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Perspectives on "tipping points"

Content

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Tipping points: How we talk about climate change in the Earth system

Humans influence the planet like no other living species. The way we live, the technologies we use, and the way we produce food now affect almost every part of the Earth system. Where do we need to take decisive action to prevent critical changes?

Self-sustaining changes

Scientists around the world are observing how these changes unfold and what effects they have. What they are finding is that the Earth system does not always respond in proportion to the forces acting on it. Some parts of the Earth system reach a critical state beyond which their structure and function continue to change even without the original external driver. Once set in motion, these changes continue on their own. They may accelerate, intensify, or reach unforeseen proportions. Many researchers refer to the point at which a change begins to continue on its own as a system's tipping point. It is characterized by a threshold. The Greenland Ice Sheet provides one example: if its thickness falls below a critical level, the ice will continue to melt even without further global warming. Scientists use the term climate tipping elements for parts of the global climate system that enter a state of self-sustaining change once a certain level of global warming is reached. Their tipping point therefore corresponds to a particular global average temperature.

Gerrit Lohmann, an expert in climate dynamics at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), cautions against using the term too loosely. "Talking about a tipping point gives the impression that the threshold can be precisely defined, as though a particular temperature or CO_2 level would automatically trigger an abrupt shift," he says. But transitions between states in the climate system do not necessarily occur at a fixed value. "The climate is a highly complex, stochastic system. It undergoes natural fluctuations that can cause large swings. And systems can tip sooner or later depending on random variations, weather events, and internal feedbacks." Lohmann and many other researchers therefore prefer to speak of "critical ranges" rather than tipping points. "We do not want to suggest a degree of precision that the research cannot provide."

Processes amplify or counteract one another

Feedback mechanisms play an important role in the nonlinear processes of change in tipping systems. They can amplify or accelerate processes both before and after tipping occurs. The Greenland Ice Sheet, for example, melts faster the thinner it becomes. This is because melting lowers its surface into progressively warmer layers of air, causing it to melt even more rapidly. Some feedbacks also counteract changes set in motion by global warming. Feedbacks, and particularly amplifying ones, make these changes all the more consequential for humanity and more difficult for researchers to predict. Individual feedback effects can be simulated in models to some extent. In reality, however, many mechanisms operate simultaneously in different parts of the Earth system, such as the atmosphere, ocean, soil, and biosphere, and interact with one another.

No return in the foreseeable future

Once triggered, processes in a system that has tipped continue under their own momentum. Even if the external conditions that existed before tipping were restored, the system may be unable to return to its original state. So even if the global average temperature were to fall back to preindustrial levels in the future, a melting Greenland or West Antarctic Ice Sheet would not grow back. This is what is meant when the tipping of certain parts of the Earth system is described as irreversible. Different parts of the climate system respond to global warming on different timescales. In the short term, over periods ranging from years to decades, weather patterns, sea ice, and climate patterns change. Over the longer term, spanning centuries to millennia, major ocean currents, ice sheets, and carbon storage, for example in the ocean, forests, peatlands, and permafrost, are affected.

Preventive strategies require a nuanced understanding of risk Once a tipping element in the climate system has embarked on a path of change, it becomes difficult to change its course. This is why it is important to identify and understand tipping elements, such as the Greenland Ice Sheet, and their dynamics: a system may reach its tipping point long before the full extent of the resulting changes becomes apparent. The impacts may unfold over timescales far beyond the span of human generations on which political and societal planning is usually based. To develop strategies that can prevent a system from tipping or enable adaptation to its consequences, societies and policymakers need an understanding of risk that takes these dynamics into account.

Tipping cascades

Many of the Earth system's known tipping elements are closely interconnected. If one tips, it can affect other parts of the Earth system in ways that cause them to reach their own tipping points more quickly. Researchers refer to this knock-on effect as a tipping cascade. One example is the interaction between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation (AMOC). Meltwater from the ice sheet affects the AMOC, which in turn shapes the climate across large parts of Europe, Africa, and the Americas. If the Greenland Ice Sheet were to melt substantially or even completely, there are concerns that the AMOC could weaken significantly. This enormous ocean circulation system is a key component of the global climate system. A weakening of the AMOC would alter ocean dynamics and atmospheric circulation around the world and, consequently, affect carbon stores such as forests and peatlands. At the same time, like other parts of the climate system, this ocean circulation naturally fluctuates and exhibits considerable variability. This makes a potential tipping event difficult to predict.

Other systems thought to be capable of tipping are also important climate regulators that influence the global climate. Permafrost in the far north, for example, represents an important carbon store. Healthy forests and peatlands can actively absorb CO_2. They are therefore not only indicators of a changing climate, they also influence how the climate develops.

Reading the warning signs: Signs of approaching tipping

Some research focuses on identifying early indications that a climate system or ecosystem may be approaching a tipping point. Scientists analyze observational data, for example, to determine whether a system is becoming progressively less able to recover from external disturbances. A forest, coral reef, or mountain glacier may recover from damage following a period of extreme heat if it has enough time and favorable conditions to do so. But if heat events occur at increasingly short intervals, there may not be enough time or sufficient resources for recovery. Declining resilience, that is, a reduced ability to withstand disturbances or recover from them, is considered a warning sign. It may indicate that a system is at risk of tipping, whether relatively gradually or abruptly.

How many tipping systems are there?

Researchers have used different definitions of tipping systems in the scientific literature to date. These definitions differ, for example, in whether changes after tipping are considered irreversible and whether the transition occurs abruptly. As a result, there is no fixed number of known tipping elements. Many Earth system scientists are working to identify which of Earth's subsystems display characteristics of tipping dynamics, in other words, which could undergo abrupt and potentially irreversible change. The search for possible tipping elements is based on three main pillars: ongoing observations and recorded data, paleontological and geological evidence, and computer-based models of parts of the Earth system. These approaches allow researchers to assess the current state of a subsystem of the global climate, reconstruct aspects of its past development where possible, and explore potential future trajectories.

Terminology used in communication

Tipping points have become a central, but also much-debated, concept in the climate discussion. Research in this area is still relatively young, and many findings remain preliminary. What we do know is that processes within the climate system can respond to external influences in ways that are difficult to predict. Assumptions about potential tipping points are based partly on evidence from Earth's geological past and largely on computer-based modeling of parts of the Earth system. Many processes and their interactions are still only partially understood, while feedback effects and delayed responses are not yet sufficiently well understood to reliably predict the timing and consequences of change. What is clear is that global warming can dramatically alter habitats and living conditions for both people and the natural environment. These changes may unfold over shorter or longer periods. This also means that some of the consequences will be experienced by us, our children, and our grandchildren, while others will unfold over thousands of years.

There is also debate about what communication about tipping elements can or should achieve. For many researchers, the primary objective is to provide comprehensive, evidence-based information about the potential risks of climate change. This effort to raise awareness is often accompanied by an appeal to decision-makers in politics and society: to do everything possible to prevent further global warming and to prepare in good time for changing living conditions.

Many changes in the climate occur gradually. Their impacts are already serious enough to demand immediate action. But it is also important to understand the nonlinear processes that can occur within the climate system. Gerrit Lohmann believes that the concept of climate tipping points can help with this. "Even though we cannot predict tipping points precisely, they illustrate how abruptly profound climate changes can occur," he says. "And once a tipping point has been reached, we have lost the opportunity to adapt gradually to changing living conditions." The concept therefore highlights the importance of addressing climate change early and with an eye to the future. "It shows that the Earth system is vulnerable, that the consequences of climate change can affect many generations, and that early, decisive action can make the greatest difference."

