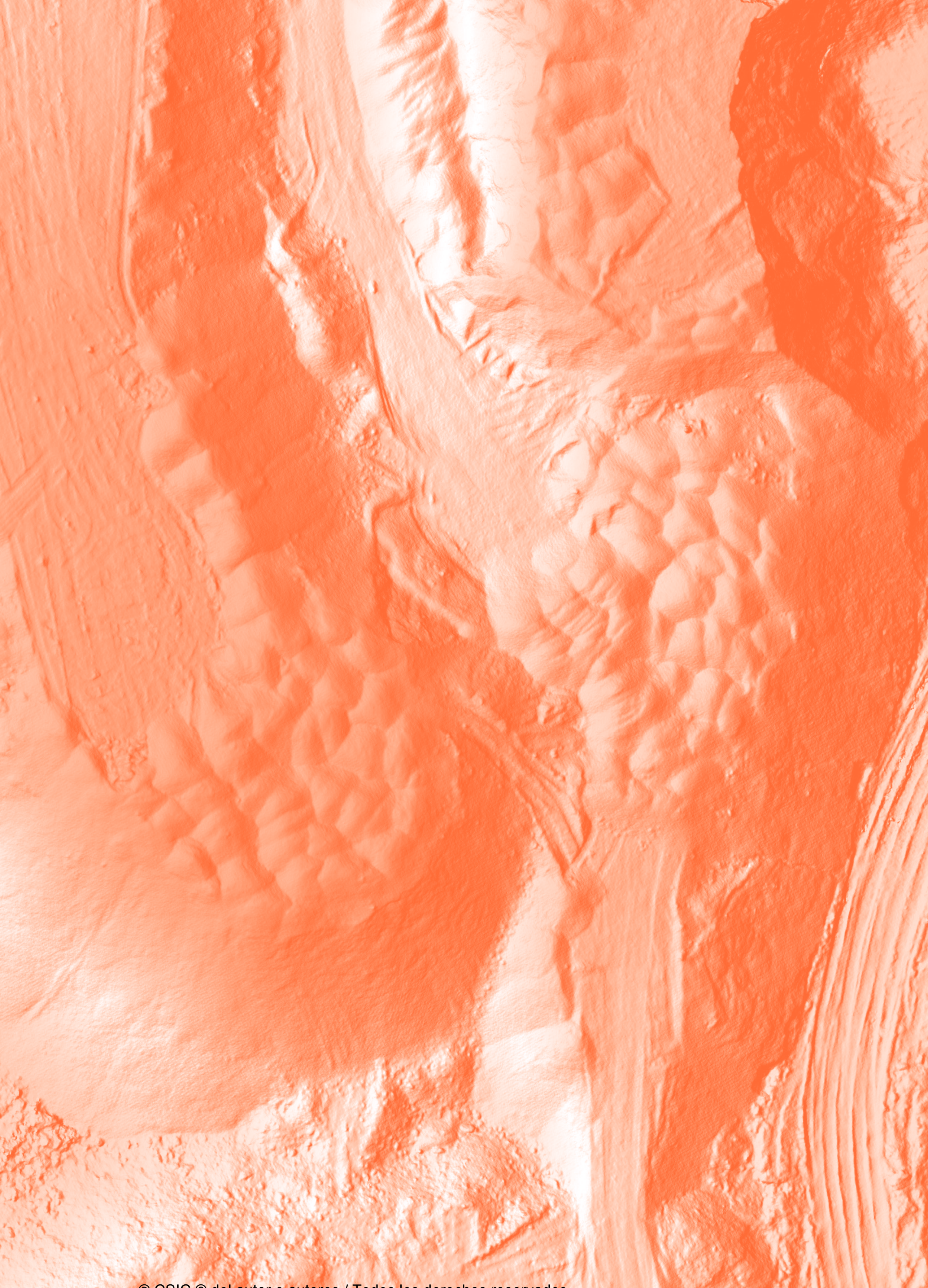
Volume 14
Dynamic Earth: Probing the Past, Assessing the Present, Preparing for the Future

Challenges Coordinators:
María Charco (IGEO, CSIC – UCM) And Joan Martí (GEO3BCN, CSIC)

Chapters Coordinators:
Challenges Coordinators:
Challenge 1: Carlos J. Garrido (IACT, CSIC - UGR), Pablo J. González (IPNA, CSIC); Challenge 2: Fernando Tornos (IGEO, CSIC), Ramon Carbonell (GEO3BCN, CSIC); Challenge 3: Adelina Geyer (GEO3BCN, CSIC), Mariano García (MNCN, CSIC); Challenge 4: Ana Moreno (IPE, CSIC) Santiago Giralt (GEO3BCN, CSIC); Challenge 5: Mar Viana, Francesc Gallart, (IDAEA, CSIC); Challenge 6: María Gema Llorens, Daniel García-Castellanos (GEO3BCN, CSIC); Challenge 7: Javier García Guinea (MNCN, CSIC), Joan Martí (GEO3BCN, CSIC)

