CHALLENGE 4

ABSTRACT

The Polar Regions are key Earth's climate regulators and, hence, any perturbation in their baseline conditions can have global repercussions. Owing their intrinsic particularities such as the presence of huge amounts of sea and continental ice, their terrestrial and marine ecosystems are highly sensitive to temperature fluctuations. In fact, both the Arctic and the Antarctic Peninsula are the regions where temperature has raised most and faster than any other Earth's place. Moreover, other environmental issues related to anthropogenic changes such as the occurrence of contaminants, invasive species, emerging diseases and exploitation of living marine resources are also affecting the Polar Regions. Therefore, sound, detailed and long-term knowledge of the polar systems functioning, interactions and feedbacks is of paramount importance to establish and characterize the main impacts and consequences in both polar and extra-polar latitudes. Only then, efficient and environmentally friendly measures would be established both to mitigate the negative effects of current anthropogenic impacts and to protect polar ecosystems.

KEYWORDS

Arctic
Greenland
Antarctica
polar terrestrial and marine ecosystems
polar oceans
polar amplification
long-range pollutant transport
polar biogeochemical cycles
cryosphere

CHALLENGE 4

GLOBAL CHANGE AT THE POLAR REGIONS

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1. INTRODUCTION AND GENERAL DESCRIPTION

There is growing scientific and political awareness of the importance of Polar Regions (PR) as an integral part of the Earth's climate system, and of the need to ensure their integrity in the context of climate change. Climate change is rapidly altering the global environment, with some of its consequences being more prominent in the PR (Figure 1). The increase of CO_2 concentration levels due to human activities has clearly affected the PR since at least the 1980s, increasing the temperature and consequently inducing ice melting. The effects are revealed as ice retreat at polar glaciers in the Arctic Ocean (Stroeve and Notz, 2018) and in areas of the Antarctic Peninsula (IMBIE Team, 2018). Indeed, 2019 was the second hottest year in the historical (140-yr long) record and a significant reduction of the sea ice extent was recorded in both poles (NOAA, 2020). Such a threat poses a severe risk for the entire planet but also makes the PR exceptional sentinels to monitor and better understand and face global change challenges.

The PR have unique geographical and climatological characteristics, with low temperatures and lack of light during the winter, as well as relatively wide temperature oscillations between day and night during summer. They include the geographical areas most affected by the recent increase of temperatures due to anthropogenic activities (Figure 1). While this warming is clearly affecting the entire North Pole (also known as the Arctic Amplification (AA) phenomenon), temperature changes display a much more complicated spatial and temporal pattern on the Antarctic continent, including an overall warming from the 1950s to early 2010s followed by a significant cooling, as well as larger warming trends in West Antarctica than in East Antarctica. The overall changes in both PR have been attributed to human activities (i.e., increasing concentrations of greenhouse gases, with an additional role of stratospheric ozone depletion in the Antarctica. However, the precise mechanisms proposed to explain the AA (sea-ice loss, reduced outgoing longwave (LW) radiation due to a stable polar temperature profile, increased downward LW heating due to increased water vapor and clouds, and increased poleward energy transport, among others) or the asymmetric E-W Antarctic warming (e.g., positive trends in the Southern Annular Mode in austral summer and autumn), and their relative importance still remain poorly understood and require large research efforts.

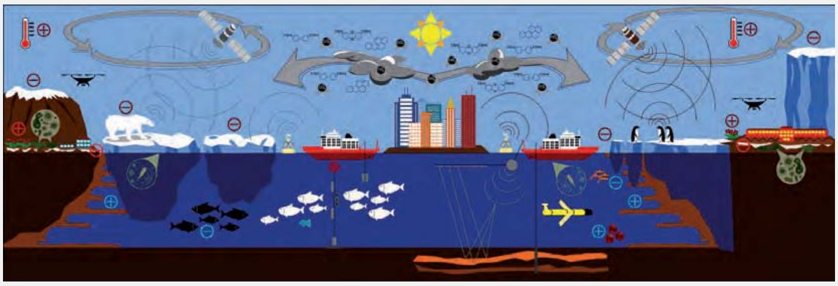
On the other hand, the Polar Oceans are undergoing a profound transformation (see also Thematic 13). The rapid decline in Arctic sea ice extent (SIE) and volume, clearly illustrates the sensitivity of PR to global warming (Figure 1). The ratio of decrease in September sea ice minima is estimated in 12.8 ± 2.3 % per decade (IPCC, 2019). The proportion of Arctic sea ice at least 5 years old declined from 30 % to 2 % between 1979 and 2018 and over the same period, first-year sea ice proportionally increased from approximately 40 % to 60–70 % (Stroeve and Notz, 2018). June snow cover extent on land in the Arctic declined by 13.4 ± 5.4 % per decade from 1967 to 2018, for a total loss of approximately 2.5 million km^2, predominantly due to the increase of surface air temperature (IPCC, 2019). The annual trends of SIE in Antarctica and its five sectors (Weddell, Ross, Bellingshausen and Amundsen Seas, and Indian and Pacific Oceans) are statistically significant, and the SIE trend of the Antarctic Peninsula cannot be explained by natural climate variability and might be linked to the recent anthropogenic temperature rise (Ludescher et al., 2019).

To date, global mean sea level (GMSL) has increased by ~22 cm since 1880, being among the clearest global responses to anthropogenic global warming. The IPCC Fifth Assessment Report (AR5, 2013) and the Special Report on the Ocean and Cryosphere in a Changing Climate (2019) identified the future evolution of polar ice sheets as one of the most dramatic unknowns in global climate projections, hampering reliable estimations of future GMSL rise. The AR5 estimates were limited by a lack of scientific knowledge of Antarctic ice sheet dynamics, which was identified as a tipping element: "*based on current understanding, only the collapse of marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century*." Quantifying the future and pace of GMSL rise and our long-term commitment to higher seas is essential. For this reason, it is critical to assess the credibility of future climate and GMSL projections, as well as past climate sensitivity estimates. Reconstructing past global climates and their impact on our planet to guide future projections is, however, a challenging task. It requires the recovery of strategically located geophysical and sedimentary sections containing the most continuous and high-resolution (decades to thousands of years) records of processes, rates, mechanisms and impacts of past natural climate variability, including abrupt climate changes and climate tipping points.

