The Alan Turing Institute

Climate aware and resilient national security: Challenges for the 21st Century

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Climate change has been identified as one of the most serious threats to national security around the world, as it puts pressures on populations, economies, livelihoods and natural resources. Increases in the incidence of extreme weather events and long-term changes in climate are already challenging water and food security and exacerbate state fragility and conflict. Additionally, transitioning to renewable energy will not just influence the power balance between countries, but will also reconfigure trade flows and create new interdependencies around renewables and commodities.

These climate-induced risks directly affect the UK's defence and security capabilities due to factors ranging from increased demand for humanitarian and disaster relief operations; supporting civil authorities and international peace-keeping efforts; infrastructure and equipment planning for operations in increasingly harsh environments; and disruptions to global food production. From a security perspective, the UK needs to find a way to protect a high quality of life for its citizens, work closely with allies and respond to global needs, especially at times of crisis.

International structures have been developed over recent years to discuss climate change and security specifically, including the Climate Security Mechanism and recent discussions at the United Nations Security Council (UNSC). Although climate change has been recognised as a national security threat, the wide range of global physical and socio-economic risks associated with climate change are not fully accounted for in the decisions of the security community.

There are a variety of reasons why action on climate change and security has been challenging. One of these reasons is the lack of appropriate, fit-for-purpose data, and another is the challenge of integrating climate change into decision-making. To integrate climate change models into existing security planning, both at national and international levels the UK needs to be able to develop timely and decisive decision-making regarding threats and hazards as well as plan for contingencies – across all risks.

As the UK's place in geopolitics shifts, it now has an opportunity to cast itself as a `smart' global power. The UK is a world-leader in a number of academic and analytical disciplines essential to quantifying and acting upon climate risks and making decisions in the light of uncertainties. Areas of strength include climate science, machine learning, AI, data analysis, complexity science, and social sciences associated with decision-making under uncertainty and war studies. This is the right moment for the UK to lead the next steps in developing state-of-the-art decision-making tools and processes for the defence and security community on climate change.

This report is one of the first by a cross-disciplinary panel of experts - providing a detailed background of the risks and opportunities that climate change poses to the UK's security, providing evidence based on recent events, and future expectations based on the latest available models. Looking ahead, the report describes an opportunity for the UK to develop more sophisticated and useful forecasting and strategic insight tools that can identify and measure climate risks, provide early warnings for climate security-related tipping points and also help policymakers carry out climate security risk assessments to identify where resilience needs to be built in and/or safeguarded.

Executive summary

The proposed methodologies and tools include data-driven as well as qualitative and future-thinking approaches to ensure that the assessment includes extrapolation of known trends, as well as consideration of outlier possibilities. **A key output will be an improved climate security risk sensing capability**. This could take the form of data-driven assessments of the changing resilience of different factors influencing climate security - spanning climate changes, impacts on resources (e.g. food), and impacts on people (e.g. migration). A further goal would be to issue early warnings of potential climate security tipping points - building on existing work that has demonstrated early warning signals exist for climate and ecological tipping points. Lastly, the research frontier is the development of new causal models that explicitly link climate and socio-economic processes together and can help policymakers create scenarios of future

It is vital that methods and tools for the UK's defence and security community be developed in a way that aligns to existing risk assessment and risk management tools used by organisations such as the National Security Council. This alignment should consider both the research outputs, as well as the decision-making chain in national security to ensure that climate change risks can be truly understood and integrated with other key risks as assessed by the UK security community. We anticipate that the novel methodologies we describe here will be of interest to GCHQ, MoD, and Dstl as well as the Foreign and Commonwealth Office-DFID, the Home Office and the Cabinet Office.

We thus recommend an urgent uplift of the research and decision-making capacity around the anticipated impact of climate-related threats on UK National Security interests in a three- to five-year timeframe. This decision-making capacity should be informed by the best available information and appropriate data-driven and complex systems methods. The scale and interdisciplinary nature of the challenge mean that defence and security should incorporate a range of experts in relation to its changing role and operational requirements including data scientists, climate scientists, designers, futurists and economists. These expert groups, currently organised in subject-oriented academic departments, should be appropriately incentivised to work together and produce focused challenge-oriented research.

One way to undertake this is via a Climate Security Research Centre whose overarching objective will be to improve the ability of the UK's security community to integrate an understanding of climate change risks into decision-making processes. This research initiative should be funded appropriately over five years to design and deliver three, highly-integrated work streams: applied research in climate security risk and resilience, capacity building and development and testing of climate security tools. The research will support the government and relevant agencies by providing targeted, user-driven, policy-relevant evidence on climate-related security risk. The close collaboration between policymakers and academics, will also ensure that this advice is truly integrated in existing decision-making, has a strong data science core and gets to the heart of understanding the increasing climate security risks as the outcome of complex, interconnected, dynamic systems.

1. Introduction

Purpose and scope of the report

In the current geological epoch, the Anthropocene, humans are a major driving force behind changes that have pushed the Earth system out of the stable dynamics of the Holocene[1]. Global pressures are increasing with the increasing demand for food, water, and energy. Recent work has shown that humanity is at risk of moving the planet beyond the boundaries of a safe operating space[2].

Climate change will increasingly lead to human and national security challenges. Between 2009-2019 approximately 250 million people were displaced by a sudden onset of disasters in more than 140 countries[3]. In 2019 alone, a total of 24.9 million people around the world were recorded as displaced, forced from their homes by disaster[4]. Climate change is projected to leave billions of people living outside of the 'climate niche' we live in now and have done for thousands of years.

Climate change is the ultimate 'threat multiplier', worsening existing social, economic, environmental risks and security risks such as conflict, migration, food insecurity, and health. These climate-nduced risks are reducing the resilience (the capacity to deal with change and return to functioning at a similar level) of both social and ecological systems and cause them to cross thresholds leading to a rapid reduction in function which may be difficult to reverse[5].

The ability of Britain to maintain its global leadership and to recast its role outside of the EU is likely to be predicated on the ability to develop timely and decisive decision-making regarding threats and hazards as well as plan for contingencies. This will also allow it to develop the capacity to be resilient to global turbulence and uncertainty in an increasingly hyperconnected world.

"Climate change is the ultimate 'threat multiplier', worsening existing social, economic, environmental risks and security risks such as a conflict, migration, food insecurity, and health."

1 Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., ... & Donges, J. F. (2018). Trajectories of the Earth System in the Anthropocene. Proceedings of the National Academy of Sciences, 115(33), 8252-8259.
2 Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., ... & Nykvist, B. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecology and society, 14(2).
3 iMDC (2020). Global Report on Internal Displacement 2020
4 ibid.
5 Lin, B. B., & Petersen, B. (2013). Resilience, regime shifts, and guided transition under climate change: examining the practical difficulties of managing continually changing systems. Ecology and Society, 18(1).

1. Introduction - purpose and scope of the report

It is noteworthy that an area where the UK has demonstrated global leadership has been on climate change, both through diplomatic brokering at the COPs (annual UNFCCC Climate Summits) and the implementation of national policies around emissions reductions and net-zero. The UK is also hosting the next COP in Glasgow in November 2021. It is in this context that GCHQ and other security bodies who set the UK's national and foreign security agenda, develop their policymaking.

It is broadly acknowledged that the capacity to support decisions which integrate the effects of climate change is limited[6]. Critical policy questions about climate change mitigation, adaptation[7], and planning require better situational intelligence and an improved forecasting capacity among other elemen

In building the transdisciplinary tools and assessments required to answer security policy questions, we need to: characterise and anticipate climate security risks; represent different socio-economic paths, and forecast when systems show increased sensitivity to climate change and begin to break down. Recent developments in data science, statstical modelling and machine learning can help us better model, predict, and forecast climate change risks and impacts relevant to national and international security. We, thus, recommend that the National Security community improves its decision making capacity around the anticipated impact of climate related threats on UK National Security interests. We propose a programme of methodologies and tools that aims to assist the development of insights in an integrated fashion.

We undertook a 4-month scoping study to assess the feasibility and resources needed to develop a new generation of models that include social processes and give us risk forecasting capability for timescales up to 3-5 years as well as indicators and early warnings to support D&S policies and societal resilience. Our study involves several independent but mutually supportive phases:

- **A rapid evidence assessment** of literature on the security implications of climate change, from various sources such as journals, reports, and proceedings that include evidence on climate change and security impacts on individuals, communities and nations.
- **Expert consultation**: We conducted semi-structured interviews with experts across a wide range of relevant disciplines —including climate science, conflict, migration, resilience and security studies— who need to collaborate to capture changes in socio-ecological systems. We also created a repository of key national and international climate security stakeholders (see Appendix Y4).
- **Stakeholder engagement**: In June 2020, we convened senior stakeholders from academia, government and the National intelligence community to discuss emerging research directions and how to best translate them into tools and policies. A summary of the Climate Security Idea Lab can be found here.
- **Synthesis**: We synthesised the above in order to guide future strategic project directions and identify key project stakeholders. We further assessed the opportunities, enablers and resources such as structures and research partnerships needed for the development of a UK research centre toward the goals outlined above.

6 Chris Lambert 2020 - A proposal to consider establishing a UK Office of Strategic Climate Threat Intelligence
7 Please refer to the glossary of terms at the end of this document.

1. Introduction - purpose and scope of the report

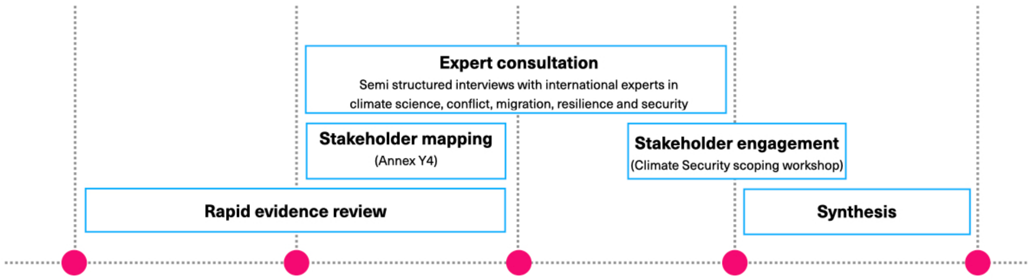

Figure 1. Overview of the synthesis process of this report.

The report has five parts: Chapter 2 describes the characteristics of climate risk. Chapter 3 gives an overview of the types and characteristics of climate security risks. These include risks to resources, livelihoods and social cohesion and transition risks from adaptation and mitigation. We also highlight notable stakeholders and national and international initiatives. Chapter 4 describes the opportunities that exist to anticipate and manage climate security risks through data-driven climate risk assessments, the development of causal models for security and the identification of climate security tipping points. In chapter 5 we discuss related barriers and enablers which are surfaced through a review of the literature and expert consultation. Finally, in chapter 6 we provide a set of recommendations about challenge prioritisation, as well as the coordination, delivery and the scale of the proposed research initiative.

2. Current and future climate change

Climate change is already having a substantial impact on natural and human systems around the world. Greenhouse gas emissions from human activities to date have caused more than 1ºC of global warming above pre-industrial levels, and warming is likely to exceed 1.5ºC between 2030 and 2052 at the current rate of increase[8]. The resulting increased frequency of extreme weather events and other climate change-induced risks will have wide-reaching impacts on socioeconomic and social-ecological systems. The global socioeconomic impacts could be substantial, will likely be nonlinear and have knock-on effects.

Climate risks, in turn, interact with a variety of other sociopolitical, structural, and economic factors and threaten human security, increase the risk of violent conflict[9], affect vital water, energy and transportation infrastructure, and increasingly shape conditions of security and national security policies.

> "The resulting increased frequency of extreme weather events and other climate change-induced risks will have wide-reaching impacts on socioeconomic and social-ecological systems."

Defining risk and resilience

- In this report, risk is used to designate the potential of shocks and stresses to affect the state of a system.
- Risk results from the interaction of hazard, exposure and vulnerability.
- To operationalise risk, we define it as the combination of the likelihood of a hazardous event occurring, multiplied by the impact of that event and the vulnerability of the system of interest to the event.
- Vulnerability is the propensity or predisposition of a system to be adversely affected.
- Resilience is the ability of a system to anticipate, absorb, or recover from the effects of a hazardous event in a timely manner.
- The risk-assessment process often begins with a risk profile, which is developed by identifying the types of events that could occur, the likelihood that events of varying severity will occur, and the impact of those events, including economic, infrastructure, and socio-cultural.
- Risks can be managed by reducing the magnitude of any of the three elements: hazard, exposure and vulnerability.
- We refer to the reduction of likelihood as mitigation and the reduction of the impact of an event as adaptation.
- Mitigation includes actions that are taken to reduce greenhouse gas emissions and adaptation is the process of adjusting to actual or expected climate change effects.

8 IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.

9 Hsiang, S.M., Burke, M. and Miguel, E., 2013. Quantifying the influence of climate on human conflict. Science, 341(6151), p.1235367.

2.1. The characteristics of climate risk

Climate risks are multifaceted, multidimensional, involve both rapid and slow onset disasters and range from local to global; and short-medium-long term. Climate risks are:

Increasing: The physical risks and socioeconomic impacts of climate change are increasing across the globe[10]. Climate-related risks to human and natural systems will be greater for warming of 1.5ºC than at present, and even greater for warming of 2.0ºC[11].

Non Linear: Nearly all modelling of future climate risks is based on an assumption that climate impacts are proportional to their drivers. Yet, there are non-linear changes in weather and climate variables, such as weather extremes[12], and responses of human and natural systems which are not captured in climate risk assessments.

Context-dependent: The impacts of climate change are context dependent as some societies have the capacity to adapt to significant levels of stress, while others suffer severe impacts from lesser pressures. Climate change should be understood as increasing the risk of insecurity[3] contextually, rather than inevitably causing it

Networked: Climate risk is transmitted across time and space due to the linked nature of climates across different regions of the world. Examples of this mechanism include spatial teleconnections such as the El Niño–Southern Oscillation (ENSO). These large-scale climatic events may occur simultaneously (e.g. see the linked Russian heatwave[14] and Pakistan flooding of 2010). Climate risk can also be transmitted across sectors and international boundaries[16] and a combination of interacting processes can result in extreme impacts.

Cascading: Risks to one sector or to one region, can cascade through networks and across multiple regions. Climate risks have multiple direct and indirect pathways that cascade through complex social–ecological systems[17]. The mechanisms of transmission include flows of material, movement of people, and economic and trade linkages[18].

Compounding: Climate risk accumulates leading to gradual build-up of disaster risk in specific locations, often due to a combination of processes, some persistent and/or gradual, such as inadequate water management, land use changes, rural-urban migration, and unplanned urban growth[19]. Security policymakers need to pay attention to how these interactions affect any particular region or, indeed, any particular generic problem.

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17 Challinor, A.J., Adger, W.N., Benton, T.G., Conway, D., Joshi, M. and Frame, D., 2018. Transmission of climate risks across sectors and borders. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2121), p.20170301.
18 Adger, W.N., Eakin, H. and Winkels, A., 2009. Nested and teleconnected vulnerabilities to environmental change. Frontiers in Ecology and the Environment, 7(3), pp.150-157.
19 Maskrey, 1993b; Lavell, 1994

3. Climate change and national and human security

Given the diverse effects of climate change in the biosphere and human societies, the security implications of climate change have attracted increasing attention in policymaking, national intelligence and research circles since the early 2000s[20]. Researchers and policy actors employ different approaches in their analyses of the broad and complex security risks posed by climate change ranging from human to community, state and international security.

We follow the approach taken in the IPCC (Intergovernmental Panel on Climate Change) 5th assessment report and will use a comprehensive understanding of security. This approach is centred on human security, defined as the absence of threat or want, but also addresses the links between different dimensions of security. Human security remains central while the other security dimensions of national interest related to trade, migration, instability, and conflict are likely to have negative effects on human security too.

Climate change directly affects the security of humans and states, both as a matter of disasters that require emergency assistance and logistical aid support, but also dealing with the threats of sea level rise and storms to infrastructure and the possible disruption of social cohesion and mobility patterns due to abrupt changes in food, energy and water resources.

Without action the impacts of climate change are predicted to:

- **Impact 80% of the world's poorest** who will be living in fragile contexts by 2030[21] and increase food prices by 20% for billions of low-income people[22].

- **Put 100 million people at risk** of being pushed into extreme poverty by 2030, and 720 million by 2050 [23].

