

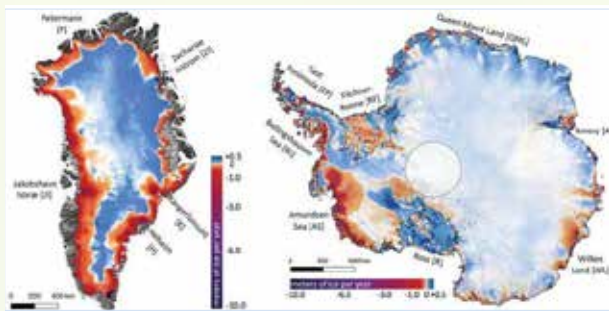
an urgent, unfolding reality. The opportunity to act is no longer in the future; it is now.

Major Climate Tipping Elements

Scientists caution that several parts of the Earth's climate system may be approaching or may have already crossed critical tipping points. The IPCC's Special Report on Global Warming of 1.5°C identifies key vulnerable tipping elements that are increasingly at risk as global temperatures rise. As the likelihood of crossing these thresholds grows, it becomes crucial to integrate tipping point risks into climate policy, adaptation, and mitigation efforts. These at-risk systems include large-scale, interconnected components such as:

Greenland and West Antarctic Ice Sheets: Both ice sheets are highly vulnerable to feedback mechanisms that could trigger irreversible ice loss. Satellite data from 2022 shows Greenland's rapid melting is now the leading cause of global sea level rise. Over the past 20 years, Greenland has lost over 5,100 billion tons of ice, enough to submerge the entire U.S. under half a meter of water.

The tipping point for Greenland is estimated to be between 0.8°C and 3.2°C of global warming above pre-industrial levels, influenced by factors like surface albedo and elevation loss. The West Antarctic Ice Sheet, particularly susceptible to Marine Ice Sheet Instability (MISI), may collapse irreversibly between 1.5°C and 2°C of warming. This collapse could unfold over millennia, with regrowth requiring substantial cooling. Projections of sea level rise range from several tenths of a meter to 1–2 meters, positioning the 1.5°C–2°C warming range as a significant risk zone for ice sheet collapse and long-term sea level rise.



Observed mass change of Greenland and Antarctic ice sheets. Mass change (mass loss in red, mass gain in blue) between 2003 and 2019 for Greenland and Antarctica, given in meters of ice equivalent per year (from Smith et al., 2020).

Permafrost Thawing: Permafrost, which remains frozen for at least two consecutive years, stores

vast amounts of methane and carbon dioxide. As it thaws, these gases are released, accelerating global warming in a feedback loop.



Permafrost Thawing

Unusually warm conditions, such as the summer of 2012 in central Yamal in Siberia, trigger a particular type of landslide in permafrost regions. These retrogressive thaw slumps erode quickly as the exposed ice in the ground thaws. The change in land cover can be monitored with satellite missions such as Copernicus Sentinel-2. Credit: Annett Bartsch (25.08.2015)

Covering regions like Siberia, Alaska, northern Canada, and the Tibetan Plateau, permafrost holds the largest carbon reservoir, around 1,400 billion tons, accumulated over thousands of years. The "active layer" above permafrost regulates heat exchange, and as global temperatures rise, thawing permafrost releases significant amounts of carbon dioxide and methane, both potent greenhouse gases. Methane is a powerful climate forcer, and its release could contribute up to 0.3°C of additional global warming. Some models predict that up to 70% of permafrost carbon could be released in high-warming scenarios, adding uncertainty to carbon budgeting. This feedback loop not only accelerates climate change but also raises the risk of triggering other critical tipping points, potentially causing cascading, irreversible changes.

