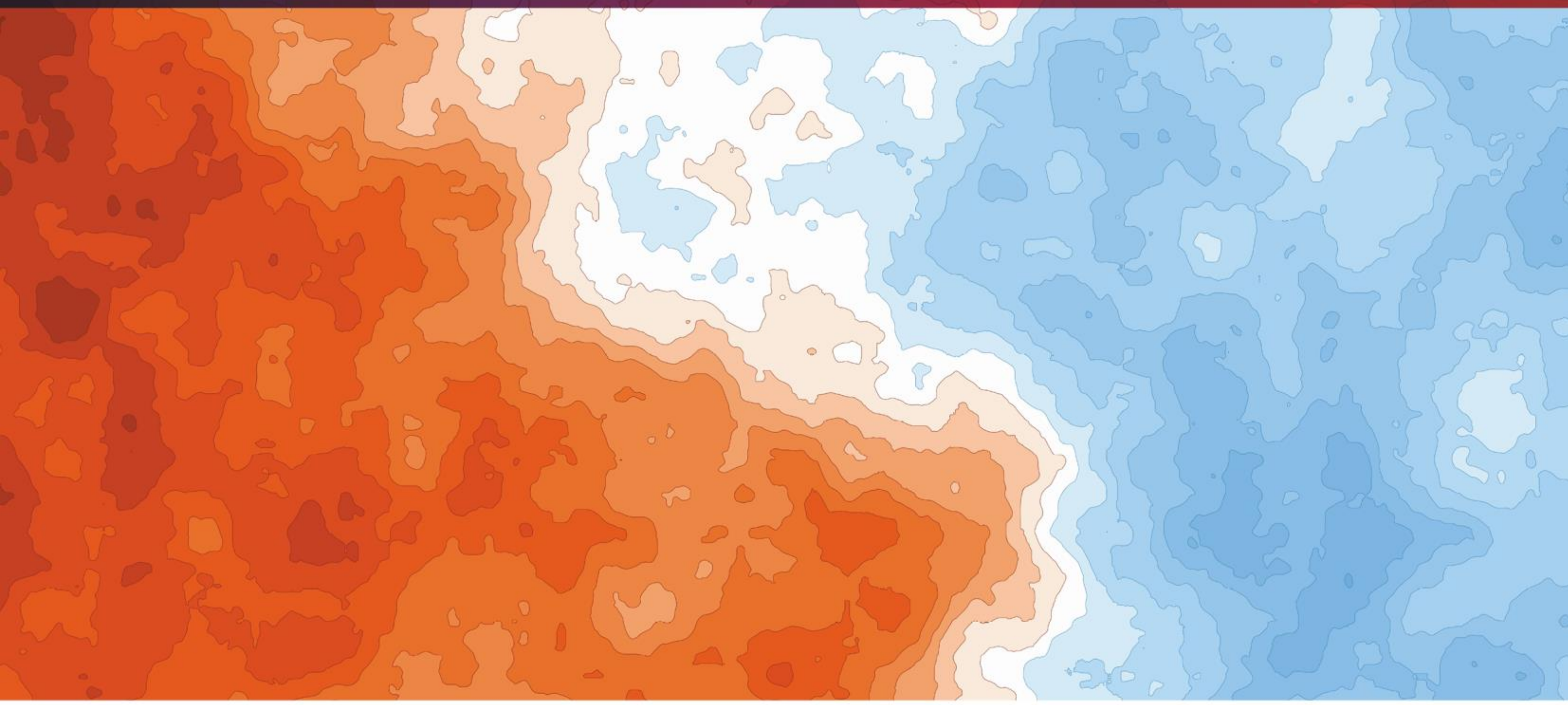
OBSERVATOIRE Défense & Climat

Note

SECURITY AND DEFENCE IMPLICATIONS OF CLIMATE TIPPING POINTS

AMOC

June 2025



DGRIS

IRIS INSTITUT DE RELATIONS INTERNATIONALES ET STRATÉGIQUES

The Defence and Climate Observatory, launched in December 2016, aims to study climate-related security and defence issues.

It is coordinated by IRIS as part of the contract carried out on behalf of the French Ministry of Armed Forces's Directorate General for International Relations and Strategy (DGRIS). The Observatory's multi-disciplinary team includes researchers specializing in international relations, security, defence, migration, energy, economics, climatology and health. It is directed by Mathilde Jourde and François Gemenne.

The Observatory has initiated numerous collaborations with European partners (Netherlands, Luxembourg) and international partners (Australia, United States, India), international NGOs and national and international public bodies. These initiatives have strengthened cooperation on climate issues and their security implications.

The Climate and Defence Observatory produces reports and notes, organises restricted seminars and conferences open to the public, and hosts the podcast "On the climate front".

www.defenseclimat.fr/en

The Ministry of Armed Forces regularly calls upon private research institutes for outsourced studies, using a geographical or sectoral approach to complement its external expertise. These contractual relationships are part of the development of the defence foresight approach, which, as emphasised in the White Paper on Defence and National Security, *"must be able to draw on independent, multidisciplinary and original strategic thinking, integrating university research as well as specialised institutes*".

Many of these studies are made public and available on the Ministry of Armed Forces website. In the case of a study published in part, the Directorate General for International Relations and Strategy may be contacted for further information.

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SUMMARY

Introduction

The Defence and Climate Observatory has published numerous reports on the geopolitical and defence implications of disruptions linked to climate change. Climate change is often **perceived as a slow, gradual, and predictable phenomenon, allowing for the progressive adaptation of human systems, particularly defence and security ones**. This perception overlooks risks posed by **certain phenomena with strong kinetic dimensions or involving feedback loops (see Part 1.B), such as climate tipping points**. Recognizing these challenges, the Defence Advanced Research Projects Agency (DARPA) funded a project in 2022 – AI-assisted Climate Tipping-point Modeling (ACTM) – focused on improving **modelling of climate phenomena, particularly tipping points, thresholds, and associated bifurcations**. Within a complex climate system[1] with highly interconnected components, **thresholds have been identified**, beyond which **feedback loops self-amplify and rapidly accelerate climate change**. Therefore, understanding **accelerating factors and associated tipping points** is crucial to complement the climate security studies already conducted.

The tipping points examined in this series of notes will be those identified by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018; Collins et *al*., 2019). This first note focuses on **the slowdown, or even collapse, of the Atlantic Meridional Overturning Circulation (AMOC)**. This system of ocean currents redistributes heat accumulated around the equator towards the North Atlantic. It is central to the balance of the climate system. Therefore, it has been studied for several decades. It was at the heart of a United States' security study as early as 2003 (see Part 2**). While scientific uncertainties had long hindered its integration into strategic documents on climate security**, the recent **convergence of climate model results** around an AMOC slowdown has reignited research dynamics.

Through a **literature review, maps, and visualisation tools**, this note aims to **provide relevant data for political and economic decision-makers on the security and defence implications that the slowdown, or collapse, of the AMOC could represent**. An annex provides a methodology for approaching tipping points, which will be common to the various notes in this series.

[1] The climate system is a highly complex one, composed of five major elements: the atmosphere, cryosphere, lithosphere, and biosphere, all of which are closely interconnected.

PART 1
UNDERSTANDING THE AMOC AND ITS SECURITY IMPLICATIONS

Climate tipping points

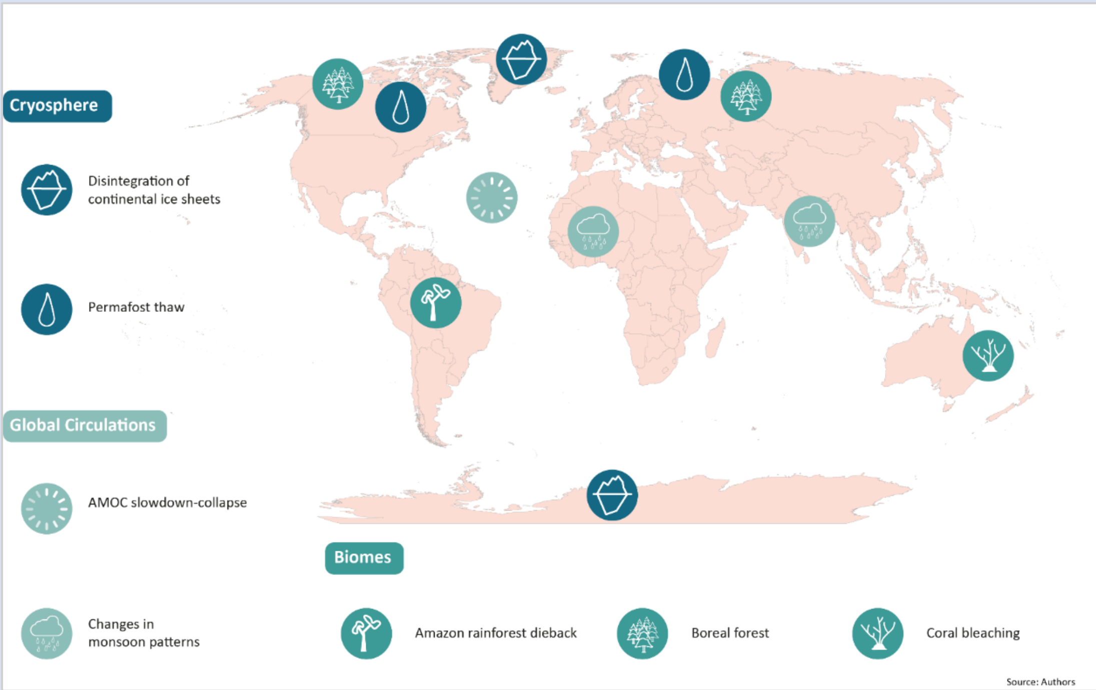
A tipping point is defined as **a level of change in the properties of a given system beyond which it reorganises itself, often in a nonlinear manner** (Collins et *al*., 2019). An appendix to this note dives into how a system can tip from one state to another, and various approaches to detect such tipping.

In the context of the climate system, a tipping point refers to a **critical threshold which, once crossed, triggers a shift of all or part of the global system toward a new state of stability**.

It is important to stress that the **initial state cannot be returned to, even if the drivers of change are abated**. In the case of climate tipping point, drivers are associated with **increasing global temperature** due to anthropogenic greenhouse gas emissions. The concept of threshold often carries with it the idea of **feedback loops**, through which the system self-sustains triggered dynamics (Lenton et *al,* 2023).