Researchers & Centers::
José Javier Álvaro Blasco (IGEO, CSIC-UCM)
Mónica Álvarez de Buergo (IGEO, CSIC-UCM)
Joaquina Álvarez Marrón (GEO3BCN, CSIC)
Concepción Ayala Galán (GEO3BCN, CSIC)
Ricardo Amils (CAB, CSIC)
Dennis Brown (GEO3BCN, CSIC)
Antonio Castro Dorado (IGEO, CSIC)
Joaquín Ceballos Cáceres (IMSE-CNM, CSIC)
José M. Cebriá Gómez (IGEO, CSIC-UCM)
Antonio Delgado Huertas (IACT, CSIC - UGR)
José Fernández Torrres (IGEO, CSIC - UCM)
Rafael Fort González (IGEO, CSIC)
Penélope González-Sampériz (IPE, CSIC)
Javier Huertas Puerta (IACT, CSIC - UGR)
Alberto Jiménez Díaz (URJC)
Francisco Jiménez Espejo (IACT, CSIC - UGR)
José López Gómez (IGEO, CSIC-UCM)
Teresa Moreno (IDAEA, CSIC)
Ana Negredo Moreno (IGEO, CSIC-UCM)
Jens Olof Ormö (CAB, CSIC)
Olga Prieto Ballesteros (CAB, CSIC)
Xavier Querol (IDAEA, CSIC)
Cesar Rodrígez Ranero (ICM, CSIC)
Martin Schimmel (GEO3BCN, CSIC)
Valentí Sellarés (ICM, CSIC)
Josep Maria Soler (IDAEA, CSIC)
Josep Trigo Rodríguez (ICE, CSIC)
Blas Valero Garcés (IPE, CSIC)

Copia gratuita / Personal free copy http://libros.csic.es



© CSIC © del autor o autores / Todos los derechos reservados

CONTENIDO

Copia gratuita / Personal free copy http://libros.csic.es

Copia gratuita / Personal free copy http://libros.csic.es

CHAPTER 4

ABSTRACT

Humankind is facing unprecedented climate and environmental crises with economic and social consequences that may compromise our development. Therefore, to design science-based policies for our fair and sustainable development we need to consider the long-term, natural evolution of Earth ecosystems and biogeochemical cycles. Characterizing the temporal context for environmental changes is necessary to understand the impacts at a planetary scale of the current climate change and increased human pressure. The concept of "safe planetary boundaries" for humankind development critically frames the drivers, dynamics and challenges, like the present global warming, the biodiversity crisis, and the alteration of geochemical cycles that are currently affecting us. However, the definition of boundaries for our "safe" development and the "natural" Planet dynamics can only be properly carried out if a larger temporal scale than the last few decades when instrumental records are available is taken into account. The three objectives in this challenge are related to understand i) the short and long-term climate variability, the dynamics of past abrupt climate changes and the main forcing and their impacts on Earth dynamics and human populations, ii) past changes in ecosystems, landscapes and surface processes and their feedbacks and finally, iii) the long-term changes in the biogeochemical cycles.

KEYWORDS

global warming · great acceleration · paleoenvironments · paleoclimate modelling · biogeochemical cycles · rapid climate changes

© CSIC © del autor o autores / Todos los derechos reservados

CHAPTER 4

UNDERSTANDING PAST GLOBAL CHANGES TO FACE FUTURE CHALLENGES

Coordinators
Ana Moreno
(IPE, CSIC)
Santiago Giralt
(GEO3BCN, CSIC)

1. INTRODUCTION AND GENERAL DESCRIPTION

Humankind is facing unprecedented climate and environmental crises with economic and social consequences that may compromise the development of our societies on Planet Earth. Changes in our Planet dynamics have played a determinant role in the evolution, migration and extinction of hominids and controlled the onset of sedentary societies, the development of agriculture and the Neolithic revolution, and the rise and fall of civilizations and empires. The history of the Homo genus is linked to the natural evolution of the Planet, although the detailed interplays of environment-climate-humans remain unclear in crucial milestones as the origin of bipedalism in the first hominids. the fate of Neanderthals, the onset of agriculture, the first cities and the Neolithic revolution, and the recent impact of humankind in the Planet owing to complex and often non-linear relationships. To design science-based policies for a fair and sustainable development of the societies we need to consider the long-term, natural evolution of Earth ecosystems and biogeochemical cycles and to understand the impacts at a planetary scale of the current climate change (Global Warming) and increased human pressure (Great Acceleration). To prepare as species and humankind to the planetary-scale challenges we need a complete knowledge and comprehension of our planet, an Earth-System strategy and vision and a time perspective that only geological records can provide.