At the same time, communication about climate tipping points requires careful judgment. In the worst case, the prospect of abrupt and unstoppable change could leave people paralyzed by fear. Resignation could then lead to inaction. But the opposite impression is equally unhelpful: people may assume that they - and the planet - remain in a safe zone as long as no tipping point has been reached. "But we left the safe zone long ago," says Gerrit Lohmann. More than ever, it is now crucial to mobilize and combine society's efforts to counter further climate change - regardless of whether changes occur abruptly or gradually.

Clear and transparent communication about the risks of climate change can help governments and municipalities adapt infrastructure, planning, and social practices in good time - before options for action are irretrievably lost. What is clear is that every increment of global warming increases the risk of severe, unforeseeable, and in some cases irreversible consequences, and that humanity must now address adaptation to a changing climate. "We should describe more concrete scenarios for the future," Lohmann says, "so that we can develop concrete options for action."

Tipping points in technology, the economy, and society

The discussion is not limited to tipping points in the natural climate system. Tipping points can also occur in other areas that may be crucial to climate action, including technological development, economic systems, and society. A new technology, for example, may cross a tipping point once essential components begin to be mass-produced. This can be seen with solar cells and batteries. The more people involved in manufacturing them and the greater the quantities produced, the faster practical knowledge and expertise in the production process grow. Processes become more efficient and therefore less expensive. Step by step, the technology moves closer to another tipping point - an economic one.

- Tipping point: A critical threshold that, once crossed, often leads to abrupt and sometimes irreversible changes.
- Tipping system: A general term for systems that, in response to external influences, often shift abruptly into a state that is at least partly irreversible, for example, a chair tipping over.
- Tipping element: The term was coined in discussions of tipping systems within the Earth system. A tipping element generally refers to an individual part of the climate system that, once a particular threshold is crossed, often shifts abruptly into a partly irreversible state, such as a rainforest or an ice sheet.

Once a new technology becomes available at the same price as the technology it is intended to replace, its spread can become difficult to stop, and it may ultimately displace the older technology.

Self-reinforcing and cross-sector effects

As in the climate system, self-reinforcing mechanisms play an important role in bringing technological and economic development processes to a tipping point. If, for example, a company powers the production of solar panels using electricity generated by its own solar installations, production not only becomes more climate-friendly but also less expensive. More solar cells can then be produced and sold at lower prices. This stimulates demand, and an increasing amount of electricity is generated from solar energy.

Cross-sector effects also play a role, for example between the energy and transportation sectors. Electric vehicles can complement energy infrastructure by serving as mobile, flexible electricity storage systems. In this way, they can facilitate the use of wind and solar power, which varies depending on the time of day and weather conditions. The more electric vehicles are used as temporary storage, the easier it becomes to integrate more energy from climate-friendly sources - and the more climate-friendly transportation can become as well.
Governments are called upon to actively identify climate- and environmentally friendly innovations and specifically support their development, market entry, and wider adoption. Modular systems such as solar technology are particularly promising because their use can now be scaled almost without limit. Whether installed on a single-family home, deployed at the neighborhood level, or used in a centralized power plant, the basic components used to generate electricity are essentially the same.

When the new becomes normal

In addition to technological and economic tipping points, researchers also study social tipping points. The term describes moments when changes in norms, attitudes, or behavior within groups or entire societies become sufficiently widespread and deeply rooted to bring about lasting changes in established practices. This usually requires a critical share of the population to adopt a new technology, lifestyle, or perspective.
When around 20 percent of a society uses a particular technology, for example, a threshold is often crossed after which the majority begins to adopt it as well. Whether this happens depends, among other things, on communication with and perceptions of so-called early adopters, the more risk-tolerant minority who are the first to try innovative ideas. If their behavior is viewed positively and as something worth emulating, the new practice has a good chance of moving from the exceptional to the new normal.

Positive social tipping points, such as a shift toward predominantly plant-based diets, could help counter the progression of climate change. A key challenge will be to better understand how social norms change and how they can be used as leverage to establish climate-friendly behavior more broadly across society.

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Biosphere: Ecosystems at the limits of their resilience

Climate change is altering living conditions for animals, plants, and microorganisms. Together with other forms of human interference in the natural environment, it is pushing entire ecosystems to the limits of their ability to survive. These ecosystems do more than reflect the changes taking place: when healthy, they can also help regulate the climate.

Bacteria, fungi, plants, and animals inhabit almost every part of the Earth, forming very different communities depending on their environment. Together with their surroundings, they form ecosystems – forests, soils, and coastal and marine environments. Ecosystems sustain the Earth's essential cycles of matter. They recycle the basic building blocks of life: water, the fundamental basis of life; carbon and oxygen as carriers of energy; and nitrogen and phosphorus as essential nutrients. Taken together, these ecosystems make up the planet's biosphere.

The biosphere potentially contains more tipping elements than any other part of the Earth system. Some of them are presented here. Because living organisms interact with one another and with their environment in such diverse and complex ways, identifying, describing, and predicting dynamics within the biosphere is particularly challenging. Interactions within an ecosystem can also vary considerably depending on external conditions. Yet these interactions – or perhaps precisely their complexity – help maintain stable equilibria. Researchers are working to better understand when an ecosystem is in equilibrium, when it begins to lose its resilience to external pressures, and when it may be at risk of tipping into an entirely different state. To do so, they need detailed observational data and robust models of the relationships within ecosystems.

Here, we describe several important ecosystems that are at risk of losing their stability as a result of climate change and transforming into entirely different landscapes.

The Amazon rainforest

Perhaps the best-known example of an ecosystem of global importance is the rainforest of the Amazon Basin in South America. Other tropical rainforests are found in Southeast Asia and in western and central Africa. Scientists currently believe that the Amazon rainforest is at the greatest risk of undergoing an abrupt transition to a completely different state as a result of climate change and human exploitation. But why is the Amazon rainforest particularly vulnerable to suddenly shifting into a different type of landscape? One reason is that it generates a large share of its own rainfall. Vast amounts of water evaporate from the forest canopy and often fall again as rain in the same region. If the forest in a particular area is weakened, whether by deforestation or exceptional drought, evaporation from the canopy decreases. Fewer clouds form, although they would normally reflect some of the sunlight, causing the affected areas to warm further. Reduced evaporation and cloud formation also mean that forest areas downwind receive less rainfall. As a result, local disruptions to the water cycle can affect very large areas.

Deforestation is considered the main cause of declining rainfall over the Amazon rainforest. Asian rainforests are less vulnerable to the feedback between drought, reduced evaporation, and declining rainfall because they receive more moisture from the surrounding oceans. For certain regions of Central Africa, meanwhile, climate models tend to project an increase in rainfall, making the rainforest there less vulnerable to drought.

A second feedback mechanism concerns the rainforest's susceptibility to fire. In a healthy forest, the dense canopy formed by multiple layers of vegetation retains so much moisture near the ground that there is virtually no combustible material on the forest floor. Logging, drought, and slash-and-burn clearing open up the forest. More sunlight reaches the ground and dries out the layer of dead leaves and branches. Deliberately set fires can then spread more easily. What remains is a heavily thinned and fragmented forest, or even completely cleared land. Repeated fires, often set illegally, prevent former forest areas from recovering and spread farther into the forest from its edges.

Rising global temperatures and deforestation have already meant that the Amazon rainforest can no longer fulfill its role as the "green lung of the Earth." In recent years, there have been increasing indications that it now releases more CO_2 than it removes from the atmosphere through photosynthesis. Researchers consider around 40 percent of the forest area to be at acute risk of transitioning to open woodland or savanna within the coming decades. As a result, the affected areas could release around 30 gigatons of carbon - several times the amount of annual human caused CO_2 emissions.