- Increase the number of people who lack sufficient water from **3.6 billion today to 5 billion by 2050**[24].

- **Force hundreds of millions out of coastal cities**, with a cost to coastal urban areas of more than GBP 800 billion every year by 2050[25].

- Increase the cost of climate-related disasters to a **GBP 2.17 trillion by 2040.**

20 "The World Climate and Security Report 2020." Product of the Expert Group of the International Military Council on Climate and Security. Authors: Steve Brock (CCS), Bastien Alex (IRIS), Oliver Leighton Barrett (CCS), Francesco Femia (CCS), Shiloh Fetzek (CCS), Sherri Goodman (CCS), Deborah Loomis (CCS), Tom Middendorp (Clingendael), Michel Rademaker (HCSS), Louise van Schaik (Clingendael), Julia Tasse (IRIS), Caitlin Werrell (CCS). Edited by Francesco Femia & Caitlin Werrell. Published by the Center for Climate and Security, an institute of the Council on Strategic Risks. Feb 2020.; Campbell, K.M. ed., 2009. Climatic cataclysm: The foreign policy and national security implications of climate change. Brookings Institution Press.; Campbell, K.M. ed., 2009. Climatic cataclysm: The foreign policy and national security implications of climate change. Brookings Institution Press; Gemenne, F., Barnett, J., Adger, W.N. and Dabelko, G.D., 2014. Climate and security: evidence, emerging risks, and a new agenda.; Rüttinger, L., Smith, D.F., Stang, G., Tänzler, D. and Vivekananda, J., 2015. A new climate for peace: Taking action on climate and fragility risks: An Independent Report Commissioned by the G7 Members. Adelphi.; Board, C.M.A., 2014. National security and the accelerating risks of climate change. CNA Corporation.; Louise van Schaik et al, March 2020, Ready for take-off? Military responses to climate change, Clingendael Report, Available at: https://www.clingendael.org/sites/default/files/2020-03/Report_Military_Responses_to_Climate_Change_March_2020 pdf Accessed: 22 June 2020

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23 Hallegatte, S., Bangalore, M., Bonzanigo, L., Fay, M., Kane, T., Narloch, U., Rozenberg, J., Treguer, D. and Vogt-Schilb, A., 2015. Shock waves: managing the impacts of climate change on poverty. The World Bank.

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3. Climate change and national and human security

Additionally, transitioning to renewable energy will not just influence the power balance between countries, but will also reconfigure trade flows[26], create new interdependencies around renewables and commodities and could change the incidence of certain kinds of conflict that are driven by oil, gas, and water rivalries.

Climate impacts will directly affect the UK's Defence and Security capabilities due to factors ranging from increased demand for humanitarian and disaster relief operations; supporting civil authorities and international peace-keeping efforts; disruptions to global food production; and shifts in geopolitics due to conflicts triggered by climate change and associated migration which could have knock on effects on the UK. In fact, it is estimated that double the number of people in non-conflict areas will need humanitarian assistance by 2050 costing USD20 billion[27].

Additionally, the UK's banking sector is particularly exposed to extreme climate events elsewhere in the world due to banking's centrality in the UK's economy and its dependence on global assets[28]. As such, extreme events elsewhere could lead to increased unrest in the UK as a result of abrupt shocks to the UK economy.

"Given the diverse effects of climate change in the biosphere and human societies, the security implications of climate change have attracted increasing attention in policymaking, national intelligence and research circles since the early 2000s."

26 Dellink, R., Hwang, H., Lanzi, E. and Chateau, J., 2017. International trade consequences of climate change.
27 United Nations. Office for the Coordination of Humanitarian Affairs. Policy Analysis and Innovation Section, 2019. World humanitarian data and trends 2018. UN.
28 Mandel, A.(2020). Economics of Climate Change and Green Finance. http://www.bachelier-paris.fr/cours/source/ressources/2020-mandel.pdf

3.1. Types of climate security risks

Climate change affects the biosphere and human societies in various ways, so there are different approaches to security analysis. Human security risks spill over into higher-order security risks, such as political instability, intra-state and inter-state tensions, major natural disasters requiring military responses, mass displacements of people as well as threats to critical resources and infrastructure.

We distinguish 3 types of security risks that are relevant for the national security:

- **Physical risks** to resources and infrastructure which include direct security risks to ecosystems, resources such as food, water and energy and critical infrastructure. To understand the direct physical risks on resources we will use the nexus approach, which considers the interconnected nature of water, land and energy resources and associated infrastructure.
- **Risks to human mobility and social cohesion** that occur when people's livelihoods are threatened and can result in increased violence, conflict and shifts in migratory patterns as a response to social and environmental changes.
- **Transition risks** which include the impacts from the shift towards a low-carbon economy and may entail policy, legal, technology, and market changes to address both climate change mitigation and adaptation requirements. Depending on the nature, speed, and focus of these changes, transition risks may pose varying levels of national and human security risks.

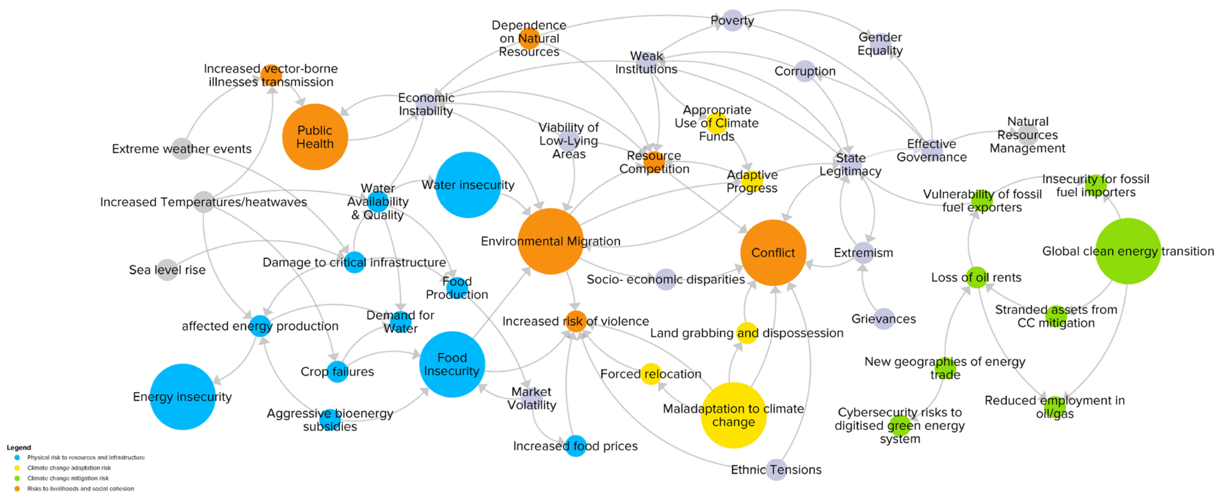

Figure 2. This diagram illustrates the connected nature of climate security risks

3.1.1 Physical Risks to resources and infrastructure

Water, energy, and food are vital for human wellbeing. The three resources are strongly linked and any climate impact on one affects the other two. Climate change and extreme events are also projected to damage a range of critical infrastructure, with water and sanitation, energy, and transportation infrastructure being particularly vulnerable[29].

Agriculture is highly vulnerable to climate impacts with climate shocks being the leading causes of food crises in 2017[30]. Climate variability impacts food security by making production less reliable, which increases food price volatility and reduces access to food[31]. Increases in pests, weeds and diseases put further pressure on food production[32]. The UK imports 40% of the food it consumes, thus impacts of climate change on agriculture across the globe has direct implications for UK food security through trade networks[33].

> "Climate change and extreme events are projected to damage a range of criticial infrastructure, with water and sanitation, energy, and transportation infrastructure being particularly vulnerable."

A key constraint on crop production will be water availability[34] which will decline in regions such as southern Europe, China and the USA[35] affecting irrigation systems and food production. Climate change will affect the availability, quality and quantity of water for potentially billions of people. Water scarcity, exacerbated by climate change, could cost some regions up to 6% of their gross domestic product, while spurring migration and sparking conflict[36].

The energy requirements for irrigation and drinking water further increase when the water has to be brought from greater distances or from deeper groundwater bodies. Conversely, energy production also requires water. Although this is probably most evident for growing biofuels or for mining fossil fuels (e.g. hydraulic fracturing, or 'fracking') hydropower reservoirs and dams can affect the availability and quality of water too.

Extreme weather events will directly impact energy security. The demand for energy is correlated with increases in temperature which will limit our capacity of power generation and the ability to reliably deliver electricity. The links between food and energy have also become quite apparent in recent years as increases in the price of oil lead very quickly to increases in the price of food[37]. Food security can also be endangered by energy demand shocks, for instance, with aggressive bioenergy subsidies and quota policies.

29 Habitat, U.N., 2011. Cities and climate change. Global report on human settlements.
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3.1.2. Risks to human mobility and social cohesion

Migration and displacement

The dynamics between mobility and climate change are multifaceted. Sea level rise and natural disasters and food insecurity can lead to migration but it's difficult to establish direct causation. Climate change affects several drivers of human movement[38], such as conflict, the (perceived) opportunity for a better life in another country and factors affecting governance and the resilience of societies. The uncertainties in the response of global and regional precipitation patterns to climate change and the level of future greenhouse gas emissions make it difficult to accurately predict the increase in climate induced migration.

The type of migration varies according to the type of environmental event[39]. Sea level rise, which makes low-lying coastal regions uninhabitable, can cause permanent migration while extreme weather events may lead to temporary movements within a region. More research is needed to establish which climate impact (e.g. drought, floods, food and water scarcity) contributes the most to displacement.

Most environmental migration takes place internally, as there are typically fewer physical, institutional, and financial barriers to mobility. In most cases, the migration destination is large coastal cities that offer more employment prospects[40] and most migrants return to their original residence as soon as practical.

Environmental migration can be linked to political instability, but the security literature warns us to be wary of cause-effect assumptions[41]. Migration due to a short-term climatic event such as a flood is less likely to cause conflict than migration due to a long-term climatic event such as a drought. This is because migrants responding to short-term climatic events are unlikely to compete with locals in the receiving areas for jobs and public services. The lack of conclusive evidence linking climatic changes with migration and conflict is largely due to the difficulty in adequately modelling the complexity of this relationship.

Security risks in relation to migration should also focus on those who are left behind. The poorest of the poor, are often concentrated in locations that are highly exposed to climate hazards[42] and their livelihoods are directly tied to natural resources[43]. These populations typically have few adaptation options, and may not have the ability to migrate at all which traps them in poverty[44]. More research is needed to compare across countries and populations and forecast which groups are most likely to be subject to climate induced migration.

38 Burrows K., and Kinney P. 2016. "Exploring the Climate Change, Migration and Conflict Nexus". International Journal of Environmental Research and Public Health 13 (4): 443.
39 Hunter, L.M., Luna, J.K. and Norton, R.M., 2015. Environmental dimensions of migration. Annual Review of Sociology, 41, pp.377-397.
40 Fafchamps M., and Shilpi F. 2013. "Determinants of the Choice of Migration Destination". Oxford Bulletin of Economics and Statistics 75 (3): 388– 409.
41 Burrows, K. and Kinney, P.L., 2016. Exploring the climate change, migration and conflict nexus. International journal of environmental research and public health, 13(4), p.443.; Fröhlich, C. and Brzoska, M., 2015. Real Risk or Overrated? Environmental Migration and Violent Conflict.; Bernauer, T., Böhmelt, T. and Koubi, V., 2012. Environmental changes and violent conflict. Environmental Research Letters, 7(1), p.015601.
42 McLeman, R.A., 2011. Settlement abandonment in the context of global environmental change. Global Environmental Change, 21, pp.S108-S120.
43 Burgess, R., Deschenes, O., Donaldson, D. and Greenstone, M., 2014. The unequal effects of weather and climate change: Evidence from mortality in india. Cambridge, United States: Massachusetts Institute of Technology, Department of Economics. Manuscript.
44 Government Office for Science (UK government). 2011. "Migration and global environmental change: future challenges and opportunities". https://www. gov.uk/government/publications/migration and global-environmental-change-future-challengesand-opportunities; Adger, W.N., Arnell, N.W., Black, R., Dercon, S., Geddes, A. and Thomas, D.S., 2015. Focus on environmental risks and migration: causes and consequences. Environmental Research Letters, 10(6), p.060201. McLeman, R.A. and Hunter, L.M., 2010. Migration in the context of vulnerability and adaptation to climate change: insights from analogues. Wiley Interdisciplinary Reviews: Climate Change, 1(3), pp.450-461.

3.1.2 Risks to human mobility and social cohesion

Lastly, there has been a tendency to focus on the negative consequences of climate induced migration, but mobility is a widely used strategy to maintain livelihoods in response to climate and environmental changes[45]. Governments are using planned relocation as a potential policy option to protect affected populations[46]. Even though data on internal environmental migration and planned relocation have improved in recent years[47] we lack comparable quantitative, longitudinal, disaggregated and georeferenced data needed to assess the benefits and risks of different forms of mobility as adaptation strategy.

Conflict

In the past decade, despite the improved data and analytical sophistication, scholars haven't converged on a single robust association between climate and conflict. Several patterns have been reported in detailed syntheses of the literature[48] but more nuanced and context specific analyses are required to firmly establish the security dimensions of climate change[49].

While the impacts of climate change are expected to increase over time, many climate-related disasters are seasonal and affect the dynamics of conflicts differently. For instance, farmers may take to the streets in sporadic protests in response to a weather shock that damages crops. However, when faced with long-term decline in rural incomes as the result of aridity, pressure to move to the cities may mount, possibly leading to different types of social tension.

Most research to date, has focused on the links between climate variability and intrastate conflicts. Shocks to agricultural production in fragile settings, where droughts or floods may disrupt production can lead to localised violence and food insecurity. Climate climate also affects food prices and higher food prices can increase conflict risks[50]. Other analyses have found that with each one-degree increase in temperature interpersonal conflict increased by 2.4% and intergroup conflict by 11.3%.

45 McLeman, R.A. and Hunter, L.M., 2010. Migration in the context of vulnerability and adaptation to climate change: insights from analogues. Wiley Interdisciplinary Reviews: Climate Change, 1(3), pp.450-461.
46 Ionesco, D., Mokhnacheva, D. and Gemenne, F., 2016. The atlas of environmental migration. Taylor & Francis; Benton 2017, https://georgetown.app.box.com/s/v1496c75f0saouevj5yfump4k5am8shz; Ferris, E., 2017. A toolbox: Planning relocations to protect people from disasters and environmental change. Institute for the Study of International Migration, UNHCR, The UN Migration Agency: Georgetown University, Washington DC.
47 Norwegian Refugee Council/Internal Displacement Monitoring Centre (NRC/IDMC), Global Report on Internal Displacement - 2020, available at: https://www.internal-displacement.org/publications/2020-global-report-on-internal-displacement
48 Bernauer, T., Böhmelt, T. and Koubi, V., 2012. Environmental changes and violent conflict. Environmental Research Letters, 7(1), p.015601; Buhaug, H., 2015. Climate–conflict research: some reflections on the way forward. Wiley Interdisciplinary Reviews: Climate Change, 6(3), pp.269-275; Gemenne, F., Barnett, J., Adger, W.N. and Dabelko, G.D., 2014. Climate and security: evidence, emerging risks, and a new agenda.; Gleditsch, N.P., 2012. Whither the weather? Climate change and conflict.; Hsiang, S.M., Burke, M. and Miguel, E., 2013. Quantifying the influence of climate on human conflict. Science, 341(6151), p.1235367; Simmons, E., 2013. Harvesting Peace: Food security, conflict, and cooperation. Environmental Change and Security Program Report, 14(3), p.02.
49 Adam Day and Jessica Caus, Conflict Prevention in an Era of Climate Change: Adapting the UN to Climate-Security Risks (United Nations University: New York, 2020)
50 Katharine J. Mach et al., "Climate as a Risk Factor for Armed Conflict," Nature 571 (2019): 195.

3.1.2 Risks to human mobility and social cohesion

Moreover, the risk for armed conflict increases immediately after climate-related disasters which trigger rebels to act violently. For instance, a drought affecting Mali in June 2009 helped Al-Qaeda recruit fighters and extend its area of operation in the country.