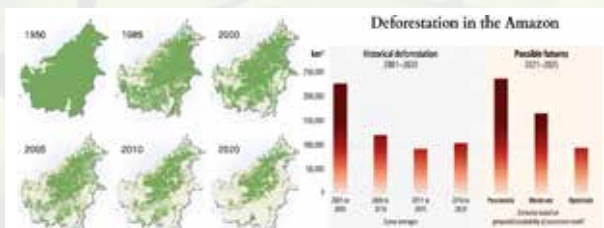
Atlantic Meridional Overturning Circulation (AMOC): The AMOC, including the Gulf Stream, is a vital component of the Earth's climate system, acting as a global conveyor belt that redistributes heat between the tropics and the poles. It regulates the climate across the North Atlantic, stabilizes weather patterns, supports rainfall in tropical regions, and maintains mild temperatures in Europe. However, the influx of freshwater from melting glaciers, particularly in Greenland, is weakening the system. Over the past 50 years, the AMOC has declined by around 15%, with projections indicating a 24–39% reduction by 2100. Currently, it is at its weakest in over 1,600 years. A continued weakening could trigger a cascade of disruptions, including reduced rainfall in Africa's

Sahel, weakened Asian monsoons, increased sea level rise in the Atlantic, intensified European winter storms, and drought in the Amazon and sub-Saharan Africa. Some researchers warn of a partial collapse, like the Younger Dryas event 12,000 years ago. While the IPCC considers a collapse unlikely this century, emerging studies suggest it could occur by mid-century under current emissions. Recent data suggests the AMOC is nearing a critical tipping point with potentially far-reaching global consequences.

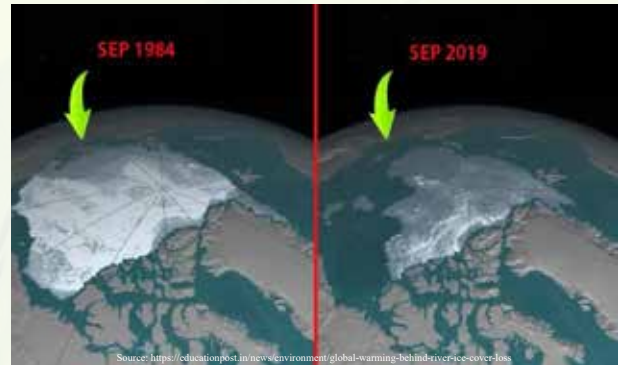


How the Atlantic Ocean circulation would change as it slowed. IPCC 6th Assessment Report.

Amazon Rainforest: The Amazon Rainforest, often called “the lungs of the Earth,” absorbs a quarter of the CO₂ captured by all land ecosystems. However, deforestation has reduced its carbon absorption by about 30% since the 1990s. The primary cause is cattle ranching, driven by global beef demand, especially from China and the U.S., along with cropland expansion for soybeans. Although deforestation rates improved in Brazil in 2023, the Amazon remains under severe threat. As the largest tropical rainforest, it generates around half of its own rainfall through moisture cycling. But climate change impacts and high deforestation rates have caused significant dieback, transforming parts of the forest from a carbon sink to a net emitter. Scientists warn that losing 20-25% of its cover could push the Amazon past a tipping point, potentially turning it from rainforest to savanna and triggering severe regional and global climate disruptions.



Arctic Sea Ice: The Arctic is warming 3-4 times faster than the global average, leading to significant sea ice loss. The darker ocean surfaces, which absorb more solar radiation than ice, trigger a feedback loop that accelerates warming and ice melt, intensifying regional and global climate instability.



The Arctic holds enough ice to raise global sea levels by 7.2 meters (22 feet) if fully melted. Studies suggest that a global temperature rise of 1.5°C could make Arctic ice melt irreversible, with severe long-term impacts on sea levels and coastal communities. Projections indicate ice-free summers in the Arctic as early as the 2030s, potentially marking a tipping point that disrupts global weather patterns. However, some studies, including those in the IPCC’s Fifth Assessment Report, indicate that Arctic Sea ice loss may not be irreversible.

Coral Reef Dieback: Coral reef dieback, primarily driven by climate change and other human activities, refers to the decline and death of coral reefs worldwide. This decline is characterized by coral bleaching (expulsion of symbiotic algae due to rising water temperatures) and ultimately leads to coral death, impacting biodiversity and ecosystem services.