Several factors interact in the Amazon rainforest: on the one hand, human-driven deforestation and slash-and-burn clearing, and on the other, climate change. Climate change is altering the dynamics of seasons and rainfall. Based on different models, researchers project that the threshold for the irreversible transformation of large parts of the rainforest could lie between 2°C and 6°C of global warming. Whether the rainforest survives, and in what state, will depend to a large extent on how governments, economic stakeholders, and consumers act now. To prevent the rainforest from tipping into a less productive state and to restore it as far as possible, CO_2 emissions must be reduced rapidly and substantially. Deforestation must also be curbed.

One of the main drivers of ongoing land conversion is the way people produce and consume food: rainforest is cleared to create cattle pasture and land for growing soy. The soy, in turn, is used as feed for pigs, poultry, and cattle. Growing consumer interest in the environmental impacts of dietary choices could lead to a positive social tipping point, after which a rapidly increasing majority of people shift toward diets containing little or no meat. Their consumption choices can in turn influence decisions by investors and major agricultural companies that may help determine the future of the Amazon rainforest.

Expanded reforestation can also help the forest recover. Within a few decades, young trees can grow back, releasing water through their leaves and gradually restoring the regional water cycle. National and international policymakers should promote a shift toward resource-efficient food production and diets, support local farmers in securing sustainable livelihoods, and advance reforestation initiatives.

Boreal coniferous forests

Far to the north, boreal coniferous forests form a belt around the globe. They extend across large parts of Canada and Alaska, Russia, and Scandinavia. These vast forests are home to moose, bears, wolves, and wood bison. Logging and oil extraction have severely damaged boreal forests and fragmented their ecosystems. Large areas have been heavily affected by human activity.

The effects of climate change are particularly evident along the southern margins of these forests. Changes in wind patterns and moisture transport promote drought and, in turn, intense wildfires. Wildfires are fundamentally a natural mechanism of forest regeneration. In recent decades, however, fires have increased in extent and intensity and have occurred so frequently that burned areas are no longer able to recover. Following severe fires such as those that affected large areas of Siberia in 2021 and extensive parts of Canada's forests in 2023, landscapes can remain profoundly altered. More frequent and prolonged droughts and severe storms make it harder for burned forests to recover. Climate change also frequently favors the spread of insect pests, which can readily attack weakened trees.

The loss of tree cover affects air circulation near the ground, while evaporation from the forest canopy is also lost. On the one hand, this leads to greater warming, an effect that can persist for decades. At the same time, forest dieback generally exposes surfaces that reflect more sunlight than the dark tree canopy. The greater reflectivity of these surfaces, known as albedo, has a cooling effect and counteracts warming of the ground. The forest's natural temperature-regulating processes are thrown completely out of balance.

The various disturbances affecting the ecosystem can therefore reinforce one another or interact in complex ways. What is clear is that the forest's capacity to regenerate has been significantly weakened, and young seedlings are unable to establish themselves under the new conditions. As a result, large areas can abruptly transition to a treeless state. Based on various models, researchers estimate that the temperature threshold for irreversible change in the southern parts of the boreal forests lies between 1.4°C and 4°C of global warming. These projections are subject to considerable uncertainty because the various effects of climate change and other human influences interact in complex ways, biogeophysical effects such as albedo and evaporation influence one another, and not all of these relationships are fully understood.

Meanwhile, along the northern edges of many boreal forest regions, the tree line is shifting northward. Trees and shrubs are spreading into the adjacent Arctic tundra, a process researchers refer to as shrubification, or the expansion of shrubs into previously treeless landscapes. The spread of woody vegetation is facilitated in some areas by thawing permafrost. The northward expansion of forests has ecological consequences of its own for species composition and the stability of natural open landscapes. It does not, however, compensate for the loss of trees in the southern parts of the boreal forests.

Open landscapes

It is far less widely known that open landscapes such as tundra are affected by climate change in ways similar to rainforests. Yet researchers are also seeing clear signs in some of the world's drylands and grasslands that abrupt change may be possible.

Low-rainfall drylands cover more than two-fifths of the Earth's land surface and are home to large portions of the populations of Africa, Asia, and North America. Some are forested, others are dominated by grasslands, and some are used for agriculture. As climate change drastically alters precipitation patterns in many regions, these areas are at risk of widespread losses in soil quality and fertility and, in some cases, desertification.

In the Earth's tropical and subtropical regions, savannas often form the natural transition between rainforest and desert: grasslands with scattered trees and distinct wet and dry seasons. Grasses and herbaceous plants dominate the vegetation, while regular natural fires promote regeneration and limit tree cover. This natural regime changes when savannas are extensively grazed and fires are deliberately suppressed as a result. Once trees and shrubs become established, they prevent fires from spreading through the extensive grasslands as they once did, thereby facilitating their own further expansion. This self-reinforcing effect can drive the landscape toward a change that may not be readily reversible: once tree cover reaches a certain level, the natural fire regime could be permanently disrupted and woodland could take over. In some regions of Africa, increasing rainfall associated with climate change may further promote the spread of trees into savannas.

Although "more forest" may sound like a good thing at first, the encroachment of woody vegetation into savannas creates a "forest in the wrong place." A distinct, species-rich, and productive ecosystem is lost in the process. Savannas are iconic habitats for herbivores such as zebras, giraffes, elephants, and rhinoceroses; predators such as lions and leopards; and scavengers such as hyenas and vultures. Their habitat has already been severely reduced by human land use and is coming under increasing pressure from climate change. If savannas are converted into wooded areas, whether locally or across large regions, the consequences remain largely unpredictable. Soil quality and structure, water and carbon cycles, and the species composition of the original landscape would all undergo far-reaching changes. This is why, for example, reforestation projects promoted as climate protection measures need to be assessed carefully. In the past, valuable habitats have already been destroyed by planting non-native tree species in unsuitable environments.

Warm-water corals

Coral reefs are not only beautiful to look at; they are also an indispensable part of marine life. More specifically, we are looking here at reef-building stony corals found in warm coastal waters in tropical and subtropical regions of the world. These cnidarians, which are more closely related to jellyfish than their appearance might suggest, form calcium carbonate skeletons that accumulate over thousands of years to create the famous reefs. Coral reefs in the Indo-Pacific, along Australia's east coast, and off Central America provide food for millions of people. They also protect coastlines from flooding. And not least, they are tourist attractions that can support livelihoods in many regions when managed and marketed responsibly.

Because of the extraordinary diversity of species they harbor, coral reefs are often referred to as the tropical rainforests of the sea. They serve as nurseries and feeding grounds for thousands of animal and plant species. The abundance of life in coral reefs stands in stark contrast to the nutrient-poor waters in which they thrive. Scientists are only gradually unraveling the mystery of how corals can flourish in these waters and form the foundation of such exceptionally species-rich habitats. Around one-quarter of all marine species depend on this habitat for at least part of their life cycle. The key to the corals' success appears to lie precisely in the unique diversity of their interactions with many different organisms. Tiny algae use photosynthesis to produce energy-rich carbohydrates, which they share with the corals in exchange for protection and nutrients. Bacteria living on the corals supply their hosts with vital nitrogen compounds. Mollusks and other invertebrates such as snails and sea urchins help keep the reefs free of excessive algal growth, allowing the symbiotic microalgae to receive enough sunlight for photosynthesis. Fish feed on these animals and, in turn, become prey for larger predators such as sharks.

But the delicate balance among all these different organisms is vulnerable to disruption. Human-caused CO_2 emissions affect two key factors that determine the stability of coral-based ecosystems: the greenhouse effect is warming the oceans, while the absorption of CO_2 from the atmosphere is making seawater increasingly acidic.

