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Underestanding Tipping Points Caused by Climate Change in Iran: A review

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Abstract
Climate tipping points are caused by global warming and refer to critical thresholds in the climate system, crossing which leads to irreversible changes in climate conditions, ecosystems, and even socio-economic structures. These changes may occur over long time scales, ranging from several decades to hundreds of years, and their effects are often negative and threatening, although some positive consequences may also exist. Given the intensity and extent of the impacts of these points, studying and identifying them is essential for better prediction of climate changes and adopting effective adaptation and damage reduction policies. In Iran, multiple negative tipping points due to climate change and global warming have been observed and projected, including the shift of about 90% of the country's cities to a drier climatic zone under the high greenhouse gas emission scenario of SSP5-8.5, the reduction of snow's share in total precipitation, the increase in the duration of heatwaves from the current 5 days to about two weeks under the low emission scenario of SSP1-2.6 and one season under the high emission scenario of SSP5-8.5, doubling drought vulnerability by the end of the 21st century according to the high emission scenario, the displacement of one-third of Iran's population over the next 25 years (by 2050) to the northern third of the country, weakening of Caspian Sea precipitation and parts of the northeast due to weakening migratory high-pressure weather systems, making agriculture unprofitable in some provinces including saffron farming, and increasing flood-prone areas and peak discharge of the Shandiz river up to fivefold. On the other hand, positive tipping points have also been observed, such as the increase of tropical cyclones in the northern Indian Ocean and the Arabian Sea and increased extreme precipitation in the southern strip of the country, as well as the replacement of fossil fuels with renewable energy sources. These developments call for special attention to climate risk management and the development of sustainable adaptation policies.

Keywords: Climate Tipping Points, Climate Change, Iran, Heatwaves, Climate zones

Introduction
Climate tipping points represent critical thresholds in the Earth's climate system, beyond which small perturbations can cause large, often irreversible changes in climate conditions, ecosystems, and socio-economic structures. These points act as pivotal markers in the complex climate network, demarcating where the system crosses from one state to another, often with disproportionate and cascading effects. The concept of tipping points encompasses not only physical climate components, such as ice sheets, ocean circulation, and biosphere feedbacks, but also the intertwined human and ecological systems influenced by these changes. This understanding has become central in climate science because crossing tipping points could lock the planet into new, less hospitable climate regimes that are challenging or impossible to reverse with current technologies (Lenton et al., 2008; ESA, 2023).
The scientific consensus highlights that many climate tipping points are closely linked to the global rise in temperature caused by anthropogenic greenhouse gas emissions. The historic surpassing of the 1.5 °C warming threshold in 2024 underscores the urgency; this critical level dramatically increases the likelihood that several vulnerable components of the Earth system will pass their tipping points in the near future (Tandon, et. al., 2025; Earth.Org, 2023). Examples of global tipping elements include the accelerated melting of polar ice sheets leading to irreversible sea-level rise, the weakening or shutdown of major oceanic

currents such as the Atlantic Meridional Overturning Circulation (AMOC), wide-scale dieback of the Amazon rainforest, and rapid permafrost thaw releasing stored greenhouse gases. Each element has the potential to set off feedback loops that exacerbate climate change and disrupt associated ecosystems and human livelihoods (Lu et. al., 2025).

While much of the research and public focus has remained global, regional climates—such as that of Iran—are also facing identifiable tipping points with profound implications. Iran is situated in a climatically sensitive region with an already arid and semi-arid environment, making it especially vulnerable to climate change impacts. Observations show that Iran's warming rate is roughly twice the global average, with average temperatures increasing by about 0.4 °C per decade. This rapid warming amplifies the frequency and severity of climate extremes including prolonged heatwaves, intense droughts, and episodes of heavy precipitation and flooding. Such extremes are signs of tipping points where climatic patterns exceed their historical variability, threatening water resources, agriculture, human health, and ecosystems. One major tipping effect underway in Iran is the shifting of climatic zones. Approximately 90% of Iranian cities are projected to transition towards drier climatic zones under high emission scenarios, reflecting a substantial decrease in precipitation coupled with higher temperatures causing increased evaporation rates. These shifts threaten to destabilize local agriculture systems, particularly traditional crops such as saffron, and increase vulnerability to desertification. Furthermore, snowpack, which constitutes a critical water storage, is progressively diminishing, shrinking the fraction of snowfall in total precipitation. This transformation reduces spring and summer runoff critical for agricultural irrigation and drinking water supply. Heatwaves in Iran are also becoming longer and more intense. Under low emission scenarios, the typical duration of heatwaves is expected to extend from about five days to two weeks, and under higher emission scenarios, heatwaves could persist for an entire season in parts of the country. This not only impacts human health and labor productivity but exacerbates drought conditions, increasing desertification and dust storm activities. The drought vulnerability index for Iran is projected to double by the late 21st century under high emission scenarios, signaling a dramatic rise in both frequency and intensity of drought episodes (Babaeian et. a., 2019; Kouzegaran et. al., 2020; Shahsavan et. al., 2024).

