VOLUME 7

GLOBAL CHANGE IMPACTS

Topic Coordinators
María Begoña García
& Pedro Jordano

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030
Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

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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*
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7. *Global Change Impacts*
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14. *Dynamic Earth: Probing the Past, Preparing for the Future*

CSIC scientific challenges: towards 2030
Challenges coordinated by:
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Volume 7
Global Change Impacts

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VOLUME 7 SUMMARY

CHALLENGE 2

ABSTRACT

Climate change is one of the main threats for our planet, but there are still remarkable knowledge gaps and uncertainties. Further studies are thus required to establish a robust and comprehensive assessment of climate change and variability. Current challenges in Climate Science are: i) evaluation of the climate change with a focus on data rescue and analysis to better contextualize current anthropogenic forcing and natural climate variability; ii) assessment of physical processes, including feedbacks between thermodynamics and dynamics, and interactions between the Earth System components; iii) monitoring and forecasting of extreme events, which account for the largest socio-economic and environmental losses associated to climate change; iv) analyses of future changes at global and regional scales; and v) provision of reliable and transparent climate services to user communities. Advances in a better understanding of the processes and mechanisms of climate change should guide the design and implementation of mitigation and adaptation strategies and policy, which will alleviate and improve future human life on earth.

KEYWORDS

climate change
climate variability
circulation mechanisms
climate extremes
climate services
climate modelling

CHALLENGE 2

CLIMATE CHANGE PROCESSES, MECHANISMS AND FUTURE SCENARIOS.

THE BASIS TO DEVELOP CLIMATE SERVICES AND TO IMPROVE ENVIRONMENTAL AND SOCIETAL ADAPTATION

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1. INTRODUCTION AND GENERAL DESCRIPTION

Nowadays, climate change is one of the main threats to our planet. Human activities, in particular the increased atmospheric concentrations of greenhouse gasses, have altered the global energy balance. The most noticeable consequence has been the increase of the near-surface temperature at the rate of 0.1 ºC/decade over the last century (Intergovernmental Panel on Climate Change, 2014). There are multiple consequences of this global warming, with countless socio-economic and environmental costs such as sea-level rise, polar and mountain glaciers melting, snow cover retreat, more frequent land and marine heatwaves, changes in animal and vegetation phenology and more severe forest fires. The fingerprints of anthropogenic climate change are complex, involving spatial variations related to regional processes and superposition with the non-linear natural variability of the climate system. Therefore, there are still remarkable knowledge gaps and uncertainties, and further studies are required to establish a robust and comprehensive assessment of climate change and climate variability. Uncertainties affect mostly dynamical aspects in all components of the Earth System, and their effects on the energy and water cycles. These uncertainties directly affect the robustness of future climate projections. They also affect our capability to forecast extreme events accurately (e.g., tropical and extratropical cyclones, droughts, among others), which have considerable hydrometeorological implications and severe socio-economic and environmental impacts. The assessment, understanding and attribution of climate change is the first mandatory step to deal with a large number of impact-related processes framed under the concept of global change (e.g., impacts in biodiversity and primary production), since climate is the principal driver of these processes.

To bridge these gaps and reduce uncertainties, it is necessary to better quantify the rates of change in all physical components, for a range of spatial and temporal scales. This first challenge must consider a variety of climate elements (i.e. not only air temperature and precipitation), with focus on the rescue and analysis of available historical observations and proxy records to better contextualize and discriminate natural climate variability and the current anthropogenic forcing. This research niche is of high priority for under-sampled and historically inaccessible sites such as polar regions (Challenge 5), deep oceans (Thematic 13), upper atmosphere (Challenge 3 in Thematic 12) or mountain areas, where climate conditions are highly variable in space and time, and very sensitive to changes in the radiative forcing. The assessment of physical processes, including feedbacks between thermodynamics and dynamics, and interactions between the Earth System components (land-atmosphere-ocean-ice coupling) is a second priority in order to understand the past evolution of the climate system, constrain the range of natural variability and quantify its responses to anthropogenic forcings. The third priority aims at quantifying the observed changes and covers the triggering factors of extreme events, which are still challenging to identify, monitor and forecast. A fourth challenge refers to the uncertainties of climate projections and the need for constraining future changes at global and regional scales in support of more efficient mitigation and adaptation strategies. The latter requires the implementation of sophisticated computational resources, improved representation of processes and the development of more comprehensive global and regional Earth System models with higher spatial resolution. Finally, the last challenge concerns a timely provision of reliable and transparent climate services to user communities, since many economic and social activities, as well as policy decisions, depend on the availability of accurate climate information, including long-term climatologies, monitoring systems, forecasts (from days to decades) and long-term projections. This information must be summarized in customized climate products and services to fit the needs of end-users, therefore requiring end-to-end engagement from the implicated actors.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

In recent decades, enormous effort and resources have been invested in monitoring climate evolution and providing scientific evidence of the anthropogenic origin of the ongoing climate change. The vast body of science generated (Intergovernmental Panel on Climate Change, 2014), the sustained warming of the globe and the increasing occurrence of extremes (Sillmann *et al.*, 2017) have shifted the perception of society and decision-makers from scepticism to a majority acceptance of the anthropogenic origin of climate change. The signing of the Paris agreement in 2015 (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement; last accessed 1 August 2020) is perhaps the main milestone in this transformation because, despite the actual level of commitment, most governments recognized the human role in climate change. Simultaneously, the efforts in observing the Earth System are higher than ever, with an observing and modelling capacity able to generate petabytes of data, most of them freely accessible. This availability of data opens the road to a new stage for climate scientists.