Warm-water corals thrive only within a temperature range of approximately 20 to 29°C. If the water becomes even slightly too warm, their symbiotic relationship with the microalgae that supply them with carbon compounds breaks down. If these conditions persist, the corals eventually die from a lack of nutrients. When reefs lose their symbiotic algae, they also lose their color, which is why this response to heat is known as coral bleaching. Increasing acidity alters the chemistry of seawater and makes it more difficult for cnidarians to build their calcium carbonate skeletons – much like the way vinegar-based cleaners dissolve limescale.

A reef takes many years to recover fully from a bleaching event. In recent decades, however, heat events have occurred at increasingly short intervals. At the same time, ocean acidity continues to increase worldwide. In addition to ocean warming and acidification, numerous local and regional factors affect the survival and recovery of coral reefs. Overfishing disrupts finely balanced food webs. Coastal construction or erosion following deforestation can wash sediment onto reefs, interfering with the corals' energy and nutrient balance. Chemical pollution and plastic waste add further pressures and can severely damage individual organisms, species populations, or parts of the ecosystem. Taken together, these pressures can push the entire ecosystem out of balance.

Researchers are observing irreversible losses of coral reefs on local and regional scales. A reef, or a section of one, needs to retain a minimum size and level of species diversity in order to recover from a crisis. In many places, these thresholds have already been crossed. If a reef fails to recover for ten years, researchers classify the ecosystem as collapsed.

Over the past 50 to 150 years, around half of the world's warm-water coral reefs have been lost. Scientific assessments indicate that as early as 2005, around 44 percent of the remaining corals were already living under suboptimal environmental conditions.

It remains unclear whether ocean warming and acidification will lead to a global tipping point for warm-water corals. Different coral species and regional ecosystems vary in their sensitivity. Based on observations to date and computer-based modeling, researchers project widespread reef loss at just 1.5°C of global warming. At 2°C of global warming, they expect the ecosystems built around warm-water corals to undergo an almost complete collapse. Given the bleaching events observed over recent decades, there are concerns that some reef regions may already have crossed their tipping point.

On the other hand, relatively little is known about the ability of different coral species to adapt to warmer temperatures. In many places, coral reefs are also under intense pressure from local factors such as pollution and overfishing. This also offers some grounds for optimism: implementing local measures to protect reefs at the political and societal level is considerably easier than reaching international agreement on global climate targets. There are also excellent examples of coral reefs being saved from destruction, for the benefit of the many animal and plant species, as well as the people, that depend on and live alongside them.

Coastal marine ecosystems

In addition to coral reefs, there are other marine and coastal ecosystems that researchers believe could shift into alternative states as a result of climate change, permanently losing diversity and ecological function in the process. These include kelp forests, which can thrive in calm, shallow, clear coastal waters throughout the world's oceans. They, too, are affected by ocean warming and acidification. Marine storms that are becoming more intense and, in many regions, more frequent can also weaken or even destroy kelp forests. In many places, food webs are also being disrupted. As waters warm, sea urchins can thrive and graze kelp forests down extensively. Where predators of sea urchins, such as sea otters or starfish, are themselves under pressure from global warming or are hunted by humans, kelp forests often cannot recover from such intense grazing.

Seagrass meadows and mangrove forests are affected in similar ways by changes in seawater temperature, currents, and chemistry. Seagrass meadows can spread across large areas of the seafloor. They stabilize coastal sediments, store large amounts of carbon, and produce oxygen. They also provide shelter and food for a perhaps surprisingly diverse range of animals. Seahorses live here alongside mussels, snails, and shrimp, while manatees, sea turtles, rays, whales, and sharks find abundant food.

Mangrove forests occur along many tropical and subtropical coastlines. Salt-tolerant tree species thrive in the brackish waters of estuaries and bays, creating a distinctive habitat at the boundary between land and sea. These areas serve as important breeding and nursery grounds for many species of birds, reptiles, fish, and insects. With their root systems anchored in the mud of the intertidal zone, mangroves also protect coastlines from storm surges and erosion.

Alongside climate change, human alterations to natural coastal structures, land use, and water pollution are contributing to the decline of these ecosystems. Researchers are seeing regional signs of self-sustaining or abrupt change. And with every kelp forest, seagrass meadow, or mangrove forest that disappears, an important part of the global biosphere is lost. The Earth loses another carbon sink, countless plant and animal species lose their habitat, and coastal communities lose an important form of natural protection.

For the biosphere, as for other parts of the planet, the message is clear: emissions must come down. Only by reducing human-caused greenhouse gas emissions can the irreversible transformation of important components of the Earth system into less productive or even climate-damaging states still be prevented. The second essential pillar of ecosystem stability is biodiversity conservation. The tipping elements of the biosphere make particularly clear how closely climate protection and biodiversity conservation are interconnected. Only by addressing both together can we preserve the conditions for life on our planet.

Scientific review and consultation:

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Cryosphere: Where are worlds of ice at risk of thawing?

Worlds of ice help regulate the Earth's climate, store freshwater, and support unique ecosystems of their own. Climate change is altering the dynamics of these frozen environments and, in many places, the lives of both people and wildlife.

Massive ice sheets, floating sea ice, glaciers, and permafrost all form part of the Earth's cryosphere. The cryosphere plays an important role in regulating the global climate and water cycle. The vast ice sheets of Greenland and Antarctica, as well as sea ice, reflect some of the Sun's radiation back into space, thereby reducing the amount of energy absorbed by the Earth. Glaciers cool their surroundings in a similar way. Glaciers and ice sheets also store nearly three-quarters of the Earth's freshwater. Mountain glaciers serve as important seasonal and long-term water reservoirs. As temperatures rise in spring, they release valuable freshwater for plants and animals. The livelihoods of many people and agricultural practices around the world depend on these water reserves. Deep permafrost helps stabilize landscapes in Arctic regions and acts as a barrier to near-surface water. Where it thaws, the ground can literally shift and collapse, threatening the foundations on which both people and ecosystems depend. Lakes and their winter ice cover, which provide an important source of drinking water in permafrost regions, are also threatened by these changes. In addition, frozen soils preserve enormous amounts of organic material from past plant and animal life. Rising temperatures allow microorganisms to break down these ancient carbon stores, releasing greenhouse gases such as methane. These emissions, in turn, contribute to further global warming. Here, we describe several elements of the cryosphere that may shift into a new state as a result of global warming and reinforcing mechanisms once certain thresholds are crossed.

The Arctic: Greenland Ice Sheet and sea ice

The island of Greenland extends from 60° to 83° north, from the North Atlantic to the Arctic Ocean. Parts of the island have been covered by ice to varying extents for more than two and a half million years. Over thousands of years, layer upon layer of snowfall has accumulated. The weight of newly fallen snow compresses the deeper layers into ice. This process has formed an ice sheet that today covers four-fifths of Greenland and is more than three kilometers thick at its highest points.

Scientists have been observing and measuring the ice sheet for more than a century. In 1930, an expedition led by polar researcher Alfred Wegener established the first permanently staffed research station in the middle of Greenland. Since then, researchers have drilled thousands of meters into the ice sheet to uncover its history stretching back through the millennia. Since the 1980s, satellite-based measurement techniques have made it possible to study ice-sheet dynamics in ever greater detail.

Although they may appear static at first glance, ice sheets are constantly moving and changing. New snow accumulates at the surface year after year, while deeper layers are compressed into ice. At the same time, ice continuously flows outward from the center toward the coast. In several places, enormous streams of ice flow into the sea. Like rivers moving in slow motion, these outlet glaciers discharge into the ocean, where they melt and release ice that has been transported from the interior.