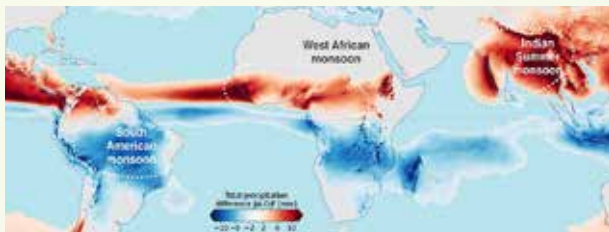
Bleached coral on the Great Barrier Reef outside Cairns Australia during a mass bleaching event, thought to have been caused by heat stress due to warmer water temperatures as a result of global climate change. Credit: Brett Monroe Garner/Getty Images.

Boreal Forests Transitioning to a Carbon Source:

Boreal forests, which have historically acted as significant carbon sinks, are increasingly transitioning to become net carbon sources, meaning they are releasing more carbon dioxide into the atmosphere than they absorb. This shift is primarily driven by climate change, leading to increased fire frequency and severity, altered precipitation patterns, and changes in tree species composition.



Indian and African Monsoon Disruptions: Indian and African monsoons, both crucial for their respective regions, are experiencing disruptions attributed to climate change. These disruptions can have cascading effects on both regions, impacting agriculture, water resources, and potentially leading to increased risks of droughts or floods. Specifically, the Indian Summer Monsoon (ISM) and the West African Monsoon (WAM) are considered potential climate tipping points.

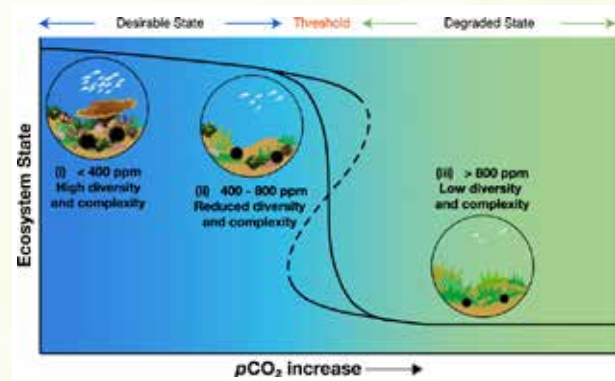


Monsoon systems. Shown is the total precipitation difference between Northern hemisphere summer (June-August, JJA) and winter months (December-February, DJF), highlighting the dominant precipitation patterns over South America (SAM), West Africa (WAM) and India (ISM). Generated using Copernicus Climate Change Service information (Hersbach et al., 2023), with monthly averages over 1980-2010.

Ocean Acidification and Ecosystem Shifts:

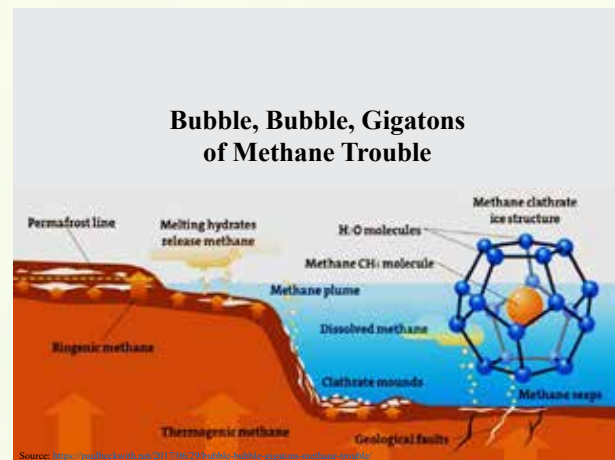
Ocean acidification, caused by the absorption of atmospheric carbon dioxide, leads to significant shifts in marine ecosystems. These changes primarily affect calcifying organisms, such as corals

and shellfish, making it harder for them to build and maintain their shells and skeletons. This can lead to decreased biodiversity, changes in community composition, and altered food web interactions.