As we move into an unknown warmer World, new questions arise that need to be addressed while filling critical gaps in the current state of basic science. Understanding and quantifying changes at regional and local scales in the unequivocal warmer world is perhaps the main scientific challenge ahead due to the complex dynamics and interactions of the major components of the climate system. The massive data available, jointly with the increasing computing facilities derived from the development of high-performance computers and cloud computing services, pave the way to cope with this challenge and allows including new disciplines into the climate sciences. The combination of earth physics and chemistry, data science and soft computing techniques (Thematic 11) may be a fundamental tool in this context.

Climate is one of the key elements defining the ecological ceiling of human wellbeing (Raworth, 2017), and it impacts socio-economic sectors including health, energy, agriculture, infrastructures and economy (National Academy of Sciences, 2019). The improvement of comprehensive observing and modelling systems has allowed climate scientists to provide climate services (Street, 2016). The advances derived from a better understanding of the processes and mechanisms of climate change at different scales will also increase the added value of these services. Once the society has fully acknowledged climate change, mitigation and adaptation policies represent the basis for integrating the climate dimension into decision- making processes. Advanced climate science can now contribute to guide the ecological transition to a greener economy and the achievement of Sustainable Development Goals (SDGs). For instance, the recovery from the devastating economic repercussions of the COVID-19 pandemic can be a chance to improve the interactions between climate and economy. The recent FEDEA report (*Fundación de Estudios De Economía Aplicada*; https://www.fedea.net/quinto-informe-del-gmtc-porunaeconomia-competitiva-verdey-digital-tras-el-covid-19/) considers that the foreseen European Fund for Reconstruction will be mostly based on the Objectives of the European Green Deal and the Digital strategy. Projects contributing to decarbonization and climate change fight should be a priority since they can stimulate economic activity with a long-term impact on attaining sustainable growth. To this end, governments and research agencies must invest more funds in climate observation and the evaluation of climate change and climate variability. Only sustained funding support can cope with the increasing demand for better climate science and services.

The specific challenges described below are well aligned with the United Nations SDG 13: Climate action. As climate science sets the grounds of climate change and provides projections for the development of adaptation and mitigation strategies, and the quantification of impacts, these challenges are also relevant for other SDGs, such as SDG 3: Good Health and Well-being; SDG4: Clean water and sanitation; SDG 7: Affordable and Clean Energy; SDG 11: Sustainable cities and communities; SDGs 14 (Life below water); and 15 (Life on land).

3. KEY CHALLENGING POINTS

3.1. Evaluation of climate change at different spatial and temporal scales

Climate research has brought increasing levels of public awareness and policy commitment on climate change since the 1990s (e.g., Earth Summit, Rio Janeiro, 1992), and climate change is now acknowledged as a major environmental issue for the society. During these three decades, there have been considerable achievements in the evaluation of past climate variability and trends at different spatio-temporal scales, as summarized by the quasi-periodic Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC 1990, 1996, 2001, 2007 and 2013). The main conclusion of its Fifth Assessment Report (Intergovernmental Panel on Climate Change, 2014) is that contemporary warming of the land and ocean is unequivocal (e.g., the past five years are the warmest on record, and, since the 1980s, each successive decade has been warmer than any preceding one of the 1850-2019 period), and primarily caused by anthropogenic emissions of greenhouse gases. However, the non-linearity of the climate system, the limited availability of climate records over large regions (e.g., Southern Hemisphere, polar regions, the Tibetan Plateau –known as the "Third Pole Region" –), and the representation of small-scale processes and internal variability in climate models make the detection and attribution of climate change a big challenge (Otto *et al.*, 2016). Figure 1 outlines the state-of-the-art in climate change and climate variability, and critical challenges that require future in-depth investigations to improve our understanding of the climate system.

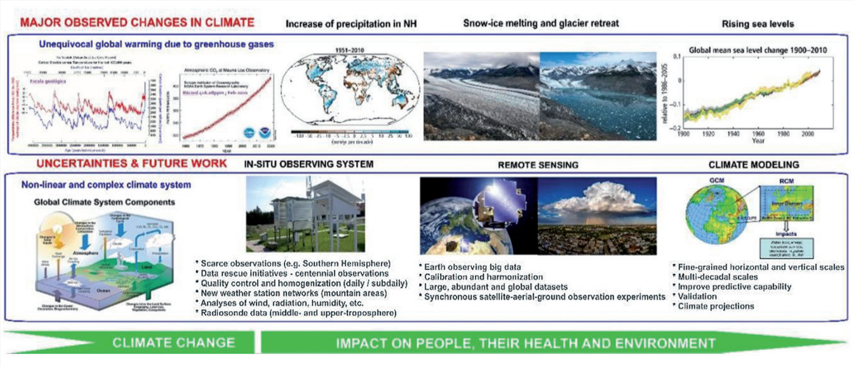
In particular, comprehensive climate studies are needed to understand physical processes better (see section 3.2), move forward in the detection and prediction of extreme events (section 3.3) and improve the realism of climate models (section 3.4). As in these issues, the assessment of climate change relies on observational data collected from in-situ networks, satellite observing systems and indirect proxy records, as well as on physically consistent data simulated by models of diverse complexity, some of them assimilating observations. Accurate and homogeneous long-term observational records are still crucial to quantify the observed changes over the industrial period. In particular, data rescue initiatives (e.g. from books or documentary sources available at weather archives in the National Weather Services and libraries) are strongly needed over under-sampled regions where surface, sub-surface and upper-air climate information exists such as developing countries, the Southern