For decades, researchers have observed increasing ice loss, with more ice now being lost on average each year than is replenished by snowfall. Because temperatures in the Arctic are rising three to four times faster than the global average, increasing amounts of snow are melting even at higher elevations. Once the darker ice beneath the snow is exposed, an amplifying effect comes into play: the darker ice absorbs more solar radiation than a reflective layer of white snow and therefore melts more quickly. Algae can also grow on the ice and darken the surface further. The reflectivity, or brightness, of a surface is known as its albedo. This feedback process is therefore known as the ice-albedo feedback. Deposits of soot and fine particles from wildfires and industrial emissions, as well as the formation of meltwater ponds on the surface, can also reduce the albedo of the snow and further accelerate melting.

The ice sheet is thinning most rapidly around its margins. Here, another feedback mechanism accelerates ice loss: as the ice sheet becomes thinner, its surface drops into warmer layers of the atmosphere and melts even faster. At higher elevations, however, researchers measured increased snowfall in some areas between 2003 and 2019. This, too, is linked to Arctic warming: warmer air can hold and transport more moisture, leading to more frequent heavy precipitation. "The observed increase in ice-sheet elevation does not necessarily mean an increase in mass," explains Ingo Sasgen, a glaciologist at the Alfred Wegener Institute. "A few years with slightly more snowfall are not necessarily significant for the overall mass balance of the ice sheet." Ice losses around the margins are much greater in any case, and even a possible increase in mass in the interior would not be enough to offset them. Another problem is that precipitation is increasingly falling as rain rather than snow. "That does not contribute to the ice sheet's mass balance, on the contrary, it reduces the surface albedo, causing the ice to melt more quickly." Researchers consider the Greenland Ice Sheet one of the tipping elements of the global climate system. Given current trends in average temperatures, continued melting cannot be ruled out even if global warming were successfully stabilized over the long term. Over thousands of years, Greenland could gradually become largely ice-free. This could raise global sea levels by more than seven meters. In addition, the freshwater released by the melting ice would alter regional and global ocean currents, with far-reaching consequences for the global climate.

Sea ice: The warmer it gets, the less of it there is

The image of a polar bear on an ice floe has long been – and remains – an icon of climate change communication. As the Earth warms, polar bears are quite literally losing the habitat beneath their feet. Arctic sea ice, on which polar bears hunt and many seal species raise their young, has been declining in both extent and thickness for decades. By the middle of this century, the North Pole is expected to be ice-free during the summer months for the first time. During winter, too, an increasingly smaller area of the ocean surface freezes. Here, however, it is not primarily the extent of the ice but its thickness that is decisive. The ice is younger and less stable. Much of the sea ice that forms in the shallow marginal seas of the Arctic Ocean melts before it can even reach the central Arctic.

According to current findings, the trend is clear: the warmer it gets, the less ice forms in winter and the smaller the frozen area becomes in summer. In geographically constrained straits, the decline in sea ice is initially delayed. Where the ice lies over the open Arctic Ocean, more of it melts each year because it is exposed to warmer water. If the Earth were to cool significantly again in the distant future, the extent of sea ice would increase again as well.

Incidentally, Antarctic sea ice is also declining. Since around 2015, increasingly less sea ice has been forming in the Southern Ocean – a marked reversal of the trend seen in previous decades, when the total volume of annual sea ice had actually increased. Recent studies suggest that this decline may indicate an abrupt change in the Antarctic climate system.

Antarctic Ice Sheet: Undermined from below in the west

The Antarctic Ice Sheet covers the Antarctic continent around the South Pole. It is considerably older than the Greenland Ice Sheet and much larger. It first became permanently established around 34 million years ago. Today, with an area of approximately 14 million square kilometers, it is around eight times the size of the Greenland Ice Sheet. At its thickest points, the ice is almost five kilometers deep.
East Antarctica makes up the largest part of the ice-covered southern continent, while West Antarctica and the Antarctic Peninsula extend to the west. East and West Antarctica are separated by the Transantarctic Mountains. The ice sheet can therefore be divided into three parts: the East Antarctic Ice Sheet, the West Antarctic Ice Sheet, and the ice-covered regions along the mountainous Antarctic Peninsula. These areas are currently being affected by global warming to different degrees, with changes in atmospheric and ocean temperatures playing different roles in different locations.

Large parts of the West Antarctic Ice Sheet lie below present-day sea level. The ice rests on the geological bedrock far below the water surface, with only a small part protruding above it. Numerous glaciers and ice streams carry ice toward the margins of the ice sheet and into the surrounding ocean. Still connected to the ice sheet, it floats on the ocean surface in the form of vast ice shelves. A large number of extensive ice shelves surround Antarctica. They fringe roughly half of the Antarctic Ice Sheet, holding back the ice flowing toward the coast and slowing its discharge into the ocean.

When the water beneath the ice shelves warms, however, the shelves begin to melt from below and become thinner. Their buttressing effect weakens, allowing ice to flow increasingly rapidly into the ocean. The faster the ice flows, the thinner the glacier becomes farther inland. Once the ice reaches a certain thickness, it loses contact with the underlying bedrock and begins to float. In this way, the ice sheet progressively detaches from the land beneath it and retreats inland from its margins. The boundary where the ice remains in contact with the bedrock is known as the grounding line. Warm ocean water follows the retreating grounding line. Retreat is particularly pronounced where the bedrock slopes downward toward the interior of the continent. In these areas, the ice sheet retreats into regions lying increasingly far below sea level.

Warmer water now melts more ice from below, while increasingly thick ice farther inland continues to flow toward the margins – accelerating both melting and ice transport. Ice flow speeds up as the grounding line retreats farther inland. This self-reinforcing process is known as marine ice sheet instability (MISI) and is a major concern for polar researchers. Model-based projections and paleontological evidence suggest that beyond a certain level of warming in the surrounding ocean, the process may become unstoppable.

While the Greenland Ice Sheet is melting primarily because of rising air temperatures, Antarctic ice is particularly threatened by ocean warming and the resulting acceleration in the transport of ice toward the ocean. The West Antarctic Ice Sheet in particular, much of which rests on land below sea level, has been losing mass for decades. Even at current levels of warming, West Antarctica is considered especially vulnerable to long-term, self-reinforcing ice loss. If the ice shelves and the West Antarctic Ice Sheet were to melt completely, global sea level would rise by three to four meters. Ongoing ice loss also alters albedo, ocean temperatures, and ocean currents around and across the Antarctic continent. Entire ecosystems are coming under pressure as ice habitat disappears and water temperatures and nutrient levels change. These effects are felt throughout marine food webs and coastal ecosystems around the world.

East Antarctica: Ice sheet and underlying basins

Most of the East Antarctic Ice Sheet rests on the continent above sea level. However, it too has vulnerabilities to ocean warming: extensive basins lying below sea level. These include the Wilkes, Aurora, and, farther west, Recovery basins. Using satellite observations and measurements from probes, researchers are observing warm seawater penetrating into some of these depressions.
The Greenland, West Antarctic, and East Antarctic ice sheets are considered core tipping elements of the global climate system. While Greenland and West Antarctica are already sensitive to current temperatures, a complete collapse of the East Antarctic Ice Sheet would likely occur only under sustained global warming of around 5°C above preindustrial levels. According to model calculations, it would take more than ten thousand years for all of East Antarctica to become ice-free.

Some of the low-lying basins of East Antarctica, however, are considered unstable at around 2°C of warming and could become ice-free over the long term if this threshold were exceeded. The East Antarctic Ice Sheet could then retreat over many thousands of years, considerably more slowly than the ice sheets of West Antarctica and Greenland. The entire East Antarctic Ice Sheet contains enough ice to raise global sea level by approximately 52 meters. Individual basins each account for several meters of that total. Complete melting would profoundly alter the climate and ecosystems of Antarctica and far beyond.