Copia gratuita / Personal free copy http://libros.csic.es

We have entered a new phase (so called the Anthropocene) characterized by abundant empirical evidence of the unprecedented rate and global scale of impact of human influence on the Earth System since the Industrial Era (Steffen *et al.*, 2016). The concept of "safe planetary boundaries" for humankind development critically frames the drivers, dynamics and specific challenges, such as the present global warming, the crisis in biodiversity, the alteration of geochemical cycles and other environmental threats that are currently affecting Earth's population. However, the definition of boundaries for the "safe" development of our societies and the "natural" Planet dynamics can only be properly carried out if a larger temporal scale than the last few decades when instrumental records are available is taken into account. Hence, past global changes provide the only possible analogs of Earth scenarios and the only validation for forecasting models for climate and environmental evolution at the end of the 21st century. Geological records hold the key to our understanding of what lies ahead. Besides, to understand the uniqueness of the rapid nature of the changes we are witnessing in the Planet in recent decades, we need to identify other periods in Earth History when abrupt changes happened. Fortunately, geological records provide such opportunities, mainly related to the Precambrian Snowball episodes, the regional glaciations recorded at the end of the Hirnantian (Ordovician), the Carboniferous, the Permian crisis and along the Quaternary Period (last 2.58 Ma), when our species (*Homo sapiens sapiens*) begun and developed, as well as generalized greenhouse episodes, such as those recognized in the Early Palaeozoic and Early Mesozoic. Therefore, to better define the natural boundaries of a safe Planet for humankind and set in a context for the recent trends we will focus on three main but complementary perspectives: climate, biodiversity and biogeochemical cycles. The recent biodiversity crisis and its relationship with previous ones and the Biosphere dynamics will be dealt with in Challenge # 7, although Geoscience teams will also contribute with paleoecological strategies. Similarly, climate change as a main driver of the Global Change dynamics is considered in other Challenges but limited to its instrumental and documentary range, not with the full needed temporal range of its variability provided by the geological record.

The three main objectives in this challenge will be related to climate, environmental and biogeochemical cycles, particularly understanding i) the short and long-term climate variability, the dynamics of past abrupt climate changes and the main forcing (insolation, volcanics, ocean-atmosphere-hydrosphere-biosphere interactions) and their impacts on Earth dynamics and human populations, ii) past changes in ecosystems, landscapes and surface

© CSIC © del autor o autores / Todos los derechos reservados

processes and their feedbacks iii), the long-term changes in the biogeochemical cycles (C, N, P, S...). Although Quaternary records are more likely to have the chronological resolution and sensitivity to address these objectives, deeper time archives (since Archean to Neogene times) will also be used to constrain climate, environment and biogeochemical cycles.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Understanding the impacts of the undergoing global warming, the increasing human pressure on the Planet and their consequences in the different Earth domains is of paramount importance to correctly design both sustainable and environmental friendly strategies and to establish long-term policies that might allow reducing the negative impacts that the current rise of carbon dioxide might have on our development. Our strategy aligns with the Sustainable Development Goal 13 (Take urgent action to combat climate change and its impacts) defined by the United Nations.

2.1. Past constrains to our future climate

Reliability of future global warming projections depends on how well climate models reproduce the observed climate change over the twentieth century (Kravtson *et al.*, 2018). At present, climate models reproduce with a significant degree of confidence the seasonal, annual, and multi-annual climate variability owing to both the excellent availability of instrumental meteorological datasets and the large computational capacity that allows the use of sophisticated climate models. However, decadal climate variability present in the instrumental meteorological datasets is poorly modeled in terms of its magnitude, spatial patterns and its sequential time development. Longer data series are clearly needed to improve the models predictability.

Decadal-scale climate variability is crucial for understanding present and future climate as it allows us to contextualize the response to anthropogenic forcing with natural changes due to internal climate dynamics (Cane, 2010). The modes of variability affect global, hemispheric and regional climates on different spatiotemporal scales and can therefore have important societal impacts. They are often associated with severe climate events such as droughts, floods, heat waves and cold spells affecting agriculture, water resources and blue economies, which, in turn, modulate air quality, fire risk, energy availability and human health (Zubiate *et al.*, 2017).

Copia gratuita / Personal free copy http://libros.csic.es

Geological records are the best archives for studying this decadal-scale climate variability as it is their most often temporal-scale resolution. Therefore, the main efforts of the CSIC researchers will be focused on obtaining the control of long-term climate reconstructions in the replacement of microbial and shelly, benthic and pelagic ecosystems, although shorter (i.e., seasonal, annual) and longer (i.e., centennial, millennial) temporal scales will not be disregarded.