Methane Release from Clathrates:

Methane release from clathrates, or methane hydrates, occurs when the stable, ice-like structure that traps methane gas is destabilized by temperature and pressure changes. This release can happen in permafrost regions, ocean sediments, and potentially on other icy bodies. The released methane, a potent greenhouse gas, can contribute to climate change and even cause abrupt warming scenarios if released in large quantities.

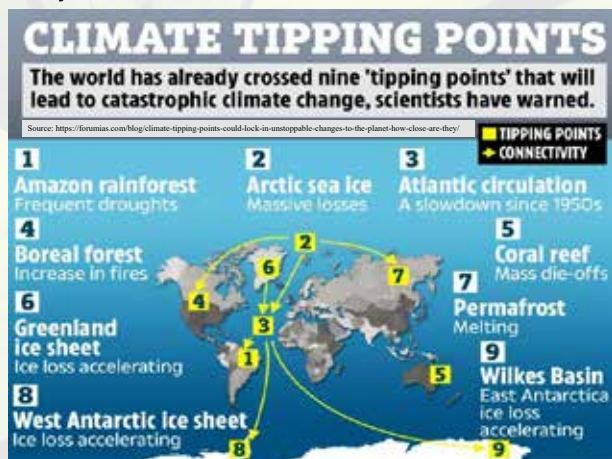


Desertification and Land Degradation:

Desertification is a form of land degradation that occurs in arid, semi-arid, and dry sub-humid areas, leading to a decline in the biological productivity of the land. It is not solely about the expansion of deserts, but rather about the degradation of dryland ecosystems due to factors like climate change and unsustainable land management practices.



Tipping elements in the Earth’s climate system are deeply interconnected, leading to **Domino Effects** where crossing one threshold increases the risk of triggering others. For example, the melting of Greenland’s ice could disrupt ocean currents, which may then destabilize monsoons or rainforest ecosystems.

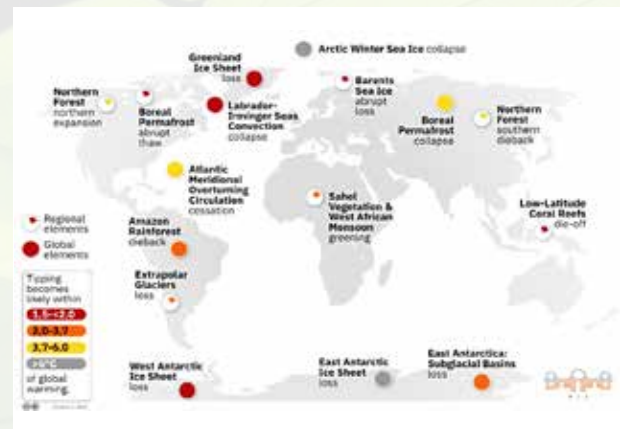


This interconnectedness adds complexity to the challenge and raises the stakes. Recent studies warn that crossing multiple tipping points in quick succession could push the planet into a “Hothouse Earth” state marked by runaway warming, widespread ecological collapse, and drastic changes in human habitability. This emphasizes the urgent need for bold climate action and systemic resilience.

Climate Tipping Points: Timing, Uncertainty, and the Urgency for Action

Determining when climate tipping points will be reached is a complex and evolving challenge, given the nonlinear nature of Earth systems and the interplay of various climatic, ecological, and human-

driven factors. While the timing remains highly uncertain, some tipping points could occur as early as 2050, depending on the rate of global warming and environmental changes. For instance, up to 50% of the Amazon rainforest could cross a tipping point by 2050 due to water stress, deforestation, and climate change. Historically, it was believed that most tipping points would only be triggered with a 4°C rise in global temperatures above pre-industrial levels. However, the IPCC’s AR6 has revised this, suggesting that surpassing even 1.5°C could push several critical systems beyond their stability thresholds. With the Earth’s surface temperature already nearly 1.2°C higher than in the 1850–1900 period, the 1.5°C threshold may be reached between 2026 and 2042 unless substantial emissions reductions are made. If temperatures reach 1.5°C–2°C, the likelihood of crossing additional tipping points increases significantly.