Mountain glaciers

The effects of global warming are becoming increasingly apparent even in the world's cold, high-altitude regions. Mountain glaciers, which occur at high elevations on almost every continent, have been losing mass worldwide since the late 19th century. This loss has accelerated significantly since the 1990s. In September 2025, the Watzmann in the Berchtesgaden Alps made troubling headlines when the Ice

Chapel, a famous formation in the glacial ice, collapsed. Winters with little snow and hot summers had weakened the structure considerably in recent years.

Many glaciers are affected by reinforcing mechanisms such as the relationship between ice thickness and elevation: as a glacier becomes thinner, its surface drops into progressively warmer layers of air, further accelerating melting. If winter snow melts early in the year or precipitation increasingly falls as rain rather than snow, darker ice is exposed. It absorbs more radiation than snow, accelerating the melting process. Sun-warmed rock and debris can intensify this effect locally. A thin layer of debris on the surface can also promote melting.

These effects are similar in different regions of the world and are occurring simultaneously as temperatures rise.

"If there are no longer any areas at high elevations that supply the glaciers farther downslope with ice, they are irreversibly lost on human timescales," says glaciologist Ingo Sasgen.

Glaciers support unique ecosystems and serve as important seasonal and long-term water reservoirs for both people and nature. As glaciers shrink, the habitats of many animals and plants change, and species are lost. Water resources and the freshwater supply for many people around the world are at risk.

Permafrost: Localized thaw worldwide

Permafrost refers to ground that remains permanently frozen for several consecutive years. Permafrost covers roughly one-sixth to one-fifth of the land area in the Northern Hemisphere. It is found primarily in Russia, but also in Canada, the United States (Alaska), Norway, Greenland, and on the Tibetan Plateau. The layers closest to the surface, known as the active layer, generally thaw during the warmer months of the year. Beneath them, the ground can remain frozen to depths of several hundred meters depending on the region, and to as much as 1,500 meters in central Yakutia.

Permafrost responds very differently to warming depending on the characteristics of the underlying ground. At local and regional scales, researchers are observing signs of abrupt thaw. Where large masses of ice are embedded in the ground - in cavities or as wedge-shaped bodies within cracks - the surface can subside dramatically as the ice melts. This creates an uneven landscape of trenches, ponds, and large lakes. Because accumulating surface water transfers heat into the ground, it accelerates permafrost thaw. In some parts of Siberia, such sudden changes are already creating major challenges for people and entire ecosystems. As temperatures rise, abrupt landscape change is becoming more likely in individual regions. Researchers estimate that such self-reinforcing processes could occur across one-fifth of Arctic permafrost areas.

Other areas thaw gradually, with the depth of thaw increasing as global temperatures rise. Viewed globally, permafrost thaw is progressing roughly in step with climate change, even though it can occur abruptly in some locations. Summers are becoming longer, and winters are not always cold enough for the active layer to refreeze completely.

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Whether thawing occurs abruptly or gradually, it initiates the decomposition of plant material that had been preserved by the permanently frozen ground. This releases carbon dioxide as well as methane, which in turn intensify the greenhouse effect. This feedback is known as the permafrost carbon-climate feedback.

The upper three meters of vulnerable permafrost alone contain more carbon than the entire present-day atmosphere. Microbial decomposition also warms the ground and could further accelerate thawing. However, it remains uncertain how strong this feedback will ultimately be and over what timescales the thaw will progress. Taken together, current evidence suggests that, at the global scale, permafrost thaw will broadly track rising temperatures. Researchers consider an abrupt, unstoppable thaw of permafrost worldwide relatively unlikely. If it were to occur, however, northern permafrost regions would thaw much more rapidly than the ice sheets described above. They could be irreversibly lost over periods ranging from a few decades to several centuries. These examples from the cryosphere show that the Earth's frozen environments are important habitats, help regulate the global climate, and form essential parts of the freshwater cycle. Rising temperatures worldwide threaten their stability, and in some places they are at risk of being irreversibly lost. Only decisive action to reduce greenhouse gas emissions now can help preserve these vulnerable worlds of ice.

These examples from the cryosphere show that the Earth's frozen environments are important habitats, help regulate the global climate, and form essential parts of the freshwater cycle. Rising temperatures worldwide threaten their stability, and in some places they are at risk of being irreversibly lost. Only decisive action to reduce greenhouse gas emissions now can help preserve these vulnerable worlds of ice.

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In motion: The Earth's ocean and atmospheric currents

Currents in the oceans and atmosphere distribute heat throughout the Earth system. They are changing as global temperatures rise, with far-reaching effects on the climate in different regions of the world.

Water and air, the flowing components of the Earth system, transport energy and chemical substances – between regions of the planet and between different parts of the ocean and atmosphere. Over the course of Earth's history, these flows have taken on different patterns. For around ten thousand years, the prevailing patterns of heat distribution have provided relatively stable conditions for human life in many regions of the world. Here, we describe some of these dynamics that are at risk of being disrupted by human activities.

Heat transport in the Atlantic

The Atlantic Meridional Overturning Circulation is a subject of intense discussion among Earth system scientists. In 2025 in particular, several research groups published new findings on this vast ocean circulation system, which helps give Western Europe its consistently moderate climate.
The AMOC (Atlantic Meridional Overturning Circulation) carries warmer water northward along the west coast of Africa and the eastern coasts of Central and North America. One branch of this circulation is the better-known Gulf Stream, which transports warm water from the Gulf of Mexico along the east coast of the United States and toward Europe. Countries such as the United Kingdom, northern France, the Benelux countries, and Germany benefit from the heat it carries. Monsoon winds and rainfall in regions of West Africa also vary depending on the amount of heat transported by the AMOC. Farther north, cooling water sinks to greater depths and flows southward. The AMOC continuously overturns water throughout the Atlantic Ocean and thereby shapes the heat balance of the surrounding land regions. This circulation is driven by regional differences in water temperature and salinity and is therefore also referred to as thermohaline circulation. As surface water flows northward, it cools. Because some of the water evaporates, the remaining seawater becomes more saline. The higher its salinity and the colder the water becomes, the denser it is, causing it to sink. In the cold North Atlantic, sea ice can also form at the ocean surface. When seawater freezes, salt is excluded from the ice, leaving particularly saline water at the surface. In the North Atlantic, especially south and west of Greenland, large volumes of cold, highly saline water sink into the deep ocean. There, the water flows southward and merges with other deep currents in the Southern Ocean. In this way, the world's ocean currents are interconnected. Ocean water circulates around the globe through this global network over timescales of centuries.

Human-caused climate change affects the Atlantic overturning circulation. Because surface temperatures are higher, the water cools less and sinks less readily into the deeper layers of the North Atlantic. Warmer air in the atmosphere can also hold more moisture, leading to heavier precipitation in some regions. This lowers the salinity of near-surface seawater. Near the coasts of southern and western Greenland, meltwater from the Greenland Ice Sheet further dilutes the seawater. However, it remains unclear how strongly and over what timescales meltwater directly affects the AMOC. This depends in particular on how quickly the ice melts.

Because this research is both highly current and of considerable public interest, headlines such as "AMOC: Will it collapse or won't it?" regularly appear in the media. At first glance, research findings can appear contradictory, especially when reduced to headlines. Climate researchers, meanwhile, continue to debate whether the available data already show signs of a human-caused weakening of the AMOC.