Hemisphere or the Pacific Ocean. Long-term series based on terrestrial and marine observations before the 1960s represent valuable sources to fill the gaps, improve the characterization of climate variability at decadal timescales and assess with more confidence the observed changes. For example, the Copernicus Climate Change Service (C3S), the Atmospheric Circulation over the Earth (ACRE), or the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) are international initiatives promoting and supporting the rescue, digitization and harmonization of documented instrumental data records, underpinning 3D weather reconstructions (reanalyses) spanning the last 250 years (Slivinski *et al.*, 2019). For the assessment of past climate changes further back in time, the reader is referred to Challenge 1 in this Thematic.

The development of high-quality networks for climate monitoring in, e.g. mountain areas, the Arctic and Antarctic regions, and the maintenance of long-term observing systems is also a priority. Thus, international initiatives are required to support the continuity of existing analogical observational networks, which represent the fundamental pillars of climate change assessments. Moreover, the improvement of algorithms to advance in the quality of data at finer temporal resolutions (i.e., daily and sub-daily data) is mandatory. The detection and attribution of trends in climate extremes requires at least daily resolution, and some weather phenomena, such as daily peak wind gusts, are even more demanding (resolution of the order of seconds). However, long-term time series (>30-years) at this resolution are still scarce, since these measurements started with the automatization (data-logging) of the observational network in the mid-1980s. The main goal for the assessment of climate change and variability is combining the assimilation of ground-based observations (e.g., air temperature, precipitation, wind speed) with the calibration-harmonization of satellite (e.g. clouds, aerosols) data in a comprehensive way, and reduce biases and inhomogeneities in the current generations of reanalysis. These products also have benefits for the evaluation of models employed for climate projections and operational forecasts.

Most studies on climate change and variability have focused on air temperature and precipitation and their related extremes (heat/cold waves, droughts, heavy precipitation events and floods), while other variables have only been investigated in recent years. Alternative power sector decarbonization strategies demand comprehensive climate studies of changes in other atmospheric parameters such as wind speed (stilling *vs* reversal; Zeng *et al.*, 2019), solar radiation (dimming *vs* brightening), relative humidity or evaporation. There

FIGURE 1–Overview of observed climate trends, uncertainties and future work.



is also a limited understanding of climate variability and change in the middle and upper troposphere, as well as in other components of the climate system (ocean, land and ice; e.g. Challenges 2 and 6 in Thematic 13), which are major carbon sinks and significant contributors to the long-term responses to climate change. It is therefore critical to effectively analyze different climate datasets in order to evaluate the real dimension of the ongoing climate change at different spatial (from local-mesoscale to hemispheric-global) and temporal (from sub-daily to multidecadal) scales, and quantify the role of anthropogenic factors. The latter requires a better characterization of climate responses to external natural forcings (e.g. Challenge 3 in Thematic 12) and internal variability, which ultimately relies on a better understanding of past global changes from improved proxy reconstructions and models (Challenge 1). The scientific leitmotiv is "knowing the past climate to understand the present climate change and better predict climate projections needed for climate change adaptation".

3.2. Physical mechanisms of climate change processes

Global warming processes are consistent with a thermodynamic response to anthropogenic forcing. Therefore, achieving the global targets established by the Paris agreement will depend on human decisions, i.e. the pathway of greenhouse gasses emissions. Regarding physical aspects of global climate change, the indirect effects of aerosols and cloud feedbacks are the primary sources of uncertainty in radiative forcing and climate sensitivity, respectively (Bony *et al.*, 2015).

External forcings with large spatial variations (e.g. anthropogenic aerosols), regional forcing (e.g. land-cover changes) and regional-scale cloud, vegetation or snow cover feedbacks cause spatial departures from the global warming response (Figure 2). At regional scales, there is a need for a better understanding and quantification of these feedbacks and improved model implementation of atmosphere-ocean-land-ice interactions (Roe *et al.*, 2015). For example, the relative roles of cloud, water vapour, sea ice and snow feedbacks in Polar amplification or, similarly, the influence of vegetation dynamics and subsurface processes in land-atmosphere coupling over transitional regions, are poorly understood, scarcely measured and underrepresented in climate models. Some of these processes show multiple equilibrium states and irreversible transitions that can be represented by hysteresis cycles. Specifically, characterizing feedbacks and hysteresis is a priority for the understanding of abrupt and irreversible changes if critical thresholds are transgressed ('tipping elements'; Lenton *et al.*, 2008), e.g. the collapse of the Atlantic Meridional Overturning Circulation (AMOC), Amazon dieback, instability of ice-sheets.