Climate tipping points identified by the IPCC structuring this series of notes cover **the melting and thawing of cryosphere elements** (Greenland and West Antarctica icecaps melting, sub-arctic permafrost thaw), **major changes in global circulations** (slowdown, or even collapse, of the AMOC, West African and Indian monsoon changes) or **biome changes** (coral bleaching, boreal forest shrinkage, Amazon rainforest dieback).

Figure 1 – Map showing the different climate tipping points identified by the IPCC



These tipping points are associated with uncertainties, both regarding the **timescale** of their crossing and the associated **consequences**. Yet, these **uncertainties must not invalidate the relevance of tipping points integration into security and defence policies**. **Omitting a low-probability[2] yet high-impact event from strategic monitoring would be a hazardous decision.**

Evolution of scientific uncertainties about the AMOC

According to Harper *et al.* (2024), four distinct states elucidate the dynamics of a tipping point: an **initial stable state**; a **transitional state** characterized by growing instability; a **critical tipping point**; and a subsequent shift toward a **new equilibrium state**.

The difficulty to precisely model the evolution of AMOC lies in the **lack of historical data** (Ben Yami et *al*., 2024a), limiting the capacity to **clearly define an initial stable state and thus detect a potential critical slowing down (see appendix)**. Furthermore, challenges of complex phenomena integration into models (effect of vortex, trajectory of the circulation, consequences of biochemical characteristics changes of waters off the coasts of Newfoundland… (Jackson *et al.*, 2023)) **limit the understanding of the interactions of the various components of the AMOC**. As for every climate tipping point, **uncertainties remain**, revolving around the **AMOC transition timescale and the impacts** of its potential collapse. These impacts constitute the purpose of this note. Regarding its timescale, uncertainties are linked to the pace of the slowdown: hypotheses range from a collapse by 2095 (Ditlevsen et *al*., 2023) to the continuation of circulation through other mechanisms (Antarctic Circumpolar Currents (Baker et *al*., 2025)), or even a gradual slowdown leading to a collapse over the course of a century (van Westen et *al*., 2024). The IPCC Special Report on the Ocean and Cryosphere states that a slowdown is very likely during the 21st century, and that an AMOC collapse cannot be ruled out (IPCC, 2019). The authors of this note thus consider an AMOC collapse as a possibility that requires strategic reflection.

The latest scientific conclusions support the idea of a substantial slowdown of the AMOC. This can be explained by **1)** the continuous development of new measurement tools and **2)** the ongoing improvement of modelling capabilities. Many studies previously assumed the AMOC to be highly stable in the models they used. However, the CMIP[3] models, which form part of the data considered by the IPCC, do not account for the consequences of ice sheet melting and the associated freshwater inputs on the evolution of the AMOC[4]. **The most recent studies (2020-2025) converge on the hypothesis of a significant slowdown by the end of the 21*st* century, or even a collapse of the AMOC, the timing of which remains much more uncertain.** This **reduction in uncertainty regarding the timescale and extent of the AMOC slowdown** provides an additional justification to integrate the study of tipping point repercussions into discussions on national security and defence.

[2] "The AMOC is projected to weaken during the 21st century (*very likely*), but a collapse is deemed *very unlikely* (albeit with *medium confidence* due to known biases in the climate models used for the assessment)." IPCC 6th report, p188. (Masson-Delmotte et *al*., 2021). Scientific uncertainty is often misunderstood. As highlighted by the UK National Preparedness Commission (2024), the IPCC has established a reference framework for addressing uncertainty, which states that an event or phenomenon is described as 'unlikely' if its probability of occurrence is below 33%, and 'very unlikely' if it is less than or equal to 10% (IPCC, 2007).

[3] Coupled Mode Intercomparison Projects (CMIP) are climate modelling research programs aiming at coordinating and archiving climate simulations, based on international team sharing their models' data. These results support the basis of IPCC's Assessment Reports.

[4] Yet the Greenland ice sheet is losing 280 million tons of ice per year due to climate change (Mouginot, 2019).

A – Cross analysis of climate change and tipping points

1. *First-order* and *cascading* impacts

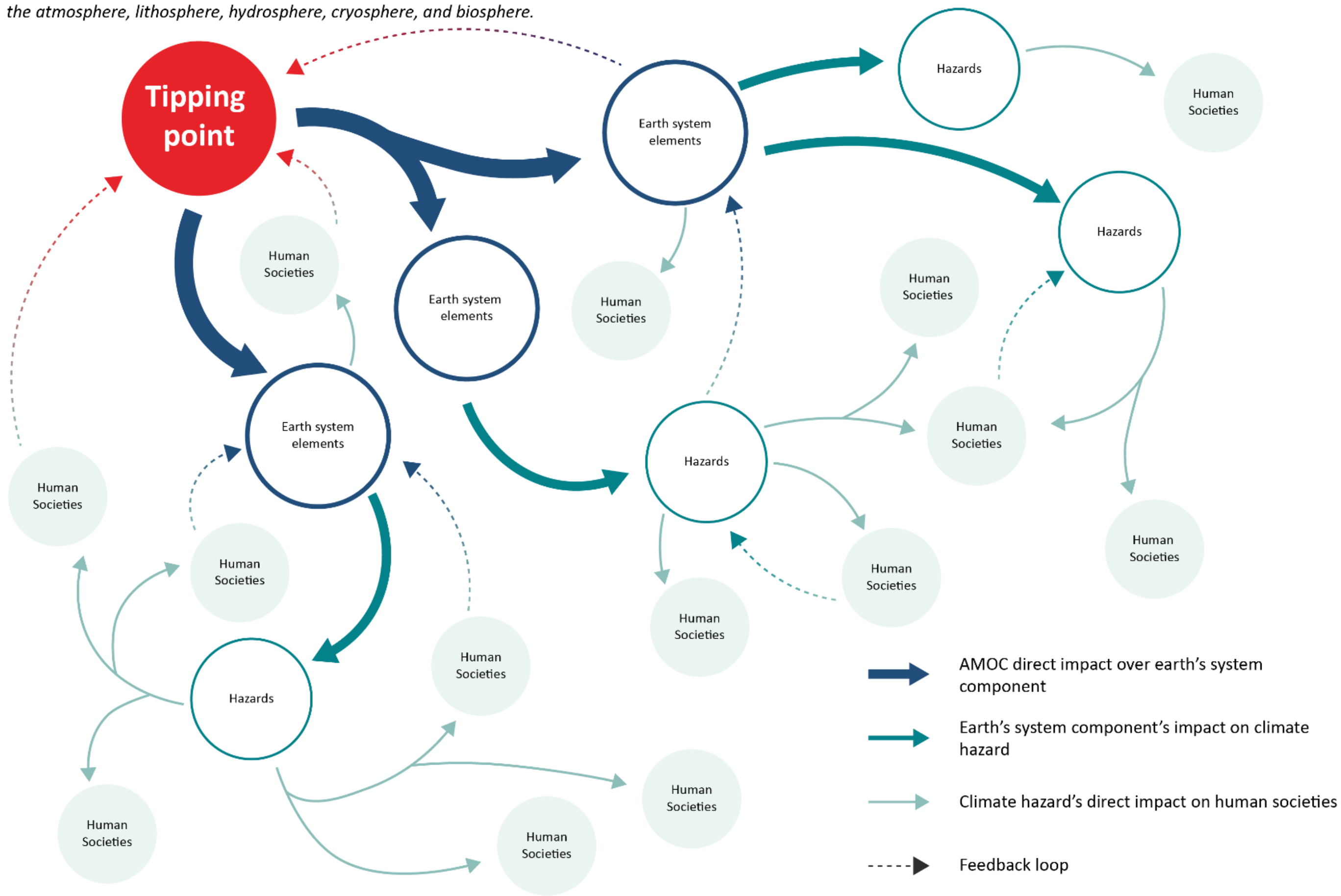
Anthropogenic climate change manifests **through global or regional modifications of the climate system's components**, which can be summarised as follows: the atmosphere, lithosphere (continents), hydrosphere, cryosphere (the ice), and biosphere (ecosystems). These modifications will result in an increase in the mean surface temperature of land and ocean, a higher atmospheric water vapor concentration, or changes in the spatial distribution of some ecological niches. **Environmental hazards associated with these modifications** can unfold through extreme climate events (hurricanes, heatwaves…) or ecological events (such as species extinction). **These modifications and associated hazards will be considered as *first-order impacts***.

These phenomena modify the living conditions of populations. Crop yields, worker productivity, functioning of infrastructures, are parameters dependent on rainfall, atmospheric and ocean temperatures, or the occurrence or absence of hurricanes. Therefore, these first-order impacts induce **cascading impacts** over human systems[5]. These **impacts on the latter will be referred to as *cascading impacts* in the following sections**.

[5] Responses to these cascading effects feed back into climate change through adopted solutions and associated greenhouse gas emissions (for example, the deployment of air conditioning to combat heatwaves constitutes a case of maladaptation, reinforcing the phenomenon it is supposed to address).

Figure 2 – Cascading impacts: Links between climate tipping point, earth system elements and human societies ***(source: authors, realization: Antoine Diacre)***

Only three components of the Earth system are presented on this , but these cascading effects apply to all five components: the atmosphere, lithosphere, hydrosphere, cryosphere, and biosphere.