Climate change has the potential to increase rivalry between countries over shared resources such as land, water and food[51] but this is unlikely to lead directly to warfare between states. The links between climate change and conflict are mediated by a number of contextual factors, such as the level of urbanization, poverty, the distribution of land and governance structures[52]. Climate change, thus, represents a challenge to the institutions responsible for addressing acute resource shortages and disputes in a non violent manner[53].

Given these contextual variations, more empirical research is needed to establish the localized ways in which climate change is driving violence. Quantitative climate-conflict studies need to focus on spatial and temporal disaggregation of data at a subnational level.This can reduce the chances of missing important conflict related events or causal mechanisms at a local scale. Future research also needs to provide comparability of findings as most climate-conflict analyses are often conducted at different geographic, temporal and social scales, making comparisons across studies quite challenging.

"While the impacts of climate change are expected to increase over time, many climate-related disasters are seasonal and affect the dynamics of conflicts differently."

51 von Uexkull N. Sustained drought, vulnerability and civil conflict in Sub-Saharan Africa. Polit Geogr. 2014;43(0):16–26.; Halvard Buhaug et al., "Climate Variability, Food Production Shocks, and Violent Conflict in Sub-Saharan Africa," Environmental Research Letters 10 (2015); Benjaminsen TA, Alinon K, Buhaug H, Buseth JT. Does climate change drive land-use conflicts in the Sahel? J Peace Res. 2012;49(1):97–111; Jaroslav Tir and Douglas M. Stinnett, "Weathering Climate Change: Can Institutions Mitigate International Water Conflict?," Journal of Peace Research 49, 1 (2012): 211-225.

52 Nina von Uexküll, "Sustained Drought, Vulnerability and Civil Conflict in Sub-Saharan Africa," Political Geography 43 (2014): 16–26.

53 von Uexkull N, Croicu M, Fjelde H, Buhaug H. Civil conflict sensitivity to growing season drought. Proc Natl Acad Sci U S A. 2016;113(44):12391–6; Jaroslav Tir and Douglas M. Stinnett, "Weathering Climate Change: Can Institutions Mitigate International Water Conflict?," Journal of Peace Research 49, 1 (2012): 211-225.; Linke AM, Witmer FDW, O'Loughlin J, McCabe JT, Tir J. Drought, local institutional contexts, and support for violence in Kenya. J Conflict Resolut. 2017

3.1.3. Transition Security Risks

Risks from climate change adaptation

A safe and just climate transition requires governments to create plans to address resilience and disaster risk[54]. Adaptation is not necessarily or always a benign or risk free process[55] and the security risks arising from adaptation are much less studied by the national intelligence community.

Policy responses that claim to support climate change adaptation can be an additional source of human insecurity[56]. For example[57] in Gambella, Ethiopia, land is being made available to national and foreign investors for agricultural investment as part of national plans for economic modernisation and perceived benefits of increased food security through connection to global food markets. These policies in turn, have increased insecurity by devaluing the capacity of traditional means of resilience (e.g. shifting cultivation) toward hydro-climatic changes[58].

Actions[59] taken in response to climate change can aggravate existing inequalities or grievances over resources and limit access to land and other resources required to maintain livelihoods. For example, in Tahoua, Niger, unreliable rainfall, loss of soil quality and growing populations has prompted agro-pastoralist farmers to adapt by expanding arable farming into areas reserved for pasture, which puts stress on the livelihoods of pastoralists.

Social unrest and violence can also be a result of adaptation policies[60].

Social unrest can develop as a result of involuntary land-use changes, often framed as "land grabbing" by governments. For example, countries dependent on food imports, and which are particularly affected by food shortages made worse by climate stresses such as Saudi Arabia, Japan and South Korea, are increasingly looking for fertile farmland in developing countries like Uganda, Brazil and Kazakhstan[61].

Security risks arise as various governments are moving settlements as part of their adaptation strategies. For example, when people have to leave a forest in order to preserve it as a carbon sink under REDD+ or when people move away from coastal areas in anticipation of sea-level rise or floods. Last but not least, poorly planned relocation of communities that does not adequately consider people's housing needs has been found to create significant new insecurities for those relocated, reduce social capital and trust[62].

There is currently no robust, evidence based framework for assessing and anticipating these climate maladaptation risks that can help policy makers determine the potential side effects of an initiative before it is implemented. There is thus a need to move from an exclusively ex post assessment of observed side effects to an ex ante approach of the expected side effects. Climate risk assessments require better data on lead times required to convert policy plans into implementation, as this translation may be delayed by institutional or societal barriers, and may have residual security risks.

54 van Schaik, L., Born, C., Sellwood, E. and de Bruin, S., 2019. MAKING PEACE WITH CLIMATE ADAPTATION.
55 Barnett J, O'Neill S. Maladaptation. Glob Environ Change 2010, 20:211–213.; Juhola S, Glaas E, Linnér B-O, Neset T-S. Redefining maladaptation. Environ Sci Policy 2016, 55:135–140
56 Macintosh A. Coastal climate hazards and urban planning: how planning responses can lead to maladaptation. Mitig Adapt Strat Glob Change 2013, 18:1035–1055; Zografos, C., Goulden, M.C. and Kallis, G., 2014. Sources of human insecurity in the face of hydro-climatic change. Global environmental change, 29, pp.327-336.
57 Milman, A. and Arsano, Y., 2012. Climate adaptation in highly vulnerable regions: The politics of human security in Gambella, Ethiopia. CLICO case study (on file with authors).
58 http://www.clico.org/
59 Marino, E. and Ribot, J., 2012. Special issue introduction: adding insult to injury: climate change and the inequities of climate intervention; Snorek, J., Renaud, F.G. and Kloos, J., 2014. Divergent adaptation to climate variability: a case study of pastoral and agricultural societies in Niger. Global Environmental Change, 29, pp.371-386
60 Hegre, H., Buhaug, H., Calvin, K.V., Nordkvelle, J., Waldhoff, S.T. and Gilmore, E., 2016. Forecasting civil conflict along the shared socioeconomic pathways. Environmental Research Letters, 11(5), p.054002
61 Cotula, L., 2009. Land grab or development opportunity?: agricultural investment and international land deals in Africa. lied.
62 Gebert, N., Kloos, J., Birkmann, J. and Rosenfeld, T., 2012. Emerging Risks: sea level rise and potentially forced and planned relocation-Case study from Greater Alexandria, Egypt. Institute for Environment and Human Security, United Nations University, Final Report of CLICO project.

world's transition to cleaner energy forms will change the geopolitical map and create new alliances and commercial routes as countries are beginning to rethink their

Risks from climate change mitigation

The intelligence community has mostly focused on the direct physical risks and has overlooked the security implications of climate change mitigation which are likely to bring the biggest geopolitical changes in the next 10 years. This ongoing transition involves a much deeper transformation of the world's energy systems that will have major social, economic and political implications which go well beyond the energy sector[63] .

Nationally, dams often built for hydropower that substitutes fossil-fuel powered energy production are likely to be impacted by changes in water resources affected by climate change. While the damming of major rivers may increase the energy security of upstream states, it could harm water supplies, agricultural productivity and fish stocks in downstream states.

Negative emissions technologies such as bioenergy with carbon capture and storage, enhanced weathering of minerals, afforestation and reforestation can have potential security risks[64]. For example the rapid expansion of biofuels production leads to trade-offs between water use, energy security and food security and is connected to land grabbing, land dispossession[65], and social conflict that reproduces existing inequalities.

The widespread adoption of renewable energy technologies, such as solar panels and electric vehicles is expected to increase the demand for a range of minerals and metals required for their production and it could potentially increase intrastate conflict. For example, in Colombia, a country in which the longest-running interna armed conflict has taken place, various armed groups have controlled and exploited illegal tin, tungsten, tantalum and gold mining resources.

The widespread adoption of renewables drives among other factors the increasing digitalisation of the energy grids which raises additional security and privacy risks. Criminal groups, terrorists, or the security services of hostile countries may hack into the digitized systems that control utilities and grids, either for criminal purposes such as fraud and theft, or to commit military or industrial espionage.

The energy transformation may also deepen existing national political divisions. For example, in many of the countries in which governments have attempted to phase out fossil fuel consumption subsidies, protesters have frequently taken to the streets to oppose these reforms[66].

63 Cavanagh, C. and Benjaminsen, T.A., 2014. Virtual nature, violent accumulation: The 'spectacular failure' of carbon offsetting at a Ugandan National Park. Geoforum, 56, pp.55-65.
64 Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E. and Van Vuuren, D.P., 2016. Biophysical and economic limits to negative CO 2 emissions. Nature climate change, 6(1), pp.42-50.
65 Benjaminsen, T.A. and Bryceson, I., 2012. Conservation, green/blue grabbing and accumulation by dispossession in Tanzania. Journal of Peasant Studies, 39(2), pp.335-355; Lund, J.F., Sungusia, E., Mabele, M.B. and Scheba, A., 2017. Promising change, delivering continuity: REDD+ as conservation fad. World Development, 89, pp.124-139.
66 https://www.iisd.org/gsi/subsidy-watch-blog/how-reforming-fossil-fuel-subsidies-can-go-wrong-lesson-ecuador; Rentschler, J., & Bazilian, M. (2017). Reforming fossil fuel subsidies: drivers, barriers and the state of progress. Climate Policy, 17(7), 891-914.

3.1.3 Transition Security Risks

Internationally, the energy transformation is expected to increase the vulnerability of oil, gas or coal producing countries. It will put pressure on fossil fuel prices and oil rents as well as reconfigure the global supply chains of oil. The loss of oil rents in countries with weak governance could lead to fractures in society and political instability. Countries that are highly dependent on fossil fuel rents are also highly exposed to stranded assets. 12 trillion US dollars of financial value could be lost in the form of stranded assets and international bodies leaving certain countries like Qatar and UAE more exposed to transition risk.

The reduced flow of oil rents could subsequently affect non-oil producing countries and increase the energy insecurity for fossil fuel importers[67] such as Lebanon, Egypt and Jordan. Fossil fuel importing countries are vulnerable to risks of supply disruption and price volatility caused by political instability, terrorist attacks, or armed conflicts that may occur in oil- and gas-exporting nations. Smaller energy-importing countries may also be subject to pressure or coercion with regard to their energy supply[68].

Abrupt changes in climate policy would introduce ‘shocks’ to the global financial system, with wide-ranging impacts[69]. Most financial institutions have large direct and indirect exposure to climate-related sectors, although standard risk assessments do not take these into account.

Last but not least, we have to consider new risk conceptualisations which might evolve in possible dynamic and disruptive futures. For example, will geoengineering pose a significant security risk? Will solar radiation management be weaponised? Will coercive power and therefore potentially military operations be undertaken to protect natural capital or climate global public goods ? (as is effectively already done by `Blue-Water' Navies that protect global maritime shipping routes to ensure the free flow of international trade). The security risks of energy transition and geoengineering are relatively uncharted territory and we lack evidence of the intelligence community considering these risks extensively.

“Actions taken in response to climate change can aggravate existing inequalities or grievances over resources and limit access to land and other resources required to maintain livelihoods.”

67 The secretariat of the Global Commission on the Geopolitics of Energy Transformation en Thjis Van de Graaf, “A New World: The Geopolitics of the Energy Transformation” (Abu Dhabi: IRENA, 2019), http://hdl.handle.net/1854/LU-8588274.

68 Expert Working Group on Climate-related Security Risks, “Iraq Climate-related security risk assessment”, August 2018, https://www.eastwest.ngo/sites/default/files/iraq-climate-relatedsecurity-risk-assessment.pdf.

69 Battiston, S., Mandel, A., Monasterolo, I. et al. A climate stress-test of the financial system. Nature Clim Change 7, 283–288 (2017). https://doi.org/10.1038/nclimate3255

3.2. Climate security stakeholder landsape

Several military and intelligence organizations around the globe now recognize the security dimensions of climate change. Many find themselves increasingly confronted with extreme weather or its impact as a threat multiplier. Organisations, including the UN, NATO and the EU[70] are working on this issue in an attempt to foster cooperation by military organizations in addressing climate change at multiple scales. These stakeholders have different capabilities and the UK National intelligence community should identify the best mechanisms to engage with them.

National

British security and defence strategies already identify climate change as a factor impacting the armed forces, in particular in terms of emergency operations, both at home and overseas. The National Security Council, which consists of 4 ministerial sub- committees considers the threats, hazards, resilience and contingencies, nuclear deterrence and security matters relating to implementing the Strategic Defence and Security Review (SDSR) and the National Security Strategy (including cyber matters) cross-government funds. The Ministry of Defence is supported by the Defence Infrastructure Organisation and the Development, Concepts and Doctrine Centre for assessing future trends.

The climate security landscape in the UK includes various other institutions who have adopted climate security and resilience in their practices. These are the Department for International Development, the Overseas Development Institute and the Foreign and Commonwealth Office. Through the Climate Change Act 2008, the UK introduced legislation that requires the government to undertake a cyclical Climate Change Risk Assessment (CCRA) and National Adaptation Programme.

On the research front, the UK Research and Innovation, the National Environmental Research Council & the Met Office are financing large scale research programmes, such as the Strategic Priorities Fund's Climate Resilience Programme, which aim to better quantify climate risk and design adaptive strategies for the UK. These efforts address national and international security risks but they are not linked to the strategic priorities of the national intelligence community.

Regional

Climate-related security risks have become increasingly mainstream among policy makers across regional organisations. At the regional level there are organizations such as the AU, ASEAN and the EU, which address climate change from the perspectives of both human and state security.

70 Fetzek, S. and van Schaik, L., 2018. Europe's Responsibility to Prepare: Managing climate security risks in a changing world. Center for Climate and Security, Clingendael & Planetary Security Initiative.

3.2. Climate security stakeholder landsape

Intergovernmental

The scale, depth and transnational nature of climate-related security risks challenges the capacity of national and regional governments to respond adequately. Intergovernmental organizations for climate security —such as the United Nations (UN), the European Union (EU), the Organization for Security and Cooperation in Europe (OSCE), the African Union (AU), the Association of Southeast Asian Nations (ASEAN) and Comunidad Andina (CAN)—frame and incorporate climate-related security risks in their agendas

The United Nations Security Council since early 2017 have stressed the need for adequate climate risk assessment and management strategies. At present, there are several initiatives dedicated to the assessment and coordination of climate-related security risks including **the formation of a Group of Friends on climate security, the Climate Security Mechanism** which is the UN's response to climate-related security risks (by UNDP, UNEP, UNSC) and the **independent Climate Security Expert Network** established with support from Sweden and developed further by Germany which helps inform UN responses to climate risk management.

Notable research organisations working on climate security include: **The Center for Climate and Security (CCS)**, a non-partisan institute of the Council on Strategic Risks, **The Climate Diplomacy Initiative** by the German Federal Foreign Office in cooperation with adelphi, **The Planetary Security Initiative (PSI)** and **The Stockholm Climate Security Hub** which provides evidence-based insights on building security and prosperity and strengthening resilience in the face of a changing climate.

Currently, there is no equivalent global hub of standardised, authoritative climate security information that reflects the security and/or social science consensus on the issue, that ranks the confidence of certain relationships in the climate security nexus, or that presents credible climate security futures.

The institutional fragmentation and the transnational nature of climate risk creates difficulties in sharing of data and adopting common data standards and methodologies when hazard monitoring is spread across multiple jurisdictions. There is thus a need for increased multi-disciplinary, multi-agency coordination and collaboration in order to improve forecasting tools.

> "Organisations, including the UN, NATO and the EU are working on this issue in an attempt to foster cooperation by military organizations in addressing climate change at multiple scales."

4. Developing early warning systems for climate security

Could we have predicted the risks we describe above? Could we have anticipated the political impacts of climate change around the world and in the UK? Could we have prepared and helped our allies prepare too? How can we best embed climate risk in our strategic decision-making processes? This section addresses these questions.

Climate risk decision-making is a complex, multi-scale, often nested, process. It takes place on a range of time and spatial scales and involves complex connections (i.e. social networks, governance structures, multiple sectors) that are increasingly important. Importantly it requires the development of expert judgement to be used in ever-changing systems where past data is not a reliable predictor of future data.

Decision support tools like early warning systems for climate security, are critical components of the decision-making chain for climate risk.

It is estimated that implementing effective disaster-risk actions can result in a 90% decrease in people needing international humanitarian assistance after climate-related disasters by 2050 and that spending USD 4 billion on early warning systems in developing countries can have a benefit cost ratio between 4 to 36.