Direct observations of the strength of the circulation extend back only around 20 years – too short a period to draw reliable conclusions about its long-term natural variability. Depending on its route, a single circuit of the AMOC can take several decades to centuries. Our current understanding of its dynamics therefore also relies on geological and paleontological evidence and on computer models of ocean circulation and its drivers. One difficulty is the large number of factors that determine seawater density, ranging from freshwater input through precipitation and melting ice to warming at the ocean surface and atmospheric circulation that influences evaporation. These factors interact with one another. Changes in the AMOC can also trigger feedbacks that either amplify or dampen the change. Many key factors remain insufficiently understood, important regions of the AMOC remain poorly studied, and existing measurements provide only an incomplete picture. In addition, even with supercomputers, models cannot simulate every process. Several studies published in 2025 used computer models of the Earth system and oceans to estimate how the AMOC might develop in the future. One study describes the potential breakdown of winter convection in the North Atlantic: if the water no longer cools sufficiently in winter to sink into the deep ocean, Atlantic overturning could come to a halt within a few decades. Other studies instead emphasize the AMOC's stability. Certain wind-driven components of the circulation, for example, could persist even if the circulation driven by temperature and salinity weakened substantially.

"These studies are important for investigating the fundamental behavior of the AMOC under changing climate conditions," says Arne Biastoch, a physical oceanographer at the GEOMAR Helmholtz Centre for Ocean Research. "However, they do not provide a basis for directly predicting changes in the AMOC over the next few decades." Biastoch is a co-author of an assessment of AMOC stability that the European Joint Programming Initiatives (JPIs) Oceans and Climate are expected to publish next year.

There is broad agreement that heat transport through the Atlantic will weaken noticeably by the end of this century. People across large parts of the Western world would feel the effects. Europe and the Arctic could become noticeably cooler and experience more frequent episodes of extreme cold. The amount of land suitable for agriculture could decline, with serious consequences for the global food supply.
Whether the AMOC will actually come to a complete halt, however, remains unclear. According to the current assessment report of the Intergovernmental Panel on

Climate Change (IPCC AR6), the AMOC is expected to weaken gradually if greenhouse gas emissions continue to rise substantially. The authors consider a complete collapse within the coming decades unlikely. Some researchers have used current evidence to estimate the global average temperature at which a critical threshold might be reached. These highly uncertain estimates range from 1.4°C to 8°C of global warming above preindustrial levels. If such a threshold were crossed, the AMOC could shift into a new state or cease altogether within several decades to a few centuries. The assessment by the European JPIs Oceans and Climate mentioned above will reevaluate these risks based on the latest available data.

We still know relatively little about how the transport of oxygen, carbon, and other nutrients in seawater would change if the AMOC weakened. Nevertheless, changes in ocean currents and ocean warming can affect phytoplankton and populations of fish and marine mammals, with consequences for people living in many regions bordering the oceans.

An important gyre in the north

The North Atlantic Subpolar Gyre carries water from west of the United Kingdom and Ireland, around the southern tip of Greenland, and along the Canadian coasts of Labrador and Newfoundland. Within this enormous gyre, cold, saline water sinks into the deep ocean. It forms deep water that flows southward hundreds or thousands of meters below the surface, contributing to the Atlantic Meridional Overturning Circulation. This sinking process, known as convection, occurs particularly in the Labrador and Irminger Seas around southern Greenland. The "collapse of Labrador and Irminger Sea convection" is therefore also identified as a potential climate tipping point. A weakening or complete cessation of convection south of Greenland would alter the entire Subpolar Gyre.

The Subpolar Gyre regulates water and air temperatures in the North Atlantic and helps stabilize Western Europe's climate. Scientists have found evidence that the gyre has weakened in recent decades. Among other indicators, they monitor seawater density at different depths. As described for the AMOC, density decreases as more freshwater enters the ocean. Precipitation and meltwater dilute the seawater. The more diluted it becomes, the more slowly it sinks. Deep-water formation in the North Atlantic Subpolar Gyre is part of the wider Atlantic circulation system and contributes to the AMOC. Scientists are, however, observing changes in convection within the gyre that may be progressing more rapidly than changes in the AMOC itself.
Changes in the Subpolar Gyre could have far-reaching consequences. If the gyre weakens, the polar jet stream could shift northward, exposing Europe to more extreme weather. Atmospheric circulation and rainfall patterns in the southern Atlantic as far as the equator are also linked to ocean circulation and could change noticeably.
Researchers are also discussing possible effects on air temperatures around the southern tip of Greenland. Remarkably low temperatures are being measured in this region. Scientists are still investigating how this phenomenon, known as the Cold Blob or Warming Hole, is related to ocean circulation.

In the depths of Antarctica

The second major driver of global ocean overturning lies in Antarctica. Here, extremely cold and saline water forms Antarctic Bottom Water at great depths around the continent. Bottom-water formation begins when seawater freezes at the surface in the extreme cold of Antarctica. The salt is left behind, producing extremely saline, very cold water beneath the ice. This dense water sinks down the slopes of the continental shelf to depths of several kilometers. It then spreads along the seafloor into the Pacific, Atlantic, and Indian Oceans. In various regions it rises again into shallower layers of the ocean. This process, known as upwelling, occurs, for example, where strong winds drive surface waters apart, drawing deeper water upward. Mixing caused by waves and ocean eddies also contributes to the upward movement of deep water.

Meanwhile, strong offshore winds around Antarctica push surface ice farther out to sea. This exposes new areas of open water where additional seawater can freeze, leaving salt behind and further driving the formation of deep water.
The Antarctic overturning circulation is closely linked to both regional and global climate dynamics. Sinking bottom water transports carbon from the atmosphere into the deep ocean, helping to mitigate the effects of human-caused CO_2 emissions. Many food webs and nutrient cycles around the world depend on ocean circulation, one of whose major driving forces is located here in Antarctica. Researchers therefore regard the Antarctic overturning circulation as a key component of global climate and ecosystems.

Various climate models project that the Antarctic overturning circulation will weaken as global temperatures rise. Researchers are observing changes in water temperatures and the formation of sea ice at the surface. Some suspect that a threshold could eventually be reached beyond which alternative circulation patterns become established. However, the mechanisms behind the changes observed so far are only partially understood.

Whether and how much seawater freezes at the surface depends on several factors. These factors interact with one another and are themselves changing as a result of climate change: it affects the direction and strength of winds that are critical to sea-ice formation and alters both the salinity and temperature of the waters around Antarctica.

For many years, researchers observed a relatively large extent of Antarctic sea ice, which, interestingly, could partly be explained by rising global temperatures. Warming causes Antarctic ice to melt. Meltwater from the Antarctic Ice Sheet and ice shelves flows into the surrounding ocean. Because this meltwater is very cold and has a low salt content, it remains at the surface. This reduces mixing with warmer water from the deep ocean and thereby promotes sea-ice formation.

Since around the mid-2010s, however, annual sea-ice extent has declined conspicuously compared with previous decades. Researchers recently detected an unexplained increase in the salinity of Antarctic seawater. This reduces the stability of the water column, allowing warmer water from the deep ocean to rise toward the surface. This could explain why less sea ice is forming. Researchers are now investigating further questions: How will this development affect bottom-water formation and, in turn, overturning circulation in the Southern Ocean?

Because many uncertainties remain regarding the effects of global warming on Antarctic circulation and the global circulation systems connected to it, predictions remain uncertain as to whether Antarctic Bottom Water formation could weaken irreversibly – or even cease altogether – at particular global average temperatures.

Tropical winds and rain: The global monsoon system

A monsoon is an atmospheric circulation pattern characterized by winds that reverse direction with the changing seasons. This large-scale circulation is driven by seasonal changes in solar radiation. The winds and the characteristic rainfall associated with them originate near the equator, where the Earth receives the most solar radiation. The zone where winds from the Northern and Southern Hemispheres converge is known as the Intertropical Convergence Zone (ITCZ), or the equatorial low-pressure trough. It shifts regularly over the course of the year between latitudes south and north of the equator. This is because the Earth's axis is tilted relative to the Sun, causing incoming solar energy to vary with the angle of incidence. The seasonal migration of the Intertropical Convergence Zone divides the year into wet and dry seasons in regions near the equator.