2. Data collection and analysis

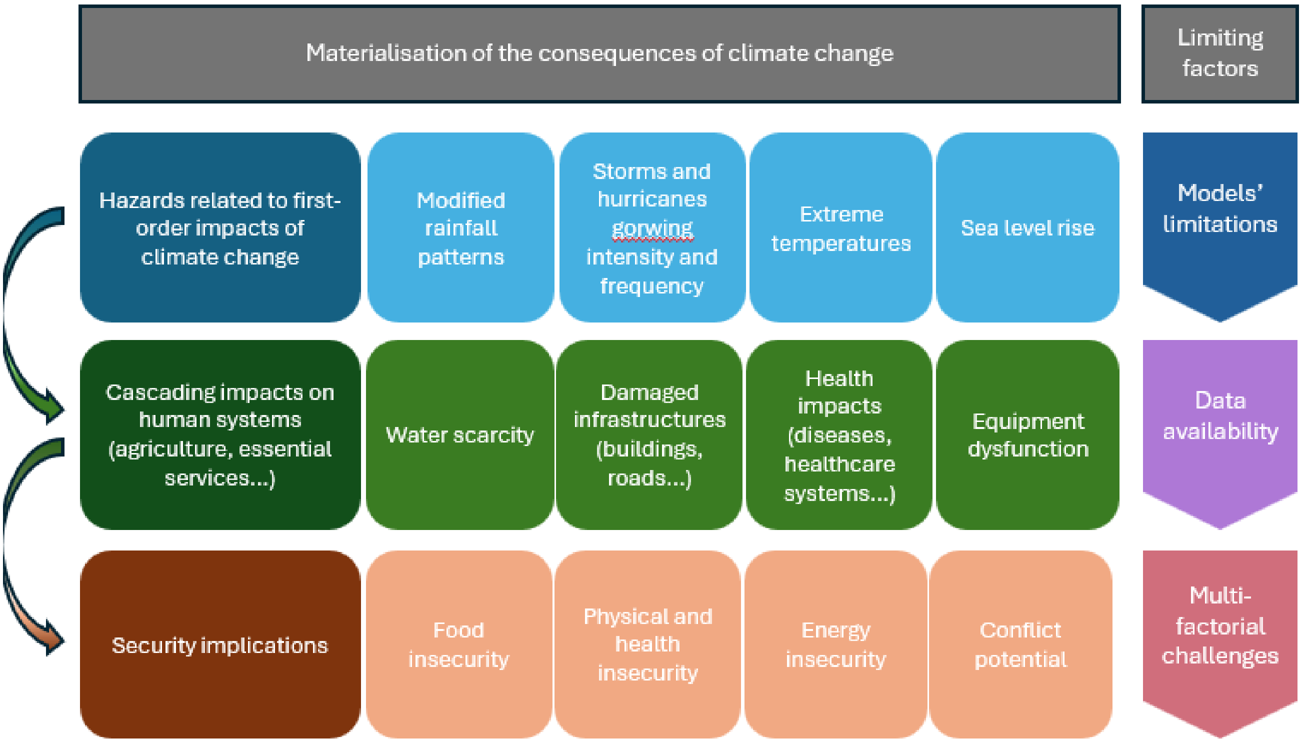
Defence and security stakeholders are exposed to first order impacts of climate change. The *Stratégie Climat & Défense* (Climate & Defense Strategy, ministère des Armées, 2022) aims at anticipating such impacts. However, **a comprehensive knowledge of associated cascading impacts** to prepare for its security dimensions is essential to these stakeholders.

First order impacts of climate change are subject to numerous scientific studies, often based on modelling and meta-analysis (CMIP, IPCC Assessment Reports…) Therefore, they **are better documented, and uncertainties are limited** by cross-cutting results of multiple studies. Working groups such as the IPCC, or the Intergovernmental Sciences-Policy Platform on Biodiversity and Ecosystem Services (IPBES), as well as institutions such as the World Meteorological Organization, seek to collect data and refine knowledge of these first-order impacts.

A second step consists of mapping cascading impacts, which often contributes to **reinforcing multifactorial phenomena**. At this stage, it is often useful to define spatial delimitation for the study. Indeed, whereas first-order impacts can have global consequences, **most cascading impacts will be spatially determined, structured by local ecosystems, geographical characteristics and pre-existing climate conditions**. These cascading impacts are associated with the **exacerbation of vulnerabilities**, which result both from first-order impacts and from the **preparedness, adaptation, and coping capacities** of exposed human systems. First-order impacts will have consequences which can initially be **absorbed** by adaptation measures, then **mitigated** by the preparedness of institutions and populations to such shocks. **These human systems will persist as long as their resilience/coping capacity is not overwhelmed**. Cascading impacts have security and defence implications, which become even more significant as **limits of the coping capacities of the system approach**.

The different **stages of this phase** are presented below.

Figure 3 – First order and cascading impacts, limiting factors, including uncertainty (from low in blue to high in red) associated to climate change



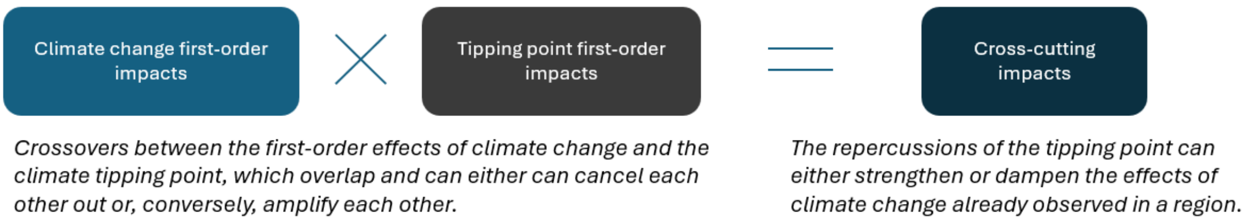
Source: authors

Colors associated with limiting factors, on the right side of the diagram, represent the level of uncertainty, depending on the amount of available and consistent data. We aim to represent this uncertainty because **the more multifactorial a phenomenon is, the harder it becomes to establish reliable causality**. Furthermore, some elements of the climate system **or tipping points are associated with greater uncertainty, due to a lack of data and modelling integration challenges**.

Low uncertainty High uncertainty

A second step consists of **integrating repercussions of a <u>tipping point</u> into these cascading impacts of climate change**. Studying tipping points as an integral part of climate change through this categorisation into first-order and cascading impacts aims to achieve the following objective: **to clarify security and defence repercussions specific to this tipping point**, depending on whether it reinforces or dampens some of the consequences of climate change.

Figure 4 – Link between the first order impacts of climate change and the first order impacts of tipping point



Source: authors

The intersection **of climate change and tipping point** may involve increasing uncertainty, due to the limited available data.

Figure 5 – First-order and cascading impacts ; limiting factors of a tipping point

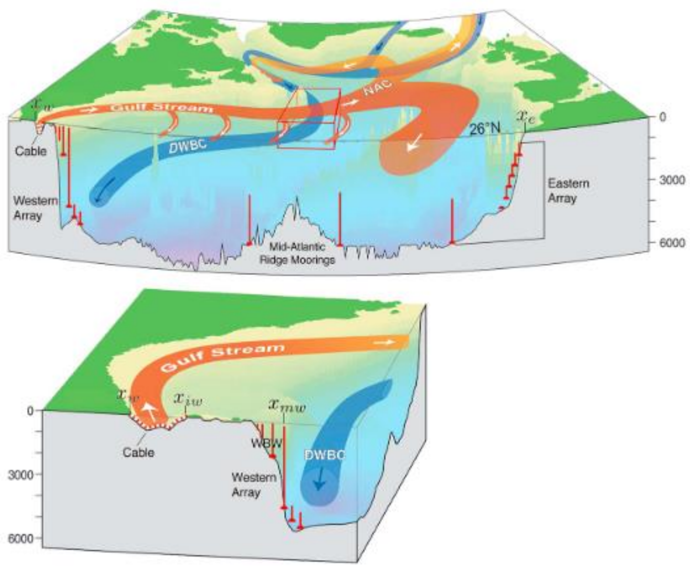
Source: authors

B – Understanding the AMOC

1. The AMOC and its drivers

The AMOC is **part of global oceanic circulation**. It is defined by the transport of warm, salty surface water from South Africa up to northern parts of the Atlantic Ocean (Buckley et *al.*, 2016), and deep, cold water from the North Atlantic southward to the equator. When warm surface waters move northward, part of the heat is transferred to the atmosphere, and the water becomes cooler and denser. Upon reaching high latitudes, very salty waters coming from the Atlantic mix with colder, fresher polar waters (Abot et *al.,* 2023). The combination of cold Arctic waters and the salinity brought by Atlantic waters increases the density of surface waters. This density can exceed that of deep waters, causing surface waters to sink. This process, called **deep water formation**, is **one of the main drivers**[6] **of global ocean circulation**.

Figure 6 –Schematic representation of North Atlantic oceanic circulations



Surface currents are shown in orange (Gulf Stream, North Atlantic Current – NAC) transporting heat toward the Northern Hemisphere. Deep currents are shown in blue and flow in the opposite direction (Deep Western Boundary Current – DWBC).

Source: Buckley et al., 2016

However, the **AMOC should not be confused with the Gulf Stream**: the latter is a surface current **whose existence depends on the Earth's rotation**. The Gulf Stream is therefore part of the complex system that makes up the AMOC, but it is **not driven by the same mechanisms** (Cailloce, 2021). Along with the prevailing westerly winds, which help move warm air masses, it contributes to the transfer of heat from tropics to the North Atlantic. This heat transfer allows Europe to experience a milder climate than North America at similar latitudes (Buckley et *al.,* 2016)

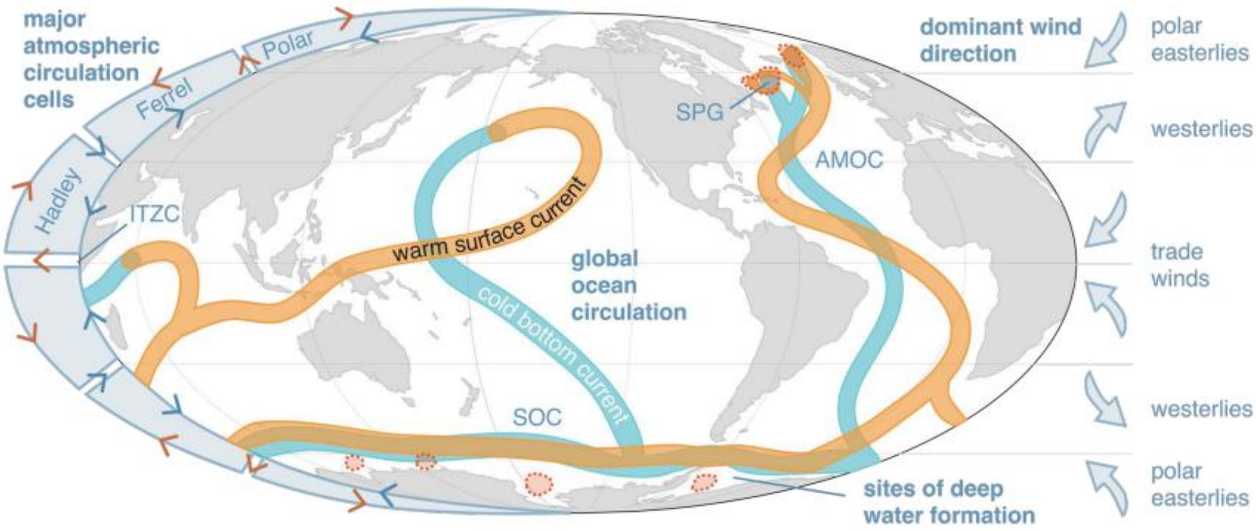
The state of AMOC, namely the strength of the circulation and heat transfer as well as deep water formation, is therefore a **key element in the stability of the climate system** as we know it. However, **consequences of climate change** (more intense polar warming, ice sheet melting, disruptions of precipitation patterns, etc.) **are altering the functioning of this mechanism**, which, if it were to collapse, could completely disrupt the global climate (Benton, 2020; Drijfhout, 2015). Paleoclimate analyses reveal that, in the past, significant variations in the AMOC have led to major cooling periods in the Northern Hemisphere, along with an opposite

[6] While the AMOC is closely linked to deep water formation in the subarctic regions, there is debate about the role of other mechanisms in the functioning of this circulation and their ability to compensate for a weakening of deep-water formation in the subarctic regions. This is particularly the case for the Antarctic Circumpolar Current and the Antarctic winds, which could help maintain a certain level of circulation (Baker et *al*., 2025).

trend in the Southern Hemisphere (Gulev et *al*., 2021).[7] That is why the slowdown, or even collapse, of the AMOC is considered a **climate tipping point**. Due to the global nature of this circulation, this tipping point could strongly interact with other tipping points (Boot et *al*., 2025; Lenton et *al*., 2008) (see Figures 8 and 9).