At the current pace of CO_2 emissions, global mean temperatures would reach 1.5 °C above pre- industrial levels by the 2040s (2030-2052, [5-95] % confidence level; IPCC, 2019). Earth's paleoclimate records reveal that warming between 1 ºC and 2 ºC (within the Paris Agreement range) and higher (>2 ºC) has resulted in very different states of Greenland and Antarctica ice sheets and wide ranges of GMSL change. Sediment records show the risk of ice sheet melting increases substantially even at 1.5 °C, causing 6-9 meters GMSL rise. Paleoclimate archives in marine sediments show that above 2 °C sustained global warming enhances melting and calving, and catastrophic collapse of ice shelves can occur, before removing marine ice sheets grounded in deep sub-glacial basins.

Long-range atmospheric and oceanic transport of organic pollutants, including legacy Persistent Organic Pollutants (POPs) and contaminants of emerging concern, and their bioaccumulation in polar food webs, represent major threats for both natural ecosystems and humans (Figure 1). Climate change affects both transport and fate of organic contaminants in the abiotic environment, ecological and ecosystem changes, and uptake and accumulation in the food webs. Therefore, it can reshape contaminant exposures in wildlife and humans through both physico-chemical processes and ecosystem-related changes. For instance, the rates of degradation of environmental contaminants can change under changing environmental conditions; melting of ice and snow, as well as thawing of permafrost and warmer temperatures may enhance the release of chemicals that have accumulated in soils, glaciers and surface ocean waters. In the context of combined climatic and

FIGURE 1—Main threats currently affecting the Polar Regions (PR), and some of the main techniques employed to characterize these threats. Minus signs indicate decline (i.e., wild life and sea-ice) whereas plus signs mark increase (i.e., temperature and invasive alien species). Horizontal arrows indicate transport towards PR. See the text for further details.



biogeochemical factors, global change involving different temperatures and organic matter stocks in the sea and land will affect the re-volatilisation and reservoirs of organic contaminants (Cabrerizo et al. 2013). Today, the field of POPs research faces the challenge of quantifying and forecasting the impact of POP contamination in the PR in the absence of a robust understanding of past and present contaminant input, environmental behaviour and biological effects, especially in Antarctica. Developing such robust understanding as well as the main adverse effects on the polar ecosystems is therefore essential. Furthermore, recent studies have witnessed that the levels of some legacy POPs have decreased in the Arctic, reflecting their ban in the last decades under the Stockholm Convention or previous national or international regulations, but are being remobilizing due to climate change. However, the steadily increasing list of new chemicals of concern poses further financial and technical challenges to comprehensively assessing the pollutant occurrence at monitoring stations and their impacts. Impact of organic pollutants can be triggered by the joint effect of complex mixtures rather than individual chemicals, with mechanisms that have received little attention (Cerro-Gálvez et al. 2019). It is of paramount importance to solve these challenges in order to understand the chemical behaviour and interactions of legacy and emerging pollutants.

Trace metals (TMs) occur naturally in the ocean, mostly as colloids or absorbed onto organic and inorganic suspended particles, and tend to accumulate in living organisms and bottom sediments. Some TMs, such as cadmium

(Cd), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn) or zinc (Zn), among others, are critical for marine life and therefore influence the functioning of ocean ecosystems and the global carbon cycle (Figure 1). For example, they play a key function in carbon fixation (Fe and Mn), CO_2 acquisition (Zn, Cd, Co), silica uptake by diatoms (Zn, Cd), calcifiers (Co and Zn), nitrogen fixation and synthesis of photopigments (Fe), nitrification, denitrification and organic nitrogen utilization (Cu and Fe), methane oxidation (Cu), etc. On the other hand, these elements may be present in excess due to human activities and, along with other metals [e.g., arsenic (As); mercury (Hg); lead (Pb)], can negatively affect ecosystem health (Morel and Price, 2003). Despite the recognized importance of these trace elements in the ocean, our ability to exploit the knowledge of their attributes is limited by uncertainties in their sources, sinks, internal cycling and chemical speciation.

Terrestrial ecosystems of PR are hard for life; they are ice covered during a large part of the year and marine ecosystems are affected by seasonal changes in sea ice. However, both harbor microbial communities specially adapted to these conditions and vulnerable to environmental changes (Figure 1). In addition, in the Polar Oceans there are important physico-chemical changes during the warm season, such as a decrease in salinity, an increase in inorganic and organic nutrients and the absorption of CO_2 due to seasonal sea ice melting (Anderson and Jones, 1991). This results in blooms of different groups of phytoplankton and the consequent increases in the abundance, activity and diversity of their immediate predators (zooplankton), as well as of microorganisms (prokaryotes, protists and viruses). In both polar regions, the capacity of marine ecosystems to withstand the cumulative impact of a number of pressures, including climate change, pollution and overexploitation, acting synergistically is of greatest concern and must be investigated.

Polar wildlife is characterized by showing adaptations on physiology, morphology and behaviour that allow species to survive in extremely cold environments. Such adaptations however, make polar species highly vulnerable to environmental changes considering the narrow range of tolerance they can bear (Figure 1). While temperate species can move toward the poles tracking the presence of more suitable environments to scape warming, polar species cannot find new places as they live in the end of the planet, and their probability of extinction increases. Despite the different human fingerprints in the Arctic and Antarctica, there are evidences of changes in the ecosystems of both

PR in the most remote regions. Climate change or contamination, invasive species, emerging diseases, fisheries exploitation are some of the factors contributing to the global change whose effects affect directly or indirectly the animal species inhabiting PR as some of the most iconic species like polar bears (Molnar et al. 2020) or penguins (Barbosa et al. 2012). The identification of the effects of global change on polar species and the underlying mechanisms are fundamental to understand the magnitude of effects and to evaluate their resilience to establish mitigation strategies that alleviate the effects and eventually reverse their consequences. This only can be achieved by developing a set of biological indicators (i.e., population size, breeding success, diet, habitat use, health parameters among others), collecting data at long-term and throughout experimental work.