2.2. Abrupt and Rapid climate changes

Long-term climate changes might be led by variations in the dominance, intensity and relationship among the modes of climate variability as can clearly be seen during the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). These rapid changes have proven to be responsible of many of the migrations that societies have faced through time, especially when living in areas vulnerable to drought, flood, and abrupt and significant temperature changes (Kaczan and Orgill-Meyer, 2020). The Mediterranean area in general, and the Iberian Peninsula in particular is a high vulnerable area (IPCC, 2013). There are evidences of increase in the frequency and intensity of some extreme climate events as a consequence of global warming and it is expected to continue to increase under medium and high emission scenarios, strongly affecting ecosystems as well as economic goods. In fact, the projected changes for the end of the 21st century under high-warming scenarios are greater than those under historic climate change. The scientific efforts will be focused to determine the periodicity and recurrences of these abrupt climate changes further analyzing the available geological archives, such as lake and marine sediments, speleothems, peatbogs, ice, and corals. Although some efforts have been carried out to perform this task they have always been done from the qualitative perspective and not from the quantitative one. The qualitative reconstructions are very useful to describe past climate and environmental evolutions. However, these reconstructions can be really useful when incorporated in global climate models as quantitative reconstructions since they can be then employed to validate climate variability when testing the performance of these models. This cutting-edge research field, between the climate modelers and the paleoclimatologists, who work in climatic models from Archaean-Proterozoic- Phanerozoic to the Quaternary, is currently being developed and it will become a significant hot topic in the next few years since both research communities have already agreed that, if global climate models must be employed to forecast future challenges that society will face, they should perfectly simulate well-known past climate and environmental conditions (Phipps *et al*., 2013).

© CSIC © del autor o autores / Todos los derechos reservados

The coupling (uncoupling) of the modes of climate variability might enhance (reduce) the intensity and periodicity of these abrupt climate changes. In fact, the main climate chronozones of the last 2,000 years in the Iberian Peninsula can be explained by changes in the coupling/uncoupling of the North Atlantic Oscillation and the Easter Atlantic climate modes (Sánchez-López *et al.*, 2016). Despite the large effort carried out to characterize in detail the decadal climate evolution of a given climate chronozone, like the LIA (Oliva *et al.*, 2018) and the MCA (Moreno *et al.*, 2012) there is still a scarce knowledge of the forcing mechanisms responsible of their evolution. The correct assessment of the intensity and frequency of these abrupt climate events as well as of their most probably forcing mechanisms can only be performed if longer than instrumental meteorological datasets are available.

One side effect of the present global warming is linked to the significant modification of the ice mass balance. The ice mass balances of Antarctic and Greenland ice sheets represent the largest uncertainty for predicting future sea-level rise worldwide (Dowdeswell, 2006). The mass balance is determined by the ratio between the snow accumulated inland of the ice sheet and the ice removed in the coastal zone. However, the mechanisms controlling the flow of ice flow in polar ice sheets are not yet understood. It is therefore crucial that these mechanisms must be understood in detail in order to predict the volume of polar ice that arrives to the oceans thus controlling sea level evolution (Kopp *et al.*, 2017). According to the Intergovernmental Panel on Climate Change (IPCC, 2014), the current climate change is expected to directly impact ecosystems and human societies by enhancing processes like sea level rise. The prediction of ice-sheet discharge is highly relevant in times of intensive warming in polar regions.

2.3. The current Biodiversity crisis and previous extinctions

Five mass extinctions are known in the past, some of them related to sharp paleoclimatic shifts. These are the Ordovician, Devonian, Permian, Triassic-Jurassic and Cretaceous-Tertiary (or the K-T) Mass Extinctions. Climate change and increasing anthropogenic impacts on the environment are projected to become the leading drivers of biodiversity loss, eroding the natural capital that sustains human wellbeing and prosperity. The challenge of understanding these large-scale changes and their consequences for human wellbeing have led to the development of a set of planetary boundaries to guide Earth system governance. These boundaries identify key biophysical limits which, by staying within these limits, humankind may reduce the risk of crossing thresholds that could lead to devastating and potentially irreversible environmental change, ensuring the

Copia gratuita / Personal free copy http://libros.csic.es

maintenance of critical ecosystem services (Nash *et al.*, 2017). However, it is not clear when during this 21st century ecological assemblages might suffer such losses, and whether the process will be gradual or abrupt.

Most of the existing biodiversity forecasts lack the temporal perspective needed to answer these questions because they indicate the number and locations of species threatened by climate change for just a snapshot of the future, often around the end of the century (Trisos *et al.*, 2020). Usually, these biodiversity forecasts focus at the level of several target species rather than ecological assemblages. However, many of the most sudden and severe ecological effects of climate change can occur when conditions become unsuitable for several co-occurring species simultaneously, causing catastrophic die-offs and abrupt 'regime shifts' in ecological assemblages.

