Decadal Predictions to Climate Services:

How Understanding Climate Change in the Arctic can Support Climate Adaptation Decision-Making across the Northern Hemisphere

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The Arctic is warming twice as fast as the rest of the world, but is intricately connected to it through oceanic and atmospheric circulation. Improved observational networks quantifying these connections and subsequent climate model development are enhancing our ability to describe, model, and predict Arctic climate change and its impact on northern hemisphere weather and climate, including their extremes. These developments have made skilful predictions from a sub-seasonal to a decadal timescale possible. Decadal prediction lies in the middle between short to medium range weather forecasts and global-scale climate change projections, and allows predictions of time-evolving regional climate conditions. These predictions are very relevant to the time period that many communities need in order to plan for the near future and beyond, where adaptation is possible and understandable for a wide range of sectors and new opportunities can be explored.

Here, we talk about climate change in the Arctic, and the mechanisms by which it can influence the northern hemisphere weather and climate. We discuss how recent scientific work on understanding these mechanisms can increase predictive skill. We present case studies demonstrating the potential for these outputs to be translated into climate services across the region, providing specific and relevant information for businesses, communities and policy-makers on evolving future conditions and allowing dynamic adaptation. Finally, we look ahead to the next developments in this area, and discuss the scientific requirements for future progression.

Introduction

The changing climate is affecting all aspects of our environment and society, including weather, food production, biodiversity loss, energy generation and freshwater availability. As many of the changes we are seeing are predicted to continue or accelerate, understanding future climate impacts are a policy priority in many sectors, including risk management, sustainable development and human health. For example, the EU Strategy on adaptation to climate change highlights that economic losses from weather and climate-related extremes are on average already EUR 12 billion

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per year, and that "Adaptation is about understanding, planning and acting to prevent the impacts in the first place, minimise their effects, and address their consequences."

At the science-policy interface, there is therefore a need for robust and reliable climate predictions that can allow for longer-term planning on policy-relevant timescales, beyond the short-term value of weather forecasts and on a more localised and societally-relevant scale than the long-term climate projections. In particular, there is demand to understand the scale and frequency of extreme events that can have devastating impacts, and how it is possible to adapt in a way that will minimise the economic and social costs of these events. The growing need for predictions on a seasonal to decadal timescale is being matched by the developing skill in this field of research, but the challenges of improving our capacity to predict future weather and climate are enormous. Here, we explain how providing policy-relevant information on future weather and climate across Europe involves exploring the huge complexities of a global interconnected system, beginning with understanding the importance of the Arctic climate.

Climate change in the Arctic

It is no surprise to communities living in the northern regions that the Arctic is warming rapidly. The Arctic region has been observed to be losing sea ice, glacial ice and snow cover in all seasons since the satellite era (Stroeve et al., 2007; Meredith et al., 2019). Sea ice is estimated to have declined by around 13% per decade since 1979, and the scale of this loss is unprecedented even in relation to reconstructions of the region over the past 1400 years (Kinniard et al., 2011). In fact, some areas including the surface layers have warmed two or three times faster than the global average since the late 20th century, a phenomenon termed "Arctic amplification" (Serreze & Francis, 2006; Davy et al., 2018).

Arctic amplification has implications for those living across the region and beyond. Over 2 million people live within the Arctic Circle, where the loss of sea ice and changes to glaciers and ice sheets profoundly alter the land- and sea-scape. Warming temperatures in such a sensitive climate lead to destructive thawing (leakages from pipes, collapse of roads and infrastructure, air pollution), and the cities can generate urban heat islands, further exacerbating the effects (Varentsov et al., 2018). Climatic changes degrade Arctic ecosystems, which affects not only endemic species but also the communities that rely on them (Bhatt et al., 2010). Increasing methane emissions from degrading permafrost and warming feedback loops can accelerate the impacts of climate change on a wider scale (Schurr et al., 2015). Indeed, the amplification observed so far is expected to become stronger in the coming years. Increasing our scientific knowledge of warming in the Arctic is therefore a fundamental component of climate science.