The social impacts of these tipping points are equally alarming. It is estimated that within the next 25 years (around 1430 in the Iranian calendar), a third of Iran's population may be displaced internally due to climate-induced stresses, relocating predominantly to the northern provinces such as Razavi and North Khorasan. This population movement imposes significant challenges on urban planning, infrastructure, and social services, potentially triggering socioeconomic instability (Jahangirpour et al., 2020; Zare, M., 2024).

Hydrologically, Iran faces a weakening of Caspian Sea precipitation and parts of the northeast attributed to the degradation of migratory high-pressure systems that sustain regional rainfall patterns. Some rivers like are experiencing increase in peak flood discharge, expanding flood-prone areas and raising risks to settlements and agricultural lands. Such hydrological tipping points necessitate urgent improvements in water resource management and disaster preparedness(Samant and Prange, 2023; Mashari et al., 2018).

Conversely, some positive tipping points are emerging. Increased frequency of tropical cyclones in the northern Indian Ocean and Arabian Sea has been noted, contributing to localized increases in extreme precipitation events in southern Iran, which if properly managed, could partially offset water deficits. Additionally, a shift towards renewable energy sources is occurring, replacing fossil fuels and offering a pathway to reduce Iran's carbon footprint, potentially mitigating future warming and its associated tipping risks (ESA, 2023).

Collectively, these physical and social tipping points in Iran underscore the critical importance of advancing climate adaptation policies grounded in robust scientific understanding. Integrated approaches combining mitigation, adaptation, and socio-economic planning are essential for enhancing resilience and sustainable development in the face of accelerating climate change impacts. Such strategies must include monitoring of

early warning indicators, improving water resource efficiency, diversifying energy portfolios, strengthening agricultural practices, and preparing urban centers for population shifts (Armstrong et al., 2020).
In summary, climate tipping points driven by global warming are not abstract future possibilities but present realities with observable effects in vulnerable regions like Iran. Their complexity and interconnection demand holistic and urgent responses to avoid crossing further irreversible thresholds that would compromise the wellbeing of current and future generations (Steffen et al., 2025; Lenton et. al., 2023). Accordingly, in this article, we review the most important findings regarding the observed and projected tipping points due to climate change.

Climate Tiping Points and Mechanism

Climate tipping points represent critical thresholds in the Earth's climate system where small changes in global temperatures or environmental conditions can lead to large, often irreversible, shifts in climate behavior and associated ecosystems. Crossing these thresholds results in abrupt transitions to new states that differ markedly from the previous stable climate regime, potentially triggering severe consequences for natural and human systems. Tipping points are a fundamental concept to understanding the nonlinear and systemic risks posed by climate change (Fig. 1). Mechanistically, tipping points are often driven by positive feedback loops and self-reinforcing processes within the climate system. For example, the melting of polar ice reduces the Earth's albedo (reflectivity), causing more solar energy to be absorbed and accelerating further warming and ice melt. Similarly, thawing permafrost releases methane and carbon dioxide, potent greenhouse gases that enhance atmospheric warming, which in turn promotes additional permafrost degradation. These feedbacks amplify the initial forcing and push the system beyond the threshold into a new equilibrium state (Igini, 2023; Lenton et. al., 2012). Tipping behavior can vary in speed and scale. Some tipping points manifest abruptly over short time spans—such as rapid shifts in ocean circulation patterns—while others unfold more gradually yet remain effectively irreversible on human timescales, like the slow collapse of large ice sheets. Importantly, the critical thresholds themselves may depend on both the magnitude and the rate of climatic changes, meaning rapid warming can prompt tipping even before more gradual warming would produce the same effect (Tandon, et. al., 2025).

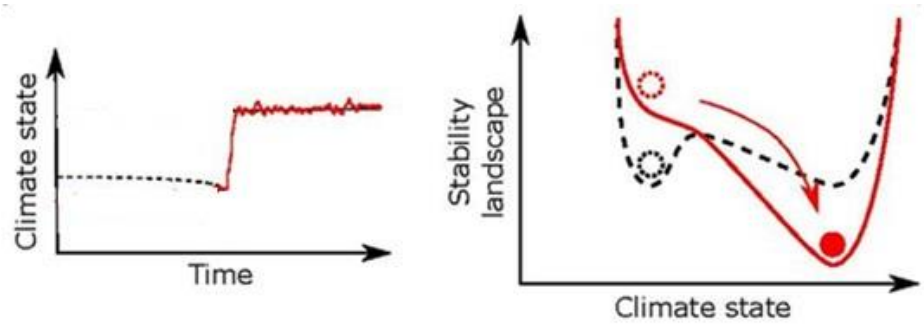

Figure 1- Illustration of a tipping point (TP): When a climate forcing, such as 1.5°C of global warming, is reached, a previously stable climate system undergoes a transition to a new climate state (Lenton et al., 2012).