Therefore, a holistic and long-term characterization must be carried out in order to characterize how these biodiversity losses are initiated, which are their evolution and main driving mechanisms, and which are the thresholds that led to these abrupt 'ecological shifts' (i.e., long-term climate fluctuations, anthropogenic exploitation of natural resources). The geological record offers a unique opportunity to reconstruct and characterize the onset, evolution and offer clues about the main drivers of past global diversity crises. These reconstructions of past global crises in biodiversity, including extinctions, help to frame the current biodiversity trends in a longer time-scale context and to understand how life responds to environmental perturbations, such as climate loss of habitats, in order to provide the boundary conditions for engineers and policymakers working to mitigate impacts and hazards. Reconstructions of past global crises evolution show, in addition, the potential role of resilience, if exits, and how usually is the post-crisis scenario.

The recent biodiversity crisis and its relationship with previous ones and the Biosphere dynamics will be dealt with in Challenge # 7, although Geoscience teams will also contribute with paleoecological strategies.

2.4. Anthropogenic impacts

Concern about the anthropogenic impact on climate has led to predictions of how people living in areas vulnerable to drought, flood and temperature extremes will respond to such events. Although some recent studies have focused on observed climate events and trends to document how migration flows vary as a function of both the severity of the event and the ability of people to migrate, among other factors, most of these studies lack a long-term perspective

© CSIC © del autor o autores / Todos los derechos reservados

that might help to design and implement more effective environmental and political measures to mitigate the adverse effects of these climate events. Indeed, hydrology, surface processes, biological dynamics and even socio-economic evolution are particularly sensitive to both climate and environmental changes at varied temporal scales (http://www.ipcc.ch/). Short- and long-term Pleistocene and Holocene climate and environmental fluctuations have influenced human migrations and territory occupations as well as agricultural productivity, food security, health risk, and conflict level of preindustrial societies. However, discrimination between climate, environmental and anthropogenic impacts on past humankind evolution remains difficult because of the complex and often non-linear interactions between multiple driving mechanisms.

Therefore, the use of a new transdisciplinary and cutting-edge approach employing historical, archaeological, paleoenvironmental and paleoclimate data is strongly encouraged since it will provide access to long-term perspectives on human ecodynamics (interaction between human social and cultural systems, and climate and environment) and offer a unique basis for counteracting the recent political and fiscal reluctance to mitigate projected climate change (Büntgen *et al*., 2011). In this context, high-resolution temporal-scale, multi-disciplinary, and robust paleoclimate and paleoenvironmental reconstructions are of paramount importance since they provide key information on this long-term human ecodynamics evolution.

Human activities now rival the great forces of nature in driving changes to the Earth System and this fact has led to the proposal that Earth has entered a new geological epoch called the Anthropocene (Gaffney and Steffen, 2017). Although there is a lack of consensus on the spatiotemporal onset of the Anthropocene, otherwise called "Age of Humans", which will be the main indicators that will define this geological period, and how this geological epoch will be formally defined, human action is undoubtedly the main driver in the origin of many current landscape configurations and their recent evolution. Therefore, its definition and characterization is key to determine from when the Earth System might have been functioning beyond the natural climate and environmental Earth variability for the last millennia or even millions of years.

The nature and dynamics of environmental changes can only be approached throughout long-term studies of landscape evolution using a multiproxy and multidisciplinary methodology, evaluating independently both climate and human action through robust and well-dated evidences.

Copia gratuita / Personal free copy http://libros.csic.es

2.5. A longer term perspective of recent and future biogeochemical cycles

The third complementary perspective of reconstructing past global changes is related to the long-term characterization of the biogeochemical cycles. The onset of the intensive agriculture in the 1950s has strongly increased the N/P (nitrogen/phosphorous) ratio in the atmosphere and thus in natural, semi-natural and managed ecosystems. This ratio increase, together with high levels of carbon dioxide in the atmosphere due to anthropogenic emissions, has a profound and yet uncertain consequences on the phosphorus cycle and N:P stoichiometry for the structure, functioning and diversity of terrestrial and aquatic organisms and ecosystems as well as threats biodiversity, ecosystem productivity, food security, and human health (Peñuelas *et al.*, 2020). This abrupt modification of the biogeochemical cycles, among other factors, served to define the term 'Great Acceleration' in order to capture the holistic, comprehensive and interlinked nature of the post-1950 changes simultaneously sweeping across the socio- economic and biophysical spheres of the Earth System, encompassing far more than climate change. This Great Acceleration has become an iconic symbol of the Anthropocene and it is being used as an indicator of the trajectory of this new geological epoch.