Our understanding of the causes and consequences of Arctic warming has grown over recent years, through integrated assessments of observations and results from climate simulations. A central part of climate research is model development and testing: creating and refining computer simulations that aim to tease apart the relative physical, chemical and biological (earth system) processes that make up the climate. Modelling the Arctic is particularly challenging, as it is hard to get long-term, sustained observations to feed into models, and ultimately compare to the outputs. It has taken international efforts to produce shared arrays of instruments that can provide observational data in the Arctic region, such as the international collaboration of the Year of Polar

Prediction (www.polarprediction.net) and the ongoing EU project INTAROS (http://www.intaros.eu).

Observations and models have suggested that the warming can be influenced by local processes in the Arctic, such as the amount of snow cover, cloud cover, sea ice melt or moisture in the air (Shindell, 2007; Stern et al., 2019). For example, periods with higher amplification are associated with larger sea ice loss, and models with larger sea ice loss produce larger amplification ("positive feedback", Kumar et al., 2010). Feedback between the increasing temperatures intensifying sea ice melting, and the darker open waters absorbing more heat radiation, accelerate the warming effect across the Arctic (Winton, 2006).

Arctic amplification has also been shown to be influenced by remote processes, including moisture and heat transport from lower latitudes by air and oceans (Årthun et al., 2019; van der Linden et al., 2019), and direct and indirect aerosol effects (Shindell, 2007). In particular, poleward transport of heat through ocean and atmosphere circulation is considered a major source of temperature increases across the Arctic (Marshall et al., 2014). To the west of Europe, the Atlantic Meridional Overturning Circulation (AMOC, which encompasses part of the Gulf Stream system) can be seen as a large "conveyor belt" system of ocean currents moving heat from the tropics to the Arctic, driven by winds and differences in temperature and salinity. This redistribution of heat across latitudes by the AMOC is an important component of the global climate system.

Although numerous studies have investigated the various processes influencing warming in the Arctic, the relative contribution of these processes is still under debate. For example, Screen & Simmonds (2010) showed that Arctic warming is strongest at the surface, and is consistent with reductions in sea ice cover. However, a model by Alexeev et al. (2005) kept the sea ice effect fixed, and found that energy transport from lower latitudes alone could result in Arctic amplification. Overall, it is now recognised to be "an inherent characteristic of the global climate system, with multiple intertwined causes operating on a spectrum of spatial and temporal scales" (Serreze & Barry, 2011).

Links between Arctic and European climate

Many people are aware of changes in the Arctic, and several of the narratives exploring the effects of climate change have centred around the dramatic transformation being observed in the Polar Regions. For those living below the Arctic Circle, changes in the highest latitudes can seem remote and less significant for day-to-day living. However, a growing body of evidence shows that variability within the Arctic system is associated with corresponding effects much farther afield (e.g., Liang et al., 2020), from weather events across the Northern hemisphere to feedback loops that influence European climate and beyond. As the potential impact of Arctic influences on economies and societies across Europe, North America and Asia are more widely acknowledged, policy-makers are increasingly focused on the Arctic, as shown by the updated EU Arctic strategy.

The idea that the Arctic can influence other regions in a global climate system is of course not new. As far back as the early 1900s, scientists hypothesized that winter conditions in Europe were related to sea ice cover in the Arctic (Hildebrandsson, 1914). However, nearly a century later, the science linking Arctic amplification to weather and climate in the mid-latitudes is still debated. While there are comprehensive underlying theories of the mechanisms by which Arctic changes could also be a driver of this variability, untangling the relative contribution of different factors is an area of ongoing research. Large consortia of researchers are working to progress the scientific understanding in EU-funded projects such as Blue-Action (www.blue-action.eu) and APPLICATE (www.applicate.eu).