We have outlined some clear gaps of knowledge of polar systems functioning, interactions, and feedbacks. Only by filling those gaps, we will be able to design and implement sound, effective and environmentally friendly policies to protect these fragile but vital ecosystems, and to mitigate the negative effects of the ongoing anthropogenic impacts. Here, we list nine key-challenges to highlight the gaps of knowledge that currently exist in the different spheres of polar systems (atmosphere, cryosphere, oceans, biosphere, geosphere), and possible ways for tackling them.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Prospective analyses about future research in both Arctic and Antarctica have been recently carried out (ICARP III, 2014, Kennicutt et al., 2015). These analyses have identified a number of relevant questions that should be addressed in the next 20 years to prompt major advances in basic science and develop more effective strategies for adaptation and mitigation of the impacts of human activities. All these questions are directly linked to three of the Sustainable Development Goals defined by the United Nations: 13: Climate Action, 14: Life below water, and 15: Life on land.

The challenges we are presenting in this chapter aim to address the following key questions, which are a synthesis of current high-impact priorities included in Kennicutt et al. (2015) and international polar assessment reports (ICARP III 2014):

2.1. Observations for monitoring, understanding and forecasting

- Establishing observatories as part of observing systems to provide comprehensive measurements over the PR.
- Supporting the development and deployment of new technology to improve our understanding of the physical, ecological and social environments of the PR.

2.2. Global change in PR and associated impacts

- Assessing and understanding the causes of rapid Arctic and Antarctic amplification, including their impacts on atmosphere and ocean circulation and connections to the global climate system.
- Constraining future changes in polar subsystems (marine and terrestrial ice, polar ozone, etc.) and their impacts on the global climate system.
- Benchmarking teleconnections, feedbacks, and ranges of climate variability at decadal and longer temporal scales, their role in the ice sheet response for the last millennia, and their potential to forecast short- and long-term climate trends and impacts on PR.
- Assessing the diverse impacts of climate change and human activities on PR biodiversity and its consequences for ecosystem goods and services and societal impacts.
- Characterizing what is the exposure and response of polar organisms and ecosystems to atmospherically deposited contaminants (e.g. black carbon, mercury, sulphur, POPs, etc.), and determining the perturbations on their sources, biogeochemistry and fate over time.
- Determining which are the impacts of changing seasonality and transitional events on terrestrial and marine polar ecology, biogeochemistry and energy flow, and how changes in extreme events can be used to improve our understanding and forecasting of these impacts.
- Assessing what are the synergistic effects of multiple stressors and environmental change drivers on PR organisms and ecosystems, how the threshold transitions will vary over differential spatial and temporal scales and how they will impact ecosystem functioning and linkages between marine and terrestrial ecosystems under future environmental conditions.
- Determining which food webs are most vulnerable, and which organisms are more likely to disappear.

- Characterizing what is the genomic basis of adaptation in PR organisms and communities.
- Determining how invasive species and range shifts of indigenous species will change polar ecosystems, and how climate change will affect the risk of spreading emerging infectious diseases to PR.

PR and global climate changes

- Enhance understanding and representation of processes of the fully coupled climate system (atmosphere-ocean-ice-permafrost-ecology) at several spatial and temporal timescales, to better constrain future projections.
- Improve our understanding of the physical interrelation between the climates of PR and extra- polar ones to assess global drivers of PR and remote impacts of PR changes.
- Understanding how climate change will affect the physical and biological uptake of CO_2 by the Polar Oceans.
- Determining how changes in freshwater inputs will affect ocean circulation and ecosystem processes.

3. KEY CHALLENGING POINTS

3.1. Stratosphere-troposphere coupling and polar ozone

It is now well established that the stratosphere plays an important role in tropospheric climate, mainly due to ozone loss and recovery, changes in stratospheric water vapor and stratosphere-troposphere (ST) dynamical coupling (Figure 2).

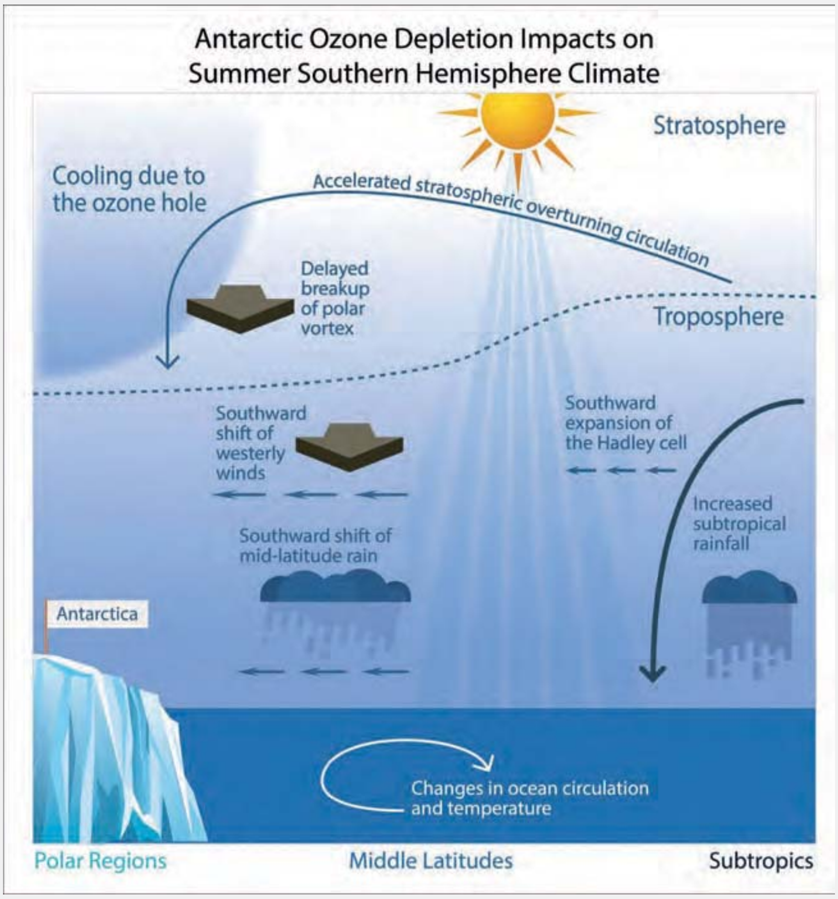
Salient examples of the latter are abrupt temporary warming events of the polar winter stratosphere called Sudden Stratospheric Warmings (SSWs). The associated weakening of the polar vortex (westerly winds in the polar winter stratosphere) can propagate to the troposphere and cause longlasting temperature and precipitation anomalies (e.g. Kidston et al. 2015). Therefore, SSWs are powerful sources of subseasonal-to-seasonal predictability, mainly in the extratropics of the Northern Hemisphere (NH; Challenge 3 in Thematic 12). The modulation of the NH polar vortex by internal modes of variability, such as the Quasi-Biennial Oscillation (QBO) or El Niño-Southern Oscillation (ENSO) also promotes ST coupling and remote teleconnections to the Euro-Atlantic sector, therefore representing additional sources of winter predictability. However, the diversity of drivers of polar vortex variability, their co-occurrence in the short observational records, and relative efficacies in stratosphere-troposphere coupling are major issues. Additional challenges concern the stratospheric vs tropospheric control of SSWs, the dissimilar tropospheric effects of SSWs, the mechanisms of downward propagation and how they are influenced by the initial state of the troposphere and stratosphere.