Figure 7 – Global ocean circulations, deep water formation zones and major atmospheric circulation cells.

ITZC *: Inter-Tropical Convergence Zone ;* ***SOC*** *: Southern Ocean Circulation ;* ***SPG*** *: Subpolar Gyre (cf Part 2. 1.1)*

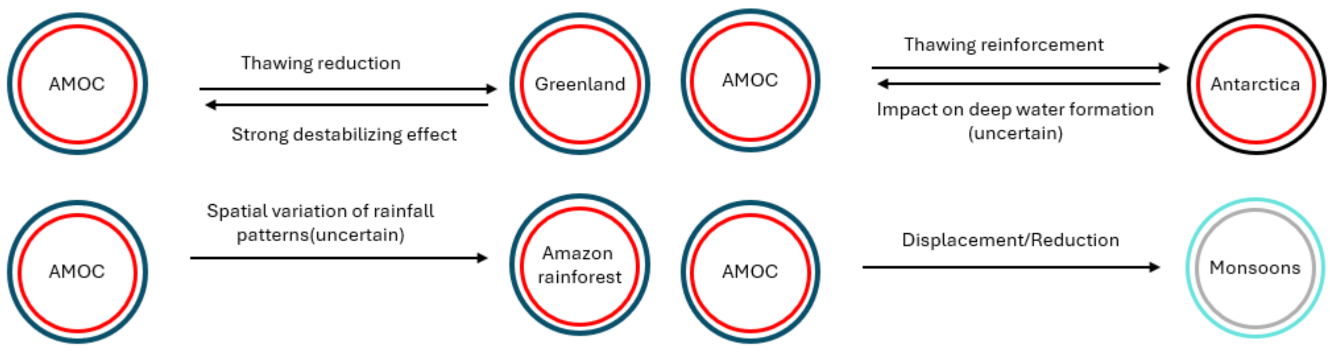


Source: Lenton *et al*., 2023

Considering its global dimension, **the AMOC presents numerous interactions with other climate tipping points**. These **feedback loops** can either be **positive** (the action of *A* reinforces the action of B), **negative** (the action of *A* mitigates the action of B), or **uncertain**, in terms of both their dynamics and existence, according to the current state of the art (Lenton et *al*., 2023). The diagram presented below summarises the main interactions between the AMOC and other key components of the climate system.

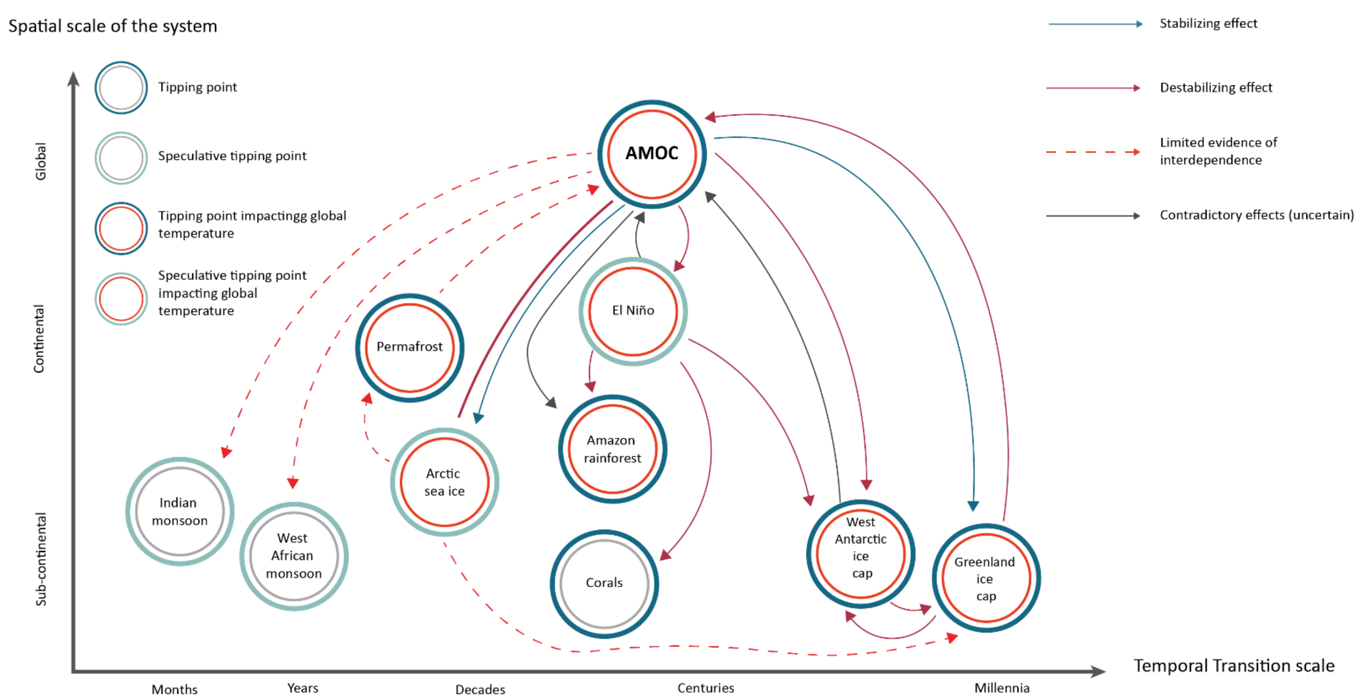
[7] Among these examples are the so-called 'Dansgaard-Oeschger events'. These periods have been identified through ice core data and sediment records in North Atlantic. They are characterized by a rapid warming phase, followed by a slowdown of the AMOC and a subsequent gradual, then abrupt, cooling of the Northern Hemisphere (Lenton et *al*., 2023).

Figure 8 – Main interactions between the AMOC and other tipping points identified by the IPCC



Sources : Lenton et *al.,* 2023 ; Ben Yami et *al.,* 2024

Figure 9 – Main feedback loops between tipping points



Some tipping systems are particularly speculative (such as ENSO or the Arctic Sea ice) and denoted as such (outer blue border).
Adapted from Lenton *et al*., 2023

2. First-order impacts of a slowdown, or even collapse, of the AMOC[8]

The slowdown, or even collapse, of the AMOC would affect all components of the climate system. Ocean capacities for absorbing and redistributing heat and CO_2 would be severely impaired (Buckley et al., 2016), leading to **an acceleration of climate change[9]**. These changes would not be evenly distributed: the Northern Hemisphere would cool, particularly the European continent, while the Southern Hemisphere would experience substantial warming (Drijfhout, 2015). Temperature changes, along with the interruption of the ocean carbon pump, would lead to an **acceleration of ocean acidification**[10] (Lenton *et al.*, 2023) and the **risk of a significant decline in fishery resource production in the North Atlantic Ocean** (Boot et al., 2025), although uncertainties remain on this issue (Tagliabue *et al.*, 2021). The North Atlantic cooling could also lead to an increase in sea ice formation in winter (Liu *et* al., 2022), affecting shipping routes around the Arctic. Finally, **the slowdown, or even collapse, of the AMOC would increase ocean stratification[11], which could significantly impair submarine and anti-submarine warfare capabilities**: by studying the evolution of acoustic propagation in six areas of the North Atlantic and Western Pacific using IPCC climate projections (SSP5-8.5), Gilli *et al*. (2024) observed a marked **increase in acoustic transmission loss** in the North Atlantic. While the conclusions of these various studies are limited to the areas studied, the Arctic region appears to be particularly affected (NATO, 2024).

The evolution of climatic conditions of the European continent is foreseen as increased seasonality, with **drier summers and more frequent and intense heatwaves, alongside harsher and stormier winters** (Lenton *et al*., 2023). On a multi-year scale, some projections estimate a **decrease in average temperatures ranging from -4°C (Ritchie *et al*., 2020) to -10°C (Van Westen et *al*., 2024) across the continent[12]**. The drastic reduction in precipitation in Western Europe, particularly in the north, and the shortening of the growing season would have **negative consequences for agricultural production** (Ritchie et *al*., 2020).

[8] Scientific publications constituting the basis of the present conclusions mostly model an AMOC collapse. Their results allow for the identification of the main climatic, physical, and biological repercussions of this collapse. The consequences of a substantial slowdown, though of lesser magnitude, would follow similar dynamics.

[9] The shutdown of the AMOC would alter the ocean's carbon absorption capabilities through a decrease in carbon dioxide solubility. It would no longer be transported by deep water formation. Therefore, with constant greenhouse gas emission trajectories, the reduction of the ocean carbon sink would increase the proportion of CO_2 remaining in the atmosphere (Rahmstorf *et al*., 2024a).

[10] The shutdown of the AMOC would concentrate the CO_2 captured by the ocean at the surface, accelerating ocean acidification and the consequences of the phenomenon [coral bleaching, extinction of marine species, increased ship corrosion, etc. (NATO, 2024)].

[11] In the ocean, water masses are layered according to their density. Density varies depending on salinity and temperature. European Institute of the sea.

[12] The variation in model projections is primarily due to differences in parameterization and the representation of certain climatic processes, such as precipitation, cloud cover, and sea ice formation.