Arctic effects on mid-latitude climate

Although the theories underlying links between Arctic warming and midlatitude climate are robust, actually demonstrating they apply in the real world is much more difficult. This is partly due to the complexity of the multiple connections, which vary across time and space. When correlations are observed, it can also be difficult to determine cause and effect. An interesting example relates to the North Atlantic Oscillation (NAO), which is a "see-saw" of atmospheric pressure across the North Atlantic. "Positive" NAO years are thought to lead to high sea ice concentrations in some areas of the Arctic such as the Labrador Sea, possibly due to wind-driven heat fluxes within the ocean (Deser, 2000). However, negative NAO years have in turn been linked back by recent research to the reduction of sea ice extent in the Arctic (Caian et al., 2017). Overall, the mechanisms underlying NAO variability are not well-understood, but the frequency of negative NAO events seem to be increasing, leading to winters becoming colder and more extreme across parts of the northern hemisphere.

Equally, ocean circulation such as the AMOC brings warmer waters north to the Arctic, and changes to the circulation or temperature can increase the heat transport to the region. However, changes in the Arctic can in turn affect the water travelling south. In particular, melting sea ice causes the cold waters of the Arctic region to become warmer and less salty, and therefore less dense, reducing the sinking of cold water part of the circulation system back towards the midlatitudes and beyond (Sevellec et al., 2017). Several other factors, such as the melting of the Greenland ice sheet, the increase in precipitation, and river runoffs, might also lower the salinity and density of the upper North Atlantic, also leading to a potential weakening of the AMOC (Swingedouw et al., 2007). As the warming influence of the AMOC is fundamental to the mild climate of areas of Europe, a slowing of the circulation could have long-term profound implications for societies built around a stable and temperate environment.

Arctic effects on mid-latitude weather

More noticeably for most people, there is increasing discussion that Arctic warming could be a leading contributor to recent unusual weather patterns. Over the past few years there has been an increased frequency and intensity of extreme weather events across the mid-latitudes of the northern hemisphere, from heatwaves in Russia to severe winters in North America (Cohen et al., 2014; Francis & Vavrus, 2012). Studies have suggested that these are likely to become normal for many regions, and have begun to unravel the mechanisms that may link a changing Arctic to weather impacts further south (Walsh 2014).

Many of these mechanisms centre around the effect on atmospheric circulation. The rotation of the Earth influences wind systems that are generated by differences in temperature across space, and flow west to east in the high latitudes. This general flow is accompanied by meanders that create high or low pressure gradients, which ultimately influence the weather. The magnitude and position of these meanders can also be affected by external "forcings," non-local factors that have an influence (Overland et al., 2016). External forcings from remote areas that influence the atmospheric patterns of the midlatitudes are known as teleconnections.

In the Arctic, the reduced sea ice cover and therefore warmer ocean creates warmer and wetter air over the region and beyond (Overland & Wang, 2010). A warming Arctic can create forcings caused by a reduced temperature differential between the Arctic and the lower latitudes. This temperature differential influences a number of atmospheric phenomena, such as the jet stream, a band of fast-flowing air in the troposphere over the North Atlantic, which causes changes in areas of high and low pressure, and therefore the weather we experience at the surface. A reduced latitudinal temperature gradient leads to a weaker jet stream, which can result in systems moving more slowly and a particular weather pattern becoming more persistent over a specific area and reaching lower latitudes (Barnes & Screen, 2015). Persistent weather can itself be the basis of an extreme event, such as drought, flood or heat or cold wave.

Equally, changing temperatures in the stratosphere can cause downward planetary waves, incursions of frigid air to the lower latitudes. These planetary waves can account for most of the recent winter cooling trends over Europe and Asia (Kretschmer et al., 2018.) Interest in these polar vortex instabilities has been heightened by the dramatic impact of sudden temperature drops across North America and Europe in recent years, and the concomitant effects on human health.