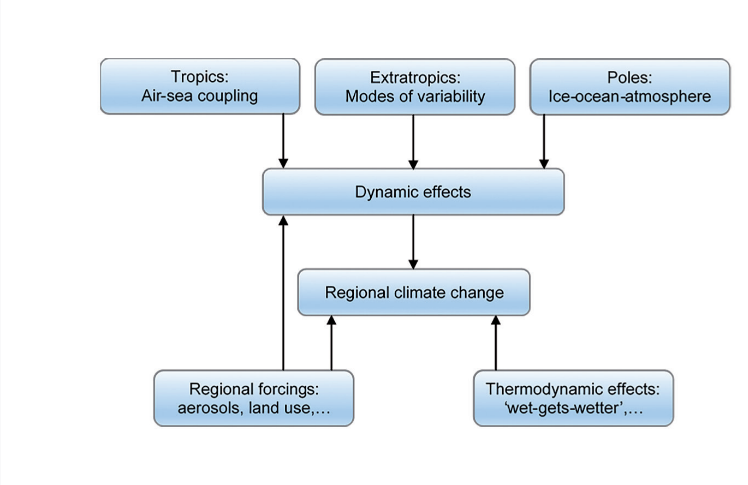
At scales from global to regional, the climate is also strongly affected by dynamics, such as monsoons, storm tracks and planetary-scale waves in the atmosphere, tropical waves, ocean convection, currents and large-scale energy transport in the ocean, or ice fluxes in the cryosphere (Figure 2). In contrast to thermodynamics, dynamical responses to natural (see Challenge 3 in Thematic 12) and anthropogenic forcings are often not robust in observations or models, leading to low confidence in past or future changes in related variables (e.g. precipitation, drought; Shepherd, 2014). Dynamical changes can counteract global warming- induced increases in water vapour, and cause regional precipitation departures from the expected thermodynamic response (i.e. the 'wet-gets-wetter, dry-gets-drier' pattern; Xie *et al.*, 2015). For example, circulation trends have dominated over thermodynamic changes in the summer Asian monsoon, causing rainfall decreases over the 20th century, and future precipitation changes in some mid-latitude areas depend on the magnitude of the projected slowdown and poleward expansion of the Hadley circulation.

In polar regions, marine and terrestrial ice fluxes, and their interactions with the atmosphere and ocean govern the dynamics of the ice-sheets and are important sources of uncertainty for global sea level rise (Challenge 6, Thematic 13). In the equatorial and tropical regions, the atmospheric circulation is coupled with Sea Surface Temperature (SST) anomalies, as in El Niño-Southern Oscillation (ENSO), and so are their changes. However, observations and models do not show robust forced responses in this and other tropical phenomena (Intergovernmental Panel on Climate Change, 2014). Therein, the governing processes are thought to involve delicate balances between opposite feedbacks modulated by the background state. Therefore, improving observations and reducing model biases in the mean state (e.g., the double Inter-Tropical Convergence Zone, ITCZ) is expected to bring an understanding of regional processes, tropical-extratropical interactions and their responses to climate change. Small-scale processes such as clouds, wind gusts, convection or gravity waves, are unresolved (parameterized) in global and even regional climate models, highlighting the need of collaboration between the weather and climate communities, as well as increases in resolution and physical details (Palmer and Stevens, 2019).

In the extratropics, where internal variability is large, observed trends and climate change responses in atmospheric circulation are comparatively smaller, with a tendency to project onto modes of internal variability (Intergovernmental Panel on Climate Change, 2014). Therefore, distinguishing the forced signal from 'climate noise' represents a major challenge (Figure 2). Although internal variability is more considerable on smaller spatial scales, decadal modes of SST variability and interactions between ocean basins may favour temporary global warming hiatus (Collins *et al.*, 2018). However, this low-frequency variability is poorly characterized due to the limited length, coverage and quality of instrumental records. Blended approaches combining paleoclimate reconstructions and modelling (Challenge 1) as well as new reanalyses with coupled assimilation of ocean and atmospheric data are promising tools to constrain internal variability, with implications for mechanistic understanding, model evaluation and climate change attribution.

Increasing computational resources has allowed large ensembles of model simulations accounting for internal variability and a better assessment of forced signals and associated mechanisms. However, the spread of simulated responses across global and regional models (model uncertainty) is large, sometimes involving opposite changes (Shepherd, 2014). Unlike internal variability, model structural uncertainty should be reducible by improving our computational capabilities and understanding of the Earth system components and their interactions. Despite their increased comprehensiveness and realism in the representation of small-scale processes, the robustness of

FIGURE 2–Physical origins of regional climate change (adapted from Xie et al., 2015).



climate projections at regional scales has improved little in recent years, pointing at pervasive problems in fundamental processes through model generations (Collins *et al.*, 2018). Earth System models of very high resolution capable of simulating storms, convection, mesoscale ocean eddies and relevant land-atmosphere interactions will allow an explicit representation of essential processes. As a result, a reduction of systematic biases in current models is expected (Palmer and Stevens, 2019). The development of this new model generation should be sustained, multinational, and coordinated to achieve the necessary level of high-performance computing and information technology. In the meantime, approaches to understand model uncertainty are emerging and inform on relevant mechanisms of climate change. They include the use of a hierarchy of models of diverse complexity, pacemaker experiments with partial coupling or 'storylines' (Collins *et al.*, 2018). These frameworks have shown that some uncertain projections arise from competing influences (so-called 'tug-of-war') of climate change responses across the multi-model ensemble (Shaw *et al.*, 2016). Future progress depends on mapping these drivers of regional climate change (e.g. the stratospheric polar vortex).