The slowdown, or even collapse, of the AMOC would also have consequences for global atmospheric circulation, particularly a southward shift of the Intertropical Convergence Zone (ITCZ)[13]. Such a phenomenon would result in a **significant reduction in monsoons in West Africa and South Asia**, leading to a **20 to 30% reduction in annual precipitation volumes** (Ben Yami *et al.*, 2024). Such disruptions would **strongly impact regions highly dependent on subsistence agriculture**, as well as the global production of certain cereals integrated into international markets. Environmental conditions for maize cultivation in Europe would thus collapse. Wheat, on a global scale, would experience a similar pattern (OECD, 2021).

3. Cascading effects of a slowdown, or even collapse, of the AMOC

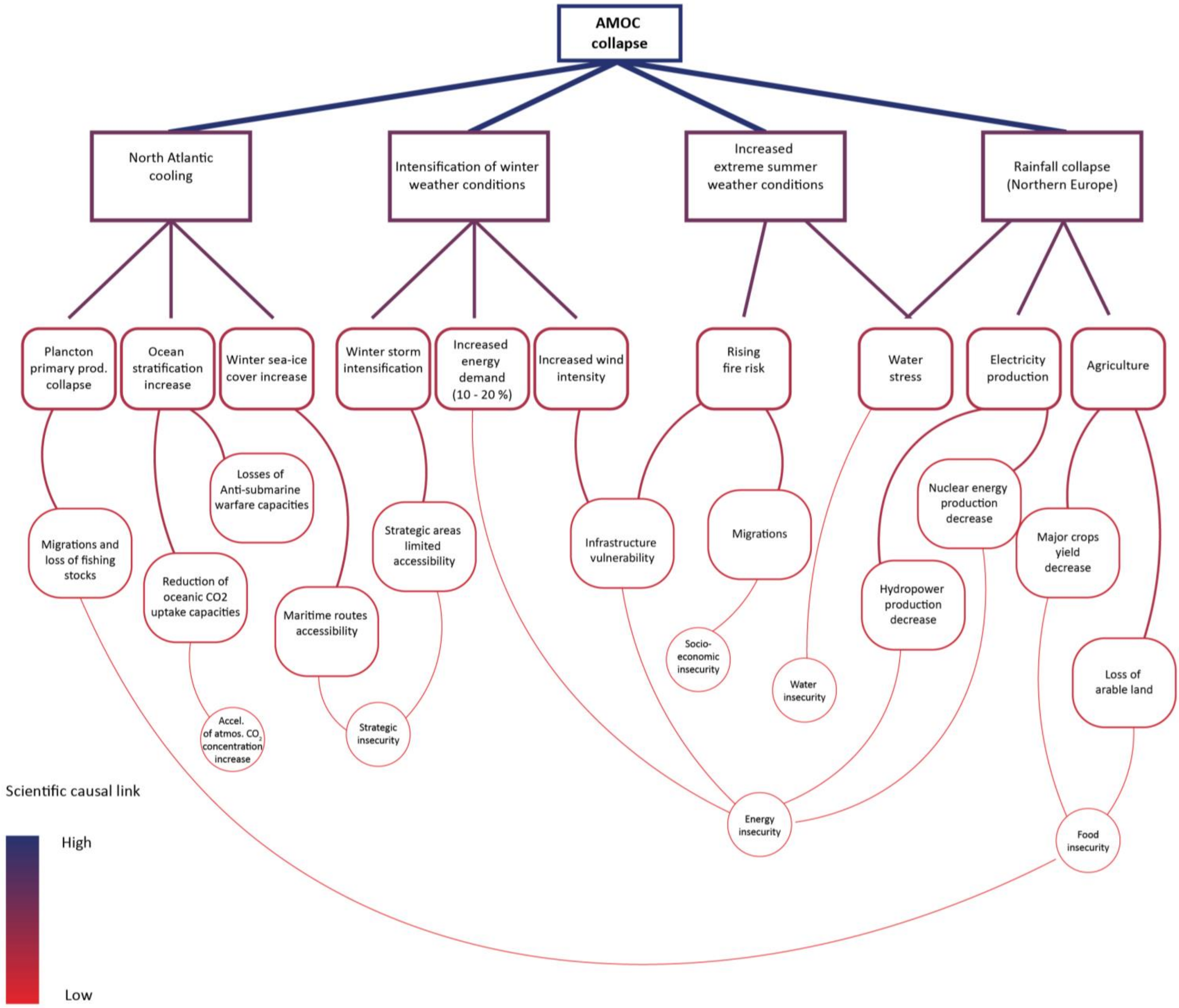
Given its role in climate stability, particularly across the European continent**, the slowdown, or even collapse, of the AMOC would lead to major cascading repercussions** across all human systems. Extreme weather conditions, both in **summer** (hotter) **and winter** (colder), would most likely result in a **multiplication and intensification of extreme climate events** (Drijfhout, 2015). Beyond exacerbating disasters already intensified by climate change, and for which the level of preparedness varies, **such changes would expose European societies to risks that have so far been little or even entirely unconsidered** (Laybourne et *al*., 2024). The intensification of winter conditions and storms could, for example, severely **damage energy infrastructures**, while also driving an increase in energy demand. The worsening of water cycle disruptions would have **consequences for public health**, with the collapse of the AMOC exacerbating water scarcity already experienced by many European countries (Duffau et *al*., 2024).

Global food security would also be compromised. European agricultural production would be severely impacted by the reduction in the growing season, induced by the decrease in temperatures, as well as by the reduction in precipitations (see below). This risk would be compounded by the **collapse of the production of many grain hubs around the world**, particularly due to changes in monsoon patterns in West Africa and South Asia (Lenton *et al.*, 2023). Such consequences could lead to **significant migration flows from Northern European countries towards the south of the continent**, to cope with climate degradations experienced by northern regions of Europe, which are most exposed to climate changes (Schwarz *et al.*, 2003). The **entire European economic system** would be disrupted by a global degradation of living conditions, with local consequences having cascading effects in the context of the **high interconnection of markets within the European Union** (Hald-Mortensen, 2024).

[13] A form of meteorological equator, a zone where the trade winds from the Northern and Southern hemispheres converge and where the Hadley cells meet (see Figure 6, shown on the left). (Encyclopedia Universalis., Jean-Pierre Chalon., n.d)

Geopolitical consequences could also be numerous: the range of possibilities extends **from an increase in cooperation**, particularly in broader frameworks addressing climate action, in response to rising costs of inaction, **to regional fragmentation and unilateral adaptation strategies**, such as geoengineering, which have a very high conflict potential (Dimsdale *et al.*, 2022; De Guglielmo Weber *et al.*, 2023). Cascading effects of the AMOC are more specifically outlined in the following diagram.

Figure 10 – Schematic representation of the main cascading impacts of the AMOC slowing or collapse and representation of associated scientific causality level of confidence



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PART 2

INTEGRATING THE AMOC COLLAPSE INTO DEFENCE STRATEGIES

A – Implementing AMOC tipping detection tools

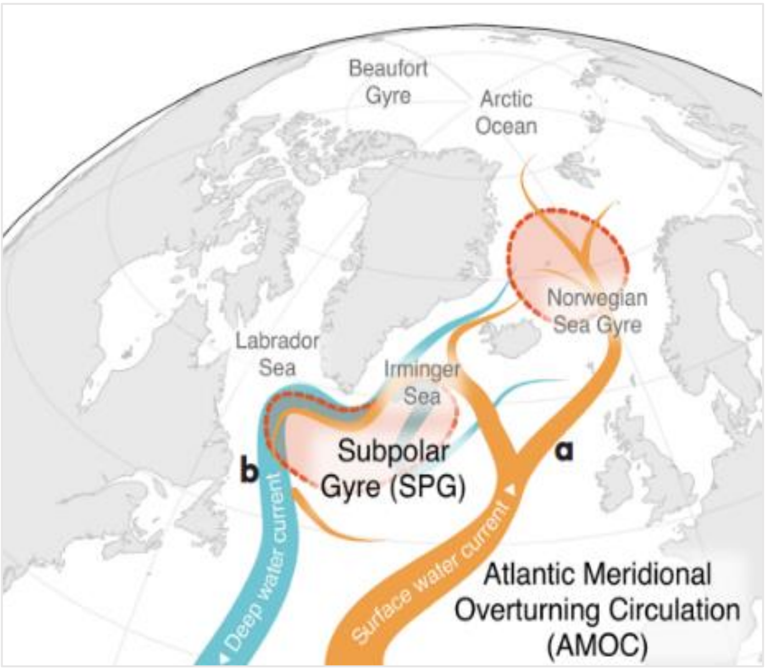
The study of climate tipping points for defence foresight purposes involves preparing systems for the occurrence of such an event. This preparation is twofold: on the one hand, it requires **having the capacity to detect the destabilisation** of the climate system, and on the other, it involves **planning the adaptation of infrastructures, equipment, and practices** to the subsequent hardening of living and operational conditions.

1. Methodological tools for detecting tipping points

1.1. Early Warning Signals

Identifying early warning signals can help **detect the destabilisation** of the AMOC. While the complexity of this circulation **prevents us from identifying with certainty a single parameter** as an early warning signal, several phenomena **recurrently appear in scientific literature**. Among these are the **Agulhas Current,** off the coast of South Africa—whose state appears to be influenced by the AMOC (Zhang et *al*., 2023)—and the **subpolar gyre**, both of which may represent relevant monitoring indicators. We will focus on the subpolar gyre, whose destabilization is frequently cited in scientific studies as a **potential early warning signal of an AMOC tipping point.**

Figure 11 – Schematic representation of the Subpolar Gyre, located at the core of AMOC's deep water formation process



Source: Lenton *et al*., 2023

The subpolar gyre is a system of oceanic currents located south of Greenland (see figure 11). It plays a **key role in the deep-water formation process (which is intrinsic to the functioning of the AMOC).** This gyre and its kinetics are studied by numerous scientific institutions.

Monitoring scientific advancements concerning the subpolar gyre is therefore a promising approach for identifying a potential early warning signal of a significant destabilisation of the AMOC. The British agency ARIA, modelled after DARPA and linked to the Ministry of Science, **invested £81 million early 2025** in a project aimed at identifying early warning signals of tipping points**. It will investigate the possibility that the subpolar gyre could serve as an early warning signal** for several tipping points.