Future research

At present, many observational studies support that Arctic amplification is related to weather at lower latitudes but most models do not currently reproduce this connection, leading to a divergence between model and observational studies (Barnes & Screen, 2015; Sellevold et al., 2016). One of the problems is that observational data in the Arctic, in terms of both temporal and spatial coverage, is often insufficient to allow in-depth analysis of such long-term variability. Our climate models are built on our knowledge of the physical processes involved, but the relative contribution and interactions between them are less well understood. The more we can determine whether models are successfully reproducing observed effects, the better representations of actual climate processes in our models become, and the more skilfully we are able to predict the future. Understanding and observing Arctic warming is therefore important to understand the future of the region itself, but is also vital to prepare for the extreme impacts across the globe.

Moving towards predictions

A central purpose for climate science is not only to increase our understanding of the fascinating physical processes governing the global climate system, but to reach a sufficiently detailed representation that we can move beyond recreating the current system to predicting what it will look like in the future. The most high-profile of these predictions, climate models that simulate various scenarios to project global temperature trends up to a century into the future, are now part of our public discourse (e.g. IPCC, 2014). Simple versions of these models have been created since the 1970s, and recent evaluation found that most models were accurate in projecting future global warming (Hausfather et al., 2020).

Decadal predictions

While projections of global mean temperature may be powerful in stimulating discussions about emission scenarios, the scales are so immense that the public cannot relate average wide-ranging changes to the potential impact on their own lives. Most people are more familiar with using weather forecasts that provide sufficient information for flexibility over a few days to weeks. With a rapidly changing climate however, there is a growing need for robust information that allows longer-term planning on a more local scale (Meehl et al., 2014). Decadal climate predictions - predictions typically up to a decade ahead - were for the first time included and discussed in the last IPCC report, and will also contribute to the sixth report from IPCC (Boer et al., 2016). As these decadal climate predictions have increased in skill, now they can begin to support meaningful adaptation for individuals, businesses and policy-makers (Smith et al., 2019).

The difficulty with making predictions longer than a few days or weeks ahead is that proving success can be a long wait. Instead, research on decadal climate prediction focuses on developing models that simulate the actual variations in climate, then testing the credibility of the results by making retrospective forecasts, known as hindcasts. By testing how well the models predict events that have been observed in the past, it is possible to assess the "skill" of the model (e.g., Goddard et al., 2013; Robson et al., 2013). Models may never perfectly predict real world outcomes because so much within the system is stochastic rather than deterministic, but with greater understanding of the mechanisms and interactions in the climate system that provide predictability, we will likely achieve more robust climate predictions (e.g., Årthun et al., 2017; Borchert et al., 2018).

A key aspect of making skilful predictions of weather and climate is understanding where the main part of the predictability comes from. For example, many researchers refer to the "memory" of the ocean, which - slow to move and slow to change - is a great source of long-term predictability (Bjerknes, 1964). In fact, a recent study showed that a cool period in the Earth's climate around 700 years ago is still detectable in the Pacific deep ocean (Gebbie & Huybers, 2019). On a decadal scale, climate predictions show promising results in predicting ocean heat content and ocean surface temperature. In some ocean regions, such as the subpolar North Atlantic, it is possible to predict ocean temperatures several years ahead (e.g., Yeager & Robson, 2017). By looking at evolving ocean temperatures in the North Atlantic it is therefore possible to make predictions about the climate in western Europe years into the future (e.g., Årthun et al., 2017; Smith et al., 2019; Borchert et al., 2019).

Decadal climate predictions are now beginning to reach the stage where the outputs are sufficiently accurate to input into decision-making, and research indicates that there is great potential to further enhance this skill (Smith et al., 2020. Still, climate variability beyond the North Atlantic region and towards the Arctic Ocean appears to be more predictable than models imply (Langehaug et al., 2017). Moreover, in decadal climate predictions, ocean skill does not translate into significant atmospheric skill over northern Europe. Understanding why requires further research into the underlying mechanisms and interactions, and development of Earth System models that can resolve these.