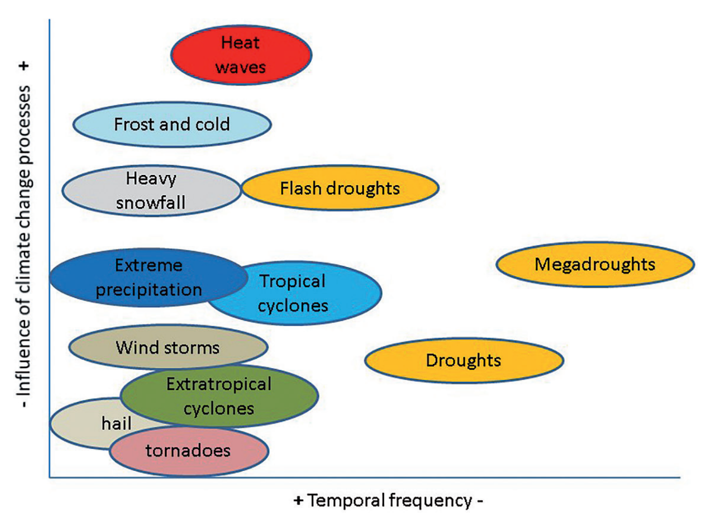
In summary, uncovering the governing processes of climate change poses a range of challenges in terms of the observational record, physical understanding and model simulations. Priority research questions for the next years range from the quantification of feedbacks, the role of small-scale processes (and model parameterizations), the characterization of internal variability or the development of theoretical grounds for the dynamical mechanisms of climate change. Advances in any of them will ultimately require moving forward in the physical understanding of dynamical aspects of the atmosphere, ocean, land and ice subsystems, and their interactions, as well in our capabilities to simulate them.

3.3. Extreme events

Climate extreme events involve complex processes and multiple factors causing unusual values of a climate quantity. Extremes of greater concern are related with air temperature (e.g. frost days, cold spells, heatwaves), precipitation (e.g. heavy rainfall and snowfall events, hail, droughts), wind (e.g. extreme wind, tornadoes) or specific weather systems (e.g. tropical and extratropical cyclones). The assessment of some of these extremes is challenging given the limited availability of long observational records, e.g. for hail, snowfall or tornadoes (Seneviratne *et al.*, 2012). Different spatio-temporal scales characterize extreme events, and the evidence of anthropogenic influences also varies among them (Figure 3). The attribution of specific extremes to climate change is currently a major priority (Trenberth *et al.*, 2015), but still challenging for some types of extremes (e.g. those unrelated to air temperature or occurring at small spatial scales), given model limitations and uncertainties, and short observational records (Paciorek *et al.*, 2018). As extremes are intrinsic to the climate system, they are also influenced by natural variability. Therefore, historical data rescue initiatives, including the development of proxies is pivotal to characterize the influence of natural variability in the occurrence and intensity of extremes and to advance in the detection of trends attributable to anthropogenic factors. An additional common challenge to all types of extremes is the improved prediction, particularly at sub-seasonal-to-decadal (S2S) time scales, i.e. from 10 days to three months (see also Challenge 3 in Thematic 12). Relevant issues include the need of sustained observation and advanced data assimilation, understanding and representation of physical processes with predictive skill, the initialization, coupling and ensemble size of forecast systems, the quantification of uncertainties, and the correction or reduction of model imperfections and drifts (including the signal-to-noise paradox).

Some evidence suggests that some extremes are becoming more frequent, persistent or severe because of anthropogenic climate change. This is

FIGURE 3–Temporal frequency of different types of extreme climate events and the influence of climate change processes



particularly evident for temperature-related extremes such as heat waves (e.g. Barriopedro et al., 2011). Despite this, the understanding of thermodynamical and dynamical influences and their interactions in the severity and persistence of heatwaves is still limited. While there is general agreement on the type of weather systems promoting heatwaves, the relative importance of the involved physical mechanisms (e.g. warm advection *vs* adiabatic processes) remains poorly understood, as well as their future changes. When combined with antecedent dry conditions persistent high- pressure systems have shown to amplify air temperature anomalies during major European heatwaves, and even instigate extreme conditions in surrounding regions (self-propagation; Miralles *et al.*, 2014). However, there are large uncertainties in the magnitude of this land- atmosphere coupling and its importance for heatwaves in other regions and under future climate conditions. Other potential precursors (e.g. anomalies in sea surface temperatures) remain less explored.

Differently, climate dynamics largely drive other extreme events. For example, depending on the region, extreme precipitation is triggered by extratropical depressions, tropical cyclones, convective systems or upper-level cut-off lows, which frequently cause severe floods, large socio-economic impacts and sometimes human causalities. However, observed trends in extreme precipitation are often uncertain, and in some regions (e.g. the Mediterranean) model projections do not even agree on the sign of future changes (Intergovernmental Panel on Climate Change, 2014). Developing long-term and homogeneous time series of weather extremes and advancing on the understanding of the atmospheric circulation responses to climate change are the main challenges to advance on these issues. Moreover, it is necessary to move towards a sub-daily characterization of these extremes, which is the most relevant timescale to quantify their severity and associated impacts. Similarly, the assessment of changes in wind-related extremes is also hampered by intrinsic difficulties to measure wind and by the quality and temporal homogeneity of wind observations. These limitations in the observational record also pose challenges to the development of statistical models capable of reproducing the tails of the distribution or the spatial mapping of these extremes.