Effective early warning systems embrace all aspects of emergency management, such as: **risk knowledge and assessment; monitoring and predicting the location and intensity of events; disseminating and communicating warnings; and planning a response**. In this chapter we will focus on the opportunities for future work on a) improving our risk knowledge about climate security, and b) developing novel resilience monitoring and early warning systems, while we address the complexity of the decision-making process around climate change in the following chapter.

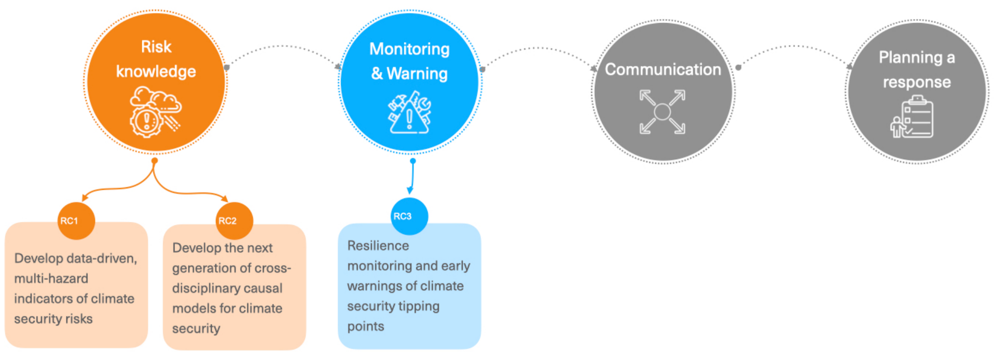

Figure 3. Overview of the components of early warning systems and the identified research challenges around improving climate risk knowledge and resilience monitoring.

71 The cost of doing nothing: The humanitarian price of climate change and how it can be avoided, International Federation of Red Cross and Red Crescent Societies, Geneva, 2019
72 Hallegatte, S., 2012. A cost effective solution to reduce disaster losses in developing countries: hydro-meteorological services, early warning, and evacuation. The World Bank.
73 Grasso, V.F. and Singh, A., 2011. Early warning systems: State-of-art analysis and future directions. Draft report, UNEP

4.1 Improved climate security risk knowledge

Risk analysis has been the centrepiece of security planning for many years. Assessing the risk of climate-related impacts on natural and human systems requires an understanding of changes in the climate system (including natural variability and anthropogenic climate change), as well as changes in socio-economic processes (including climate change mitigation and adaptation actions). Both elements, and the complex interactions between them, are drivers of hazard, exposure and vulnerability of natural and human systems.

The severity of climate change impacts depends not only on the nature of climate hazards and the resilience of natural ecosystems but also on human factors such as the degree of socio-economic development, social inequalities, human adaptive capacities, health status and health services, demographic characteristics, economic livelihood alternatives, etc.

The most fundamental components for understanding and analysing climate-related risks are clear, verifiable, timely, and comparable climate and socio-economic data. These data sources consist of measurements of past and current changes based on historical data (see Appendix Y1), as well as projections of what future changes may look like (see Appendix Y2), informed by modelling and scenario approaches (see Appendix Y3).

Any new climate risk model will rely on current climate modelling capabilities, either explicitly as data sources, or as an integrated part of a larger model. Indeed, the first step of a predictive climate security model will be to predict the change in the climate. However, the predictability of a given climate variable can vary widely, depending on how far in advance you are looking and on what scale.

For example, the weather tomorrow is highly predictable at a very local scale, whereas we can only make projections of the average temperature in 50 years at a regional scale. Seasonal climate forecasts for the next 6 months are commonly produced (Appendix Y2.1), and there is a reasonably good skill in forecasting the El Nino Southern Oscillation (ENSO), which plays a substantial role on these timescales.

There is currently limited skill at forecasting climate data on a multi-year timescale (Appendix Y2.2), although average temperature, and to lesser extent precipitation, have some predictability over some regions and periods. Due to internal variability of the climate system, decadal predictions can only be made in probable ranges, not absolute values. For longer-term projections, e.g. to the end of the century, model and scenario variability are the dominant sources of uncertainty (Appendix Y3.2).

Process-based modelling of the physical climate with so-called general circulation models (GCMs) is a mature field, albeit subject to continual improvement. Well-established methods are used to assimilate data into these models to improve forecasts on hourly to decadal timescales (see appendix Y3 for more details). However, such physical models rarely exist for socio-economic systems. Only in specific cases have socio-economic data been assimilated into such models to improve forecasting - for example, forecasting cholera in Haiti after Hurricane Matthew[74].

74 Pasetto D, Finger F, Camacho A, Grandesso F, Cohuet S, Lemaitre JC, et al. (2018) Near real-time forecasting for cholera decision making in Haiti after Hurricane Matthew. PLoS Comput Biol 14(5): e1006127. https://doi.org/10.1371/journal.pcbi.1006127

4.1 Improved climate security risk knowledge

A different class of process-based models, known as integrated assessment models (IAMs), are commonly used to model how human development and societal choices affect each other and the natural world, and to explore the costs, benefits and impacts of different climate policy and mitigation options. IAMs rely on economic theories and evidence from historical data to model socio-economic systems.

IAMs typically include several separate but interconnected modules which are simplified representations of the economy, the energy system, land use and agriculture, and the climate system. Simplifying these individual systems makes IAMs more computationally feasible, allowing them to run the modules together in a reasonable time and explore how they interact. IAMs form the basis for the development of the Shared Socioeconomic Pathways (SSPs - see Appendix Y3.4).

Where a process-based model does not exist, perhaps because our understanding of a complex system is not good enough to make one, statistical methods can still be used to draw out useful information about the underlying dynamics of the system. This works because whatever the complex system, a change in the balance of feedbacks (closed loops of causality) causes generic changes in resilience. The major caveat here is that other changes in a system that are not related to feedbacks and resilience, can sometimes give rise to the same statistical signals.

Much of our current uncertainty in forecasting climate security risks stems from the fact that, although we may have a reasonable model for the future behaviour of physical climate systems, even on a seasonal or regional basis to some extent, and while IAMs allow us to explore the interactions between physical and socio-economic systems, there remains considerable uncertainty about the outcome of modelling the impact of climate change on real-world systems.

This is because we do not have a fully capable model of the overall system. Hence the driving force for change may be understood, but the response of the system (agriculture, water resources, populations, etc.) to change is not. This is exacerbated in many cases where the factors which govern the response are not only physical but economic, social and of other nature. Also, global models often focus on predicting general patterns at regional scales, but are not designed to address dynamics at local scales, while at the same time, the necessary local scale information may often not be available. There is thus a need to downscale (provide higher resolution) environmental information, and to upscale the information on societies[75].

This is an ideal opportunity to explore how AI and machine learning tools could help by combining different kinds of information. These tools could also help by seeking to understand the system in question through the analysis of previous climate forcing, which produced evidence-based responses. This, in turn, could allow the prediction of outcomes under changed climate forcing.

AI and machine learning can thus be a powerful tool to make predictions about unmodeled outcomes. We outline two possible approaches below:

Firstly, taking existing historical climate and socio-economic data and linking them with a machine learning model, that can then use either long-term climate projections or decadal climate predictions to predict future security risk

Secondly, building a new causal model that explicitly links climate and socio-economic processes together, using a sophisticated cross-disciplinary approach to create projections of future security risk.

75 Verburg, P.H., Dearing, J.A., Dyke, J.G., Van Der Leeuw, S., Seitzinger, S., Steffen, W. and Syvitski, J., 2016. Methods and approaches to modelling the Anthropocene. Global Environmental Change, 39, pp.328-340.

4.1.1 Challenge 1: Integrated Climate Security Risk Assessment

There is an opportunity to develop integrated data-driven, multi-hazard indicators of climate security risks, drawing on global risks meaningful to decision-makers at national and local scales and connecting local and global dynamics.

We can use innovative AI and machine learning approaches to combine physical climate parameters with economic, social, and other non-climate datasets. Such a data-driven statistical approach, incorporating machine learning techniques, is already being applied in certain sectors, for example in the development of a city-based climate change business risk index at the University of Cambridge[76] , or the development of country-specific food insecurity, health and urban climate change risk indices[77], or location-specific indices of crop yield, heat/cold risks in the built environment, and flood risk [78].

A climate risk index translates long-term projections from process-based climate models onto policy-relevant timescales (e.g. 5-20 years) and regional geographies, by applying innovative machine learning techniques to perform the downscaling and bias-correction of the process-based model output (see appendix Y2.3 for more detail on downscaling). Alternatively, the risk index could be based on probabilistic decadal climate forecasts. We can assimilate recent historical climate and weather measurements (from observations or reanalysis products, see appendix Y3.3) to train the machine learning model, and to form a recent historical baseline for the current level of risk.

The index can then calculate the future likelihood of extreme events that exceed climate and weather thresholds specific to the security context, which would be defined in collaboration with security experts and may be informed by data using AI/ML techniques.

If we take temperature as an example variable, the index could be based on certain temperature thresholds (e.g. 25ºC, 30ºC, 35ºC etc.), and return levels of likelihood of a limit being exceeded in any given year (90%, 50%, 10%, 5%, 1% exceedance probability), on multiple time horizons (e.g. 2025 and 2040). These thresholds and timescales can be adapted to suit the relevant regional context of the climate security threat in question.

Different levels of risk can then be analysed and presented. For example, in the Cambridge business climate risk index, Level 1 is the recent historical baseline from observations (or current level of risk). Level 2 is the (downscaled and bias-corrected) climate change modelled view, taken as the multi-model mean of different climate model projections over the period 2018-2059. Level 3 is a stress test view accounting for the tail risk, taking the maximum model pathway plus one standard deviation.

76 Cambridge Climate Change Business Risk Index, in prep: https://www.jbs.cam.ac.uk/fileadmin/user_upload/research/centres/risk/downloads/CCBR_5_OliverCarpenter.pdf
77 NERC EMERGENCE project (Cambridge/Exeter/MetOffice), see e.g.: https://www.metoffice.gov.uk/food-insecurity-index/
78 Cambridge AI4ER CDT, in prep.: https://ai4er-cdt.esc.cam.ac.uk

4.1.1 Challenge 1: Integrated Climate Security Risk Assessment

Such an index, which describes the likely future hazard and its probability of occurrence, can then be combined with specific exposure and vulnerability metrics. These include other environmental and socio-economic data and can provide a comprehensive understanding of the likely current and future climate security risks. For example, an index quantifying heatwave hazard from climate model outputs can be combined with scenarios of societal development based on the Shared Socio-Economic Pathways, to derive a combined index that describes the impacts of different future levels of warming for a range of scenarios of societal development[79]. These indices and metrics must be co-designed with security policy stakeholders to address the needs of the security sector specifically.

There are many opportunities in this space to also apply existing AI and machine learning tools in innovative ways to use new kinds of data to assess the non-climate variables (i.e. human exposure and vulnerability to hazards), as well as using AI to map relationships with the climate data.

There is significant potential to make more use of remotely sensed satellite data for this purpose, and improve on existing machine learning methods to automate detection processes, for example by using unsupervised deep feature learning to detect and characterise unplanned settlements[80], applying machine learning to count the number of structures in refugee camps[81], or detecting and monitoring the number of vehicles on roads[82].

Data from other novel sources can also be incorporated into this process, such as crowdsourced data from social media platforms or mobile phones, for example by using data from Twitter to detect and locate flooding events in the UK[83].

The most significant improvements in the modelling of climate security risks are likely to come from improvements in connecting the elements of security risk with the properties of the climate. However, there is also the opportunity to improve decadal climate forecasts by integrating machine-learning techniques while the field is in its infancy[84].

> "There is an opportunity to develop integrated data-driven, multi-hazard indicators of climate security risks, drawing on global risks meaningful to decision-makers at national and local scales and connecting local and global dynamics."

79 Russo, S., Sillmann, J., Sippel, S. et al. Half a degree and rapid socioeconomic development matter for heatwave risk. Nat Commun., 10, 136 (2019). https://doi.org/10.1038/s41467-018-08070-4
80 Li et al, 2017, Unsupervised Deep Feature Learning for Urban Village Detection from High-Resolution Remote Sensing Images
81 Quinn et al, 2018, Humanitarian applications of machine learning with remote-sensing data: review and case study in refugee settlement mapping
82 Cao et al, 2016, Vehicle detection from highway satellite images via transfer learning
83 Arthur R, et al., 2018, Social sensing of floods in the UK. PLoS ONE 13(1): e0189327.
84 Stephan Rasp, Michael S. Pritchard, Pierre Gentine, "Deep learning to represent subgrid processes in climate models." Proceedings of the National Academy of Sciences Sep 2018, 115 (39) 9684-9689; DOI: 10.1073/pnas.1810286115

4.2.2 Challenge 2: Develop the next generation of cross-disciplinary causal models for climate security

Society can have multiple stable points, where well-being and development and security are established. These can be either sustained peace and prosperity (e.g Europe in the last few decades) or protracted violence (e.g Mexico Narco-War, Sudan Civil War). These points are stable in the respect that usual approaches that push them out of that state, such as diplomacy for peace, subversion to create war, etc., do not work.

A single catastrophe in any one sector can be mitigated by the others, but a combination (coincidence) or cascade (causal) of catastrophes can lead to the collapse of global order. Instead, it requires a compound set of catastrophes - causal or coincidental- to create a chain effect. These are self-amplifying phenomena, just as are tipping points in climate or ecological systems.

For example, the person who starts a political protest makes it incrementally easier for the next person to join them, and so on. Such mathematically positive feedback can propel abrupt change. Beforehand the incumbent regime may show loss of resilience, i.e. slowing recovery from perturbations. In our example, this could take the form of incipient protests decaying (or being quashed) more slowly.

Threats to our ecosystem must consider a wide context consisting of food and water security, rare minerals and carbon fuels, new disruptive technologies, as well as arable land and smooth coastal access. We often take these foundational civilisation cornerstones for granted in the current quasi-static environment. Still, as we step into a new century of accelerated change, we must think of how they all come together to create compound effects and push us over social tipping points.

Some societies can be resilient to these changes due to socio-economic equality or advanced technologies. Others are vulnerable due to previous historical rifts or reliance on imports. Whatever the case, we must recognise that it is not just a cocktail of factors and disturbances that can drive societies past tipping points and lose resilience. The dynamics of the shocks may also be important (e.g. resonance), and these are not easily modelled or understood using data science and machine learning alone.

> "We must recognise that it is not just a cocktail of factors and disturbances that can drive a societies past tipping points and lose resilience."

4.2.2 Challenge 2: Develop the next generation of cross-disciplinary causal models for climate security

Currently, very few research efforts consider all of these effects in an explicit modelling framework. European research centres heavily focus on the socio-economic and political aspects of stability and well-being (e.g Uppsala UCDP, Oslo Peace Institute, German PREVIEW). Other international research hubs focus on regional specific security (ECOWARN) or are methodologically specific (e.g. annual survey of experts or dialogue-based prediction). Few efforts, like the new DARPA World Modeler (2019-), are building multi-disciplinary causal models of the world as a whole. All of these explicitly lack both climate change and social tipping point integration. Many remain pseudo models, rather than the much-needed data-driven sophisticated engines to inform policies and design decisions.

Thus, the research frontier requires a cross-disciplinary modelling programme that examines interdependent causal risks resulting from climate change, migration, and conflict. A collaborative group of experts that span both quantitative causal detection (e.g. statistics, data science) and qualitative mechanics (e.g. political science, psychologists, strategists) should come together and build causal graph models and embed them with actual behaviour of decision dynamics. Together they can create a global engine to feed in climate change data and understand current or even predict future societal impacts (e.g. civil war, migration, famine) for defence and security.

These future scenarios (rather than predictions) will be critical at the 30, 50, and 100-year time scales. Why? Because many of our critical decisions and investments are made in those time scales. Examples range from investment in allies to build a new generation weapon capability (30 years), investment in new national infrastructure (50-100), the development of human-based diplomatic and information networks in emerging strategic regions (30), developing strategic alliances (30-50), invest in R&D that can protect UK's national interests in the century to come (30-100). All of these examples require discrete scenario-based foresight.

4.2. Improved resilience monitoring and warning

Climate risk management starts with a continuous and comprehensive risk analysis where the broad risks must be identified and assessed - as described in the previous section. By identifying risks and assessing their impact on people, assets and ecosystems, it is possible to develop a range of possible responses.

The second step is the development of a management strategy that generally aims to improve adaptation or enhance resilience. Enhancing resilience requires understanding the ability of a system to absorb shocks.