Biogeochemical processes are of particular interest in the 'critical zone' defined as Earth's outermost surface, from the vegetation canopy to the zone of groundwater (Brantley *et al.*, 2006), and thus encompasses the nexus amongst all earth systems. Most terrestrial life resides in the critical zone, and it is rapidly undergoing transformation by anthropogenic changes. As ICDP stated in its Science Plan in 2019, "the critical zone is, indeed, the key record of the emerging Anthropocene".

Paleoenvironmental records from geological sequences may provide the longer perspective in biogeochemical cycles and a better understanding of current processes.

3. KEY CHALLENGING POINTS

Reconstructing past global changes face a number of challenges that hampered the achievement of the aforementioned goals. The major challenges are:

1. The limited temporal and spatial coverage of the needed geological records to obtain reliable and robust spatiotemporal short and long term evolution of key climate/ environment parameters (i.e., precipitation, temperature, chemical element cycling, ...)

© CSIC © del autor o autores / Todos los derechos reservados

2. The proxy quantification to obtain the availability of long and highly-resolved temporal records that might allow to capture decadal climate variations.The only way to overcome these two major limitations is to combine a large variety of sedimentary records (such as espeleothems, lake and marine sedimentary records and peatbogs, archeological sites, etc., at short-term chronological intervals, and climatically sensitive facies and minerals associated with fluctuations in biodiversity and evolutionary patterns at long-term chronological intervals) in order to ensure the best spatiotemporal coverage as well as to use a large array of techniques at high-temporal resolution to obtain the best information of the studied records. Also, it is of paramount importance to establish close collaborations between the different research groups to ensure that a real multidisciplinary approach is applied and that a sufficient temporal and spatial coverage is attained. To this end, the use of indirect climate indicators (also known as proxies) from natural archives becomes of paramount importance. Proxies generally respond to environmental parameters such as temperature and precipitation, and in turn may be indirectly linked to certain modes of climate variability, through for example their response to the atmospheric circulation (Bradley, 2015). Over the last decades, several studies have attempted to reconstruct a number of modes of climate variability at different time scales using historical documents and natural archives (proxy records). Major findings show evidence of the spatiotemporal variability of these modes, their impacts, interactions and possible links to external forcing since the early Holocene and especially for the last millennium (Dätwyler *et al.*, 2018).
3. More accurate and robust chronological models by integrating several absolute (AMS ^{14}C, $^{210}Pb/^{137}Cs$, $^{234}U/^{230}Th$, Optical Stimulated Luminiscence, tephrochronology) and relative (paleomagnetism, orbital tuning) techniques, depending on the type of record and its temporal scale.
4. Model- Data integration. The decadal characterization can only be carried out when working together climate modelers and paleoclimatologists and this is one of the main goals that we CSIC researchers' should focus rooting the new research in the previous expertise we have.
5. Accessible and FAIR databases. Results must be independently checked by other researchers in order to validate them. This implies that datasets employed in research should be accessible following

Copia gratuita / Personal free copy http://libros.csic.es

standardized protocols. Although, there are some public databases (i.e., NOAA Paleoclimatology: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data) in which researchers can make publicly available their datasets and scientific journals begin to compel authors to submit the employed datasets prior to the final acceptance of a given manuscript, these initiatives must be generalized.

6. Understanding ice flow in polar ice sheets. The goal to understand how ice flows from the accumulation to the ablation zone is crucial for correctly estimating the changing mass in polar ice sheets. To achieve this objective, the balance between i), the internal deformation of the ice itself, driven by gravity flow, and ii), the ice-sheet basal motion, which takes place only where the ice bed is at the pressure melting point (temperate ice) should be characterized in detail.
7. Monitoring Networks. The main challenge that might hamper the acquisition of quantitative past global reconstructions is the lack of long and continuous monitoring datasets that allow to characterize in detail how the climate and other environmental signals are transferred to the sediments. Implementing and maintaining this monitoring network is costly both in instrumentation and personnel but, without investing the required funds to conduct it, we will not be able to obtain these quantitative past global reconstructions.
8. Repositories of geological archives. Only a large and coordinated effort between all research groups involved in this task can overcome this limitation and CSIC researchers are already working in this direction.

There are also specific challenges for each dimension of the past global changes:

3.1. Climate

- How did the Earth's climate system behave during warmer / high-CO_2 worlds?
- How did the Earth's climate system behave during glacial / interglacial cycling in cold and warmer worlds, and during icehouse greenhouse transitions?
- What are the fundamental processes and feedbacks forcing climate transitions, at timescales from decadal to million years and beyond?
- How fast did permafrost and gas hydrate stability react on changing climate and vice versa?
- How does ice rheology control ice-sheet motion?