Identifying when a system is approaching a tipping point remains a major scientific hurdle. Researchers are exploring early warning signals such as critical slowing down, where systems recover more slowly from disturbances, and increased variance, where fluctuations become more erratic. While promising, these methods are still in development, emphasizing the need for proactive action instead of relying solely on predictions.

Although climate models are becoming more sophisticated, significant uncertainties persist due to the complexity of Earth system interactions and assumptions made regarding emissions trajectories, feedback mechanisms, and regional variability. For example, estimates suggest that the threshold for irreversible loss of the Greenland Ice Sheet lies between 0.8°C and 3.2°C of global warming, while

the collapse of the Atlantic Meridional Overturning Circulation (AMOC) may occur with sustained warming of 1.5°C–2°C. However, these estimates come with wide uncertainty ranges, making precise predictions difficult. Importantly, this uncertainty should not lead to complacency, as the irreversible and high-impact nature of tipping events calls for a precautionary approach. Delaying action until these thresholds are crossed could result in catastrophic and uncontrollable changes in the Earth system.

Hope in the Chaos: Positive Tipping Points for a Better Future

In the context of the climate crisis, positive tipping points are moments or processes where changes or actions can trigger beneficial, self-reinforcing cycles that accelerate progress toward environmental sustainability. For example –

- **Rapid Adoption of Renewable Energy:** As more individuals, businesses, and governments switch to renewable energy sources like solar, wind, and hydropower, it could lead to lower costs, increased efficiency, and widespread adoption, creating a self-reinforcing cycle where renewable energy becomes the dominant global energy source, reducing reliance on fossil fuels.
- **Social Movements for Sustainability:** When social movements advocating for sustainability such as those promoting plant-based diets, waste reduction, and green energy reach a critical mass, they can reshape societal norms. As more people join these movements, policies and business practices will likely align with environmental goals, accelerating the transition to a low-carbon economy.
- **Technological Innovations:** Advances in early warning & monitoring systems and clean technologies, such as carbon capture, storage, and recycling innovations, can drive significant changes in how we manage resources, energy production, and waste. These innovations can reduce carbon footprints across industries and contribute to large-scale environmental recovery.
- **Policy Shifts and Global Cooperation:** Aggressive and transformative climate policies, when implemented globally, can set ambitious targets for emission reductions,

resource management, and climate adaptation. Policies that incentivize green practices, such as subsidies for electric vehicles, stricter emissions regulations, or financial support for climate-resilient infrastructure, can lead to rapid, large-scale changes.

Conclusion and Prospects

The climate system's tipping points are no longer distant possibilities but present-day realities, escalating toward potentially irreversible changes. We are rapidly approaching, and in some instances already crossing, critical thresholds that could unleash cascading disruptions across ecosystems and societies. The urgency of the situation demands immediate and decisive action. While certain aspects of climate inertia are unavoidable, the window to avert the worst outcomes is still open, though it is closing swiftly. The decisions we make today will dictate the future of our planet and its ability to support life in the coming centuries. Proactive steps, including drastic emission reductions, transformative policy reforms, and global cooperation, are essential to mitigating the risks. By catalysing positive tipping points, such as accelerating the transition to renewable energy, we can reshape the trajectory of climate change and ensure a sustainable future for all.

Looking forward, the need for urgent action on climate tipping points has never been clearer. The challenge lies not only in slowing the existing momentum but also in reversing or preventing further crossings of critical thresholds. Future strategies must integrate cutting-edge scientific research with robust policy frameworks to identify early warning signals and respond effectively. The development of global monitoring systems, coupled with stronger international cooperation, will be vital for anticipating and managing climate risks. Additionally, fostering resilience through nature-based solutions, sustainable infrastructure, and adaptive social systems is key to ensuring that vulnerable regions are protected from the cascading impacts of climate change. The path forward requires a global commitment to systemic transformation, where human ingenuity, collective action, and environmental stewardship converge to safeguard the planet's future. The time to act is now; the cost of inaction will be far greater.