Enhancing resilience requires understanding the ability of a system to absorb shocks. However, the occurrence of shocks is not certain: either their nature, or the nature or size of the impacts, can be uncertain, or their occurrence in time is generally not known. Our ability to anticipate within uncertainty these shocks - within the system, or across scales- is critical for taking timely action. It is also essential for preventing tipping points (also referred to as ‘critical transitions’ or ‘regime shifts’) where a small perturbation can cause a profound shift in a system’s state. These changes are often abrupt and difficult to reverse.

“By identifying risks and assessing their impact on people, assets and ecosystems, it is possible to develop a range of possible responses.”

4.2.1. Challenge 3: Resilience monitoring and early warnings of climate security tipping points

Recently there has been a large amount of research into early warning signals of tipping points. This has revealed the existence of generic early-warning signals that indicate a wide class of systems if a critical threshold is approaching. The basic idea is that before a tipping point, a system loses resilience, which means it recovers more slowly from perturbations (and often is more sensitive to a given perturbation). Existing early warning systems for environmental shocks rarely extend beyond the seasonal timescale and rarely attempt to forecast tipping points.

There is a live opportunity to apply resilience monitoring and tipping point early warning methods to monitor changing risks to climate security in near-real-time. For this, we envision a global 'dashboard' of changing resilience related to climate security, which draws on a range of data sources (detailed below) and issues warnings of potential tipping points, based on early warning indicators, when a set of statistical criteria are met.

We are not referring here to tipping points in the climate system per se (important though they are), but rather to climate-related security tipping points, such as the triggering of mass protests (e.g. the 'Arab Spring') or mass migration. Climate data and weather/climate model forecasts in this context are a 'forcing' of the social-ecological systems that may exhibit changing resilience and tipping points. Specific predictions of future weather/climate perturbations - e.g. a hurricane making landfall, or seasonal forecasts of drought in parts of sub-Saharan Africa - will be flagged up. Alongside this, changes in the statistical properties of weather - i.e. the climate - will be monitored as this also affects the underlying social-ecological systems behaviour.

More targeted and specific early warning systems could then be designed for particular sectors and/or regions where climate security risks are already known to be high, and nested within the 'global dashboard' approach. An established example in a related domain is FEWS-NET, the famine early-warning system for sub-Saharan Africa. This is based on seasonal climate forecast skill but could be augmented with other resilience monitoring and tipping point early warning methods, and additional data sources to turn it into a climate security early warning system.

Identifying pertinent data

The essence of the proposed resilience monitoring and early warning system is to analyse 'big data' sources in an innovative, and as-far-as-possible automated, way. A global resilience dashboard for climate security would necessarily draw on global datasets - including global weather/climate projections, remotely sensed data, market data, and social media.

When it comes to social-ecological systems and the resources they provide, changes in vegetation and its resilience can be monitored from continuous, remotely-sensed time-series data. This includes arable croplands as well as the pastures and other landscapes used for cattle grazing. Animal movement can be inferred from remotely sensed data[85] suggesting that human movement too can be inferred if not directly observed[86].

85 Neumann, W., Martinuzzi, S., Estes, A. B., Pidgeon, A. M., Dettki, H., Ericsson, G., & Radeloff, V. C. (2015). Opportunities for the application of advanced remotely-sensed data in ecological studies of terrestrial animal movement. Movement ecology, 3(1), 8.

86 Li, D., Zhao, X., & Li, X. (2016). Remote sensing of human beings–a perspective from nighttime light. Geo-spatial Information Science, 19(1), 69-79; Sirmacek, B., & Reinartz, P. (2013). Feature analysis for detecting people from remotely sensed images. Journal of Applied Remote Sensing, 7(1), 073594.

4.2.1. Challenge 3: Resilience monitoring and early warnings of climate security tipping points

Remote sensing of other key environmental variables such as soil moisture is mature, and its resilience (e.g. recovery rate of water table depth) can be monitored. Fires and recovery rate from them can be monitored. Disease vectors and their transmission can be inferred. Dangerous oil spills and algal blooms can be detected, and overall water quality can be monitored[87] . Other resources and indicators of their resilience include less visible properties such as food commodity prices.

However, these are available from market price data, which could be analysed for changing recovery rate of fluctuations as a potential forewarning of price spikes. One approach would be to data-mine past events, to identify further sources of data that are pertinent to resilience monitoring and early warning of climate security tipping points.

Refining methods of analysis

Methods of detecting changing resilience and warning of tipping points have already been successfully tested on data prior to past abrupt climate and ecosystem changes. This approach could be extended to testing the methods on data prior to past security tipping points.

A complementary approach would be to use process-based models to identify what the best resilience indicators are and where to monitor them. This approach has been successfully applied to tipping points in the climate system[88], but not yet to climate security tipping points because of a shortage of such models. A statistical caveat here is the need to avoid selection bias - the 'prosecutor's fallacy'[89] - by also examining non-tipping-point cases. Ideally what is needed is a dataset of known past climate security 'events' ideally including some thought to have tipping point dynamics (i.e. where internal feedbacks propelled abrupt change). This might include past famines triggering conflict or large-scale migration (or both).

There is potential benefit from research to use AI to improve tipping point early warning methods. This could be carried out as currently, using artificial data generated from generic models, but more sophisticated approaches are available. There is also the potential to improve seasonal weather forecasts by, for example, the integration of different types of models[90], the elimination of subjective steps within the climate models via machine learning[91], and the global application of regional best practice[92].

87 Mishra, Deepak R., Eurico J. D'Sa, and Sachidananda Mishra (2016). Special Issue "Remote Sensing of Water Resources". Remote Sensing
88 Boulton, C. A., Allison, L. C., & Lenton, T. M. (2014). Early warning signals of Atlantic Meridional Overturning Circulation collapse in a fully coupled climate model. Nature communications, 5(1), 1-9.
89 Boettiger, C., & Hastings, A. (2012). Early warning signals and the prosecutor's fallacy. Proceedings of the Royal Society B: Biological Sciences, 279(1748), 4734-4739.
90 Strazzo, S., D.C. Collins, A. Schepen, Q.J. Wang, E. Becker, and L. Jia, 2019: Application of a Hybrid Statistical–Dynamical System to Seasonal Prediction of North American Temperature and Precipitation. Mon. Wea. Rev., 147, 607–625, https://doi.org/10.1175/MWR-D-18-0156.1
91 Zhou, K., Zheng, Y., Li, B. et al. Forecasting Different Types of Convective Weather: A Deep Learning Approach. J Meteorol Res 33, 797–809 (2019). https://doi.org/10.1007/s13351-019-8162-6
92 Ault, T. R. (2020). On the essentials of drought in a changing climate. Science, 368(6488), 256-260.
93 Barrett, S., & Dannenberg, A. (2014). Sensitivity of collective action to uncertainty about climate tipping points. Nature Climate Change, 4(1), 36-39.

4.2.1. Challenge 3: Resilience monitoring and early warnings of climate security tipping points

Turning warning into useful action

A salient lesson from existing research is that tipping point warnings are often not met with corresponding action, especially if that action is costly, unless the uncertainty around the warning (i.e. a bad outcome) is reduced below a critical level[93]. This reinforces the need for the statistical work mentioned above. Users would need to be fully informed of the statistical nature of the warnings and know how to read the proposed dashboard, as there would always be false positives and false negatives, which research would seek to minimise.

Hence warnings would benefit from being accompanied by scientific advisors that could translate new information for decision makers (in policy or the military) who are fully informed of the corresponding governance principles. This type of risk-response management is already mature in the military - frontline decisions are made on limited and imperfect information - the key offering here is to improve the information.

93 Barrett, S., & Dannenberg, A. (2014). Sensitivity of collective action to uncertainty about climate tipping points. Nature Climate Change, 4(1), 36-39.

Case study: Human migration

As large-scale human migration has been identified as a specific climate-related security concern, a resilience-monitoring and early warning system could be designed combining recent and real time data mining of human movement and its triggers/ correlates, together with future projections of population growth, climate change and associated potential for displacement, and modelling of human movement.

Human movement in a migration sense can be regarded in terms of different resources, familiarity (socio-economic, ethnolinguistic), and safety factors (climate, security, political). Extreme heat is already a direct trigger for human movement, which is escalating. Shortage of weather stations in the tropics means satellite infrared land surface emission temperatures are crucial to reconstructing temperature extremes. Analysis of this data and UK official climate change prediction data (MET Office) shows rapidly expanding areas and durations of hot extremes in India and parts of sub-Saharan Africa, consistent with areas identified in future climate projections.

> "Human movement in a migration sense can be regarded in terms of different resources, familiarity (socio-economic, ethnolinguistic), and safety factors (climate, security, political)."

This already indicates where climate-triggered migration may be expected to escalate. Under a UK Defence & Security funded initiative such as GUARD (2017-21, we were able to predict migration of 4-5bn people under RCP8.5 by 2100, mostly in India and China towards the Himalayan mountains, Manchuria, and Inner Mongolia. Significant migration in Europe will be away from the Mediterranean, and in North America will be towards northern Canada.

This significant shift in global population and demographics not only creates new potential political fractionalization, but also new frontiers of contention (Himalayan foothills). Negative climate effects on resource availability, which then trigger migration add a resource layer of complexity. Nevertheless climate limits to the production of particular resources, e.g. staple crops such as wheat are well established.

We note that due to the transnational nature of climate change, the quality and the availability of data can vary between countries and from event to event: small-scale events or disasters that occur in isolated and marginalized areas are under-reported and thus not included in the available aggregate estimates which is frequently the case with environmental migration. Also, we lack data about highly vulnerable populations affected by environmental degradation and disasters who may not be able to move due to a lack of

Human migration as a case study

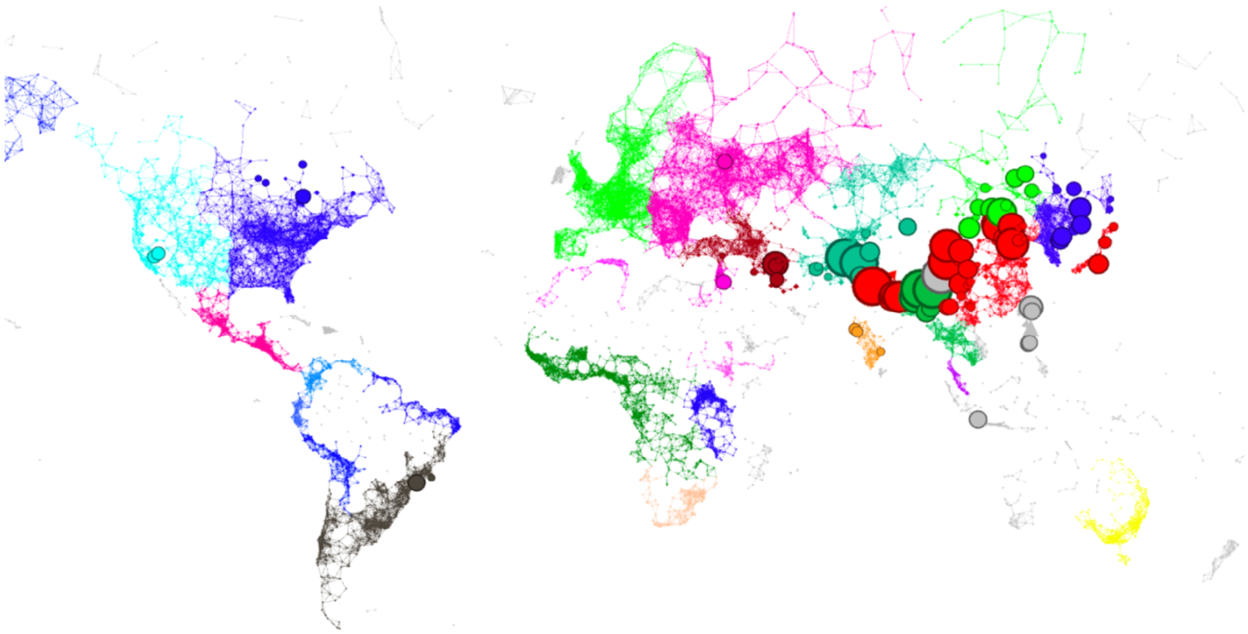

Figure 3. Projected population shift due to temperature and sea level changes. (Size of Circles) Indicate projected population sizes of new cities - prominent around Himalayan foothills in India and China, as well as Manchuria. (Colour) Indicate likely cooperative communities that form as a result of new population shifts.

5. Enablers to climate risk decision making

5.1. Introduction

Decision support tools form an integral part of the policy development process and associated decision-making in government . Even within the boundaries of the UK's security community, the systemic nature of climate risk will mean that issues cut across multiple departmental jurisdictions all of which will have different perspectives, cultures and agendas. Therefore, it is important that the use of any climate risk decision support methodologies and tools, and their integration into these existing structures, is considered alongside its design.

The following enabling factors can help ensure that climate risk considerations, are properly integrated into national security policy development:

• **Data-driven tools should be part of a wider arsenal of integrative decision support tools**. There will be a temptation to use the outputs of data-driven tools to provide definitive choices as to what to do. However, a wider set of tools should be used to assist policy makers explore the future option space and how the variables interact for any given policy problem.

• **Any new tool should be integrated with existing tools and processes**. The security community already uses decision-making and analytical tools, and anything new should be designed with this context in mind.

• **Ensure that there is adequate climate change expertise amongst the key decision makers**. Climate change is not linear, and there is the potential for cascade and threshold effects which are not reflected in historical data, making the past an unreliable predictor of the future. Therefore, the security community needs to train, develop and use experts appropriately, as well as using policy development processes that includes expert judgement.

• **Providing transparency about what the decision-support tool(s) can provide**. The new decision support tool(s) will integrate a range of input variables to provide insights into the climate dimensions of a set of policy problems. These insights will be dependent on the tool itself e.g. the assumptions, the inputs themselves, sensitivities of the interaction of the input variables in different boundary conditions etc. Outputs from the tool(s) should be accompanied by transparent information about the tool(s)' limitations. In particular, the type of uncertainty being encountered in the policy problem should be clear at the outset, and the ability of the tool(s) in dealing with uncertainty need to be stated clearly.

• **Nurture a culture of "deliberation with analysis"**. This culture can help decision makers manage decisions related to systemic disruptors, like climate change, whereby conditions of deep uncertainty, emergence and complexity are prevalent.

94 EU Better Regulation Guidelines - see link.

5.2. Using a decision support tool in a situation of uncertainty

Limitations of data-driven tools

Decision support tools which employ data and parametric modelling, whilst powerful, will not be able to fully capture either the complexity of the impacts around climate risk, nor prescribe solution sets to formulate policy prescriptions[95]. Models represent a system to help integrate disparate inputs and understand complex phenomena. Models make simplifications about `the way the world works'[96] and, with an increasing in computing power, some are becoming increasingly complex and lacking in transparency[97].

Sometimes, the inadvertent effect of this lack of transparency is that levels and types of uncertainty are poorly characterized when analyzing a policy problem. As a result, tools may be chosen, or set to deal with inappropriate levels of uncertainty. This results in two unintended outcomes: (1) decision support tools are applied inappropriately to problem sets resulting in distorted decision support analysis; and (2) outputs become used to provide definitive choices about what to do, rather than being used to explore a decision.

Understanding uncertainty to optimise the use of tools

Policy makers need to understand the extent of uncertainty that relates to a given policy decision so that they can use the appropriate set of decision support tools. Mapping uncertainty at the beginning of a policy development process forces decision makers to explore the implications of the integration of different input variables on the problem space.

This type of exercise increases transparency of the process and, most importantly, it will avoid the tendency for parametric outputs to be used to provide definitive outcomes or choices as to what to do. This approach can help ensure that modelling tools are used appropriately to explore the way that policy should be designed to achieve stated objectives, rather than as a way to confirm the realisability of stated national plans [98]. This approach can enable the full exploration of the future option space[99].