1.2. The transition period

The crossing of a tipping point threshold is crucial to anticipate, but it must be accompanied by a **thorough understanding of the transition period** between the triggering of the tipping point and the definitive change of the system. For the AMOC, this involves understanding how long it would take for a massive cooling of European climates to occur. Some publications suggest a **transition period of 15 to 300 years** from circulation to collapse (Armstrong McKay *et al*., 2022). Other publications mention a transition interval of **a few decades to a few years**, depending on the mechanisms pushing the AMOC towards its tipping point (Rahmstorf *et al*., 2024a; KuhlBrodt *et al*., 2001).

The combination of early warning signals, transition duration, and intermediate effects will help calibrate the necessary adaptations to maintain operational capabilities.

2. Monitoring of scientific work to detect the tipping point

Few ongoing research projects are listed below, the results of which are likely to have an impact on our understanding of the AMOC.

Although some of these projects are not subject to peer-reviewed scientific scrutiny, they can nonetheless provide valuable insights for defense stakeholders. Some are indeed conducted by institutional actors with strategic objectives, such as the ARIA agency. It is important to establish, through the projects below as well as numerous studies initiated in France and elsewhere, **ongoing monitoring by defense actors of the latest scientific advances concerning early warning signals and the transition period of the AMOC.**

Figure 12 – Ongoing research projects aiming at enhancing the understanding of AMOC system and the consequences of its potential collapse.

Funder	Name	Duration	Budget	Coordination	Objectives
France	LOCEAN (Laboratoire d'Océanographie et du Climat : Expérimentations et Approches Numériques)	2005 -	2,7 M €/an	Sorbonne Université	The LOCEAN laboratory conducts numerous research projects related to the AMOC, through oceanographic, climatological, and paleoclimatic studies. For more information.
	MARCARA (MArine radioCArbon Reservoir Age)	2021-2025	526 K € (ANR)	Université d'Aix en Provence	Observe and model the evolution in time of surface waters and their implications for paleoceanography, paleoclimatology, and geochronology. For more information.
European Union	**EPOC** (*Explaining and Predicting the Ocean Conveyor*)	2022-2027	4,8 M €	Hamburg University (Germany)	Develop models to understand the consequences of an AMOC slowdown on weather and climate (several days to years). For more information.
	ROVER (*Resilient Northern Overturning in a Warming Climate*)	2024-2028	3 M€	Bergen University (Norway)	Understand whether icecap retreat could impact AMOC's behavior, particularly by strengthening it (counter to expectations). For more information.
	TipESM (*Exploring Tipping Points and Their Impacts Using Earth System Models*)	2024-2027	4,8 M€	13 consortiums and institutions	Understand tipping points, particularly early warning signals and emission trajectories limiting the risk of tipping. For more information.
	Joint Action on AMOC	2024-2026	/	JPI Climate and JPI Ocean	Produce a report updating AMOC scientific knowledge since IPCC's 6th Assessment Report, as well as its potential impacts over populations.
	Medley (*MixED Layer hEterogeneitY*)	2020-2024	/	LOPS – CNRS	Improve the understanding of the spatial heterogeneity of surface waters and its impacts on energy, heat, and gas exchanges. For more information.
United Kingdom	**Forecasting Tipping Points**	2025-2030	81 M£	27 Teams	Identify tipping points' early warning signals. For more information.
Germany	**TIPMIP** (tipping point modelling intercomparison project)			Postdam Institute, Max Planck Institute and Earth Commission	Identify early warning signals and study the risks associated with simultaneous tipping of several climate sub-systems. For more information.
United States	**Quantifying Global and Regional Impacts of the AMOC Slowdown in the 21st century**	2021-2026	324K€	Yale University (United States)	Understand local and global impacts of an AMOC slowdown, particularly the cooling of the North Atlantic Warming Hole. For more information

	EXPLANATIONS *(Exploring AMOC controls on the North Atlantic carbon sink using novel inverse and data-constrained models)*	2024-2027	440K€	MIT (United States)	Refine the estimation of carbon dioxide uptake, transport, and storage capacities in the North Atlantic, as well as the role of AMOC in the variability of these capacities. For more information.

B – Documenting security implications of the cascading impacts of the AMOC

The adaptation of armed forces to the slowdown of the AMOC should be based both on **the establishment of monitoring systems and partnerships** that allow for the **eventual detection of the crossing of the threshold**, as well as on the **anticipation of its cascading impacts**. These effects could lead to economic, political, and geopolitical repercussions. These repercussions are poorly documented. Security anticipation work on the consequences of the AMOC collapse is rare at the international level. The **institutions with the most developed projects are in the United States (US) and the United Kingdom (UK)**. In the predominant geopolitical context at the time of writing this note (counting, among others, the Trump administration's disengagement from climate studies), the European Union, through the report from the European Union's Joint Research Centre, will likely play a significant role in the coming years.

Through a review of conclusions and approaches of existing work, this section aims to **propose avenues for reflection on mapping the impacts of the AMOC on French national territory**. These works may be scientific in nature or come from foresight centres.

1. To begin with: the British example

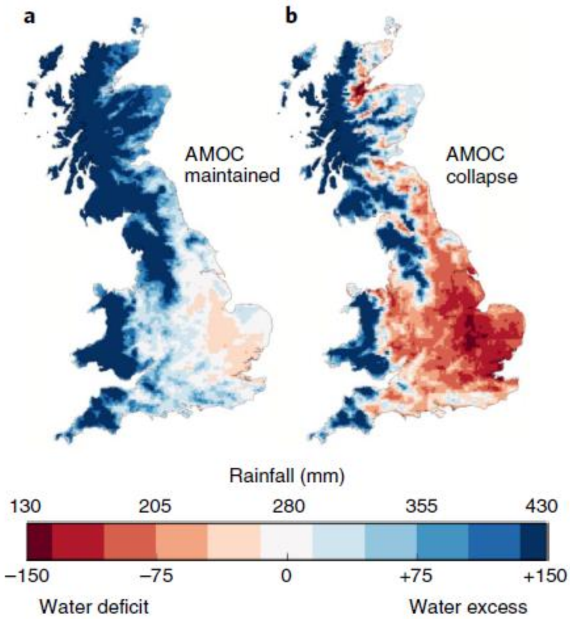
The slowdown, or even collapse, of the AMOC exposes Europe to a reduction in crop yields of around 30% (Benton *et al.*, 2017). However, it is **the northernmost regions** that will be the most severely affected, which led to a scientific study (Ritchie *et al.*, 2020) focusing on the effects of an AMOC collapse on the agricultural sector **in the UK**[14]. This study seems useful to

[14] The results of a single study are insufficient to fully understand the extent of the impacts of a climate phenomenon. However, this study is noteworthy due to its clearly defined objective linked to the analysis of cascading effects of the AMOC, as well as the visuals it employs.

present as it clearly **illustrates the importance of obtaining more data** on the impacts of an AMOC slowdown or collapse on the agricultural or industrial sectors in France.

UK territory will be exposed to a drastic rainfall reduction of the growing season (see figure 13).

Figure 13 – British water balance in 2080 during the growing season, with irrigation available, under the climate scenarios for which the AMOC is either maintained or collapsed.

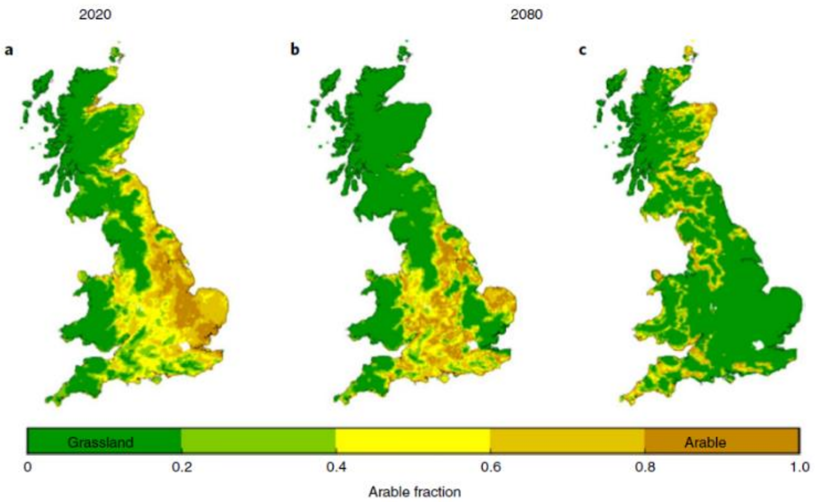


Water deficit (<280mm) during the growing season (April to September) where irrigation occurs (in red), and areas with excess of water (>280mm) (in blue) during the growing season. **On the map (a) AMOC is maintained**, whereas it is **collapsed on the map (b).**

Source: Ritchie *et al.,* 2020

The AMOC collapse and the associated drastic rainfall reduction are unequivocally linked to **the decrease in arable land area (from 32% to 7% of the total agricultural land area)**. Thus, Figure 14 clearly shows that arable land, represented in brown, almost completely disappears by 2080 in a scenario of global warming and AMOC collapse. The **associated economic losses amount to nearly €415,000,000 per year** (Ritchie *et al.*, 2020).

Figure 14 – Limiting factors from an AMOC collapse on arable lands



Source: Ritchie *et al*., 2020.

Map (a) represents arable land in 2020.

The following two maps aim to isolate climate variables (rainfall and temperature) to estimate which one would have the **most significant impact** in the event of an AMOC collapse:

(b) Arable land in 2080, temperature based on an AMOC collapse and precipitations under smooth climate change.

(c) Arable land in 2080, temperature based on a standard climate change scenario and precipitations based on an AMOC collapse.

Figure 15 – Economic projections of the UK agricultural sector based on an AMOC collapse

	Changement climatique progressif ; pas de changement technologique	Changement climatique progressif avec changement technologique	Changement climatique abrupt ; pas de changement technologique	Changement climatique abrupt avec changement technologique
AMOC	Maintenu	Maintenu	Effondrement	Effondrement
Irrigation	Non	Oui	Non	Oui
Valeur du changement agricole *(en millions de livres/an)*	40	125	–346	79
Coût de l'irrigation *(en millions de livres/an)*	0	–284	0	–807
Changement de valeur nette *(en millions de livres/an)*	40	–159	–346	–728

Source: Ritchie *et al.,* 2020

This scientific study provides a visualisation of the impacts of the AMOC collapse on the agricultural sector and offers a precise overview of the repercussions on yields. Such studies do not appear to exist at present for France.