Predicting extremes and abrupt changes

Understanding the predictability of extreme weather systems over Europe that may be influenced by remote teleconnections with the Arctic through atmospheric pathways is much more challenging. With such uncertainty and differences between models and observations still present in understanding of these interactions, making usable predictions for many sectors may be some way off. Yet there is increasing research that shows that these predictions are possible: for example, a recent study showed that the 2015 European heatwave could be predicted using a combination of ocean temperatures and atmospheric and sea ice initial conditions (Mecking et al., 2019).

Furthermore, our understanding of the Arctic impact on climate may allow us to make predictions of low probability but high impact events (Sutton, 2018), such as abrupt changes (or "tipping points"). When the idea of these "large-scale continuities" were brought into the IPCC report two decades ago, they were thought to be extremely low probability and only of concern at incredibly high levels of warming (>5ºC). More recent work has suggested that abrupt changes related to ice in the Arctic and Antarctic could become likely at much lower levels of warming (IPCC, 2019).

Due to the huge potential impacts, it is paramount to correctly estimate any risk of rapid (<10 years) changes, such as shifts in the North Atlantic oceanic circulation that may simply reverse the trend of climate warming over Europe. The Arctic is a key region for triggering such a switch in state in the ocean circulation and considerable uncertainties remain in the complex processes at play, including ocean-sea ice interactions (IPCC, 2019). Such events, even if low-probability among the available models (Sgubin et al., 2017), would have huge impacts on water availability and agriculture across regions of Europe (Sgubin et al., 2019). Furthermore, the potential impacts might also affect remote regions like the Sahelian region (DeFrance et al., 2017), where migration towards Europe is already large and would likely increase due to the severe drought. Preparing to adapt should such catastrophic shifts occur should be a fundamental part of policy-making for the future.

Future research

The success of future research into predictions relies on both observational and computational power. Sustained, long-term observations of the ocean are required, and modellers need to work together with observational scientists to ensure the data needed is prioritised. Making the kind of large-scale yet detailed measurements needed to understand the climate system is a huge commitment of funding, resources and time. Equally, changes in computing infrastructure and how research is organised are needed to match the development of ever more complex computer models, such as larger ensembles and higher resolution. Huge teams of researchers are already working together and sharing computing power to be able to develop and analyse the next stage of climate models, and future policy initiatives such as the Digital Twin of the Ocean proposal as part of the EU Green Deal will be a step forward.

Turning predictions into climate services

Thanks to improved understanding of linkages between atmosphere and oceans in the Arctic and beyond, our scientific prediction skill is improving. For an individual however, these high-level, complex outputs provided by the scientific community are remote. Increasingly, research scientists and stakeholders are coming together to discuss how to translate these data into relevant, timely information that can assist in decision-making on multiple spatiotemporal scales. This targeted output is the essence of a "climate service", supporting businesses, communities and governments who are trying to plan for the next month, season or decade.

Climate services provide climate information in a way that assists decision-making, and so need to strike a balance between what is scientifically possible and what is useful to the end-user. They are collaborative and co-developed by nature, and require a multi-disciplinary approach to tailor and translate applied science into products that are needed. These can range from products that improve economic viability of businesses, to those that improve resilience, safety and security of communities. The diversity and impact of such climate services are exemplified in two very different case studies below.

Case study: polar lows in the Arctic

Predicting the likelihood and severity of extreme or abrupt weather or climate events is a particularly important climate service due to the potential high impact and cost. This can be in the Arctic itself, where communities and industry across the region can be affected by dramatic weather phenomena such as polar lows. Polar lows are short-lived, intense periods of high winds and snowfall, often known as Arctic hurricanes (Kolstad & Bracegirdel, 2008). They can be very difficult to predict or detect, and have been the cause of numerous fatal shipwrecks.