95 Gambhir et al., 2019 - Planning a low-carbon energy transition: What can and can't the models tell us?, Joule, Vol: 3, Pages: 1795-1798, ISSN: 2542-4351
96 Mercure, J-Francois, 2019. Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use. Climate Policy Volume 19, 2019 - Issue 8 1019-1037
97 Bankes, S. (1993). Exploratory Modeling for Policy Analysis. Operations Research, 41(3), 435–449. doi: 10.1287/opre.41.3.435
98 Mercure, J-Francois, 2019. Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use. Climate Policy Volume 19, 2019 - Issue 8 1019-1037; Workman et al., 2020 Ibid; van Dorsser et al., 2018. Improving the link between the futures field and policymaking. In Futures 104 (2018) 75–84
99 Gambhir et al., 2019, Using futures analysis to develop resilient climate change mitigation strategies, Grantham Briefing Paper, Publisher: Imperial College London

5.3. Capacity building in the use of decision support tools

The capacity to recognise uncertainty and make decisions under uncertainty requires training, time and practice, but this is a worthwhile investment, especially in the case of climate change[100]. There is an urgent need to increase the skills of decision makers in using decision support tool[101] which would help policy makers in the security space make good use of the data-driven tool(s) proposed earlier in this document.

Capacity building could cover:

- the characteristics and nature of climate change risk;
- identification of the level and type of uncertainty being encountered in a policy problem;
- Selecting the appropriate decision support analysis to engage with that uncertainty;
- the implications of the inherent assumptions and inputs to decision support tools on a policy problem;
- expert judgement[102] capacity in relation to climate risk; and
- expertise in using structured decision-making (SDM) approaches.

"The capacity to recognise uncertainty and make decisions under uncertainty requires training, time and practice, but this is a worthwhile investment, especially in the case of climate change."

100 Klien, G. and Wight, C., 2016 - Macro-cognition From Theory to Toolbox. In Front. Psychol., pp5 - 29 January 2016
101 French, S., Maule, J. and Papamichail, N., 2009. Decision behaviour, analysis and support. Cambridge University Press.
102 Burgman, M.A., 2016. Trusting judgements: how to get the best out of experts. Cambridge University Press.

5.4. Structured decision-making processes and climate change risk

A structured decision-making (SDM) approach is a preferred framework for climate risk policy development as it is designed to aid logical and transparent decision-making [103] compensating for cognitive biases. The SDM framework process is shown in Figure 5.2. To apply such a framework to climate change in the security context, each component needs to be mapped onto the existing national security policy processes.

This approach will enable insight into the governance mechanisms within and between each stage and input metrics / analysis which would be required in making decisions on climate change.

The SDM framework should be designed with a range of considerations, including the many psychological barriers to, and enablers for, climate decision-making[104] the need for societal buy-in, possibly through the use of narratives[105] , how uncertainty is visually communicated and its impact on decision-making[106] and institutional architecture, incentives and clear lines of responsibility.

For systemic issues such as climate change the capacity to generate policy solution sets is compromised by the fact that the responsibility for components of the problem and policy sets often cut across multiple departmental jurisdictions.

The types of decisions required to address climate and national security policy are likely to involve multiple objectives, multiple stakeholders with different perspectives, uncertainty about actions and outcomes as well as different departmental models of cause-and-effect.

For example, the Department for International Development (DfiD) will have a more sociological perspective on their theories of change relative to the more mechanistic constructs in the MOD. These institutional challenges can lead to highly distorted decision-making, as has been exemplified in the way that the UK developed strategies in the expeditionary Afghan and Iraq campaigns[107] and indeed its ongoing response to C-19[108].

Collaboration is essential – not just at the decision-making stage, but also the analytical stage. The National Security Council (NSC) has a substantive analytical resource which it draws upon and therefore any new methodology or tool should be used with a strong connection to this team. The present suite of analysis effectively establishes the culture by which those decision-makers see the world and design policy.

103 Gregory et al 2012. Structured Decision Making: A Practical Guide to Environmental Management Choices

104 Lewis, M, 2017. The Undoing Project: A Friendship that Changed the World; The Cognitive Bias Codex: A Visual Of 180+ Cognitive Biases - see link

105 S. Bushell, T. Colley, M. Workman, A unified narrative for climate change, Nat.Clim. Chang. 5 (2015) 971–973 https://doi.org/10.1038/nclimate2726; Parliament is undertaking a Citizens Assembly around Net Zero and nascent work on Participatory Futures is being pioneered - see: Nesta 2019 - Our Futures: By the people, for the people.

106 it impacts decision-making as follows: (1) Decision outcomes; (2) Correctness of decisions; (3) 3. Kinds of errors made; (4) Decision time; (5) Confidence in a decision; (6) Willingness to make a decision; (7) How much workload decision-making causes; (8) How a decision is made; and aligned with this is the fact that quantitative outputs more broadly in their very nature will invariably be interpreted by decision makers as `predictive' and `optimal' as per Whitehead's observation in the "Fallacy of Misplaced Concreteness" (1917) when tables, graphs, etc are presented to decision makers. ; Levontin, P. et al., Visualising Uncertainty: A Short Introduction. Publisher: AU4DM ISBN: 978-1-912802-05-0

107 Elliott, C. 2015. High Command: British Military Leadership in the Iraq and Afghanistan Wars. `He reveals how the Service Chiefs were set at odds by the system, almost as rivals in the making, with responsibility diffuse and authority ambiguous. The MoD concentrated on making things work, rather than questioning whether what they were being asked to do was practicable.'

108 Sir Paul Nurse interview on Radio 4 Today Programme dated 22nd May ` Do we have a proper government system in here that can combine tentative knowledge, scientific knowledge, with political action? And the question I'm constantly asking myself is: Who is actually in charge of the decisions? Who is developing the strategy and the operation and implementation of that strategy? Is it ministers? Is it Public Health England? The National Health Service? The Office for Life Scientists, Sage? I don't know, but more importantly, do they know?"

5.4 Structured decision-making processes and climate change risk

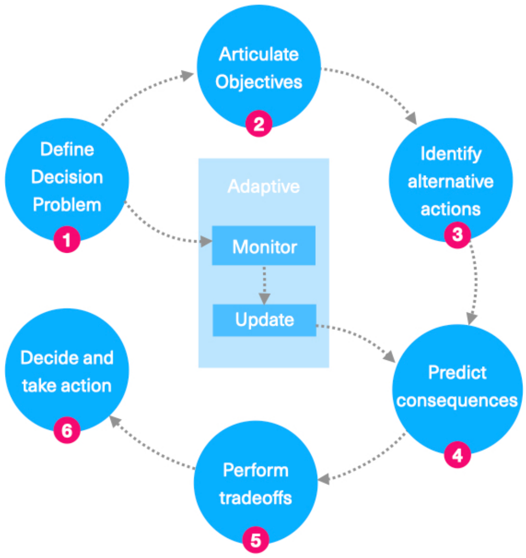

Figure 5: Stylised process of SDM

5.5. Nurturing greater "deliberation with analysis" in policy design

In addition to using an SDM structure, it is also helpful to develop greater `deliberation with analysis' around the decision-making process, generating dialogue between the actors involved in decision-making, policy design and decision support analysis.

Greater deliberation can break the entrenched `tribal' axioms that may influence policy decisions across departments. The iterative nature of deliberation with analysis encourages transparency around both individual tools and also how they are used in the policy development process. Uncertainties would be explicitly discussed and narratives co-generated between analytical and policy decision making communities within an ongoing iterative process articulated between the analytical community, decisionmakers and policy makers along the decision value chain.

The practical implications of moving from an advocacy-approval process between the decision support analysis and policy-decision maker to one with greater `deliberation with analysis' is articulated in Spetzler et al., 2016[109]. This allows development of the analytical framework around the problem so as to ensure that the policy /decision makers questions are answered and work with lead-in times to identify decision points and which elements of any high dimensional policy space is closed-off as a function of short-term decisions[110].

"The capacity to recognise uncertainty and make decisions under uncertainty requires training, time and practice, but this is a worthwhile investment, especially in the case of climate change."

109 Spetzler, C., Winter, H. and Meyer, J., 2016. Decision quality: Value creation from better business decisions. John Wiley & Sons.
110 Haasnoot, M. et al., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. In Global Environmental Change Volume 23, Issue 2, April 2013, Pages 485-498

6. Recommendations

'Plans are worthless, but planning is everything...The reason it is so important to plan is to keep yourself steeped in the character of the problem that you may one day be called upon to solve'.

— President Dwight Eisenhower

Human-driven processes are pushing the Earth system beyond the boundaries of a safe operating space[111]. In the coming decades humanity will face the decisive challenge of stewarding planetary metabolism and mitigating these Anthropocene risks that extend beyond the nation-state. Climate-related disasters such as recurring floods, droughts, desertification, or wildfires will not only cause direct damage but also lead to chains of catastrophic events such as migration, sociopolitical instability and potential armed conflicts that will cost trillions of dollars and millions of lives. If left unchecked climate change could have a severe impact on the economic and social gainsmade in countries around the world and jeopardise many of the UN Sustainable Development Goals.

For defence and security, climate change has implications on the preparedness of forces to respond, future resource planning, operational commitments and training associated with increased demands for disaster relief, humanitarian assistance and peacekeeping operations. Therefore, defence and security actors must embed climate change and sustainability impacts into its leadership, processes and policies. Based on the analysis of this report, we recommend the following actions for consideration by the National Security community:

We recommend an urgent uplift of the research and decision-making capacity around the anticipated impact of climate-related threats on UK National Security interests in a three- to five-year timeframe. This includes promoting an understanding of the characteristics and nature of climate change risk across government departments; selecting the appropriate decision support analysis to engage with this uncertainty; and ensuring that policymakers are well equipped to mitigate the security impacts of climate change proactively.

The best available information should inform the capacity to make better decisions around the anticipated impact of climate-related threats. While climate change is already included in some early warning systems and risk assessments, more could be done to assess the future effects using data-driven and complex systems methods.

111 F. S., Lambin, E., ... & Nykvist, B. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecology and society, 14(2).

To create this evidence base, a substantive research programme is required which gets to the heart of understanding changing climate security as the outcome of complex, interconnected, dynamical systems. In chapter four, we describe three research challenges that can be tackled by such a programme:

— New data driven tools and methods need to be developed that will determine where the accumulation of climatic stresses is interacting with human populations and how these dynamics are changing over time. This will provide an indication of how many people will be impacted by environmental and climatic stresses. Working with international partners will then help assess how these hotspots overlap with other structural risks to drive fragility, conflict, migration or maladaptation.

— Tools and methods are needed to identify, and to issue early warnings of, potential climate security tipping points, which can inform the development of proactive and area-specific risk reduction and resilience planning responses.

— The development of new causal models that explicitly link climate and socio-economic processes together and can help policymakers create scenarios of future security risks. These scenarios can help define the boundaries for 'safe and just operating spaces' and shape policy and programme recommendations that reduce environmental stresses and their negative impacts on populations.

Conditions for success

1. Bringing together disparate researchers

The complexity and interdisciplinary nature of the challenges described in chapter four mean that Defence and Security should incorporate a wide range of experts in relation to its changing role and operational requirements: data scientists, climate scientists, designers, futurists and economists would form the vanguard of a new platform prepared to devise climate-proof resilience plans

While the problem demands an interdisciplinary group underpinned by solid theory and data science, academic life is currently structured in subject-oriented departments. The Defence and Security community needs to bring together and incentivise a thriving network of researchers around this challenge.

Delivery options

– The proposed initiative requires establishing collaborations between the disciplines that are currently too sparse and discontinuous to address this grand challenge. This can be achieved by establishing a lean Climate Security Centre that brings together experts from across disciplines to focus on the shared problem with minimal distraction. Centres and institutes can be an effective way to organise around a challenge. (indicative resource: 50k per year for 5 years)

2. Flexible research projects and programmes designed with user groups

Key research projects should be delivered by a scientific leadership team which will be led by a combination of a high-level official from the security decision-making community and a senior academic, to ensure the integration of the user community and the research community.

The research and delivery teams should work alongside GCHQ, DSTL, MoD, the National Security Council and allied organisations nationally and internationally to understand how partner organisations make sense of information about climate-related risks. It is vital that any tools for the UK's security community be developed in a way that aligns to existing risk assessment and risk management tools. Importantly, given the nature of the challenge, the characterisation of the research challenges themselves requires a two-way engagement.

We recommend that key decision makers from the security community, across different departments, work closely with the research teams to help develop a shared understanding of the problem set and to guide the research further. They will generate a "challenge book", a shared document that is updated frequently in an agile way and will assess the research results and future plans in a coordinated fashion within government.

Some questions and challenges might require short-term respones and others might have a longer lead time. The programme of research and choice of disciplines, experts and teams needs to be flexible and agile, whilst also grounded with a core team that can ensure relevance and quality.

Delivery options

- Multiple research projects will be delivered by the scientific leadership teams (indicative resource: £5m over 5 years to develop 4 projects per year distributed across teams at £250k each)

- The latest research outputs will be transformed into demonstrators and products by a Development and Testing team. (indicative resource: £200k per year for 5 years)

3. Building capacity amongst decision-makers

A strong community of best practice on data for climate security is required. Scoping and capacity building meetings should bring together international and UK thought leaders, policy makers, domain experts, academics and practitioners from different fields and parts of the security ecosystem to help build the communities capacity to use exiting tools, and to identify additional gaps and challenges.

The latest research outputs would be transformed into relevant user-friendly demonstrators and products that support effective climate risk communication.

A team of research software engineers and designers would also map, catalogue and connect existing datasets and systems; develop and trial the technical components of the research; and ensure data ethics principles as well as data and model integrity.

These outputs can be shared and tested at the gatherings of stakeholders, allowing for their evolution whilst building skills at the same time, both of researchers and user groups.

Delivery options

– A yearly Climate Futures Retreat for national and international academics and key decision-makers from the security community can help develop a shared understanding of the problem set and guide the research further. This meeting would inform the direction of the research projects the following year, identify the need for any shorter, intensive research projects, and it would be an opportunity for the researchers to share their findings and get feedback.

– This annual retreat aims to build capacity within the security community and establish a new kind of deliberative approach to decision making. These activities would guide the work and ensure that the scientific leadership is delivering on the ambition to make this approach truly integrated with decision-making, linked to culture change, interdisciplinarity, but also with a strong data science core. Smaller "constellation" workshops will be delivered throughout the year by various government departments. (indicative resource: £30k per year for 5 years.)

4. Creating international networks

Building a coalition of international partners, including those mentioned in chapter 3.2, is a fundamental building block of the proposed research programme. It requires international community-building, events and workshops with allies around the world, such as participating in the upcoming COP26.

We recommend that the UK drives this international effort with the view to become a global hub of authoritative climate security information that reflects the security and social science consensus on the topic and presents credible climate security futures.

Delivery options

– Establishing and supporting a community of practice around data for climate security and resilience requires programme management, events, communication, participation in international workshops (indicative resouce £100k over 5 years).

5. Making the best use of UK skills and resources

We recommend that any new interdisciplinary research initiative is funded appropriately over five years to design a truly holistic climate security research programme.

The UK is in a strong position to lead this ambitious piece of research, which can bring together its national capabilities and expertise in climate change research (e.g. Cambridge, Exeter, Oxford, Reading, Leeds, Imperial College, Met Office), complex systems (e.g. Exeter, Cranfield, QMUL, Warwick, Cambridge), conflict (Essex, UCL, KCL, Oxford), and data science and machine learning (Alan Turing Institute).

The exact shape of this research effort should be further defined through a consultation phase with more stakeholders from the security community as well as a range of academics who are already working on these topics. The evidence produced by the research community can bridge the short-term and long-term timeframes adopted across and within academic disciplines as well as policy communities.

The cost of inaction will be in the trillions of pounds and millions of lives. In a rapidly changing world, the UK now has a unique global advantage to demonstrate leadership in the field and develop the analytical capacity that can provide answers to the planetary questions raised by climate change in order to improve its resilience -and that of its allies-, with all of the uncertainty attendant to this grand challenge.

Glossary

Abrupt change/abrupt climate change

Abrupt change refers to a change that is substantially faster than the rate of change in the recent history of the affected components of a system. Abrupt climate change refers to a large-scale change in the climate system that takes place over a few decades or less, persists for at least a few decades and causes substantial disruptions in human and natural systems. Some changes may be truly unexpected, resulting from a strong, rapidly changing forcing of a complex system.

Adaptation

The process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities.

Adaptive capacity

The combination of the strengths, attributes, and resources available to an individual, community, society, or organization that can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities

Anthropocene

The most recent period in the Earth's history, starting in the 18th century, when the activities of humans first began to have a significant global impact on the Earth's climate and ecosystems.

Anthropogenic emissions

Emissions of greenhouse gases, greenhouse gas precursors, and aerosols associated with human activities. These include all activities that result in a net increase in emissions.