Climate system components identified as tipping elements fall broadly into categories including cryosphere, ocean circulation, and terrestrial ecosystems. Key cryosphere tipping points include the disintegration of the Greenland and West Antarctic ice sheets, loss of Arctic sea ice, and mountain glacier retreat. Ocean circulation tipping points center notably on the Atlantic Meridional Overturning Circulation (AMOC), whose weakening or collapse would profoundly alter global climate patterns. Terrestrial ecosystem tipping points involve phenomena such as Amazon rainforest dieback and boreal forest biome shifts (ESA, 2023).

Current scientific evidence indicates that some tipping points may be close to or already crossed, especially given observed warming surpassing 1°C above pre-industrial levels, with greater risks projected at 1.5°C to 2°C warming thresholds. As the global community continues to debate the safest limits for temperature rise, understanding tipping points and their underlying mechanisms remains crucial to informing urgent climate action and guiding policy to avoid irreversible, catastrophic changes to the Earth system (Tandon, et. al., 2025; Lenton et. al., 2023).

Climate tipping points characterize the nonlinear nature of climate risks, governed by complex feedback dynamics and threshold responses. Their identification and mechanistic understanding are essential for future projection of climate trajectories, assessing risks to ecosystems and humans, and framing adaptive strategies necessary to sustain planetary stability under ongoing anthropogenic warming.

Current and future Tipping Points in Iran

Iran is currently experiencing complex manifestations of climate-related tipping points driven primarily by anthropogenic global warming. Over the past five decades, Iran's average temperature has increased by approximately 2 to 2.5ºC, with some central plateau regions experiencing rises up to 3 ºC. This warming is significantly higher than the global average and has been accompanied by decreased annual rainfall (from about 255 mm to approximately 200 mm), increased evapotranspiration rates, and more irregular precipitation patterns. Extended summers, lasting up to 4 to 5 months, exacerbate drought stress and water scarcity across much of the country (Masoodian, 204; A;izadeh and Najafi, 2017; Babaeian et. al., 2019; Khorsandi et al., 2023). Such climatic trends have pushed Iran closer to several critical tipping points, with projections indicating that if warming continues unabated, major urban centers bordering desert regions (e.g., Yazd, Kerman, Isfahan) risk becoming increasingly uninhabitable by the late 21st century. Tipping points at the regional scale involve shifts in climate regimes, where approximately 90% of cities could transition to significantly drier climatic zones(Shahsavan et al., 2024). Additionally, desertification, reduced snowpack, and longer, more intense heatwaves are expected to increase vulnerability to drought and water resource collapse (Fig. 2). Samples of prolonged heatwave duration as a negative tippimg point have ben shown ib figure 2. In the figure, single heatwave events lasting even three months are projected at the 22nd century, although such extended durations cannot be considered normal climate behavior of 22nd century. Positive tipping points, although less documented, also emerge as pathways for sustainable transition, notably in the increasing adoption of renewable energy technologies, which may facilitate a structural shift away from fossil fuel dependence. Effective policy interventions could leverage such positive tipping dynamics to mitigate climate risks, promote societal resilience, and trigger technological innovation in Iran's energy and agricultural systems. Understanding these projected tipping points enables better preparation to

manage negative impacts while fostering opportunities for adaptive, climate-resilient development. Table 1 summarize some occurred and future projected negative and positive tipping points.