While we are not yet at the stage where we can robustly predict when polar lows will occur, we have increasing capacity to predict systems that allow polar lows to form (Kolstad, 2017; Stoll et al., 2018). These are known as marine cold air outbreaks (MCAO), much larger-scale sustained transports of extremely cold air over an ice-free ocean (Kolstad, 2017). MCAOs set up a large energy imbalance, which can drive such things as polar lows and other extreme weather events. By predicting the likelihood of MCAOs forming, we can create a climate service that provides an evolving measure of risk to those involved in maritime activities in the Arctic.

The climate service being co-developed with industry stakeholders focuses on delivering consistent and accurate risk-informed decision support. Highlighting risks of extreme weather events in the area will help shipping and other maritime activities such as oil and gas platforms improve resilience towards polar lows, ultimately saving lives. Understanding and predicting these types of extreme events are fundamental to many policy frameworks such as the Sendai Framework for Disaster Risk Reduction, which has an explicit focus on climate change-induced risk management through science-based knowledge, and works in complement to the UN Framework Convention on Climate Change.

Case study: Heatwaves in middle latitudes

While there may seem to be no connection between polar lows in the Arctic and heatwaves in the middle latitudes, we are also able to use our increasing understanding of the linkages between the Arctic and midlatitudes to turn predictions of extreme events into climate services across Europe. One of the major climate change challenges faced by southern Europe in particular is the incidence of more frequent, longer and harsher summer heat waves. These heat waves can be devastating to vulnerable communities in warmer regions, such as the elderly, without preparation and adaptation.

The increase in frequency and severity of heatwaves poses a threat to societies that are widely unused to the increasing risks of climate change. Overall, about 8% of deaths across Europe are associated with the short-term health effects of environmental temperatures. In 2003, when temperatures in some parts of Europe were 13 degrees above average, some estimates suggest it was responsible for over 70,000 additional deaths (Robine et al., 2008). In 2019, the June heatwave sweeping across Europe set new all-time temperature records in France, Germany and Spain, although the death toll was significantly smaller. The danger comes not only from the continued high absolute temperatures, but the dramatic difference from "normal" that has an impact on communities affected by heat waves.

Translating modelled predictions of heat waves into climate services that could allow governments and communities to put measures in place to mitigate the effects of climatic extremes is therefore a priority for many policy-makers. Researchers can use epidemiological models to transform the output from operational weather and climate models into predicted impacts on health: initially temperature-attributable mortality, but a seamless forecast of health outcomes exploring the whole range of forecasts is theoretically possible. Public health policies are implemented at a national and regional scale, so there is scope for these types of climate services, designed to provide information from local to national levels to directly inform societal needs. Here we hit a whole new layer of challenges however: predicting climate change is only one factor in a complicated societal and policy landscape, where gaps between rich and poor, urban and rural and the youth and elderly all play a part in how climate change will ultimately play out among our communities (Achebak, 2020; Ballester, 2019).

Conclusions

So, we can trace links from large-scale Arctic warming to local policy-making in the Mediterranean. We are still in an exciting and fast-moving phase of understanding the detailed interconnectedness of the global climate system, both in terms of the underpinning science and the societal implications, but the importance of doing so is growing.

Arctic issues have risen up on the political agenda, with the high-profile EU Arctic policy explicitly designating the region as a global responsibility. Part of the updated policy highlights that "continuously improving our knowledge of the changes happening in the Arctic region, as well as identifying sustainable responses, is essential." Scientists, policy-makers and local communities are increasingly working together to understand both the future research and adaptation actions that are required.

Beyond the Arctic, our understanding of the changing climate and capacity to predict it is a vital component in policy-making, from the Sendai Disaster Risk Framework to the European Green Deal. Meeting our ambitions on global targets such as the UN Sustainable Development Goals will involve planning with as much foresight of the future as possible. Increasing knowledge of climatic changes in the Arctic and the pathways by which it influences the world is therefore now a global challenge. As stated by Virginijus Sinkevičius, Commissioner for Environment, Oceans and Fisheries: "What happens in the Arctic, does not stay in the Arctic. It concerns us all."

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