Climate change

Refers to any change in climate over time, whether due to natural variability or as a result of human activity.

Climate variability

Variations in the climate at any temporal and/or spatial scale beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability) or to variations in natural or anthropogenic external forcing (external variability) (IPCC AR4, 2007).

Complex Adaptive Systems (CAS)

Any natural system or artificial system that is characterized by apparently complex behaviors that emerge as a result of interactions among a large number of component systems at different levels of organization. Simple rules of cause and effect do not apply, they are complex, unpredictable and constantly adapting to their environments.

Downscaling

Downscaling is a method that derives higher resolution (in time or space) information from larger-scale models or data analyses. See appendix Y2.3 for further details.

Early warning system

The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities, and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss.

Earth system

The Earth system consists of the land, oceans, atmosphere and poles and the interacting physical, chemical, and biological processes within them. It includes the planet's natural cycles — the carbon, water, nitrogen, phosphorus, sulphur and other cycles — and deep Earth processes.

Earth System Model (ESM)

A coupled atmosphere–ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO2 or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, crop models) may be included. See appendix Y3 for further details.

Emissions scenarios

Quantitative illustrations of how the release of different amounts of climate altering gases and particles into the atmosphere from human and natural sources may change in the future. Scenarios are developed using a wide range of assumptions about population growth, economic and technological development, and other factors. See also Socio-Economic Pathway.

Ensemble

A collection of model simulations used for climate projections. Differences in the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterize the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences.

Feedback

The process through which a system changes in response to its own output. Positive feedback results in amplification of the system output; negative feedback reduces the output of a system.

Forcing

Factors that affect the Earth's climate. For example, natural factors such as volcanoes and human factors such as the emission of heat-trapping gases and particles through fossil fuel combustion.

Forecast

A best-estimate of the most likely future conditions in a system, based on past information only. Distinct from Prediction or Projection.

Global Climate Model (GCM)

Mathematical model that simulates the physics, chemistry, and biology that influence the climate system. See appendix Y3 for further details. IPCC
The Intergovernmental Panel on Climate Change: the United Nations body for assessing the science related to climate change. See www.ipcc.ch

Human security

Human security has two main aspects. Firstly, safety from chronic threats such as hunger, disease, and repression. Secondly, protection from sudden and hurtful disruptions in the patterns of daily life –
whether in homes, in jobs, or in communities.

Mitigation

The lessening of the potential adverse impacts of physical hazards through actions that reduce hazard, exposure, and vulnerability.

Prediction

A best estimate of the most likely future conditions in a system, based on past information and best estimates of the future forcings of the system. Distinct from Forecast or Projection.

Projection

Climate projections are based on simulations by climate models, but are designed to show a range of possible futures based on the emissions scenario/socio-economic pathway used, rather than provide a best-estimate of the most likely future. Distinct from Forecast or Prediction.

Resilience

The ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner while retaining the same basic structure and ways of functioning, the capacity for self-organization and the capacity to adapt to stress and change.

Risk

The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.

Social-ecological

Linked systems of people and nature. The term emphasizes the view that humans must be considered as part of, and not apart from, nature.

Socio-Economic Pathway

Global development pathways that depict plausible alternative future states of the society and the environment, developed by the IPCC, see appendix Y3.4.

Threshold

May refer to a boundary between two different states of a system, or a point beyond which the system changes rapidly. See also Tipping Point.

Tipping point

A level of change in the properties of a system beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated. A tipping point event may be irreversible.

Vulnerability

The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

Appendix

A1. Overview of models/reanalyses and their limitations/errors

Appendix Y1: Types of historical data and their biases

Table Y1.1: Summary of sources of historical climate data depending on their aims. These are direct observations, gridded global datasets, and global reanalyses. Table Y1.1 summarises the availability, sources, advantages, disadvantages and common uses of each data type. Generally speaking, as one moves from direct measurements to reanalyses, the biases in the data increase, but the temporal and spatial resolution improve.

Data Type	Advantages	Heading	Common uses
Direct Measurements	Low bias High time resolution	Concentrated in developed regions Small radius of relevance Varying qc methods	Localised studies -Process studies
Gridded products	Global coverage Comparable at all points in time and space	Data validity varies by location Missing data can cause aliasing	Global studies Aggregated analysis eg regional comparisons

Direct measurements are the most accurate, but are localised by nature. Organisations that manage direct measurement systems often release data close to real-time after processing by quality control systems, which account for random errors such as drift in a particular instrument. Direct measurements tend to be used for studies focusing on a local region or a particular physical process that requires high time resolution data. There is an inherent risk in basing any model on real-time direct measurements, and that is that a given measurement station can be highly reliant on local infrastructure to remain operational. This is confounded by the fact that regions which are relatively socio-economically unstable are also measured sparsely, and so the most at-risk measurements are likely to be in under-sampled regions and so of relatively high importance to any model assessing local systemic risk. Thus the benefits of using accurate data must be weighed against the risk of relying on a network of local observational infrastructure.

Gridded products are observations on a global spatial grid at regular time intervals (normally monthly). They are generated by a handful of organisations such as the U.K. Met Office and U.S. National Oceanic and Atmospheric Administration and as such are more operationally stable than individual direct measurements. Direct measurements are first homogenized, to remove non-climate signals, and then gridded by estimating missing data using neighbouring points. The exact methodology used by each organisation is different and produces different results. The resulting datasets produce more accurate global results, and allow for more meaningful comparisons between different regions, than using the direct measurements alone. Any remaining instrumentation bias not removed in the quality control process is reduced by the homogenisation process, however the gridded data still has coverage bias, meaning the accuracy of the data varies by location.

Renalyses are synthesised estimates of the climate system, which use models to fill the gaps in the observational record. The results are high time and spatial resolution datasets of a range of climate variables, spanning decades. Their workings and biases are discussed further in appendix Y3.3.

Appendix Y2: Climate forecasts and their biases

If we want to understand and potentially predict future risks, we need forecasts of climate data. As with observational data, any predictions are reliant on the quality of the forecast data. In this section we outline the type and quality of forecasts available by time scale.

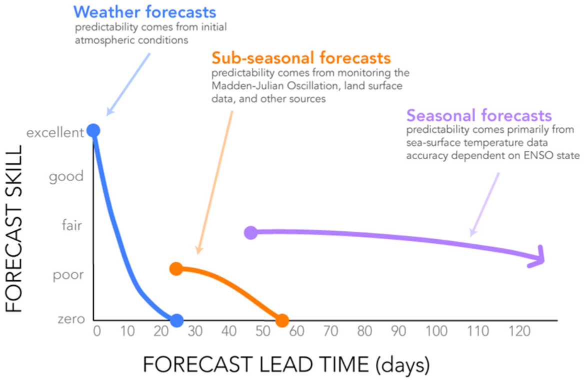

Figure Y2.1. Qualitative estimate of forecast skill against lead time of the forecast.
Credit: Elisabeth Gawthrop, iri.columbia.edu.

The weather (day-to-day changes in climate) is largely determined by changes in the atmosphere. Given accurate measurements of the atmosphere today, weather forecasts can make highly skillful predictions on timescales of days to weeks. The land and ocean change more slowly and therefore have a slower influence on the climate, and so land and ocean measurements become important for predictions further into the future. Fig Y2.1 gives an overview of how forecast skill varies with time into the future, and which kinds of data are important for that skill.

Y2.1. Seasonal forecasts
Seasonal predictions of climate variables for the next six months are regularly released by several organisations. These predictions often come from the same centres which produce historic climate reanalyses and often based on the same models. The uncertainty in such forecasts is dominated by the uncertainty in initial conditions (observational bias), with uncertainty due the model also a significant factor.

Dynamical seasonal forecasts are produced by running a physics-based climate model and give a probabilistic range of possible outcomes. Currently, the probable range of weather only varies slightly year to year, although the tropical regions can be more predictable, usually in the case of strong El Nino/La Nina forcing[112].

Statistical seasonal forecasts are produced by finding statistical relationships between different climate variables in the past and then using them to predict upcoming seasonal variables. Statistical models can be simple or complex, but are generally much faster to run than a dynamical model.

Combinations of different kinds of seasonal forecasts have been found to have greater skill than the separate methods[113], largely because the different forecasts tend to have skill in different regions or seasons. Such hybrid forecasts are normally generated for a particular region or purpose, and are not widely produced at an operational level.

Extreme events can often be derived from the output of seasonal forecasts. Thus, specialist seasonal forecasts exist for events such as tropical storms, drought, sea ice extent. These are often based on combinations of outputs from seasonal forecasts, but may also involve additional specialist models (e.g. Arctic sea ice extent); or a degree of subjectivity (e.g. tropical storm risk[114]).

However, in general, as the scale of the risk becomes more regional, the time scale of meaningful predictions also becomes smaller. Regional quantities vary much more than global quantities, and as such regional predictions have much larger uncertainty. Regional variability is often dominated by completely different processes than global variability, and smaller scale processes are more difficult to model well on a global scale.

By their nature, local operational forecasts are produced by a wide range of organisations, using a wide range of tools. This diversity means that the quality of these forecasts varies widely, and makes them difficult to compare or synthesise. For example, a recent review of European operational ocean modelling found only 23% of models assimilated observations, despite uncertainty in initial conditions being the largest source of uncertainty in such models; a number of models not using best practices in model implementation; and a range of modelling approaches, from running global models at high resolution to running regional specialised models.[115]

112 Johnson, S. J., Stockdale, T. N., Ferranti, L., Balmaseda, M. A., Molteni, F., Magnusson, L., Tietsche, S., Decremer, D., Weisheimer, A., Balsamo, G., Keeley, S. P. E., Mogensen, K., Zuo, H., and Monge-Sanz, B. M.: SEAS5: the new ECMWF seasonal forecast system, Geosci. Model Dev., 12, 1087–1117, https://doi.org/10.5194/gmd-12-1087-2019, 2019.

113 Yan, H., Moradkhani, H., & Zarekarizi, M. (2017). A probabilistic drought forecasting framework: A combined dynamical and statistical approach. Journal of Hydrology, 548, 291-304.; Schepen, A., and Wang, Q. J. (2015), Model averaging methods to merge operational statistical and dynamic seasonal streamflow forecasts in Australia, Water Resour. Res., 51, 1797– 1812, doi:10.1002/2014WR016163.

114 https://www.cpc.ncep.noaa.gov/products/precip/CWlink/ghazards/

115 Capet, Arthur, et al. “Operational Modeling Capacity in European Seas—An EuroGOOS Perspective and Recommendations for Improvement.” Frontiers in Marine Science 7 (2020): 129. https://doi.org/10.3389/fmars.2020.00129

There is large potential to improve on the wide range of local operational forecasts by implementing best practice techniques[116], and by optimally combining a variety of forecasts[117]. Using an ensemble of models could also improve estimates of model uncertainty[118].

Y2.2. Decadal forecasts

Decadal forecasts, defined as climate predictions on the scale of years to a decade, are currently only produced on an experimental basis due to their high uncertainty. As the length of the forecast increases, dependence on initial conditions decreases, whilst dependence on the forcing of the climate system increases, see figure Y2.2. The choice of model has a large impact on predictions of the next decade, whereas the exact choice of future socio-economic scenario has very little impact[119].

Assessing the state of the art climate models in 2013, the IPCC found there was high confidence that temperature could be skillfully predicted on a global or large regional average for up to a decade ahead. There was also skill in predicting precipitation over some land areas on the same time scale[120]. Recent studies have found that decadal forecasts have similar skill as seasonal forecasts at predicting temperature, precipitation, and there is also skill in forecasting the frequency of extreme events such as tropical storms or heatwaves[121] . However, predictions of other climate variables, such as sea level, remain deeply uncertain, and multiple probability distributions should be considered[122].

The latest generation of climate models are likely to prove more skillful due to advances in the past decade, and results from these models are starting to be published[123]. An assessment of the decadal prediction skill of these models is expected in the next assessment report of the IPCC Working Group 1, due in 2021.

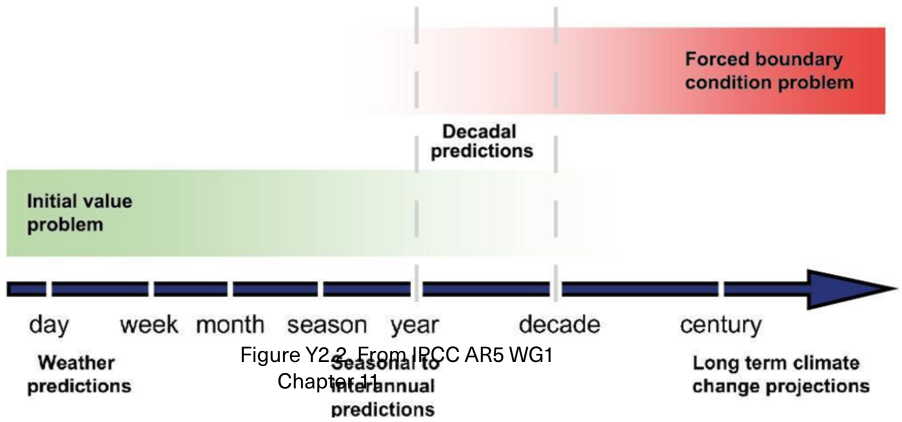

Figure Y2.2. From IPCC AR5 WG1 Chapter 11

116 Md Safat Sikder & Faisal Hossain (2019) Improving operational flood forecasting in monsoon climates with bias-corrected quantitative forecasting of precipitation, International Journal of River Basin Management, 17:4, 411-421, DOI: 10.1080/15715124.2018.1476368

117 Schepen, A., and Wang, Q. J. (2015), Model averaging methods to merge operational statistical and dynamic seasonal streamflow forecasts in Australia, Water Resour. Res., 51, 1797– 1812, doi:10.1002/2014WR016163.

118 Kauffeldt, A., Wetterhall, F., Pappenberger, F., Salamon, P., & Thielen, J. (2016). Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. Environmental Modelling & Software, 75, 68-76.

119 Hawkins, E. and R. Sutton, 2009: The Potential to Narrow Uncertainty in Regional Climate Predictions. Bull. Amer. Meteor. Soc., 90, 1095–1108, https://doi.org/10.1175/2009BAMS2607.1

120 IPCC AR5 WG1 Chapter 11

121 Kushnir, Y., Scaife, A.A., Arritt, R. et al. Towards operational predictions of the near-term climate. Nature Clim Change 9, 94–101 (2019). https://doi.org/10.1038/s41558-018-0359-7

122 Kopp, R.E., DeConto, R.M., Bader, D.A., Hay, C.C., Horton, R.M., Kulp, S., Oppenheimer, M., Pollard, D. and Strauss, B.H. (2017), Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. Earth's Future, 5: 1217-1233. doi:10.1002/2017EF000663

123 Borchert, L. F., Pohlmann, H., Baehr, J., Neddermann, N.-C., Suarez-Gutierrez, L., & Müller, W. A. (2019). Decadal predictions of the probability of occurrence for warm summer temperature extremes. Geophysical Research Letters, 46, 14042– 14051. https://doi.org/10.1029/2019GL085385

Y2.3. Downscaling

Downscaling is the term used to describe the technique of taking a climate forecast at a particular spatial and time scale, and using it to predict a quantity at a higher spatial or time scale. It has a wide range of applications, from regional flood risk assessments for the next few days[124] to predicting regional temperature variations in 100 years time[125].

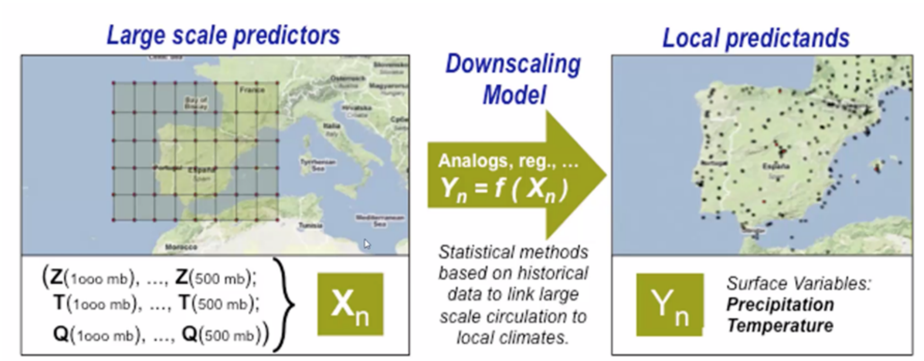

Fig Y2.3: Visual example of statistical downscaling from https://www.meteo.unican.es/downscaling/intro

Machine learning is very well suited to statistical downscaling tasks and therefore has the potential to provide the kind of local climate data required to assess local security risks from the kind of large scale climate forecasts currently produced.