© CSIC © del autor o autores / Todos los derechos reservados

- What is the influence of temperate ice in deeper parts of the ice-sheets on the ice flow properties?
- How is the ice sheet discharge enhanced due ice-sheet basal motion?

3.2. Environment/Biodiversity

- What were the biotic responses to major environmental changes (e.g., climatic, super-eruptions, impacts), at timescales from decadal to million-year and beyond?
- What were the impact of abrupt climatic / biogeochemical events at decadal to millennial timescales, and how are these propagated through the atmosphere– hydrosphere–biosphere systems?
- Calibrating the palaeoclimatic influence in the replacement and disappearance of microbial and shelly ecosystems in deep time
- High-resolution, near-time targets are also needed to fully probe questions regarding the sensitivity of land surface processes to anthropogenic perturbations.
- Lakes can enable a vastly improved understanding of phylogenies through the combined study of body and molecular fossil information in such self-contained ecosystems.

3.3. Biogeochemical cycles

- What are the key processes characterizing Earth's Critical Zone?
- How the carbon, oxygen, sulphur and phosphorous cycles were affected by biotic crisis in the past?

Copia gratuita / Personal free copy http://libros.csic.es

CHAPTER 4 **REFERENCES**

Bradley, R.S. (2015). Chapter 1 - Paleoclimatic Reconstruction, in: Bradley, R.S. (Ed.), Paleoclimatology (Third Edition). Academic Press, San Diego, pp. 1–11. https://doi.org/10.1016/B978-0-12-386913-5.00001-6

Brantley, S., White, T.S., White, A.F., Sparks, D., Richter, D., Pregitzer, K., Derry, L., Chorover, J., Chadwick, O., April, R., Anderson, S., Amundson, R. (2006). Frontiers in Exploration of the Critical Zone: Report of a workshop sponsored by the National Science Foundation (NSF), October 24-26, 2005. Newark, DE: 30

Büntgen, U., Tegel, W., Nicolussi, K., Mccormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzig, F., Heussner, K.U., Wanner, H., Luterbacher, J., Esper, J. (2011). 2500 years of European climate variability and human susceptibility. Science, 331: 578-582.

Cane, M.A. (2010). Decadal predictions in demand. Nature Geosciences, 3: 231–232. https://doi.org/10.1038/ngeo823

Dätwyler, C., Neukom, R., Abram, N.J., Gallant, A.J.E., Grosjean, M., Jacques-Coper, M., Karoly, D.J., Villalba, R. (2018). Teleconnection stationarity, variability and trends of the Southern Annular Mode (SAM) during the last millennium. Climate Dynamics, 51: 2321–2339. https://doi.org/10.1007/s00382-017-4015-0

Dowdeswell, J. A. (2006). The Greenland ice sheet and global sea-level rise. Science, 311, 963-964

Gaffney, O., Steffen, W. (2017). The Anthropocene equation. The Anthropocene Review, 1-9. doi:10.1177/2053019616688022

IPCC (2014). Intergovernmental Panel on Climate Change. Climate change 2014: mitigation of climate change. Vol. 3. Cambridge University Press.

Kaczan, D.J., Orgill-Meyer, J. (2020). The impact of climate change on migration: a synthesis of recent empirical insights. Climate Change, 158: 281-300. https://doi.org/10.1007/s10584-019-02560-0

Kravtson, S., Grimm, C., GU, S. (2018). Global-scale multidecadal variability missing in state-of-the-art climate models. Climate and Atmospheric Science, 1: 34. https://doi.org/10.1038/s41612-018-0044-6

Kopp, R.E., Deconto, R.M., Bader, D.A., Hay, C.C., Horton, R.M., Kulp, S., Oppenheimer, M., Pollard, D., Strauss, B.H. (2017). Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. Earth's Future, 5: 1217-1233.

Moreno, A., Pérez, A., Frigola, J., Nieto-Moreno, V., Rodrigo-Gámiz, M., Matrat, B., González-Sampériz, P., Morellón, M., Martín-Puertas, C., Corella, J.P., Belmonte, A., Sancho, C., Cacho, I., Herrera, G., Canals, M., Grimalt, J.O., Jiménez-Espejo, F., Martínez-Ruiz, F., Vegas-Villarrúbia, T., Valero-Garcés, B.L. (2012). The Medieval Climate Anomaly in the Iberian Peninsula reconstructed from marine and lake records. Quaternary Science Reviews, 43: 16-32. https://doi.org/10.1016/ j.quascirev.2012.04.007

Nash, K.L., Cvitanovic, C., Fulton, E.A., Halpern, B.S., Milner-Gulland, E.J., Watson, R.A., Blanchard, J.L. (2017). Planetary boundaries for a blue planet. Nature Ecology & Evolution, 1: 1625-1634. https://doi.org/10.1038/s41559-017-0319-z