Droughts are among the most complex and hazardous extreme events, with noticeable agricultural, hydrological, environmental and socio-economic consequences (Wilhite and Pulwarty, 2017). There is considerable uncertainty in the magnitude of drought trends, both globally and for many regions. Available instrumental records of precipitation-based drought indices do not reveal significant drying trends globally (since at least the 1950s; Spinoni *et al.*, 2019). However, warming of the atmosphere by human-made climate change can affect drought severity by increasing the atmospheric evaporative demand (AED). The uncertainties associated with future climate change projections in drought severity are also large. Major issues concern the relative role of radiative forcing *vs* vegetation fertilizing CO_2 effects (Vicente-Serrano *et al.*, 2020a), the complex processes affecting AED and its varying importance across drought types, and the choice of metrics for drought quantification (Vicente-Serrano *et al.*, 2020b). Progress requires an improved representation of eco- physiological processes in the current generation of Earth System Models. Besides, there is an urgent need for accurate and long-term available measurements of soil moisture and actual evapotranspiration, which are poorly sampled and understood.

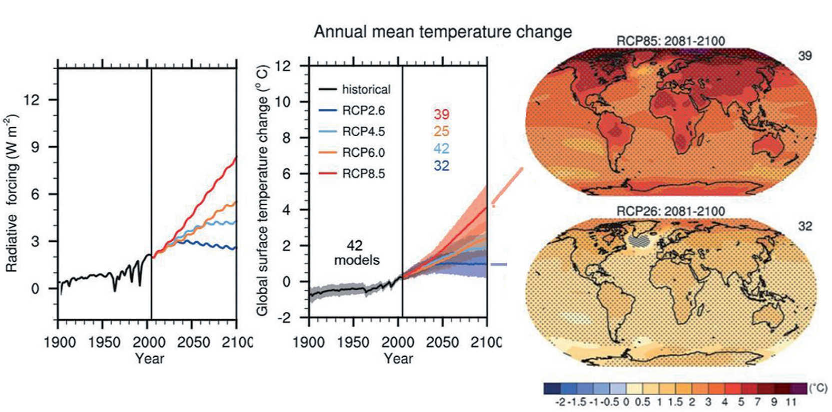
Some of the extreme events in Figure 3 are also the principal triggers of other hazards (see Challenge 3 in Thematic 14). For example, extreme precipitation and severe storms are responsible for flash floods affecting urban areas and river catchments, landslides, soil erosion and other geomorphological hazards. Advances rely on improvements in the identification and monitoring of relevant processes, their representation in impact models and the assembly of the latter with climate models. Similarly, droughts are a leading factor of forest fires, along with extreme heat, low relative humidity and gusty winds, and assessing the relative roles and interactions of these factors and implementing them in forest fire risk models is also a priority (Turco *et al.*, 2018). There are also pressing needs to develop end-to-end attribution studies of extreme events that quantify the human contribution to changing risks in the associated impacts of extreme events, which requires cross-disciplinary development.

Human and natural systems are particularly vulnerable to compound events (a combination of events, not necessarily extremes, that lead to significant impacts) or to concurrent climate extremes (i.e., multiple extremes of the same or different type occurring at the same time or in sequence at either the same place or at remotely-linked locations). In recent years, these events have received considerable attention (Zscheischler *et al.*, 2018), since they have disproportionate impacts through additive or even multiplicative effects. A complex chain of effects are usually in the origin of compound and concurrent events, e.g. mutually reinforcing cycles, which are still poorly diagnosed and understood. The best-known example is the relationship between droughts and heatwaves, or the simultaneous occurrence of heatwaves in remote regions of the same hemisphere. However, the state of knowledge of these events is at its infancy. Understanding the interaction of processes associated with different types of extremes is mandatory to characterize the physical drivers better and improve the predictive skill of current models regarding these events.

3.4. Future projections

Climate change impact, adaptation and mitigation research and policymaking require information on the foreseeable long-term (century time scale) projection of the climate (typically along the 21st century). Global Climate Models (GCMs) are the primary source for this information. GCMs simulate numerically the global dynamics of the climate system components (atmosphere, hydrosphere, cryosphere, land, and biosphere), as well as the physical and biochemical interactions between them. This includes the energy and water cycles, as well as biogeochemical cycles (Challenge 3) in the case of Earth System Models (ESMs). These simulations are computed over global grids with prescribed resolution (typically hundreds of kilometres and sub-daily time steps)

FIGURE 4—Historical and future (for different scenarios, in colours) radiative forcing (left) and resulting global air temperature change (middle, w.r.t. the 1981-2000 reference period) as simulated by the CMIP5 multi-model ensemble (spread around the solid lines, which represent the multi-model mean). The spatial patterns for the end of the century (2081-2100) for high- and low-end emission scenarios are shown in the right panels Credits: Adapted from Intergovernmental Panel on Climate Change (2014).



considering alternative scenarios as plausible future pathways for socio-economic factors (such as world population growth, economic development and technological progress) and climate and mitigation policies (Shared Socio-economic Pathways, SSP). The scenarios account for the range of inherent uncertainty associated with human decisions and result in different trajectories of greenhouse gases concentrations and radiative forcing for the climate system (Representative Concentration Pathways, RCPs) encompassing low, medium and high emissions (typically RCP2.6, RCP4.5 and RCP8.5, respectively) with the corresponding ensemble of climate change projections (Figure 4).