Dynamical downscaling involves taking the results of a larger model (such as the temperature on a very coarse grid) and using it as the boundary conditions of a regional model (such as a model of the UK). The results are therefore consistent with our understanding of the physics of the climate system, and can adapt to a changing climate, although they are computationally expensive to run and will include any biases from the larger model.

Statistical downscaling involves finding statistical relationships between large and small scale variables in historic datasets, and assuming the same relationship holds in the future. They are comparatively cheaper to run and can incorporate observational data, but they assume that statistical relationships from the past will hold for the future and are also limited by biases in the larger model. However, this assumption is likely to hold well for the near future, i.e. the next 3-5 years.

Advantages	• Comparatively cheap and computationally efficient • Can provide point-scale climatic variables from GCM-scale output • Can be used to derive variables not available from RCMs • Easily transferable to other regions • Based on standard and accepted statistical procedures • Able to directly incorporate observations into method	• Produces responses based on physically consistent processes • Produces finer resolution information from GCM-scale output that can resolve atmospheric processes on a smaller scale
Disadvantages	• Require long and reliable observed historical data series for calibration • Dependent upon choice of predictors • Non-stationarity in the predictor-predictand relationship • Climate system feedbacks not included • Dependent on GCM boundary forcing; affected by biases in underlying GCM • Domain size, climatic region and season affects downscaling skill	• Computationally intensive • Limited number of scenario ensembles available • Strongly dependent on GCM boundary forcing

124 See, e.g., the UK Flood Forecast Centre ffc-environment-agency.metoffice.gov.uk
125 Hayhoe, K., Wake, C., Anderson, B. et al. Regional climate change projections for the Northeast USA. Mitig Adapt Strateg Glob Change 13, 425–436 (2008). https://doi.org/10.1007/s11027-007-9133-2

Advantages have recently been found in combining statistical and dynamical downscaling methods[126]. The World Climate Research Programme (WCRP) - Coordinated Regional Downscaling Experiment (CORDEX)[127] is coordinating the production of ensembles of dynamical and statistical regional projections at high resolution using a range of models and observational datasets - this data will produce better regional predictions and allow for a more accurate estimate of its uncertainty.

Appendix Y3: Climate model

Y3.1. Overview of model types

When considering the type of model to use for joining different systems, such as the climate system and the socio-economic system, it is important to consider the model's purpose. Broadly speaking, model purposes fall into five broad categories:[128]

Prediction: produce estimations of quantitative or qualitative features of a system based at a specific time, based on other measurements at the same time.

Forecasting: estimating features in the future based on current measurements.

Management and decision-making under uncertainty: to support decisions or formulate problems, in 'what-if' or 'best option' type scenarios.

Social learning: help people understand a system, and thereby improve communication, learning from past behaviour, and perform collective action.

Develop system understanding/ experimentation: summarise or bring together many aspects to help improve understanding of the entire system, or understand how it might react to changes.

There are a variety of approaches that models can take to realise their purposes, which can depend on the type of data available and the type of output required, as well as the purpose itself. The main categories of model approaches for combining different systems are outlined below, although the definitions are not precise and a given model may fall into more than one category:

System dynamics: a set of concepts and numerical techniques for understanding complex systems, designed to include non-linearities and feedbacks.

Bayesian networks: systems described by combinations of probabilistic relationships.

Coupled component models: made by combining models from different sectors, which may themselves have differing approaches.

Agent based models: represents interactions between autonomous individuals that are most often humans, but can be biophysical entities.

Knowledge based models: infer outcomes based on a collection of knowledge, which can take the form of rules or logic.

126 Verdin, A., Rajagopalan, B., Kleiber, W., Podestá, G., & Bert, F. (2018). A conditional stochastic weather generator for seasonal to multi-decadal simulations. Journal of Hydrology, 556, 835-846.
127 http://cordex.org
128 Kelly (Letcher), R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., ElSawah, S., Hamilton, S. H., ... Voinov, A. A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. Environmental Modelling & Software, 47, 159–181. doi:10.1016/j.envsoft.2013.05.005

Table 3.1 summarises how one might choose a model approach based on the purpose of the model and other relevant considerations. Appropriate use of integrated modelling approaches (X = common feature, * = possible feature). From[129]

		System dynamics	**Bayesian networks**	**Coupled**	**Agent based models**	
Reason for modelling / type of application	Prediction	*	X	X	*	X
	Forecasting			X		X
	Decision-making under uncertainty	*	X	*	*	X
	System understanding	X	X	X	X	
	Social learning	X	X		X	
Type of data available to populate model	Qualitative and quantitative data	*	X	*	*	X
	Quantitative data mainly	X		X	X	X
Model focus on a complex description of specific processes or greater breath of coverage of interactions in system?	Depth of specific processes	*		X	X	X
	Breadth of system	X	X	X	*	X

129 Kelly (Letcher), R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., ElSawah, S., Hamilton, S. H., ... Voinov, A. A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. Environmental Modelling & Software, 47, 159–181. doi:10.1016/j.envsoft.2013.05.005

Y3.2. Global climate models and their biases
Projections of future climate change are made using two variants of climate models: General Circulation Models (GCMs) and Earth System Models (ESMs). Both types of models represent the global climate system through mechanistic, mathematical equations describing thermodynamics and fluid dynamics. These models divide Earth into a three-dimensional grid representing latitude, longitude and a vertical component (altitude of the atmosphere, ocean depth). At the start of a model run, each grid cell is assigned a value for each of the model's state variables (e.g., atmospheric temperature, ocean salinity). These initial conditions are based on global mean observations.

While GCMs focus on the physical climate system, representing atmosphere, ocean, and sea ice physics and dynamics, ESMs aim to also capture chemical, and biological processes in terrestrial and marine ecosystems and allow for these ecosystems to have feedback on the circulation. ESMs are global climate models with the added capability to explicitly represent biogeochemical processes that interact with the physical climate. These more complex ESMs are actually what most people mean when they talk about "climate models".

In ESMs major physical and biogeochemical processes in the Earth System are represented by mathematical equations. To calculate historical projections, models are tuned to reproduce historical observational data such as atmospheric gas composition and temperature change with reasonable parameter estimates. To calculate future projections, emission scenarios are prescribed to the models.

The Coupled Model Intercomparison Project (CMIP) coordinates the comparison of comprehensive climate models and has its roots in earlier model intercomparisons, such as the Atmospheric Model Intercomparison Project (AMIP; Gates 1992; Gates et al. 1999). There are approximately 33 modeling groups in 16 countries taking place in the latest model intercomparison project, CMIP6, for contribution to the IPCC's sixth Assessment Report. There are four main experiments each group must contribute, and a broad range of optional extra experiments, designed to answer three broad scientific questions:

1. How does the Earth System respond to forcing?
2. What are the origins and consequences of systematic model biases?
3. How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?

Earth system models have three main sources of uncertainty: scenario uncertainty, due to unknown future emissions; internal variability, natural fluctuations in the climate system; and model uncertainty, due to the fact that different models produce different predictions.

Internal variability is roughly constant in time, but the other sources grow in time, at different rates that can depend on time, location, and quantity. As an example, figure Y3.2 shows the relative contributions from the three types of uncertainty for global and regional temperature and precipitation from the CMIP5 models. In the near-term, scenario uncertainty is unimportant for all quantities. Internal variability is the largest source of near-term uncertainty, with model uncertainty a significant but quantity-dependent contributor. For example, internal variability is much more important for European decadal mean winter precipitation than for global mean annual temperature.

Thus, decadal predictions can be improved by reducing model uncertainty, which can be achieved by a variety of means, including improved initialisation, and direct model improvements such as increased resolution and improved parameterizations. Whilst internal variability cannot be eliminated, it can be better estimated using larger ensemble sizes.

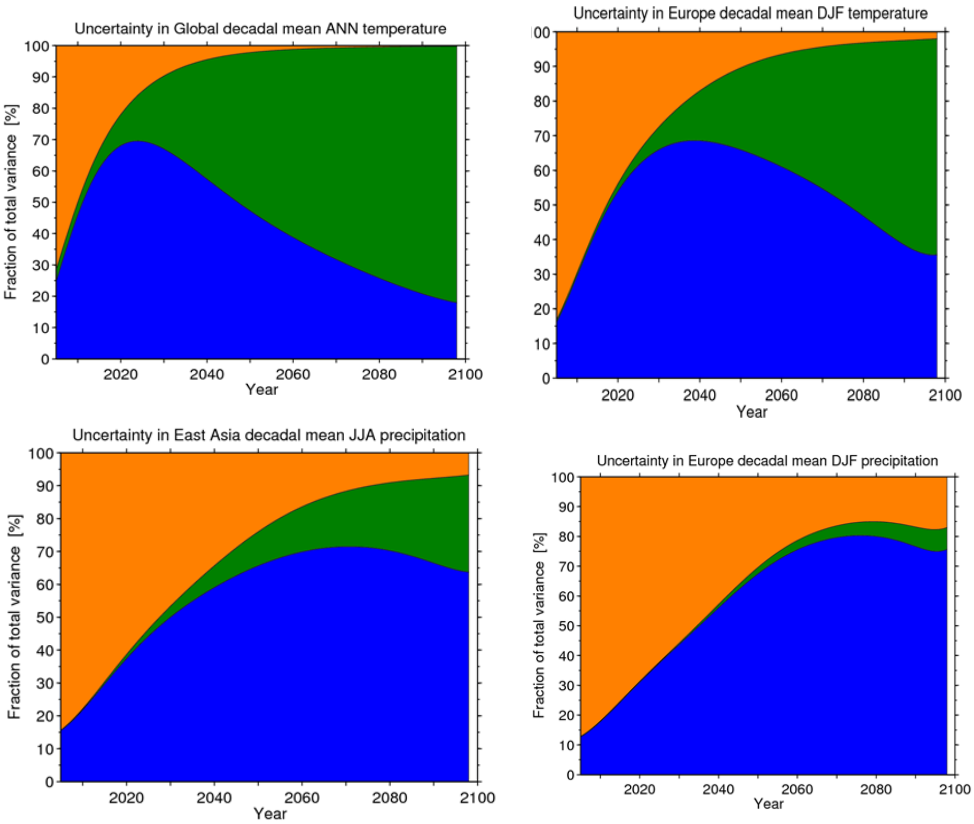

Figure Y3.2: Relative contributions of sources of uncertainty in CMIP5 models from https://www.climate-lab-book.ac.uk/2013/sources-of-uncertainty/. Orange is internal variability, blue is model uncertainty and green is scenario uncertainty.

Model bias can also be understood as the combination of parametric and structural bias, as discussed further in section Y3.3.

Y3.3. Reanalyses and their biases

Reanalysis products are based on a combination of observations and model results, designed to 'fill-in-the-gaps' of the observational record in order to provide a wide range of variables at high spatial and temporal resolution. These can be invaluable for comparing with results of models for a wider range of variables than those available in the observational record. There are currently a handful of well established products based on different models available from different institutions.

To produce atmospheric reanalysis products, a model is run for a short period of 6 hours to produce a 'forecast'. Observations are then assimilated through a variety of methods that nudge the 'forecast' towards the measurements, which produces the 'analysis'. This is then the basis of the next 'forecast', and the process is repeated continuously for the length of the reanalysis.

The results of renalyses are therefore subject to the combination of observational and model biases. Some observational biases may be reduced due to the assimilation, but others will remain. Biases will be much higher in regions where there are sparse observations, such as the polar regions, and further in the past.

Comparing the results of different reanalysis products can give an estimate of the model bias, which results from the combination of parametric bias (uncertainty in what the best parameters to use in the model) and structural bias (the failure of the model to accurately represent the underlying physics of the real climate). Some methods use an ensemble of model forecasts to create their analysis, and the spread in

these forecasts can give some estimate of the random errors (perhaps due to parametric bias or uncertainty in the initial conditions) for an individual reanalysis.

Similar reanalysis products are available for ocean variables, although the time range of these is much more limited due to the paucity of historical ocean observations at depth. In addition to reanalyses, ocean 'state estimate' products are also available, which work by adjusting model parameters to best match observations, rather than directly modifying the forecast.

Y3.4. Future Socio-Economic Pathways

In order to produce projections of the future, climate models require predictions of future socio-economic states as well as emissions. The CMIP6 models (see above) use a set of standardised scenarios called Shared Socioeconomic Pathways (SSPs), which take into account possible future social as well as climate dimensions. These SSPs are the latest set of global socioeconomic development trends designed by the IPCC to guide climate change research. They are made up of five global development pathways that depict plausible alternative future states of the society and the environment. They include key socioeconomic variables such as demographics[130], and economic growth[131]. They have been designed to span the wide range of socioeconomic challenges

to adaptation and mitigation. There is a large body of literature documenting (i) their development[132]; (ii) their quantification of key socioeconomic variables ; and (iii) their integration with climate change and greenhouse gas emissions[134].

The different scenarios for forcing the climate models are determined by a combination of socioeconomic pathway and climate forcings, see figure Y3.3 for illustration. The four main pathways are named SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, where the first number indicates the socioeconomic pathway, and the second number the strength of climate forcing at 2100. These are the same magnitude climate forcings as the previous CMIP5 RCPs.

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131 Cuaresma, J. C. (2017). Income projections for climate change research: A framework based on human capital dynamics. Global Environmental Change, 42, 226-236.
132 Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., ... & Meehl, G. A. (2010). The next generation of scenarios for climate change research and assessment. Nature, 463(7282), 747-756.; Ebi, K. L., Kram, T., van Vuuren, D. P., O'Neill, B. C., & Kriegler, E. (2014). A new toolkit for developing scenarios for climate change research and policy analysis. Environment: Science and Policy for Sustainable Development, 56(2), 6-16.; Schweizer, V. J., & O'Neill, B. C. (2014). Systematic construction of global socioeconomic pathways using internally consistent element combinations. Climatic Change, 122(3), 431-445.
133 IIASA. Shared Socioeconomic Pathways Database, Version 1.1. Available online: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.
134 Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... & Lutz, W. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change, 42, 153-168; Marangoni, G., Tavoni, M., Bosetti, V., Borgonovo, E. M. A. N. U. E. L. E., Capros, P., Fricko, O., ... & Johnson, N. (2017). Sensitivity of projected long-term CO 2 emissions across the Shared Socioeconomic Pathways. Nature Climate Change, 7(2), 113-117.

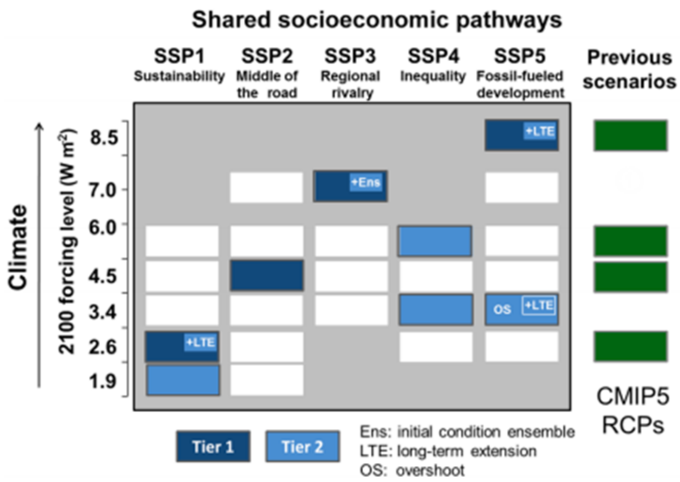

Fig Y3.3: SSP-RCP scenario matrix illustrating ScenarioMIP simulations. Each cell in the matrix indicates a combination of socioeconomic development pathway (i.e., an SSP) and climate outcome based on a particular forcing pathway that current IAM runs have shown to be feasible (Riahi et al., 2016). Dark blue cells indicate scenarios that will serve as the basis for climate model projections in Tier 1 of ScenarioMIP; light blue cells indicate scenarios in Tier 2. CMIP5 RCPs, which were developed from previous socioeconomic scenarios rather than SSPs, are shown for comparison.

Appendix Y4: Global Landscape of Climate Security -Initiatives and stakeholders

The repository can be accessed here


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