Despite years of modelling improvement in the stratosphere, no consensus exists on future changes in the NH polar vortex and ST coupling (e.g. Ayarzagüena et al. 2018). State-of-the-art climate models project a tendency to a weakening and longer-lasting NH polar vortex in the future, and slight frequency increases in SSWs. However, there are large discrepancies in the magnitude and sign of the projected changes across models, arguably due to structural differences (e.g. gravity wave parameterizations). Despite the lack of robust changes, many individual models show significant stratospheric responses to climate change, with associated effects in surface projections. Understanding and reducing this uncertainty is critical for narrowing regional climate projections (see also Challenge 2 in this Thematic).

Stratospheric ozone has also important climate implications. Lower stratospheric cooling due to spring Antarctic ozone loss (caused by anthropogenic emissions of ozone depleting substances, ODS) has been the dominant contributor to the observed changes in the summer atmospheric circulation of the SH (e.g. WMO 2018), but with larger uncertainties concerning the impacts in the southern ocean and Antarctic sea ice (Challenge 6 in Thematic 13). The comparatively smaller spring ozone depletion in the Arctic does not lead to robust surface responses in the NH. However, its large interannual variability can cause short-term effects on surface climate (e.g. Calvo et al. 2015). As Arctic ozone is largely determined by the strength of the polar vortex, disentangling their surface effects is of paramount importance for subseasonal-to-seasonal forecasts.

Following the Montreal Protocol and its Amendments, concentrations of ODS are declining since the late 1990s, despite a recent unexpected increase in CFC-11 emissions (WMO 2018). The detection of polar ozone recovery trends is more challenging because of limitations in availability, length and consistence of observations in the stratosphere, the large internal variability and the influence of multiple external forcing (e.g. volcanic eruptions, solar activity, and anthropogenic greenhouse-gases, GHGs). Still, large amounts of ozone

FIGURE 2—Schematic illustration of Southern Hemisphere climate impacts in austral summer associated with Antarctic ozone depletion. Ozone depletion has cooled the Antarctic stratosphere, leading to a delayed breakup of the stratospheric polar vortex and an accelerated stratospheric overturning circulation. Impacts have extended into the troposphere with the region of strong westerly winds and associated rainfall shifted southward, affecting the ocean circulation. The subtropical edge of the tropical circulation has also expanded poleward, leading to reduced precipitation in mid- latitudes and enhanced precipitation in the subtropics. Credit: Figure 5-12: Karpechko, A.Yu. and A.C. Maycock (Lead Authors), M. Abalos, H. Akiyoshi, J.M. Arblaster, C.I. Garfinkel, K.H. Rosenlof, M. Sigmond, Stratospheric Ozone Changes and Climate, Chapter 5 in Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project – Report No. 58, World Meteorological Organization, Geneva, Switzerland, 2018.



depletion have been avoided, and a recovery of spring Antarctic ozone has been detected over 2000-2016 (WMO 2018). The drivers of future ozone trends are ODS, but also well-mixed GHGs (CO2, CH_4 and N_2O), whose radiative effects promote ozone production and poleward transport. ODS play a larger role in Antarctic ozone recovery, while Arctic ozone recovery is more affected by GHGs, with an earlier return to historical values (WMO 2018). However, ozone recovery rates are highly uncertain and scenario dependent. Some well-mixed GHGs interfere in ozone chemistry, while ODS, their substitutes (HFCs, hydrofluorocarbons) and ozone itself act as GHGs. Feedbacks between chemistry and climate also modulate ozone trends and represent foremost issues. For example, ozone recovery partially offsets the radiative effects of GHGs, and GHG-induced changes in transport affect the lifetime of ODS.

Uncertainties are also evident in the impacts of long-term ozone changes on surface climate. In the SH, stratospheric ozone recovery is expected to drive future circulation changes that oppose those of increasing GHGs (WMO 2018). The NH surface responses to Arctic ozone trends remain less explored, even when Arctic ozone is projected to surpass historical levels, yielding a super-recovery. Negative chemistry-climate feedbacks, involving a reduced surface warming, may occur due to ozone-induced changes in stratospheric water vapor. While this feedback is robust, its importance varies among models, representing a major source of uncertainty in future projections (e.g. Chiodo and Polvani 2019).