One system, two states

When we hear the word monsoon, we often immediately think of images of India's heavy summer rains. But monsoon winds and their characteristic seasonal rainfall occur in regions near the equator around the world, including South America and West Africa. They shape the climate of many tropical and subtropical regions and are an important part of the global water cycle. Around one-third of all precipitation on Earth is monsoon rainfall. It is vital to people in agricultural regions of South Asia, South America, and West Africa. Changes in monsoon dynamics could affect as much as two-thirds of the world's population.

Researchers now view the world's monsoons as parts of a single global system. Its dynamics are subject to considerable natural variability across different timescales. Rainfall can vary substantially over just a few years or over several decades.

And in geological terms, it was not long ago that the African monsoon was considerably stronger. At that time, the Sahara was a landscape of grasses, trees, and lakes. The monsoon system has therefore undergone dramatic and sometimes rapid changes over the course of Earth's history – changes that could also be interpreted as "tipping" in the context of the current discussion of tipping points.

Based on simulations using the latest climate models, researchers consider the monsoon system itself to be bistable: it can exist in two stable states, alternating between them with the seasons. Some researchers regard this as another indication that the characteristic atmospheric circulation of the monsoons could cross a tipping point if natural or human-driven factors change. The system could then shift permanently into a new state. However, it remains unclear whether today's monsoon systems are actually at risk of suddenly coming to a halt or shifting into markedly different states.

In addition to natural external influences and internal variability, human activities affect monsoon dynamics both regionally and globally. The most important anthropogenic factors are the concentrations of greenhouse gases and aerosols in the atmosphere.

AMOC weakening affects the monsoon

The global monsoon is linked to the strength of the Atlantic Meridional Overturning Circulation (AMOC), which circulates water throughout the Atlantic and redistributes heat within the ocean and atmosphere.

In Earth's geological past, for example, a weaker AMOC was associated with a southward shift of the equatorial low-pressure trough, causing monsoon rainfall to shift as well. The weakening of the AMOC currently being observed means that less warm water flows northward from the south and surface waters in the North Atlantic become cooler.

Whether the AMOC will continue to weaken or could even come to a halt is the subject of ongoing research. Based on various models, some researchers predict that future cooling in the North Atlantic could extend into tropical latitudes. This could lead to drastic declines in seasonal rainfall in the affected regions. Tropical regions in Central America, the Amazon, and Indonesia could consequently face a greater risk of extreme drought.

More frequent extreme weather in some monsoon regions
At irregular intervals of several years, sea surface temperatures in the eastern and central Pacific rise significantly above average. This warming, known as El Niño, causes far-reaching climatic changes that can persist for months. El Niño is one phase of the El Niño-Southern Oscillation (ENSO), a recurring pattern of climate variability.

In India's central monsoon regions, researchers have observed that extreme rainfall events occur more frequently during El Niño years than in other years. Such short-lived episodes of extremely heavy rainfall can have devastating consequences for people in the affected regions. They have the potential to damage or destroy buildings, transportation infrastructure, and agricultural land.

As climate change progresses, researchers expect greater variability in ENSO patterns. In other words, they anticipate that both El Niño and its cold counterpart, La Niña, will more frequently reach extreme intensities. This would also increase the risk of extreme rainfall during the summer monsoon season in central India.

Warmer oceans, more precipitation – but where and in what form?

As the atmosphere warms because of the greenhouse effect, sea surface temperatures are rising in many regions. Because more water evaporates from warmer surfaces and a warmer atmosphere can hold more moisture, researchers generally expect global precipitation to increase. However, predicting where this precipitation will fall and what form it will take - whether as beneficial, sustained rainfall or destructive downpours - is extremely difficult.

At the same time, sea surface temperatures can also fall locally as a result of climate change, for example because of meltwater entering the ocean from ice sheets or because of the weakening of the AMOC described above. Sea surface temperature probably influences monsoon intensity. This is suggested by both geological evidence of past monsoon strength in different regions and the latest climate models. The relationships are complex, however, and are not yet sufficiently understood to reliably predict in detail how regional monsoon dynamics will change in response to sea surface temperatures.

Aerosol emissions counteract warming

Emissions of particulate matter and other aerosols, as well as changes in surface characteristics caused by land use, also affect monsoon dynamics. Emissions and land-use changes interact with the particular climatic and geological conditions of each region.

Aerosols in the atmosphere absorb or reflect sunlight, thereby altering the atmosphere's heat balance. This, in turn, affects wind and rainfall patterns, cloud formation, and vegetation. In the second half of the 20th century, for example, monsoon rainfall in India tended to decline because a cooling layer of aerosols from industrial emissions counteracted some of the effects of global warming. How aerosol concentrations develop in the future will depend to a large extent on political decisions and economic developments.

Human modifications of the Earth's surface, such as construction and agricultural land use, alter its reflectivity, or albedo. Because albedo plays a key role in surface heating and evaporation, changes in albedo can affect the intensity of monsoon rainfall. Feedback effects can also occur. If rainfall decreases in a region, for example, soils may dry out; vegetation declines and albedo increases; less heat builds up at the Earth's surface, causing less moisture to rise into the atmosphere and resulting in even less rainfall.

Uncertain projections

The strength of the monsoon is linked to the intensity of solar radiation. This varies with the Earth's orbit around the Sun, both over the course of the year and in long-term cycles spanning tens of thousands of years.

"Paleontological evidence tells us, however, that several thousand years can pass before a change in solar radiation is reflected in monsoon circulation," explains Edmund Hathorne, a geochemist and paleo-oceanographer at GEOMAR. "This points to the complex interplay and feedbacks among internal mechanisms of the global climate system—for example, the response of ice sheets to warming, changes in ocean surface temperatures and circulation, or changes in vegetation."

Once the atmospheric and ocean circulation patterns that make up the monsoon begin to change, however, the changes can occur relatively quickly and their consequences can be dramatic. "Not very long ago, in geological terms, the system looked completely different," Hathorne says. A weakening of the West African monsoon around 8,000 to 5,000 years ago triggered the transformation of the then-green Sahara into the desert landscape we know today. Processes such as the feedback between drought, vegetation, and albedo described above probably accelerated this desertification.

The monsoon system is therefore connected to a wide range of components of the global climate system, and changes can be unexpectedly severe. Whether a region is more likely to face a shortage of rainfall or an increase in precipitation depends on its geographic location, the season, and a variety of regional and global climate factors.

Short-term rainfall dynamics are also changing. The same total amount of rain may fall within a single day, for example, but if it falls in a very short period as an intense downpour, its effects are more likely to be destructive. If the rainfall is spread throughout the day instead, it may benefit agriculture. For this reason, the characteristics of monsoon rainfall and the potentially dramatic ways in which it may change as the climate warms are highly relevant to society.

To predict how the monsoon will develop, researchers need a better understanding of its dynamics and its dependence on other climate components. At present, it is hardly possible to make definitive statements about future trends, says Edmund Hathorne. "Existing climate models are broadly consistent about the direction of change—that is, whether monsoon regions around the world will receive more or less rainfall," he explains, while cautioning against generalizations. "But projections of how large these changes will be and over what timescales they will unfold differ considerably, even among the latest state-of-the-art climate models."

These examples show that as average global temperatures rise, global patterns of atmospheric and ocean circulation are changing. These currents act as major pathways for heat transport within the global climate system, meaning that changes can have effects across vast distances around the planet. Closely observing and understanding these currents and their dynamics is essential if people are to adapt to changing living conditions.

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Read publications online:

"Tipping points: How we talk about climate change in the Earth's system " (2026)

"Biosphere: Ecosystems at the limits of their resilience" (2026)

"Cryosphere: Where are worlds of ice at risk of thawing?" (2026)

"In motion: The Earth's ocean and atmospheric currents" (2026)

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