Oliva, M., Ruiz-Fernández, J., Barriendos, M., Benito, G., Cuadrat, J.M., Domínguez-Castro, F., García-Ruiz, J.M., Giralt, S., Gómez-Ortiz, A., Hernández, A., López-Costas, O., López-Moreno, J.I., López-Sáez, J.A., Martínez-Cortizas, A., Moreno, A., Prohom, M., Saz, M.A., Serrano, E., Tejedor, E., Trigo, R., Valero-Garcés, B., Vicente-Serrano, S. (2018). The Little Ice Age in Iberian mountains. Earth-Science Reviews, 177: 175-208. https://doi.org/10.1016/j.earscirev.2019.03.015

Peñuelas, J., Janssens, I.A., Ciais, P., Obersteiner, M., Sardans, J. (2020). Anthropogenic global shifts in biopheric N and P concentrations and ratios and their impacts on biodiversity, ecosystem productivity, food security, and human health. Global Change Biology, 26: 1962-1985. https://doi.org/10.1111/gcb.14981

Phipps, S.J., Mcgregor, H.V., Gergis, J., Gallant, A.J.E., Neukom, R., Stevenson, S., Acherley, D., Brown, J.R., Fischer, M.J., Van Ommen, T.D. (2013). Paleoclimate data - Model comparison and the role of climate forcings over the past 1500 years. Bullein of the American Meteorological Society, 26: 6915-6936. https://doi.org/10.1175/JCLI-D-12-00108.1

© CSIC © del autor o autores / Todos los derechos reservados

Sánchez-López, G., Hernández, A., Pla-Rabes, S., Trigo, R.M., Toro, M., Granados, I., Sáez, A., Masqué, P., Pueyo, J.J., Rubio-Inglés, M.J., Giralt, S. (2016). Climate reconstruction for the last two millennia in central Iberia: The role of East Atlantic (EA), North Atlantic Oscillation (NAO) and their interplay over the Iberian Peninsula. Quaternary Science Reviews, 149: 135–150. https://doi.org/10.1016/j.quascirev.2016.07.021

Steffen, W., Leinfelder, R., Zalasiewicz, J., Waters, C.N., Williams, M., Summerhayes, C., Barnosky, A.D., Cearreta, A., Crutzen, P., Edgeworth, M., Ellis, E.C., Fairchild, I.J., Galuszka, A., Grinevald, J., Haywood, A., Ivar Do Sul, J., Jeandel, C., Mcneill, J.R., Odada, E., Oreskes, N., Revkin, A., Richter, D.deb., Syvitski, J., Vidas, D., Wagreich, M., Wing, S.L., Wolfe, A.P., Schellnhuber, H.j (2016). Stratigraphic and Earth System approaches to defining the Anthropocene. Earth's Future, 4: 324-345. https://doi.org/10.1002/2016EF000379

Trisos, C.H., Merow, C., Pigot, A.L. (2020). The projected timing of abrupt ecological disruption from climate change. Nature, https://doi.org/10.1038/ s41586-020-2189-9

Zubiate, L., Mcdermott, F., Sweeney, C., O'malley, M. (2017). Spatial variability in winter NAO–wind speed relationships in western Europe linked to concomitant states of the East Atlantic and Scandinavian patterns. Q. J. R. Meteorological Society, 143: 552–562. https://doi.org/10.1002/qj.2943

Copia gratuita / Personal free copy http://libros.csic.es

Every day human activities involve interaction with our planet Earth. Everything around us is built upon the Earth, grows on the Earth, or depends on the environments and internal dynamics of the Earth to some degree. Indeed, Earth's dynamic processes have strong influence on our society today as they have had at any time in human history, providing both major opportunities as well as challenges. Therefore, the knowledge about the Earth is the key to develop an informed citizenry and a global awareness of a common Planet and a common future. For example, dynamic processes during interaction between the tectonic plates that make up the outer "skin" of Earth provide us with the valuable mineral deposits we need to develop our society, or the arable land and fertile soils needed to sustain it. Likewise, plate boundaries are the locus of hazards such as earthquakes, tsunamis, and volcanic eruptions that can cause large-scale disruption to, and displacement of, communities and economies. Just as one example, the March 11th, 2011 Tohoku earthquake offshore Japan, shows how a single-event natural disaster caused by one of the dynamic processes of the Earth (plate subduction) can have important socio-economic impacts that range from large-scale infrastructure damage to local and regional population relocation. Understanding the full range of Earth's dynamic processes will not stop natural disasters like the Tohoku earthquake, but it will provide important information for developing models for their mitigation.

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
EDITORIAL CSIC

© CSIC © del autor o autores / Todos los derechos reservados