In summary, there are still important gaps in the understanding and quantification of ozone evolution and its effects on surface climate at intra-seasonal and long-term scales. Major challenges involve feedbacks between ozone chemistry, radiation and atmospheric circulation. High-quality observations in the stratosphere, improved process-based understanding of the interaction between ozone and climate, and the role of natural and anthropogenic factors, along with improved modelling capacities would bring significant advances.

3.2. Polar climate variability and trends as indicators of global change

The recent temperature fluctuations are provoking a large array of impacts in all implied polar spheres (i.e., cryosphere, biosphere, oceans), especially in the polar atmosphere, where the recent warming is significantly altering

Earth's energy budget, temperature gradients, and air chemistry and circulation (Kennicutt et al., 2014; Tesar et al., 2016).

Changing the atmosphere energy budget can affect the main modes of climate variability (North Atlantic Oscillation / Arctic Oscillation (NAO/AO) for the NH and Southern Annular Mode (SAM) for the SH), with remarkable consequences for humans and ecosystems at mid-latitudes. In addition to changes induced by anthropogenic (Challenge 1 in this Thematic) and natural external forcings (Challenge 3 in Thematic 12), these modes of climate variability also experience internal fluctuations and hence exert their influence at several temporal scales, from daily to multidecadal ones. Large efforts have been conducted to describe these modes of climate variability in the NH and understand the associated impacts at seasonal and interannual timescales in the Arctic, through the use of instrumental meteorological and, more recently, satellite datasets. Comparatively, little is known about their SH counterparts affecting the Antarctica due to the poor spatial coverage of long-term instrumental measurements, as a consequence of intrinsic logistical and technical difficulties to maintain equipment in these remote and harsh areas. A long-term funding program to support this long-term monitoring should be promoted, as meteorological instrumental datasets are of paramount importance to characterize and understand recent climate trends.

Furthermore, there is poor understanding of the long-term evolution of these modes of climate variability in both poles before the mid-late twentieth century, which is essential to characterize extreme events and anomalous periods, place recent changes in a historical context and anticipate near-future consequences on PR. Efforts following some recent attempts to characterize their evolution for the last several millennia are strongly encouraged (Hernandez et al., 2020). Achieving this requires participation of CSIC researchers in collaborative national and international initiatives to obtain sedimentary records to reconstruct the long-term evolution of the polar climate modes of variability (see also Challenge 1 in this Thematic).

Climate change can also affect other extratropical (the Scandinavian (SCAND), the East Atlantic Pattern (EA)) and tropical (El Niño - Southern Oscillation (ENSO)) modes of climate variability, which, in turn, modulate the polar ones. Understanding the complex interactions between these modes of climate variability at several timescales is also challenging to better understand the past, present and future evolution of PR.

3.3. Monitoring polar changes with satellites

Processes involving the cryosphere play a central role in PR and remain an important source of uncertainty in projections of future climate change. Therefore, improved understanding of the cryosphere in a changing climate is clearly a "Grand Challenge", as stated by the World Climate Research Program (https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview). A key knowledge gap relates to the impact of thawing permafrost on the global carbon cycle. The magnitude of the positive feedback between a warming climate and the emission of greenhouse gases from natural sources, particularly methane emissions from thawing permafrost, is only starting to be systematically studied. Some experts believe that the effect of this feedback may be catastrophic (tipping point), while others are sceptical about its significance. Drawing the full picture is complicated due to the limited information on the quantity and form of carbon sequestered in permafrost, the inadequate knowledge of arctic biogeochemistry, and the insufficient understanding of the interactions among the terrestrial cryosphere, hydrology and vegetation in northern high latitudes.

In situ observations at both poles are scarce, and satellites offer an opportunity to monitor and understand high-latitude regions. In recent years, the quality and the quantity of remotely sensed data have increased exponentially, allowing comprehensive monitoring of the changes that the PR are undergoing. In terms of number of observations, satellite data dominates by far the volume currently employed for operational mapping tasks and ingested by data assimilation systems. Sea ice thickness and extension, as well as glacier melting rate, are some of the main parameters to monitor changes in PR. However, there are still some data and research gaps, which represent a challenge for the routine integration and assimilation of existing and potential new space-based products into forecasting models. Some of the identified gaps are summarized below (as identified in the context of Kepler EU project, https://kepler-polar.eu/):

- More in situ data in PR are required, in order to improve and validate retrieved parameter and products derived from remote sensing data.
- Resolution and accuracy of the current satellite observations should be enhanced to improve our knowledge on the spatial and temporal changes ongoing on the poles.
- Assessing the melting rates at ice sheets and glaciers with good accuracy is fundamental to predict the GMSL rise (IPCC, 2019).

- The main permafrost variables (i.e. ground temperature profile, active layer thickness, permafrost extent/fraction) cannot be directly observed from space (Bartsch et al., 2014). However, in some cases they can be determined from a combination of modelling and satellite data products. More effort is needed to enhance the permafrost monitoring with remote sensing data.
- Snow depth on sea-ice is very poorly measured from space, while it has a large impact on the sea ice thickness computation, among others.
- The ice thickness is also a very important essential variable with large impact on climate modelling but the uncertainty of satellite measurements is large, especially for evaluation the thickness of thin ice.
- During melting periods, and in the presence of melt-ponds, the accuracy of the estimates of sea ice concentration derived from microwave radiometers considerably decreases. Efforts are required for algorithms to achieve better observations of the ice surface fraction. In parallel, forecast models must be developed to ingest the ice surface fraction.
- After quality tests and validation, these data should be ingested by comprehensive assimilation schemes to feed global reanalyses and Climate Services (Challenge 2 in this Thematic).