Although the most considerable uncertainties in future climate projections stem from human actions (scenario uncertainty, Figure 4), there are also model-related uncertainties affecting the climate projections for a given scenario. These are associated with intrinsic limitations and imperfections of GCMs such as the limited spatial resolution (e.g. hampering the explicit resolution of cloud physics, which are parameterized); an incomplete understanding of Earth system components (e.g. dynamic ice sheet processes) and their interactions (e.g. land- atmosphere feedbacks; Seneviratne *et al.*, 2010); and missing processes (e.g. plant physiology; Brodribb *et al.*, 2020). The reduction of these model uncertainties is currently a priority in order to constrain climate projections and better inform adaption. This has fostered continuous model improvement in both complexity (from the initial atmosphere-ocean coupled models to the current Earth System Models, ESMs) and spatial resolution. Therefore, supporting the continuous validation and improvement of GCMs is a critical task for the credibility of model results and the confidence in climate projections. This, in turn, requires sustained technological development, investment on high-performance computing facilities and international collaborative effort. Ensembles of different models are used to sample structural model uncertainty, with each model providing climate projections under the same forcing conditions (multi-model ensemble; shading in Figure 4). Selecting the subset of models that better resemble the magnitude and trends in observations as a way to constrain future projections has been questioned (Herrera-Estrada and Sheffield, 2017). Alternative approaches are emerging and include weighting models according to each model's ability to reproduce observations using either empirical relationships (emergent constraints) or process- based frameworks (e.g. Bayesian techniques with perturbed model parameters; Xie *et al.*, 2015).

Model projections are also affected by internal variability (climate 'noise' from natural processes in the coupled system). Different to model formulation, internal variability is largely irreducible (as it is an intrinsic property of the system) and its uncertainty tends to dominate near-term projections at continental scales (e.g. up to half of the mid-century multi- model spread over North America or Europe). This means that climate projections must be probabilistic, especially at regional and decadal scales, which represents a challenge for climate change communication (Deser *et al.*, 2020). The uncertainty from internal variability can be sampled from a large ensemble of initially-perturbed simulations with a single climate model under a particular scenario. Important challenges concern the initialization process, the quantification of internal variability and its contribution to climate projections, or the ensemble size, which may require up to ~102 members, depending on the climate field, region, spatio-temporal scale and time horizon. These large ensembles are challenging in terms of high-performance computing facilities, long-term storage, data distribution and access, requiring technological development and big data management (Thematic 11).

Although GCMs are the primary tools used to generate climate predictions, they have limitations to assess climate change impacts at small spatial scales due to their limited resolution (typically 100-200 km). These limitations make strongly necessary to develop and improve methodologies to generate accurate information for climate change projections at local to regional scale. Generally, two main downscaling approaches have been established to bridge the gap between the coarse-scale information provided by GCMs and the regional/local climate information required for climate impact studies (Christensen *et al.*, 2008). On the one hand, dynamical downscaling is based on the use of Regional Climate Models (RCMs) to simulate the climate over a limited region of interest (e.g. Europe) driven at the boundaries by a GCM. RCMs include an improved representation of small-scale processes since they are run at high resolutions (typically 10-50 km). Dynamical downscaling activities are organized by the Coordinated Regional Climate Downscaling Experiment (CORDEX; Gutowski *et al.*, 2016) over fourteen domains worldwide (typically at 44 km resolution, but higher in some domains, e.g. 11 km in Europe). These simulations are done in coordination with the Coupled Model Intercomparison Project (CMIP, https://www.wcrp-climate.org/wgcm-cmip) and provide an additional regional dataset with higher resolution to analyze regional climate change. Despite their higher resolution and improved representation of processes, the added value of RCMs for regional climate changes is not apparent and further research is needed to properly assess the particular merits, benefits and uncertainty of the global and regional components. Given the rapidly increasing spatial resolution of global models (e.g. HigResMIP), it has been argued that RCMs may no longer be required in the coming years, so there is a pressing need for the development of more comprehensive (e.g. atmosphere-ocean coupled, convection-permitting) RCMs.

On the other hand, empirical/statistical downscaling is based on statistical transfer functions linking global circulation predictors (given by the GCMs) to local variables of interest. These empirical functions, which range from simple bias adjustment algorithms to more complex prognosis methods, are learned from historical data using both model outputs and observations. Statistical downscaling is typically applied over small areas and not at a continental scale, but there are ongoing collaborations to compare and produce CORDEX-like projections with these methods (e.g. the VALUE initiative; Maraun *et al.*, 2015). Major issues concern the lack of physical grounds in the statistical relationships, the questioned ability of some statistical techniques to extrapolate values out of its historical range from which they were trained, and other implicit assumptions (e.g. stationarity of the statistical relationships).