2. Geography of the studies

Given that other countries have considered the repercussions of an AMOC collapse, it seemed useful to gather here an **overview of the most relevant studies**, to **undertake the same work at the French level.**

In the United States, public administrations first led the topic. For example, the US Department of Defense, through its foreign affairs advisor Andrew Marshall, **commissioned a study in the 2000s** on the impact of an AMOC collapse. This study is called the foresight report by Schwartz and Randall, 2003. This was followed by a report from the National Intelligence Council, 2021.

In Europe, the collapse of the AMOC has been highlighted as a major issue by **the UK government** (Moulsecoomb, 2024), as well as by **the Scandinavian Council of Ministers** (Rahmstorf *et al*., 2024b). In the first case, a parliamentary question was addressed to the Department for Energy Security and Net Zero regarding the **assessment of security risks associated with the potential collapse of the AMOC by the end of the century**. Also in the UK, some think tanks have worked on the topic, particularly through the publication of a recent report (October 2024), written by researchers from **Chatham House**, the Global Systems Institute at the **University of Exeter**, and two other think tanks based in the UK (Strategic Climate Risks Initiative and Institute for Public Policy Research) (Laybourne *et al.*, 2024). British universities are also very active. For example, beyond the project initiated by ARIA (the UK Strategic Research Agency), Timothy Lenton (University of Exeter) directed a **meta-study (cataloguing the scientific state of the art),** published in 2023 and funded by the Bezos Earth Fund (Lenton *et al*., 2023).

Concerning the Scandinavian Council of Ministers, a **warning letter signed by 43 scientists** highlights the major risk posed by the crossing of tipping points in general, and the AMOC in particular. The authors emphasise the growing likelihood of an AMOC collapse in upcoming decades based on latest scientific publications, and associated devastating consequences, although still poorly characterized for Northern Europe.

Finally, at the **European level**, a public policy brief was made public on 28 February 2025 by **the European Union's Joint Research Centre** in cooperation with the University of Oslo and the Potsdam Institute for Climate Impact Research (PIK) (Roman-Cuesta *et al*., 2025). This document complements **a report** on tipping points and the associated geopolitical risks published **by the E3G think tank in 2022** and funded by the Swedish Foundation for Strategic Environmental Research (Dimsdale, 2022).

3. Scenarios of the studies

The aforementioned studies face the same challenges as this note: the limited availability of data on the cascading impacts of the AMOC and the uncertainty regarding both the timing of the tipping point and the duration of the transition. Therefore, they propose scenarios to help readers better figure out the cascading impacts of the AMOC.

The report by foresight specialists Schwartz and Randall (2003) clearly states its objective: "Our aim is to **further the strategic conversation** rather than to accurately forecast what is likely to happen with a high degree of certainty. Even the most sophisticated models cannot predict the details of how climate change will unfold […]. There appears to be general agreement in the scientific community that **an extreme case like the one depicted below is not implausible**." (Schwart & Randall, 2003). The report proposes scenarios such as **tensions over water resources**, particularly related to the river Rhine, situated between France and Germany; a **massive migration of Northern European populations to the south of the continent and to the US**, leading to tensions and migration control policies. They also list the repercussions such a scenario would have on energy prices and **the deployment of supply security operations**. These scenarios have sparked strong reactions from the press and public opinion (Kempf, 2005).

The *Global Tipping Point Report*, led by Timothy Lenton (2023), is a scientific review of the main studies related to climate tipping points. This report proposes a scenario of AMOC collapse, which would occur over a few decades. The cooling of Europe caused by this collapse would initially be perceived as a relief by public opinion, in a context of global warming. However, **the rapid degradation of living conditions would provoke growing resentment from populations** who would denounce their governments' failure to prepare for such events. The succession of hazards and this resentment would lead to a profound deterioration in the stability of societies, which would become trapped in "this vicious cycle further degrades the prospects for civilization." (Lenton et *al*., 2023, p. 192).

Finally, without proposing a specific scenario, the assessment report from the US National Intelligence Council (2021), studying the risks of climate change on national security, acknowledges that the collapse of the AMOC is **one of the scenarios that could fundamentally disrupt all their geopolitical assessments**. Among surprising consequences, they list the **rapid acceleration of climate action efforts** associated with a further apprehension of the AMOC. Such an acceleration could thereby **disrupt power balances** depending on the prior level of preparation of states for a rapid ecological transition.

4. Conclusions

Anticipating the consequences of an AMOC collapse on DOTMLPF (Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities) of the Ministry of the Armed Forces would involve **1) establishing a monitoring unit** within strategic and foresight departments, or a scientific body such as the Hydrographic and Oceanographic Service of the Navy (Shom). The projects listed in Figure 12 could serve as an initial basis for developing this monitoring unit. Such a unit would focus on **early warning signals** and their development, on improving knowledge concerning the **timescale of the AMOC transition**, and on **the consequences** of such a collapse.

Strengthening the anticipation of AMOC's consequences must also consider **2) the funding or commissioning of studies on socio-economic impacts** of crossing a tipping point.

Finally, **3) integrating climate tipping points** through institutions and projects such as **RADAR/RED TEAM** could provide new methodologies for addressing these issues and exploring different scenarios, which would involve decision-making reflections.

General conclusion

This operational note on the defence and security consequences of an AMOC shutdown is part of a larger series aimed at **highlighting the main security issues associated with various climate tipping points identified by the IPCC**. Through the proposed model of integrating tipping points into strategic thinking, these different notes aim **to cover a gap in studies** linking climate and security concerns. In doing so, this series is intended to contribute to **enhancing the French armed forces' strategic foresight capabilities on climate security-related issues**.

This first piece of work should enable a **quick visualisation of the potential consequences of an AMOC shutdown**, both in economic, political, and geopolitical terms. The infographics and maps clearly show, alongside figures and scenarios derived from multiple studies, that the collapse of the AMOC could destabilise the energy security of Northern and Western Europe, its food security, **and challenge crucial defence issues such as submarine and anti-submarine warfare capabilities**. Therefore, it is necessary to establish mechanisms for monitoring scientific results on this topic and to **develop response scenarios for such disruptions**.

APPENDICES

APPENDIX 1: Tipping point: definition and typology

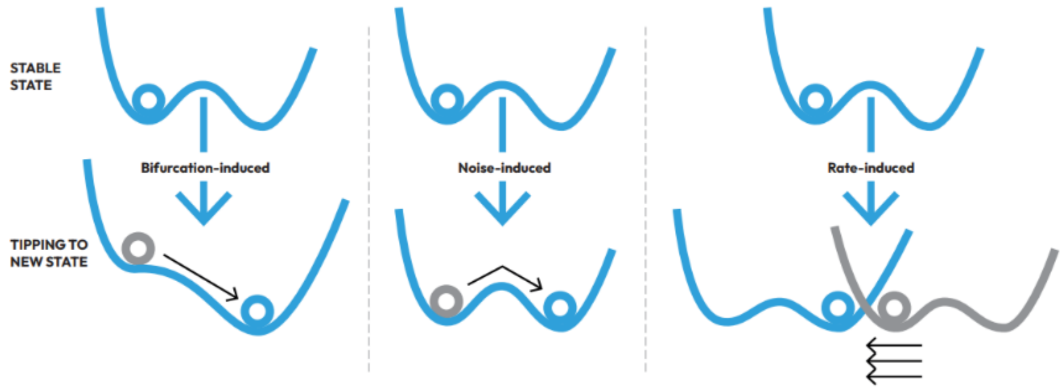
When a system is disturbed, it experiences a loss of resilience. As a result, various tipping mechanisms can be triggered (Lenton *et al.*, 2023).

Four states can explain the mechanisms of a tipping point (Harper *et al.*, 2024), namely an **initial stable state**, an increasingly **unstable intermediate state**, which can lead to a **tipping point** resulting in a **new stable state.**

Tipping mechanisms can unfold in the following ways:

- **Bifurcation-induced tipping**: External pressures lead to a sufficient change in a system's characteristics, causing it to move away from its initial state of stability. In this case, feedback loops sustain and amplify the tipping phenomenon.
- **Noice-induced tipping**: In a system subject to external pressures but not yet having reached a tipping point, variations in the intensity of these external pressures may be enough to push the system into a new state of stability. The return of these external pressures to normal does not allow the system to return to its initial state, despite the persistence of its characteristics.
- **Rate-induced tipping:** Forcing a system rapidly may bring it towards an unstable state because the system's damping feedback is not acting fast enough to counter the forcing.

Figure 16 – Schematic representation of three types of tipping



Source: Lenton *et al.*, 2023

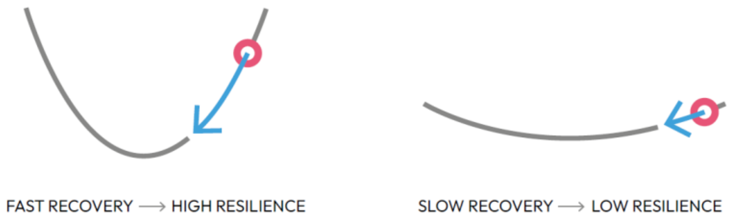
APPENDIX 2: Methodologies to anticipate climate tipping points

To **anticipate a tipping point threshold**, it is important to present the theory of critical slowing down, which is the primary method for **assessing the stability** of a given system. This theory aims to **study the system's characteristics over time and/or space** to detect the potential approach towards the threshold. We will then introduce the different applications of this theory, through the concepts of autocorrelation, spatial analysis, and structural analysis.

Critical Slowing Down Theory

This theory is based on the following reasoning: as a system approaches a tipping point, the **time required** for it to return to its initial state after undergoing a disturbance **increases**. The two concepts that underpin this theory are the **loss of resilience**, which refers to an increase in the **time needed to return to the initial state for a given disturbance**, and variance, which refers to **an increase in the amplitude of the system's responses to a given disturbance** (Drake *et al.,* 2020). The limitations of this theory primarily lie in the need for a clearly defined initial state and a clearly defined disturbing element. Several methods can be employed to detect critical slowing down.