3.4. Past ocean dynamics and ice stability under warmer than present conditions

About a third of the Antarctic Ice Sheet (AIS) is a "marine-based ice sheet", which means it rests on bedrock that is below sea level with most of the ice-sheet margin terminating directly in the ocean. Due to the major impacts that AIS melting would have on GMSL, it is also a 'tipping point' (see also Challenge 6 in Thematic 13). Marine-based ice sheets can experience non-linear and rapid melting and calving due to instabilities. Ice shelves in contact with bathymetric features on the sea floor or confined within embayments provide back stress (buttressing) that impedes the seaward flow of the upstream ice and thereby stabilizes the ice sheet. Ice shelf thinning and loss of buttressing can initiate grounding line retreat. If the grounding line is located on bedrock sloping downwards toward the ice sheet interior, initial retreat can trigger a positive feedback, resulting in a self-sustaining process known as Marine Ice Sheet Instability (MISI). The disappearance of ice shelves may allow the formation of ice cliffs, which may be inherently unstable. This ice cliff failure may also lead to ice sheet retreat via a process called Marine Ice Cliff Instability (MICI), that has been hypothesized to cause partial collapse of the marine-based parts of the Antarctic ice sheet within a few centuries (e.g., DeConto and Pollard, 2016).

Key challenges to be addressed include: 1) to understand what processes lead to the destabilisation of ice shelves and ice sheets and how do these relate to global mean atmospheric and sea surface temperature; 2) as climate continues to warm the question becomes, when will we see amplified surface warming around Antarctica, and if there is a temperature threshold for increased mass loss of the land-based ice sheet; 3) what the influence of global ocean circulation is, via a modified thermohaline circulation (THC) and the Antarctic Circumpolar Current (ACC), on the flux of heat across the continental shelf into grounding lines and ice shelf cavities, and 4) the role of associated dense saline water and freshwater feedbacks, including sea-ice, ocean stratification and polynyas on the THC and ACC. To generate this new detailed knowledge of the current state and processes that control ice sheet dynamics and related GMSL changes it is necessary to obtain geological, geophysical, and ideally direct measurements (e.g., CTDs, gliders, ROVs, etc) from beneath ice shelves, ice streams, outlet glaciers and from offshore, coast and open ocean. These data will constrain for example sub ice-shelf bathymetry, ice stream basal conditions, grounding line retreat histories, oceanic current dynamics, past sea surface temperatures, present water masses temperature and salinity profiles, and sea ice distribution, among others.

In particular, marine geophysical and sediment records inform us about ocean and ice sheet-ice/ice shelf variability under different climate conditions and states. These records can provide rates and patterns of ice sheet retreat during past deglaciations and the sensitivity of the ice sheet to past warmer climates (i.e., higher CO_2 concentrations, higher surface temperatures and/or stronger orbital forcing). Because the magnitude of climate forcing projected for the next century has not been experienced by Earth for more than 3 million years, paleoclimate reconstructions of past Greenland and Antarctic ice sheet responses are key in providing critical insights into their future behaviour. The influence of both ocean dynamics and solid Earth deformation on ice sheet dynamics are yet to be assessed against these past policy-relevant warm climates. In addition, warm intervals are not all the same. There were “warmer-than-present” intervals in the past coinciding with higher atmospheric CO_2 concentrations, but also times when CO_2 concentration was at pre-industrial levels, and orbital forcing was more important, causing warming that reduced ice volume dramatically and increased GMSL (Dutton et al., 2015; Wilson et al., 2018). Still, sedimentary core records of past ice sheet change provide key constraints on the long-term (multi-centennial to millennial) cryospheric response to climate and ocean conditions different from today. They capture the 'end-game' scenario that incorporates Earth system feedbacks across timescales (e.g. Colleoni et al., 2018), allowing a more clear picture of the full equilibrium shift (long-term commitments) that might occur under perturbed environmental conditions. Sedimentary records also provide details of ice-ocean sediment interactions and, together with simulations of oceanic circulation coupled to dynamic ice sheet and Earth deformation models grounded in an observation-based understanding of modern processes, provide powerful insights into how the ice sheets responded in the past and will respond in the future.

3.5. Impact of anthropogenic pollutants in the polar regions

The number of chemicals identified in environmental samples using emerging instrumental techniques such as improved high-resolution mass spectrometry is steadily increasing, and better tools have been developed to investigate their combined effects and mechanisms of toxicity. Environmental chemists and toxicologists have moved beyond detecting and quantifying single chemicals to characterize complex mixtures of chemicals in the environment and even delineate their potential effects in organisms and their food webs. Given the clear relevance of mixtures and the fact that thousands of chemicals are occurring in the environment, a shift in the existing regulatory paradigm toward mixture effects is urgently needed (Kortenkamp et al., 2018). In addition, determining the exact impact of organic contaminants on polar ecosystems, or forecasting future scenarios is not yet possible due to the insufficient number of studies and the current lack of representative, suitable and reliable data for the overall polar environments. Contrary to the Arctic, where long-term monitoring data on POPs allow us to investigate temporal trends, data in the Antarctic are much more scarce. Advances in these issues would bring increased capacity of environmental monitoring and diagnostic tools needed to contribute to understand the environmental fate and potential hazards associated with the accumulation of anthropogenic pollutants in the polar environments, or climate driven remobilization of legacy pollutants, and to reduce and prevent the main negative impacts of pollution in the polar ecosystem services. To achieve this, the following challenges should be addressed:

Developing novel diagnostic tools for environmental detection and monitoring of pollutants, and performing long-term observation efforts to track their trends.

Understanding the harmful effects of mixtures of pollutants on the polar biota and ecosystem function in a real scenario based on a multi-stressor food web level approach.