Current challenges involve the development of more sophisticated techniques that can account for broader domains and complex non-stationary spatiotemporal linkages, including machine learning techniques [e.g. deep neural networks; Baño-Medina *et al.* (2020); Thematic 11].

3.5. Climate services

The impacts and adaptation community widely use climate change projections (both global and regional), so communicating credibility, limitations and uncertainty in a comprehensive form is crucial for impact and adaptation studies and for informing the decision-making processes and policymaking. Climate services play a key role in this process since they develop actionable sectoral products to meet the particular requirements of the sectoral applications and considering the end-to-end role of uncertainty for the particular application.

Climate services rely on climate data, and hence the first challenge is technological, related to needs that can cope with the exponential growth of data generation, storage and dissemination (see also Thematic 11). This, in turn, requires a sustained international collaborative effort for the development and implementation of standardized methodological approaches. For example, ensembles of multi-model global climate projections are periodically produced (in cycles of approximately 5 years) in the framework of international coordinated experiments such as the CMIP, informing the IPCC Assessment Reports (https://www.ipcc.ch). The latest CMIP6 has contributions of over 40 modelling centres all around the world, resulting in a massive dataset of hundreds of petabytes (Eyring *et al.*, 2016). This information is stored using a federated system (the Earth System Grid Federation, ESGF) which is a crucial international infrastructure providing long term archival and open access to CMIP results.

A second challenge is to translate climate information to policymakers and end-users. This requires the engagement of interested sectors and the resource to multidisciplinary approaches for co-development of useable products. Climate and data scientists must engage with relevant sectoral users and stakeholders that meet the specific requirements of particular applications (e.g. climate impacts in crop yields, as part of the climate services portfolio for agriculture). This is an emerging field that has witnessed an explosion of several international and national initiatives. The best example is the Global Framework for Climate Services (GFCS) (https://gfcs.wmo.int/), promoted by the World Meteorological Organization (WMO) for the development of actionable sectoral products and tools that support and facilitate the use of climate information in specific sectors (e.g. agriculture, energy, hydrology,

FIGURE 5–. COPERNICUS services, including a climate change service providing transparent access to several data sources (satellite, in-situ and model data) to develop sectoral climate services (some end-to-end sectoral services and demonstrators are provided for several sectors). Adapted from https://www.copernicus.eu

biodiversity). The creation of the GFCS has boosted the development of a large number of data portals, frameworks and data services implementing different types of climate services, from generic to sectoral, for different temporal horizons (monitoring, seasonal prediction, climate change projections) and with different user co-development and engagement (Hewitson *et al.*, 2017). An example of generic climate service is the flagship European COPERNICUS programme (Figure 5) operated by different European institutions (ECMWF for climate) in collaboration with groups, companies and institutions from different sectors. COPERNICUS has developed proofs of concepts and demonstrators of generic climate services in several sectors (coastal areas, infrastructure, health, agriculture, insurance, tourism, water management, energy; https://climate.copernicus.eu/sectoral-impacts) and is leading the research and development of climate services in Europe (and worldwide). An example of sectoral service is the FAO Modelling system for agricultural impact of climate change (MOSAICC, http://www.fao.org/in-action/mosaicc) which allows running impact models (hydrology and crop models) driven by climate change data to deliver tailored information on crop production calibrated for the region of interest. A big challenge in this field is the distillation of different (potentially conflicting) lines of evidence (e.g. global and regional climate projections) providing actionable regional information characterizing the different sources of uncertainty [an initial work shows the complexity of this task; (Fernández *et al.*, 2019)]. A technical challenge is that the delivered product must be tailored to the specific user' needs and may not be transferrable to other regions or users of the same sector, therefore requiring a dedicated development.

At a national level, the Spanish national Meteorological Agency (AEMET; http://www.aemet.es/) provides basic climate data services for all temporal scales via its open data service (https://opendata.aemet.es) and collaborates with research groups (including CSIC) to provide sectoral services for relevant national issues (e.g. for drought monitoring). The Spanish Plan for Adaptation to Climate Change (PNACC) also supports initiatives for gathering and harmonizing existing projections (e.g. from CMIP5 and CORDEX) and generating new ones focusing on PNACC applications (Fernández, 2017). For example, the PNACC scenario portal (https://escenarios.adaptecca.es) provides visual and numeric harmonized regional climate projections for essential climate variables and generic derived indices. Notwithstanding these national efforts, there is a lack of a national structure coordinating individual initiatives and services and connecting them with users and stakeholders so they can participate in the co-development of the products.

Besides seasonal forecasts and climate change projections, climate services also deal with real-time monitoring systems. There are climate phenomena for which the forecasting skill is minimal, but monitoring is highly reliable and can provide useful early warning information if the climate phenomenon evolves slowly. An example of the latter is drought monitoring systems (https://monitordesequia.csic.es/monitor), which provide synthetic comprehensible information on the spatial extent of droughts based on climate drought indices that can be translated to different types of impacts (https://droughtmonitor.unl.edu). Drought monitoring systems adapted to defined user requirements need to be developed (e.g. monitoring for specific crops cultivations, better spatial resolution and temporal frequency). An essential issue will be to link drought monitoring information with specific impacts to translate the synthetic climate information to real uses. The development of similar climate services for other climate-related extremes is challenging and underexploited, mainly if they involve non- meteorological factors (e.g., social and land-use factors for wildfire risk).

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