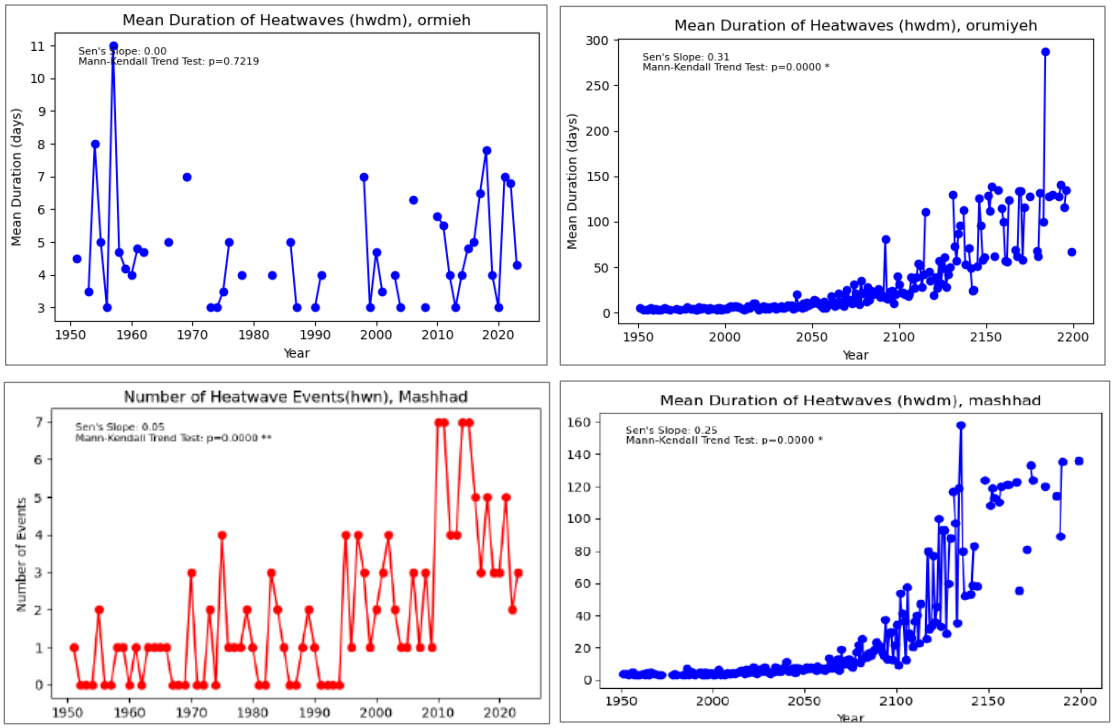

Figure 2- Observed and future projection of heatwave duration (in days) under SSP5-8.5 scenario over Orumieh and Mashhad(Babaeian et al., 2024)

Table 1- Key negative and positive Tipping Points in Iran and their impacts

Tipping Points	Type	Impact Description	Expected Consequences
Shift of ~90% of cities to drier climate zones	Negative	Transition to significantly drier conditions	Increased drought, water scarcity
Decline in snowpack contribution to precipitation	Negative	Reduced snow storage and spring runoff	Water supply stress
Prolonged heatwaves (from ~5 days to weeks/seasons)	Negative	Longer, more intense heatwaves	Health risks, crop failures
Doubling drought vulnerability by end of 21st century	Negative	Increased drought frequency and severity	Agricultural and ecosystem damage
Internal displacement of ~1/3 population by 2050	Negative	Climate-induced migration to northern regions	Social and infrastructure pressures
Weakening of Caspian and Northeast rainfall	Negative	Reduced regional precipitation	Ecosystem stress, water shortage
Undermining agriculture viability (e.g., saffron)	Negative	Loss of viable farming conditions	Economic hardship
Increase in flood-prone areas and river peak flows	Negative	Expanded flood risk	Infrastructure damage
Increased tropical cyclones in Indian Ocean	Positive	More extreme rainfall events in southern Iran	Potential water resource boost
Transition from fossil fuels to renewable energy	Positive	Shift to sustainable energy systems	Emission reductions, enhanced climate resilience

Conclusion

Climate tipping points represent critical thresholds in the Earth's climate system where small changes in forcing, such as rising greenhouse gas levels, can trigger abrupt and often irreversible shifts in climate states. In the context of Iran, these tipping points are no longer hypothetical but emerging realities under current and projected warming trends. Observations show that Iran's rapid warming, nearly double the global average, combined with decreasing precipitation and increasing evaporation, is pushing many natural and socio-economic systems toward critical thresholds. Key negative tipping points include the transition of nearly 90% of weather stations to drier climate zones, reduced snowpack and spring runoff, prolonged heatwaves, doubling drought vulnerability, and extensive internal climate migration due to water scarcity and agricultural instability.

These changes threaten fragile ecosystems and traditional livelihoods, making large regions of Iran increasingly vulnerable to desertification, reduced agricultural productivity (notably for high-value crops like saffron), and increased risks from floods and heat-related health impacts. Further complicating the picture are hydrological tipping points linked to weakened precipitation over the Caspian Sea basin and increased flood frequency in some basins, which demand urgent improvements in water management and disaster preparedness. Conversely, positive tipping points offer pathways for resilience and sustainability. The increasing frequency of tropical cyclones may improve localized water availability in southeastern Iran, while the country's ongoing shift from fossil fuels to renewable energy could mitigate future warming and reduce climate risks. These emerging opportunities stress the importance of policies promoting technological innovation, climate adaptation, and socio-economic transformation.

Given the intertwined nature of climate, ecological, and social tipping points, it is imperative that Iranian climate policy adopts integrated risk management approaches. This includes monitoring early warning indicators, investing in sustainable water and energy systems, enhancing agricultural resilience, and preparing urban centers for demographic shifts caused by climate migration. Understanding and responding

to Iran's climate tipping points is vital to avert irreversible impacts and to seize opportunities for building a sustainable and resilient future under changing climate realities.

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