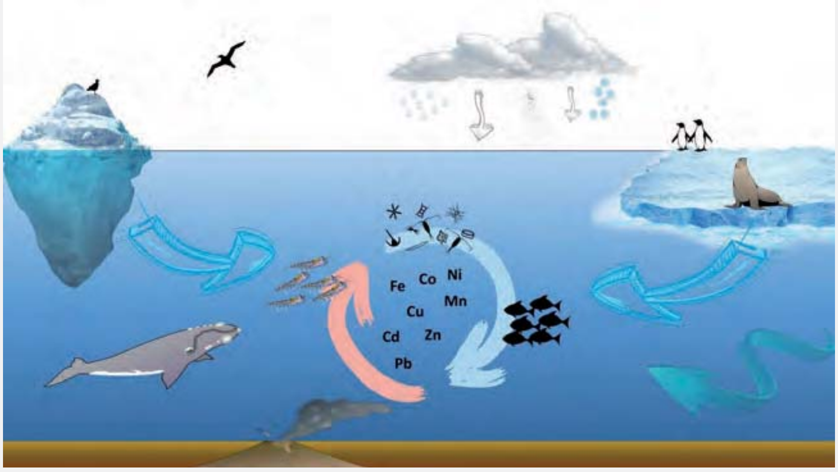
3.6. Biogeochemical cycles of trace metals in the changing Polar Oceans

The Southern Ocean is responsible for the uptake of around 75% of the ocean storage of anthropogenic heat and around 40% of the storage of anthropogenic carbon (Ludicone et al., 2016). Many areas of this ocean are considered as "high-nutrient, low-chlorophyll" (HNLC) regions, where phytoplankton stocks are unable to fully assimilate the high N and P concentrations available in surface waters, and TMs, particularly Fe, play a key role controlling phytoplankton productivity and community structure (Sunda, 2019). Our understanding of the biogeochemical cycles of TMs and their influence on the oceanic productivity in Polar Oceans is still very limited, and changes in the biological productivity by global warming increase further the complexity of these cycles (see also Challenge 6 in Thematic 13).

External sources of TMs to the Antarctic waters are typically low and are not well constrained. Some works suggest the importance of advection of water masses enriched in TMs following contact with continental margins, in addition to atmospheric deposition to surface waters and inputs from hydrothermal vents to bottom waters. In the Arctic Ocean dominant sources of TM include ice melting, atmospheric deposition, river discharges and/or oceanic water mass exchange (Tovar- Sánchez et al., 2010). Recent works have demonstrated that biological recycling is considered an important mechanism in the PR for concentrating and retaining metals in the surface layer waters (Tovar-Sánchez et al., 2007). Until recently, the primary biogeochemical role of marine animals was considered to be as consumers of carbon, converting it into fast-sinking faecal material and returning it to the atmosphere through respiration. However, a number of recent studies suggest that polar marine animals (e.g. krill, penguins, whales) are part of a positive feedback that retains and transports nutrients and TMs to the surface waters, thus enhancing primary productivity and stimulating carbon export (Figure 3).

Therefore, there are a number of sources and processes that control the biogeochemical cycles of trace elements in the polar oceans (i.e. ice melting, atmospheric deposition, biological recycling, etc.) that affect marine primary productivity and ecosystem, and that need to be monitored in order to assess

FIGURE 3–Schematic representation of the biogeochemical cycle of trace metals in the Polar Oceans.



how they are affected under different global change scenarios.

3.7. Tracking pelagic-benthic coupling in the warming cold

Ongoing atmosphere and ocean warming are accelerating glacier melting and consequently increasing fresh water, nutrient and sediment inputs into the water column adjacent to glacier fronts. These processes impact on the biologically mediated atmospheric carbon sequestration and its subsequent incorporation into the sedimentary column, which eventually ameliorate global warming (Isla et al., 2004). Glacier meltwater runoffs can stimulate primary and secondary production; however, intense sediment discharges can clog zooplankton organisms and bury benthos, drastically limiting carbon transfer to the open sea and higher trophic levels and its long-term accumulation in the seabed (Fuentes et al., 2016; Sahade et al., 2018). The rate and extent of all these processes is not completely clear yet, even more when considering other changing and influential environmental factors such as wind and water currents (Isla et al., 2009; Isla et al., 2019). A comprehensive picture of this changing scenario will enable the scientific community to accurately assembly polar and global carbon budgets, fundamental to model and predict future climatic scenarios and properly assess the ecosystem services that the polar regions provide.

3.8. Understanding vulnerability and resilience of Polar aquatic and terrestrial microbial ecosystems to climate change

Warming and ice melting of PR are translated into variations in the composition, activity and diversity of microbial communities, which will have an impact on changes in the food chain and on the life and diversity of polar organisms (Smetacek and Nicol, 2005). In addition, glacier retreat is generating wide expanses of land, which after centuries or millennia covered by ice, are being exposed to the environment and therefore susceptible of colonization through primary succession processes (Garrido-Benavent et al., 2020). Indeed, we have already a fairly amount of information on the biomass and diversity of microorganisms during the warm season, either from natural observations (Vaqué et al., 2017) and experimental approaches in aquatic (Vaqué et al. 2019) and terrestrial systems (Benavent-Gonzalez et al., 2018). Recent reviews emphasize the role of polar microbial and lichen communities as excellent bioindicators of climate change (Maranger et al., 2015; Cavicchioli et al., 2019; Sancho et al., 2019). Nevertheless, the existing diversity of surveys at PR correspond to sporadic analysis at different locations, making difficult to gain insight in specific responses. Likewise, and more concerning is the scarcity or lack of data in the sea ice and underground ice during winter for both aquatic and terrestrial microorganisms. Furthermore, information about microbial community stability and resilience to climatic change is lacking.

We seek to have an ample view of the consequences of the global change in polar microbial communities' resilience and functioning. Thus, a plan for identifying and systematically monitoring microbial, biogeochemical and physicochemical indicators should be established. To achieve this, periodic surveys of microbial community structure at representative locations of PR, in parallel to geochemical and microclimatic parameters recording, must be implemented. Characterization of microbial responses to environmental disturbances can help us to evaluate potential future changes. Potential indicators that could be implemented might be related to phytoplankton biomass changes by monitoring chlorophyll concentration via satellite all year round, although they would require challenging monitoring capabilities. Furthermore, indicators of changes in microbial abundance and distribution associated to environmental changes in sea ice, aquatic and terrestrial ecosystems by the generation of time series in one or various established representative sampling areas in Antarctica (i.e. Livingston and Deception Islands) and Arctic can also be developed. This would require monitoring microbial abundance and activity, biogeochemical and physico-chemical parameters, microclimate conditions at sampling terrestrial points, and of cryptogrammic covers extension for successive years. A third set of indicators might be related to annual and seasonal changes in taxonomic and functional diversity patterns of representative microbial ecosystems such as sea surface microlayer, sea ice, glacier forefields, soils, rocks, and cryptogrammic covers. This monitoring will be performed using different cutting-edge molecular biology techniques: i) Metabarcoding and/or metagenomics analyses to all the samples, and metatranscriptomics analyses when environmental disturbances occur; ii) Specific throughput genome sequence analyses for different aquatic and terrestrial microbial communities in selected scenarios and samples.