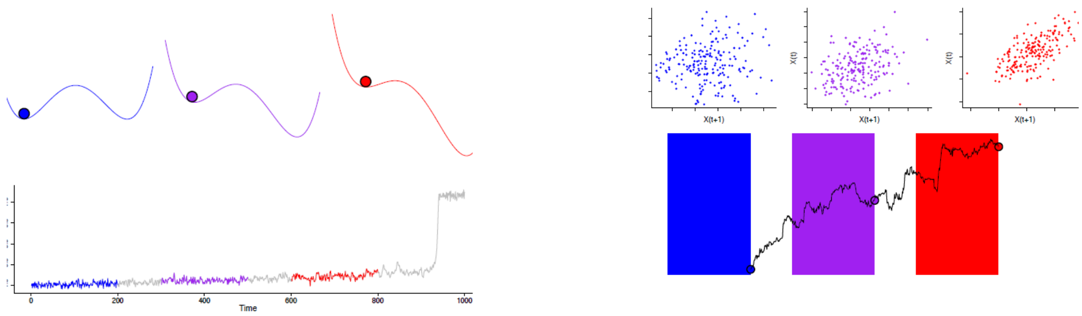
Figure 17 – Critical slowing down schematic representation



Source: Lenton *et al.,* 2023. Global Tipping Point Report

Figure 18 – Autocorrelation

The progressive concentration of the point clouds shown in the top-right section highlights the **increasing correlation** between the current state of the system and its previous state.



Source: Lenton *et al.*, 2023. Global Tipping Point Report.

Autocorrelation

This approach seeks to analyse the evolution in time of a system. As the system approaches a tipping point, its state becomes in**creasingly dependent on its previous situation** (Dakos *et al.*, 2024). This method requires the availability of **sufficiently complete data** series over a timescale, consistent with the system being studied, to analyse its developments.

Spatial analysis

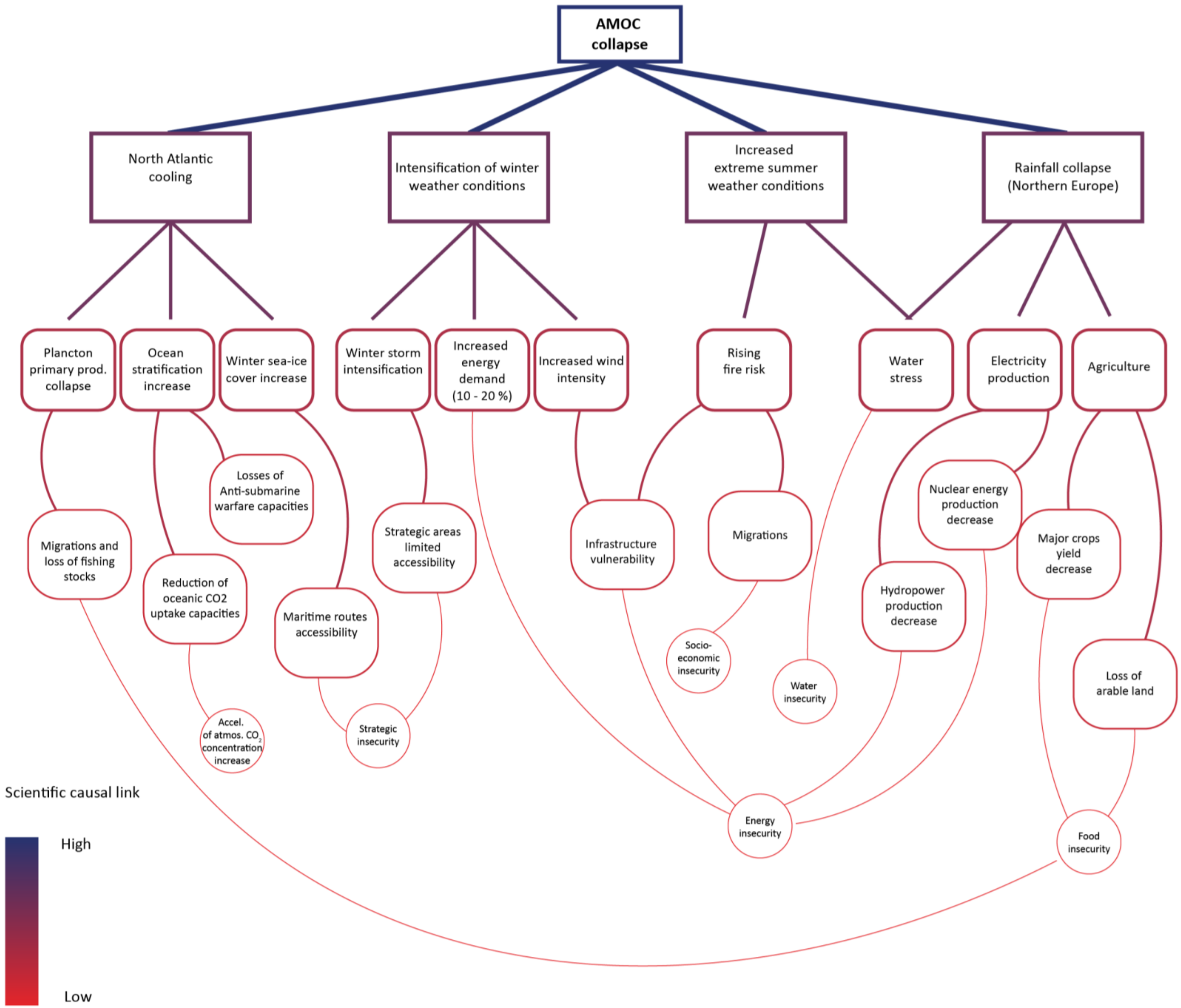
This approach aims to **substitute to the temporal dimension a spatial analysis of the system**. Many systems exhibit spatial characteristics that can enhance their resilience (Dakos *et al.,* 2024). For example, the distribution of energy infrastructure across a territory can increase or limit its exposure to certain types of risks. This method has the advantage of not relying on extensive temporal data series (which are time-consuming to compile). However, **it only allows for capturing the state of a system at a given moment in time.**

Structural Analysis

The definition of the elements composing a system, as well as their interactions, can also serve as an analytical tool to assess the system's propensity to shift to a new state of stability. This method first involves **a characterisation phase of the interactions** between the components of the studied system (Lenton *et al.*, 2023). It then allows for a **temporal analysis of the evolution of these interactions**, in other words, the reorganisation of the network when subjected to stress.

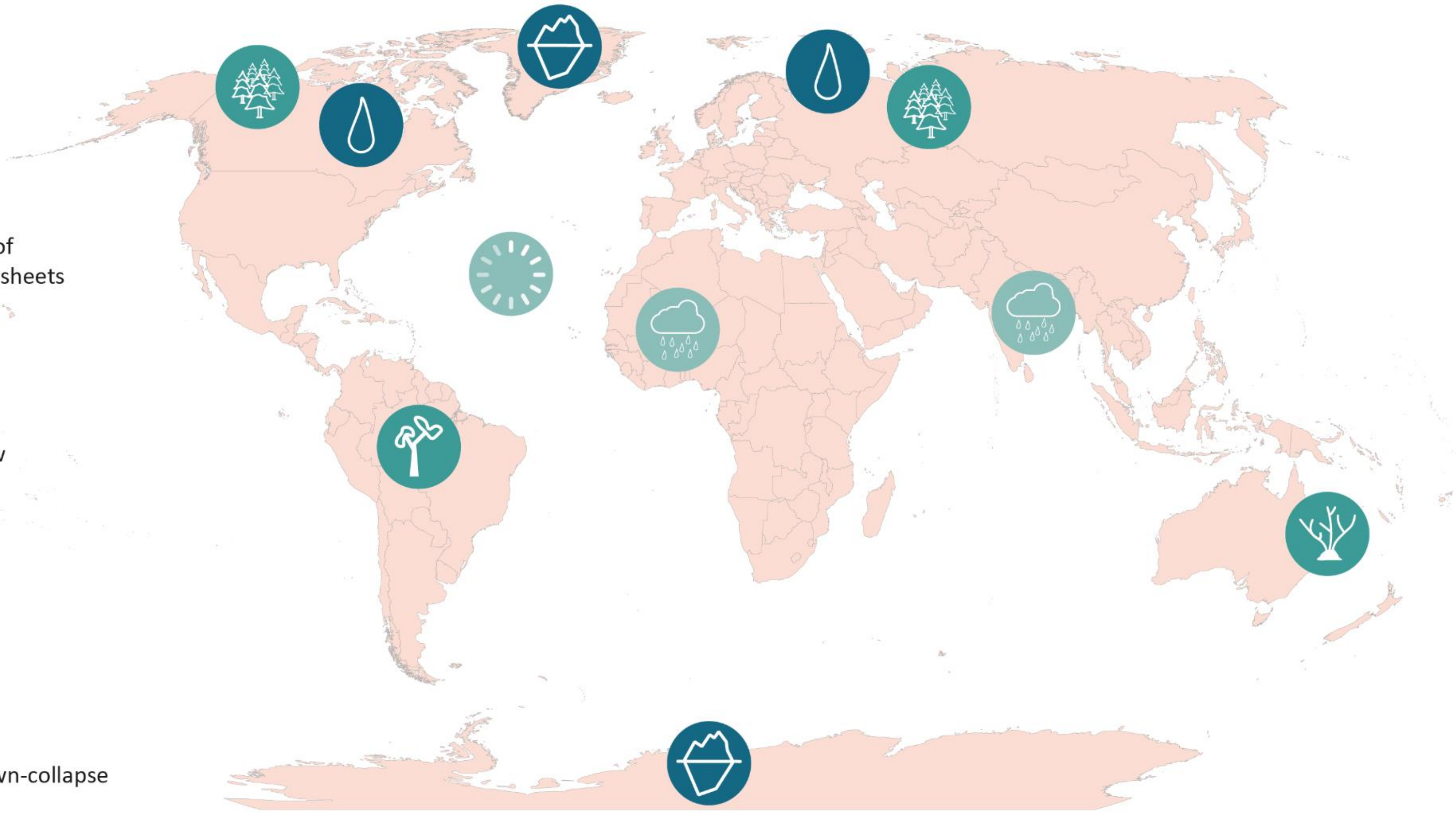
These methodological approaches structure the study of climate tipping points. These different analyses indeed help to **highlight the key indicators of the approach towards a threshold** beyond which the climate system undergoes irreversible transformation.

APPENDIX 3. Cascading effects of the AMOC interruption and associated uncertainties



Source : auteurs

APPENDIX 4. Map: Global climate tipping points identified by the IPCC



Cryosphere

Disintegration of continental ice sheets

Permafost thaw

Global Circulations

AMOC slowdown-collapse

Changes in monsoon patterns

Biomes

Amazon rainforest dieback

Boreal forest

Coral bleaching

Source: Authors

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