3.9. Polar wildlife as indicators of global change

Wildlife is a key component of the ecosystems on which the effects of global change have largely been described (IPBES 2019). Therefore, it should be a crucial part of a set of indicators for monitoring environmental changes. Polar wildlife is characterized by its low diversity in comparison with temperate or tropical environments where the number of species is much higher. For instance, only the 2% of the global fauna can be found in the Arctic (Matveyeva and Chernov 2000). This is even more remarkable in Antarctica due to its geographical isolation, where for instance, there are only one species of insect or 46 species of birds, in contrast with the 3200 and 190 species of the Arctic, respectively. Differences between both PR are also notable in the biomes used by some organisms, since there are no terrestrial vertebrates in Antarctica while in the Arctic both terrestrial and marine mammals are components of its fauna. The low diversity of animals and plants implies simpler food webs in these ecosystems, which make them more susceptible to high impacts by alterations in single components. Moreover, polar organisms are adapted to their specific conditions of low temperature, showing narrow ranges of tolerance and making them especially fragile and vulnerable (Peck et al 2004).

The analysis of the ecological consequences of a changing environment and the understanding of the resilience of its biotic components are required to respond to the challenges posed by global change. Such responses need to be based on a long-term data collection and monitoring of population trends, status, pattern and processes (Taylor et al. 2020). However, even the most necessary information, that is, trends and status, is only available for a few well-known Arctic vertebrates (i.e. caribou, muskoxen, beluga, geese and seabirds, CAFF 2013). The situation is even worse in the Antarctic, with fragmented information available for few species of seabirds and marine mammals. Developing a set of indicators

FIGURE 4—Landscape, wildlife, flora and microorganisms present in the Polar Regions.

for wildlife to monitor the deep environmental changes of PR is, therefore, a pervasive challenge since the last decades.

A first required step is the identification of key species that can be considered sentinels of the environment. These species must meet several characteristics besides easy sampling, such as responding to human activities, exhibiting clearly identifiable responses to environmental changes, affecting the functional structure of biotic interactions (i.e. food web), and showing enough abundance, wide geographic distribution (Hazen et al. 2019). The second step is to define key indicators of ecological change which should be integrative, easily measured, time-varying, sensitive to stress on the system, and with predictable and smoothed responses to stress (Dale and Beyeler 2001). Moreover, as major drivers of polar changes have a global dimension, indicators must consider the type and magnitude of the impacts, as well as the resilience of species and/or processes, considering mitigation strategies at both regional

FIGURE 5—Available infrastructure, equipment and working areas in the Polar Regions.

and global scale. In general, such indicators should include information about population abundance, breeding success, mortality, habitat use, food resources, movement patterns (i.e. dispersion/migration), physiological functions (i.e. thermoregulation) and health status (immune response, parasites/pathogens, diseases, contaminants).

Our knowledge about the wildlife as indicators of environmental change in PR is still far from being acceptable. There is only information of few species and populations, restricted geographical areas, short periods of time and few biological traits. Recent technological advances in different aspects, such as bio-logging, remote sensing, automatic recording equipment, omics techniques and modelling, among others, should be incorporated to traditional techniques, and supported by the establishment of long-term monitoring programs. Ultimately, this challenge will allow us a better understanding of the impact of global change and to predict future environmental scenarios in PR.

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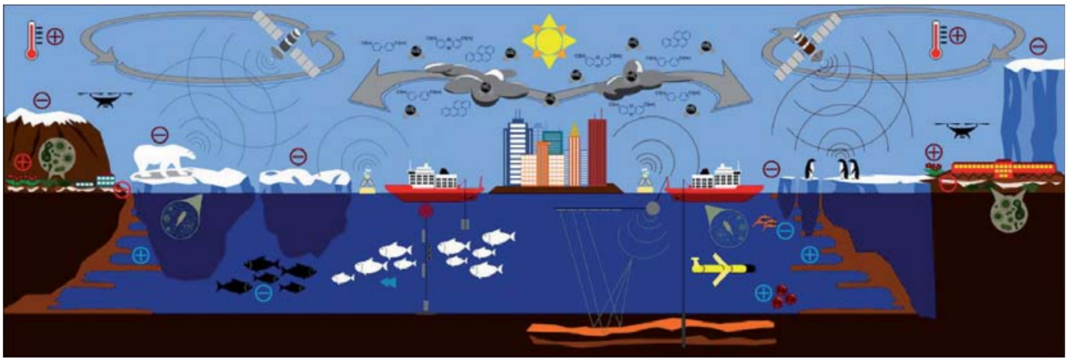
ACADEMIC SLIDE

GLOBAL CHANGE AT POLAR REGIONS—Main threats currently affecting the Polar Regions (PR), and some of the main techniques employed to characterize these threats. Minus signs indicate decline (i.e., wild life and sea-ice) whereas plus signs mark increase (i.e., air temperature and invasive alien species). Horizontal arrows indicate transport towards PR.



DISSEMINATION SLIDE

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Observatorio de zonas polares:
Horizonte 2050

OBJETIVO

Investigación del estado, magnitud y velocidad de cambio de las diferentes áreas polares para predecir su situación en el 2050

TAREAS

1. Definir y validar indicadores de cambio y su tasa de variación
2. Realizar simulaciones numéricas de escenarios futuros
3. Evaluar los peligros y riesgos derivados de los cambios en las zonas polares
4. Desarrollar proyectos de innovación tecnológica para mejorar la adquisición de datos y sistemas de monitorización
5. Incrementar la conciencia social sobre los cambios que sufren los polos y sus consecuencias medioambientales

Participantes: