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Climate Tipping Points and Abrupt Changes in Iran: A Review of Observed and Projected Risks, with Implications for Urban Sustainability

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ABSTRACT

The Earth's climate system is approaching irreversible thresholds, with the first global tipping point already crossed under current warming, according to the Global Tipping Points Report 2025. This destabilization threatens sustainable urban development, as cities face escalating risks from heatwaves, water scarcity, and ecosystem degradation, underscoring the need for climate-resilient urban adaptation aligned with Sustainable Development Goals. Iran, warming at twice the global average rate, exemplifies these challenges through multiple negative tipping points: nationwide climatic zone degradation, with 90% of its cities projected to shift to drier zones under SSP5-8.5; prolonged heatwaves, with duration extending from 5 days to two weeks under SSP1-2.6 and up to a full season under SSP5-8.5; as well as some abrupt changes, including Caspian basin precipitation decline, driven by weakening migratory weather systems; and weakening of Mediterranean low-pressure systems, reducing winter and spring rainfall over western Iran. Iran also exhibits an emerging positive trend, including increased tropical cyclones over the Arabian Sea, contributing to extreme precipitation in the south. This review synthesizes observed and projected climate tipping points and abrupt changes across Iran, from heatwave intensification and nationwide climatic zone degradation to Zagros ecosystem degradation and weakening of Mediterranean low-pressure systems, and assesses their implications for urban sustainability. The findings highlight the urgent need for integrated climate risk management, early warning systems, and proactive adaptation policies. Achieving sustainable urban development, adaptation, and resilience is unattainable without a comprehensive understanding of global warming-induced tipping points; therefore, any long-term sustainability planning must prioritize their identification and integration into policy frameworks.

Keywords:

Tipping Points, Global Warming, Iran, Urban Resilience, Heatwaves, Aridification, Sustainable Adaptation

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1. Introduction

Climate Tipping Points (TP) 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 TPs 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 TPs 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 TPs 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 al., 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 2040s), 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 socio-economic instability (Jahangirpour and Bakhshoodeh, 2020; Zare, 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 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 & Prange, 2023; Meshari Eshq Abad 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 McKay et al., 2022).

Climate tipping points represent critical thresholds in the Earth's climate system beyond which small perturbations can cause large, often irreversible, shifts in climate behavior and associated ecosystems. Crossing these thresholds results in abrupt transitions to new states that differ markedly from previous stable regimes, potentially triggering severe consequences for natural and human systems (Lenton et al., 2008; ESA, 2023). According to the Global Tipping Points Report 2025, the Earth system is approaching multiple tipping points at current warming levels of approximately 1.2°C above pre-industrial levels, with the first global tipping point—tropical coral reef die-off—already crossed. The Report further warns that at 1.5°C warming, at least five major tipping elements will enter their risk zones, and at 2°C, this number increases to at least twelve, underscoring the urgency of immediate action.

Mechanistically, tipping points are 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, 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 (Igini, 2023; Lenton et al., 2012). The Report 2025 emphasizes that these feedbacks are not isolated; rather, they interact through cascading dynamics, where the crossing of one tipping point increases the likelihood of crossing others. For instance, Greenland ice sheet melting could weaken the Atlantic Meridional Overturning Circulation (AMOC), which in turn could affect the Amazon rainforest and the West African monsoon, as well as disrupt the mid-latitude westerly systems that traverse the Mediterranean and the Middle East, thereby creating a domino effect across the Earth system and posing significant risks to regional climate stability, including rainfall patterns in West Asia.

Tipping behavior varies 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. The Report 2025 introduces a risk classification framework, categorizing tipping elements based on their probability of crossing under different warming scenarios and their potential global impacts (Fig. 1). Importantly, the critical thresholds 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).

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 on the 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). The Report 2025 provides updated risk assessments for these elements (Table 1).

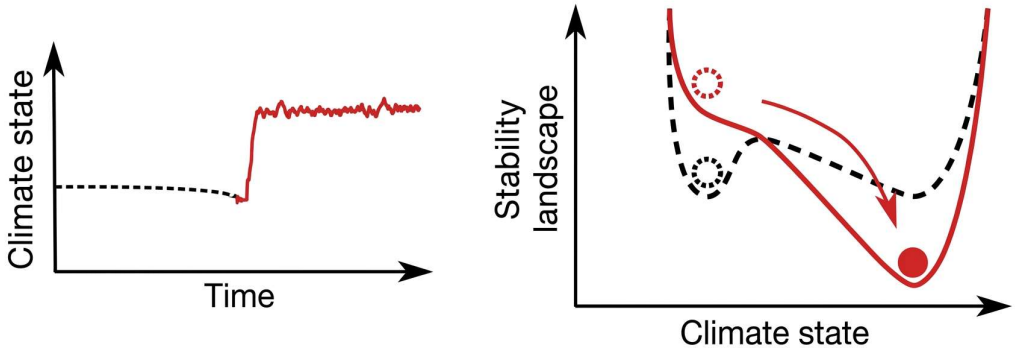


Figure 1. Illustration of a tipping point (TP): When a climate forcing, such as 1.5°C of global warming, is reached, a previously stable climate system undergoes a transition to a new climate state (Lenton et al., 2012).

These findings highlight the nonlinear nature of climate risks, governed by complex feedback dynamics and threshold responses. Understanding these mechanisms is essential for future climate projections, assessing risks to ecosystems and human societies, and designing adaptive strategies to maintain planetary stability under ongoing anthropogenic warming (Tandon et al., 2025; Lenton et al., 2023).

Table 1. Key global climate tipping elements, their estimated warming thresholds, and projected impacts based on the Global Tipping Points Report 2025 (Lenton et. al., 2025).

Tipping Points	Warming Threshold	Projected/Estimated Impacts
Greenland Ice Sheet	1.5–2.0°C	Sea-level rise of up to 7 meters over centuries (Lenton et al., 2025).
West Antarctic Ice Sheet	1.5–2.0°C	Sea-level rise of several meters over centuries, with parts potentially already destabilized (Lenton et al., 2025).
Atlantic Meridional Overturning Circulation (AMOC)	2.0–3.0°C	A projected weakening of 30–50% by 2100 under high-emission scenarios, with a small but non-negligible risk of collapse before 2100 (Lenton et al., 2025).
Amazon Rainforest	1.5–2.0°C	Widespread dieback, transforming large parts of the forest into a savanna-like state (Armstrong McKay et al., 2022; Lenton et al., 2025).
Boreal Permafrost	1.5–2.0°C	Release of 50–150 GtC (gigatonnes of carbon) by 2100 under current emission trajectories, accelerating warming (Lenton et al., 2025).

The Earth's climate system is composed of several large-scale subsystems known as tipping elements—components that may pass critical thresholds beyond which a small disturbance can trigger a large, often irreversible, qualitative change in their state (Lenton et. al., 2008). These elements are not isolated; they are interconnected through complex physical and biogeochemical interactions (Lenton et. al., 2025). The Global Tipping Points Report 2025 provides a stark and updated assessment of these elements, confirming that the world has entered a "new reality" where the risk of crossing these thresholds is escalating rapidly (Lenton et. al., 2025). The report's findings are unequivocal: the stability of the Earth system is being severely threatened. The first global tipping point has already been crossed. Warm-water coral reefs, on which nearly a billion people and a quarter of all marine life depend, are now passing their

thermal tipping point and experiencing widespread dieback (Lenton et. al., 2025). This is a direct consequence of global warming exceeding 1.2°C and the recent prolonged marine heatwaves (Armstrong McKay et. al., 2022). The report also identifies several other major tipping elements that are now at high risk of being triggered at or slightly above the 1.5°C warming threshold. At 1.5°C, at least five major tipping elements will enter their risk zones, and this number increases to at least twelve at 2°C of global warming (Lenton et. al., 2025; Armstrong McKay et. al., 2022).

A critical insight from the report is the interconnectedness of these elements. Most of the interactions between tipping elements are assessed as destabilizing (Lenton et. al., 2025). This means that tipping one system increases the probability of tipping another, creating a potential tipping cascade or "domino effect" (Lenton et. al., 2025; Lenton et. al., 2023). For instance, the melting of the Greenland ice sheet could weaken the AMOC, which could in turn destabilize the Amazon rainforest and West African monsoon systems (Lenton et. al., 2025). As the report states, "the AMOC sits centrally in a network of tipping elements and is therefore often viewed as a mediator of a possible cascade of tipping events".

The scientific consensus is clear: the window for preventing damaging tipping points is rapidly closing (Lenton et. al., 2025). To minimize the risk, the report emphasizes that the magnitude and duration of the temperature overshoot above 1.5°C must be minimized (Armstrong McKay et. al., 2022). This requires immediate and unprecedented action, including halving global greenhouse gas emissions by 2030 and achieving net-zero by 2050 (Lenton et. al., 2025). However, the report also highlights a crucial element of hope: positive tipping points—self-amplifying shifts in technologies, behaviors, and systems toward sustainability (Lenton et. al., 2023). Rapid global adoption of solar PV and electric vehicles are cited as examples where positive tipping points are already underway and can be accelerated through coordinated policy action at "super-leverage points". Triggering these positive cascades is the only credible route to a safe, just, and sustainable future (Lenton et. al., 2025; Lenton et. al., 2023).

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.

2. Data and Methodology

This study is a narrative (critical) review that synthesizes peer reviewed literature, official climate reports, and national observational datasets to assess climate tipping points in Iran and their implications for urban sustainability. The review was conducted using a thematic synthesis approach, focusing on studies published between 2000 and 2025. The literature search employed keywords such as "tipping points", "observed and projected climate impacts", "heatwaves", "climatic zone shifts/degradation", and "climate sensitive regions in Iran". Relevant studies were selected based on their direct relevance to tipping point theory, regional climate impacts, and urban vulnerability. Importantly, we have clarified that the concept of climate tipping points is relatively new and remains largely underexplored in Iran, which limits the total number of directly relevant studies. The primary data sources include observational meteorological data from the Iran Meteorological Organization, ECMWF Reanalysis data, and CMIP3 to CMIP6 climate model outputs, which were bias corrected using statistical or dynamical downscaling methods. The core focus of this review is on climate tipping points in Iran and West Asia, as well as the most critical global tipping elements that influence the climate of the region. This topic gained international attention in 2022 with the first international conference on tipping points hosted by the University of Exeter, yet it remains relatively underexplored in Iran, which further underscores the novelty and significance of this review.

In this review, we adopt the definition of climate tipping points as critical thresholds beyond which a subsystem of the Earth system reorganizes into a new, qualitatively different state, often abruptly and

irreversibly on human timescales (Lenton et al., 2008; Lenton et al., 2025). To avoid conceptual ambiguity, we distinguish between the following four categories:

- True tipping elements: Subsystems that exhibit threshold behavior, positive feedback loops, and irreversible change once a critical forcing level is exceeded.
- Abrupt climate changes: Rapid shifts in climate variables that may occur without a well defined threshold or irreversible reorganization.
- Long term climate trends: Gradual, monotonic changes in climate variables that do not involve a threshold or feedback driven reorganization.
- General climate impacts or vulnerabilities: Observed or projected consequences of climate change that do not necessarily involve a threshold or irreversible change.

Throughout the manuscript, the term "tipping point" is used exclusively for the first category, while the other categories are referred to using their specific terms (e.g., "trend," "impact," "vulnerability"). This distinction ensures that the paper maintains scientific rigor and avoids overstating the evidence for irreversible change.

3. Results

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 2.5°C, with some central plateau regions experiencing rises up to 3°C (Masoodian, 2004; Alizadeh-Choobari & Najafi, 2017; Babaeian et al., 2019; Khorsandi et al., 2023). 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 (Masoodian, 2004). Extended summers, lasting up to 4 to 5 months, exacerbate drought stress and water scarcity across much of the country (Babaeian et al., 2019). According to Iran's National Drought and Climate Centre, each degree of temperature increase raises evaporation capacity by approximately 7%. Such climatic trends have already pushed Iran perilously close to several critical tipping points; under unabated warming, major urban centers on the margins of desert regions—including Yazd, Kerman, and Isfahan—could face conditions that render them practically uninhabitable by the late 21st century (Shahsavan et al., 2024).

In this section, we examine the most direct and urgent tipping point—heatwave intensification—which poses an immediate threat to urban health, energy systems, and labor productivity. We then turn to the gradual but fundamental shift in climatic zones, a process that is systematically reshaping Iran's water resources, agricultural viability, and long-term habitability. Finally, we focus on the Zagros region as a critical case study, where the convergence of rising temperatures, changing precipitation patterns, and ecological stress is triggering cascading socio-economic and environmental consequences that extend far beyond the mountain range, affecting cities, rural communities, and national food security. This progression—from rapid-onset extremes to slow-moving structural changes, and finally to a localized yet nationally significant collapse—reveals the full spectrum of climate risks facing Iran and underscores the need for integrated, multi-scale adaptation responses.

3.1. Prolonged Heatwaves

Heatwaves in Iran are becoming progressively longer and more intense, representing one of the most direct and immediate manifestations of climate tipping points in the country. In this study, a heatwave is defined as a continuous period of at least three days with daily maximum temperatures above the 95th percentile (15-day moving window), following WMO and IPCC guidelines (IPCC, 2021; WMO, 2023), with no short interruptions permitted. During the entire observation period (1964-2023) across the ten selected metropolitan areas, the mean heatwave duration (HWDM) ranged from 3.1 to 6.6 days,

confirming that no city experienced heatwave persistence beyond one week. When the entire observational period is divided into two 30-year normal periods, the mean heatwave duration increased from approximately 4.2 days in the first normal period (1964–1993) to 5.1 days in the recent normal period (1994–2023), representing a 1.2-fold increase—equivalent to about one additional day of heatwave persistence. The strongest increases in duration were observed in Tehran, southwestern Iran, and the central Zagros region. This modest yet consistent rise in heatwave duration during the observational record serves as a clear early warning signal, indicating that Iran's urban centers are already experiencing the initial stages of heatwave-related tipping behavior, even before considering future climate projections (Babaeian et al., 2026).

To provide a comprehensive spatial-temporal perspective on heatwave evolution across Iran's major metropolitan areas, Figure 2 presents a comparative heatmap of observed and projected mean heatwave duration for ten selected metropolises under low-emission (SSP1-2.6) and high-emission (SSP5-8.5) scenarios. The color gradient from blue to dark red illustrates the increasing duration of heatwaves, with values ranging from 0 to about 180 days.

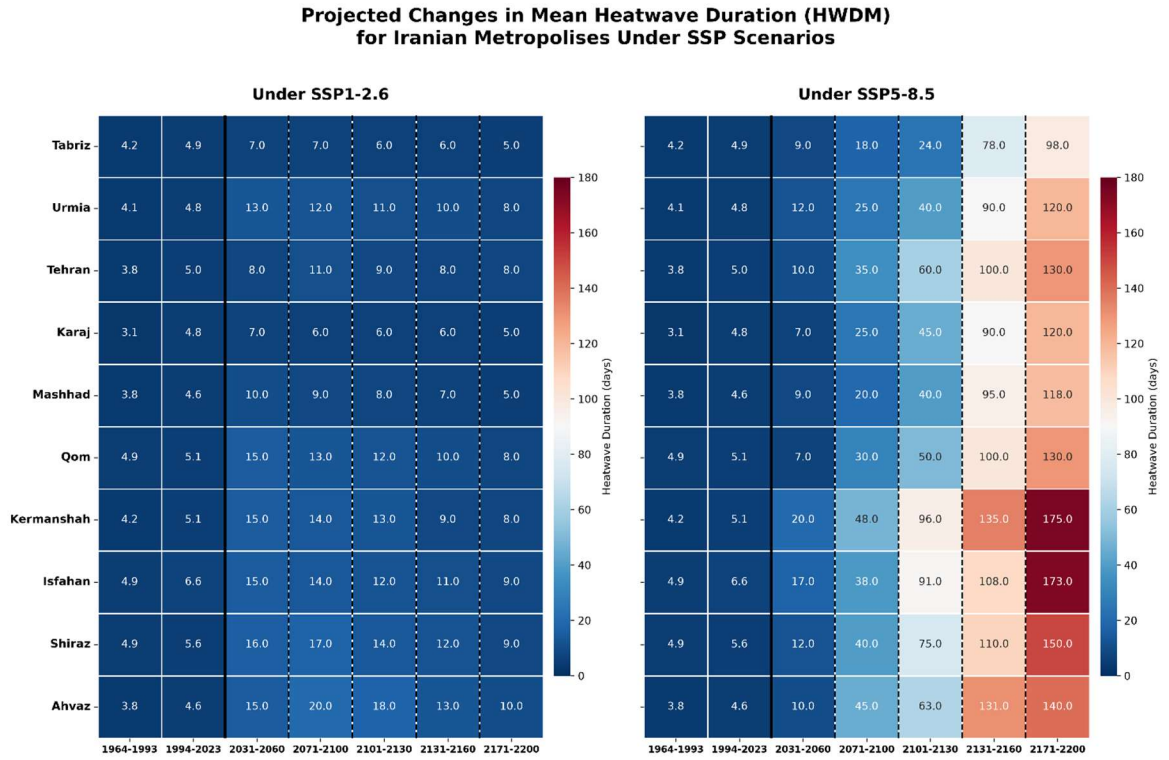


Figure 2. Comparison of observed (1964–1993 and 1994–2023) and projected (2031–2060, 2071–2100, 2101–2130, 2131–2160, and 2171–2200) mean heatwave duration (HWDM, in days) for ten Iranian metropolitan areas under SSP1-2.6 and SSP5-8.5 scenarios. The color gradient from blue to dark red represents increasing heatwave duration. Vertical lines separate historical periods from future projections. The results highlight the substantial divergence between emission scenarios, with SSP5-8.5 leading to extreme heatwave durations exceeding 100 days in multiple cities by 2171–2200, emphasizing the urgency of both mitigation and adaptation strategies.

Under the low-emission optimistic scenario of SSP1-2.6, heatwave durations peak in the mid-to-late 21st century (ranging from ~16 days in Urmia to ~21 days in Ahvaz) and then decline toward the end of the 22nd century, returning to approximately 9.5–12.5 days—still about three times longer than observed baseline durations. More specifically, by the end of the 21st century (2071–2100), most cities will experience heatwave durations of about two weeks, with no significant change through the early 22nd century (2101–2130). However, due to committed global emission reductions in the low-emission scenario, a declining trend emerges from the mid-22nd century onward, with durations falling to about

one week (average ~7.5 days) by 2171–2200. Despite these relatively stringent mitigation policies, the mean heatwave duration at the end of the 22nd century remains approximately 2.5 days longer than the recent observed period (1994–2023) and 3.5 days longer than the reference observed period (1964–1993). Under this optimistic scenario, Ahvaz exhibits the highest projected increase, reaching 20 days (about three weeks). In quantitative terms, under the optimistic SSP1-2.6 scenario, the mean heatwave duration at the end of the 21st and 22nd centuries is projected to be 3.3 and 1.8 times the reference period (1964–1993) values, respectively.

Under the pessimistic SSP5-8.5 scenario, by the end of the 21st century (2071–2100), the mean heatwave duration reaches about one month (32 days)—roughly twice that of the optimistic scenario. As shown in Figure 2, the divergence between the two scenarios becomes particularly stark after 2071–2100. Under this high-emission pathway, heatwave durations increase continuously across all metropolises through the remainder of the 21st and into the 22nd century. By the late 22nd century (2171–2200), durations surge to between 98 days (Tabriz) and 175 days (Kermanshah)—representing a 25- to 30-fold increase compared to observed conditions. At this stage, heatwaves reach seasonal scales, with an average duration of approximately 4.5 months, and individual events projected to last up to half a year (e.g., Kermanshah and Isfahan). Overall, under the pessimistic SSP5-8.5 scenario, the mean heatwave duration at the end of the 21st and 22nd centuries is projected to be 7.6 and 32 times the reference period (1964–1993) values, respectively—underscoring the profound divergence between emission pathways, a pattern clearly visualized in Figure 2.

The observed and projected intensification of heatwaves carries profound implications for public health, energy demand, water resources, and agricultural productivity. As all major cities converge toward increasingly extreme heatwave durations, the urgency of action becomes undeniable—demanding both aggressive mitigation to pursue the SSP1-2.6 pathway and transformative adaptation measures to manage the warming already committed to the system. This tipping point therefore represents not merely an environmental hazard, but a critical threat to urban sustainability, one that requires immediate, targeted adaptation interventions across Iran's metropolitan areas.

3.2. Nationwide Climatic Zone Degradation

The progressive degradation of Iran's climatic zones toward drier conditions represents a critical and potentially irreversible transition, with far-reaching consequences for water resources, agriculture, and human livelihoods. Over the past five decades, these climatic trends have already begun to reshape Iran's climate zones. Comprehensive assessments based on 279 synoptic stations confirm that climate-type transitions have been identified at 24% of long-record stations, predominantly from temperate and cold climates to arid types. These shifts are most pronounced in central, eastern, and northwestern Iran and coincide with significant warming and widespread precipitation declines, indicating warming-driven aridification as the dominant mechanism (Shahsavan, 2024).

Future projections (Figure 3) under the SSP scenarios paint an alarming picture of continued aridification across Iran. According to multi-model ensemble averages from three CMIP6 models (CanESM5, IPSL-CM6A-LR, and MRI-ESM2-0), the number of stations classified as dry and hyper-arid is projected to increase from %24 in the observed period (1985–2014) to 34% under SSP1-2.6 and 82% under SSP5-8.5 by the mid-21st century (2031–2060). By the end of the 21st century (2071–2100), the divergence between the two scenarios becomes stark. Under the pessimistic SSP5-8.5 scenario, approximately 95% of stations are projected to transition to drier classifications, while under the optimistic SSP1-2.6 scenario, 49% of stations will have shifted to at least one drier climate class. This represents a dramatic acceleration of the aridification process compared to historical rates. The trend continues into the 22nd century with even more pronounced shifts. By the mid-22nd century (2121–2150), under SSP1-2.6, approximately 95% of stations are expected to adopt a drier classification, reaching 97% by the end of the 22nd century (2171–2200). Under the SSP5-8.5 scenario, 95% of stations are projected to shift to drier classifications by the end of the 21st century, reaching 100% in the early 22nd century—a condition that persists throughout the entire 22nd century (Shahsavan et al., 2024).

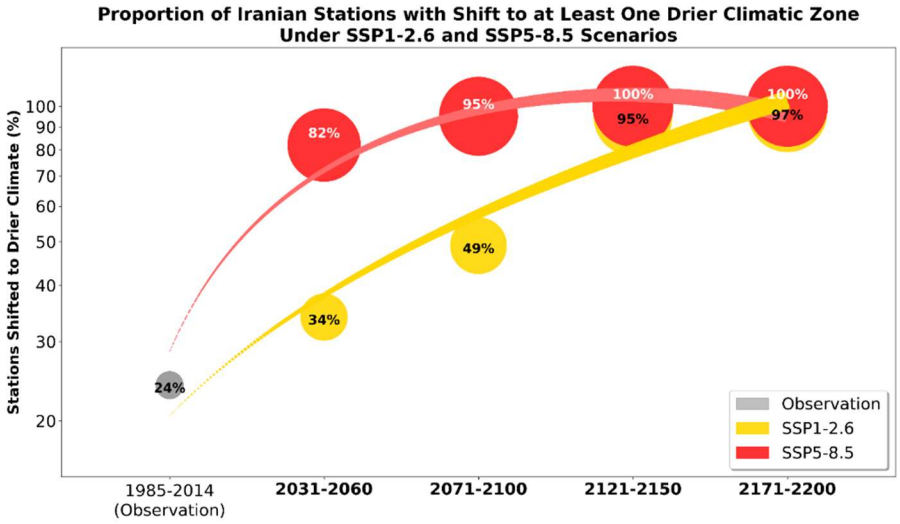


Figure 3. Projected percentage of Iranian cities shifting to at least one drier climatic zone during the observed period (1985–2014) and under SSP1-2.6 (optimistic) and SSP5-8.5 (pessimistic) scenarios for four future periods (2031–2060, 2071–2100, 2121–2150, and 2171–2200). The observed period shows that 24% of stations had already shifted to drier classifications by 2014. Under SSP5-8.5, 100% of stations are projected to shift by the early 22nd century, while under SSP1-2.6, this proportion reaches 97% by the end of the 22nd century (Shahsavan et al., 2024). The results highlight the near-certainty of continued aridification across Iran, even under the most optimistic emission pathway, underscoring the urgent need for adaptive water resource management and agricultural planning.

In quantitative terms, the transformation of Iran's climate zones becomes even more evident. In the observed climate (1985–2014), the proportion of relatively dry stations (dry to semi-dry) stood at 64%; this is projected to rise to 92% by the end of the 22nd century. Concurrently, the share of relatively humid stations (Mediterranean to very humid) is expected to decline sharply from 34% to just 8%. In absolute numbers, the count of dry to semi-dry stations is projected to increase from 74 to 106, while Mediterranean to very humid stations will decrease from 39 to 9 by 2171–2200 (Shahsavan et al., 2024).
The ecological and socio-economic consequences of these climatic zone shifts are profound. The expansion of arid and hyper-arid zones threatens agricultural productivity, particularly for rain-fed crops and high-value products such as saffron, which are highly sensitive to temperature and water availability (Kouzegaran et al., 2020). The projected doubling of drought vulnerability by the late 21st century (Babaeian et al., 2019) further exacerbates these risks, with significant implications for food security, rural livelihoods, and water resource management. Collectively, this tipping point underscores the near-certainty of continued aridification across Iran—even under the most optimistic emission pathway—and highlights the urgent need for adaptive water resource management, agricultural transformation, and long-term urban planning.

3.3. Zagros Climate -Driven Transformation: A Multidimensional Tipping Point

The Zagros region is undergoing a profound climate-driven transformation that is pushing its ecosystems toward an irreversible state change. The Zagros mountain range, stretching approximately 1,600 kilometers from northwestern Iran to the Persian Gulf, represents one of the most ecologically and socio-economically significant regions of the country. The Zagros oak forests, covering nearly six million hectares—roughly 40% of Iran's total forest area—have been in decline since approximately 2000, with climate change identified as the primary driver of this unprecedented ecological crisis.
Observed climatic trends in the Zagros region are alarming. Over the past five decades, mean annual temperatures have increased by 2.2°C—a rise that, according to the Clausius–Clapeyron relationship, enhances evaporation capacity by approximately 7% per degree. This translates to an estimated ~15% reduction in effective precipitation, meaning that a substantial portion of rainfall is effectively lost to enhanced evaporation due to rising temperatures. While annual precipitation trends

have not shown statistically significant changes across most stations, the distribution and intensity of precipitation have been fundamentally altered. In some areas, precipitation has decreased by nearly 20%. More critically, the number of consecutive dry days (CDD)—a key climate change indicator—has increased dramatically. Prolonged dry periods, combined with higher temperatures and increased evapotranspiration, have led to a 25% reduction in soil moisture, severely threatening the health of Persian oak and other tree species.

Future climate projections for the Zagros region point to an even more dire outlook. As illustrated in Figure 4, based on the multi-model ensemble approach using CMIP5 models under RCP scenarios (Babaeian et al., 2019), the Zagros region exhibits the highest vulnerability among all seven Iranian climatic regions studied. Located in the lower-right corner of the figure, the Zagros cluster is characterized by the greatest temperature rise (~8.5°C) and the most pronounced precipitation decline (~12%) by 2071–2100, relative to the 1985–2014 baseline period. The next most vulnerable regions are northwestern and northeastern Iran, with projected precipitation decreases of approximately 10% and 8%, respectively, accompanied by temperature increases of around 5.2°C. In contrast, the southern regions of the country, despite experiencing large temperature increases, are projected to witness precipitation increases of about 5% by the end of the 21st century—likely associated with the rising frequency of tropical cyclones over the northern Indian Ocean, driven by warming sea surface temperatures. It is important to note that this results are based on CMIP5, as CMIP6 data were not available at the time of above study (2019). However, multiple studies have confirmed that CMIP5 and CMIP6 projections exhibit consistent warming trends for the Middle East, with differences primarily in the magnitude rather than the direction of change.

The most severe climate change impacts are projected for the Zagros region, where conditions would be catastrophic for the region's ecosystems—potentially triggering widespread oak dieback, increased pest and disease outbreaks, and a fundamental transformation of the region's ecological structure. The Zagros climate-driven transformation collapse thus represents a complex tipping point, where the convergence of rising temperatures, altered precipitation patterns, intensified evapotranspiration, and more frequent extreme events is pushing this vital ecosystem toward an irreversible state change—with profound implications for water resources, agriculture, local livelihoods, and the broader environmental security of western Iran.

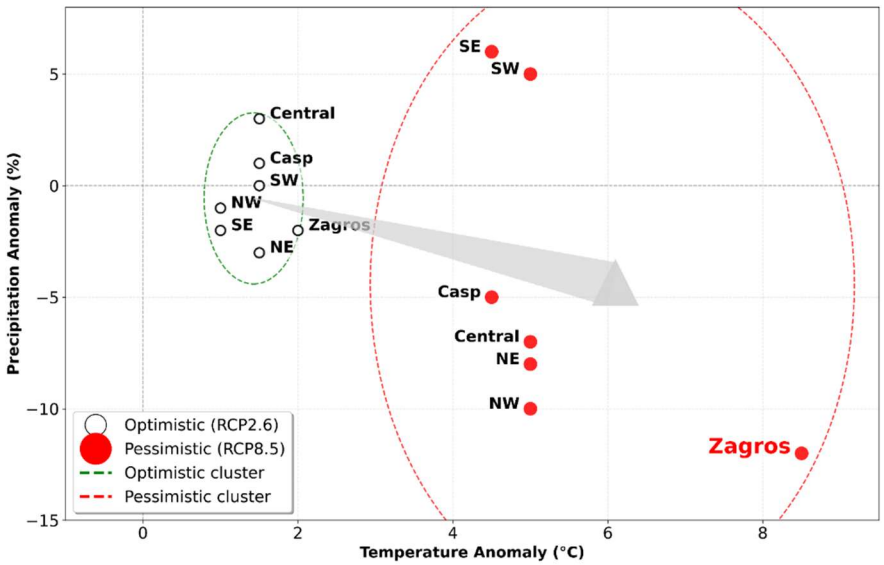


Figure 4. Comparison of temperature and precipitation anomalies for seven Iranian climatic regions under RCP2.6 (white circles) and RCP8.5 (red circles) scenarios for 2071–2100. Ellipses group scenario-based clusters, and the gray arrow indicates the shift toward pessimistic conditions. The Zagros region exhibits the highest vulnerability, characterized by the greatest temperature rise and the most pronounced precipitation decline.

3.4. Other Abrupt Climate Changes and Emerging Trends

Beyond the three major tipping points discussed above—heatwave intensification, nationwide climatic zone degradation, and Zagros ecosystem degradation—Iran faces additional climate-induced changes that, while not yet fully established as true tipping points, carry significant implications for water security, agriculture, and socio-economic stability. These supplementary phenomena, which include abrupt changes in synoptic systems and emerging hydrological shifts, are briefly summarized below.

Weakening of Mediterranean Low-Pressure Systems

One of the most critical supplementary negative tipping points is the progressive weakening of the Mediterranean low-pressure systems, which are primary drivers of winter and spring precipitation over Iran. Analysis of sea-level pressure data from 1948 to 2009 reveals that the central pressure of the Mediterranean low has increased by approximately 3.9 hpa in winter and 2.4 hpa in spring over the 61-year period. This pressure rise corresponds to a significant weakening of cyclonic activity and a reduction in the intensity and frequency of Mediterranean storm tracks that traditionally deliver substantial precipitation to western and southwestern Iran (Rasouli et al., 2012). As a result, the contribution of Mediterranean systems to Iran's seasonal rainfall has diminished, exacerbating water deficits and increasing the frequency of dry spells across the Zagros and western provinces. This trend is particularly concerning because Mediterranean cyclones are responsible for a large fraction of Iran's annual precipitation, and their continued weakening could lead to a permanent shift toward drier conditions, compounding the effects of climatic zone shifts and heatwave intensification. The weakening of these systems also reduces the likelihood of combined Mediterranean-Sudanese low-pressure interactions, which historically have produced heavy and sustained rainfall events over the country (Rasouli et al., 2012).

Caspian Basin Precipitation Decline

The southern Caspian basin, one of Iran's most climatically sensitive regions, is experiencing a sharp decline in precipitation, particularly during the autumn season. This decline is closely linked to the weakening of migratory high-pressure systems that originate over Eastern Europe and traverse the Black Sea before entering the Caspian basin. Under global warming, these migratory high-pressure systems have become progressively weaker, disrupting the established regional atmospheric circulation patterns. As a result, the northerly winds that typically develop over the Caspian Sea—responsible for transporting moisture from the northernmost parts of the sea toward the southern coastal areas—have also weakened. Under normal conditions, these moisture-laden northerly flows ascend the northern slopes of the Alborz Mountains, leading to substantial orographic precipitation, particularly during autumn and a significant portion of summer. However, the weakening of these migratory systems due to rising temperatures has reduced the frequency and intensity of such northerly wind events, thereby diminishing autumn and summer rainfall across the Caspian region. Future projections under the SRES A2 and B2 scenarios estimate annual precipitation reductions of up to 59.6% for stations such as Babolsar by 2070–2099, with the largest declines occurring during the critical wet season (Babaeian et al., 2017; Danehchin, 2024). It is important to note that precipitation originating from northward-passing systems (i.e., weather systems crossing the Alborz Mountains from the north) may not directly follow this mechanism; however, they are also likely to weaken in response to the general weakening of Mediterranean low-pressure systems, compounding the overall decline. The ecological and socio-economic consequences include reduced water availability for rice paddies and citrus orchards in Gilan and Mazandaran provinces, stress on the Hyrcanian forests—one of the world's most ecologically significant temperate forests—and potential acceleration of Caspian Sea level decline, with cascading effects on coastal wetlands and sturgeon populations.

Increased Tropical Cyclones in the Arabian Sea

In contrast to the predominantly negative changes, an emerging positive trend is the increasing frequency and intensity of tropical cyclones in the northern Indian Ocean and Arabian Sea, which has contributed to

localized increases in extreme precipitation events in southern Iran (Babaeian et al., 2024; ESA, 2023). According to Babaeian et al. (2017, 2019, 2024), precipitation over parts of southern Iran is projected to increase under multiple CMIP model generations—CMIP3, CMIP5, and CMIP6—across various emission scenarios. This projected increase in southern and southwestern Iran is likely due to large-scale atmospheric circulation changes driven by global warming. Rising global temperatures weaken the sub-polar jet stream, increasing its meridional (north–south) amplitude and enhancing wave-like meanders. Concurrently, global warming raises geopotential heights over central and southern Europe, which favors the occurrence of atmospheric blocking events during the cold season. As a result, the polar jet stream, upon approaching Europe from the Atlantic, often splits into two distinct branches: a northern branch and a southern branch. The southern branch follows a trajectory over the Red Sea and the Persian Gulf, channeling moisture-laden air masses into southwestern and southern Iran, where it can produce heavy and persistent precipitation. This mechanism was clearly manifested during the unprecedented March–April 2019 rainfall event, when a persistent blocking pattern over Europe diverted the southern branch of the jet stream toward the Middle East, leading to record-breaking rainfall across 25 of Iran's 31 provinces, with daily rainfall records broken at eight stations and a maximum of 187.8 mm recorded at Koohrang Station (WMO, 2019; CHRS, 2019).

However, this projected increase does not necessarily translate into reduced water demand in the region. A substantial portion of these rainfall events is expected to occur as intense, short-duration downpours, which often result in surface runoff rather than effective infiltration and groundwater recharge. Furthermore, due to rising temperatures associated with global warming, a significant fraction of this precipitation is effectively lost through enhanced evaporation, reducing its availability for agricultural, domestic, or ecological use. This trend therefore offers a potential hydrological opportunity only if managed proactively through rainwater harvesting, aquifer recharge, and floodwater storage systems. However, careful risk management is essential, as these cyclones also bring flash floods, infrastructure damage, and coastal hazards, requiring integrated disaster preparedness and climate-resilient planning (Najah et al., 2025)

4. Discussion

The five major climate tipping points or abrupt changes identified for Iran—comprising four negative and one positive—are summarized in Table 2. This synthesis provides a comparative overview of their types, impact descriptions, and expected consequences, drawing upon the detailed evidence presented in the preceding sections. The table highlights the predominance of adverse hydrological and ecological tipping points or abrupt changes (heatwaves, aridification, weakening of Mediterranean low-pressure systems, Caspian basin precipitation decline, and Zagros ecosystem collapse) alongside a single but potentially significant abrupt change (increased tropical cyclones in the Arabian Sea), which may offer localized water resource benefits if managed proactively. Collectively, these changes underscore the multidimensional nature of climate risks facing Iran and the urgent need for integrated adaptation and mitigation strategies.

These findings are consistent with broader regional trends across the Middle East and West Asia, where warming rates of 0.3–0.5°C per decade are driving accelerated desertification, reduced snowpack, and increased frequency of heatwaves and dust storms (Lenton et al., 2025). The projected 26-fold increase in maximum heatwave duration under SSP5-8.5 (from 7 days to approximately half a year) aligns with neighboring countries' projections, such as 100-day heatwaves in Pakistan (Saeed, 2022). However, Iran faces three compounding factors that amplify its sensitivity: (i) critical dependence on snowpack dynamics from the Alborz and Zagros mountains; (ii) the highest population concentration in the Middle East (over 80 million) in climate-vulnerable metropolitan areas; and (iii) an economy heavily dependent on agriculture and fossil fuel exports. The finding that 100% of stations will shift to drier climatic zones by the end of the 22nd century under SSP5-8.5 (Shahsavan et al., 2024), alongside the weakening of Mediterranean low-pressure systems (Rasouli et al., 2012), underscores the severity of these risks.

Table 2. Summary of key negative and positive climate tipping points or abrupt changes identified for Iran, their types, impact descriptions, and expected consequences.

Tipping Points/ abrupt changes	Type	Impact Description	Expected Consequences
Prolonged Heatwaves	Negative	Observed mean heatwave duration increased from 4.2 days (1964–1993) to 5.1 days (1994–2023), a 1.2-fold rise. Under SSP1-2.6, durations peak at ~16–21 days in the mid-21st century, declining to ~7.5 days by 2171–2200; under SSP5-8.5, durations surge to 98–175 days by 2171–2200, a 25- to 30-fold increase, with individual events lasting up to half a year (Babaeian et al., 2026).	Severe health risks (especially for vulnerable populations), increased energy demand for cooling, reduced labor productivity, exacerbated drought conditions, increased desertification and dust storm activities, crop failures, heightened mortality risks, and critical threats to urban sustainability (Babaeian et al., 2026).
Nationwide Climatic Zone Degradation	Negative	Progressive and widespread aridification across Iran; 24% of long-record cities have already transitioned from temperate/cold to arid climates (Shahsavan, 2024). Under SSP1-2.6, 49% of stations shift to drier classifications by 2071–2100, reaching 97% by 2171–2200; under SSP5-8.5, 95% shift by 2071–2100 and 100% by the early 22nd century, with dry to semi-dry zones expanding from 64% to 92% by 2171–2200 (Shahsavan et al., 2024).	Intensified water scarcity, reduced agricultural productivity (notably for rain-fed crops and high-value products such as saffron), ecosystem degradation, increased desertification, heightened drought vulnerability (projected to double by 2100), food security risks, rural livelihood losses, and potential large-scale population displacement (Babaeian et al., 2019; Jahangirpour & Bakhshoodeh, 2020; Kouzegaran et al., 2020).
Zagros Climate-driven Transformation	Negative	Rapid warming (2.2°C observed over five decades; ~8.5°C projected by 2071–2100 under RCP8.5) combined with altered precipitation patterns (~12% decline), increased consecutive dry days (up to 219 days), and 25% reduction in soil moisture across the Zagros oak forests; the region is projected to experience additional 1.2°C warming by 2060 under SSP5-8.5 (Babaeian et al., 2019).	Widespread oak dieback, increased wildfires (2,300 fires burning ~46,000 hectares by 2025), biodiversity loss (25% decline), reduced carbon sequestration (18% decrease), weakened water cycle regulation and soil stabilization, loss of livelihoods for local communities, and potential transformation of the region's ecological structure—with profound implications for water resources, agriculture, local livelihoods, and the broader environmental security of western Iran (Babaeian et al., 2019).
Weakening of Mediterranean Low-Pressure Systems	Negative	Progressive increase in central pressure of Mediterranean low (3.9 hPa in winter, 2.4 hPa in spring over 1948–2009), indicating reduced cyclonic activity and diminished storm track intensity; reduced likelihood of combined Mediterranean-Sudanese low interactions (Rasouli et al., 2012).	Reduced winter and spring rainfall over western and southwestern Iran, increased dry spell frequency, compounded aridification effects, diminished water supply for agriculture and reservoirs, and reduced potential for heavy rainfall events from combined Mediterranean-Sudanese systems (Rasouli et al., 2012).
Caspian Basin Precipitation Decline	Negative	Sharp decline in autumn and summer rainfall due to weakening of migratory high-pressure weather systems and associated northerly moisture transport over the Caspian Sea; projected annual precipitation reductions up to 59.6% by 2070–2099 under SRES A2 and B2 scenarios (Babaeian et al., 2017).	Reduced water availability for rice paddies and citrus orchards in Gilan and Mazandaran provinces; stress on Hyrcanian forests (one of the world's most ecologically significant temperate forests); acceleration of Caspian Sea level decline; cascading effects on coastal wetlands and sturgeon populations (Babaeian et al., 2017).
Increased Tropical Cyclones in the Arabian Sea	Positive	Increasing frequency and intensity of tropical cyclones; projected precipitation increases over southern Iran under CMIP3, CMIP5, and CMIP6 models (Babaeian et al., 2017, 2019, 2024), linked to large-scale atmospheric circulation changes including weakening of the sub-polar jet stream and increased blocking over Europe, which diverts moisture-laden air toward Red Sea-Persian Gulf region (WMO, 2019; CHRS, 2019).	Potential groundwater recharge and water resource boost in southern Iran if managed through rainwater harvesting, aquifer recharge, and floodwater storage; however, accompanied by flash flood risks, infrastructure damage, and coastal hazards requiring integrated disaster preparedness and climate-resilient planning (Najah et al., 2025). A substantial portion of rainfall is lost to surface runoff and enhanced evaporation due to rising temperatures, limiting its availability for agricultural, domestic, or ecological use.

Among Iranian metropolises, Tehran emerges as the most vulnerable due to the convergence of extreme heatwave intensification (7.8-fold frequency increase), severe water scarcity (subsidence rates up to 25 cm/year), and hazardous air quality. Ahvaz exhibits the most severe heat extremes (>50°C), while

Mashhad faces the highest temperature increases and loss of snowpack water storage. Kermanshah exhibits the highest flood risk, while Isfahan and Yazd face the highest risk of irreversible desertification. The Caspian region faces the unique challenge of declining autumn and summer rainfall, threatening its agricultural base and Hyrcanian forests. This spatial heterogeneity demands localized adaptation interventions rather than generic strategies. The return period analysis for Tehran reveals that a 10-year heatwave event under SSP5-8.5 could last 98 days with intensity exceeding 41°C by 2100, while under SSP1-2.6, the same event would last only ~21 days—highlighting that emission pathway choices profoundly affect urban exposure to extreme heat (Babaeian et al., 2026).

A striking finding is the absence of formal Climate Action Plans (CAPs) in Iranian cities (RIMAS, 2026), despite observed climate shifts already affecting 27% of long-record stations and projections showing that even under the optimistic scenario, 97% of stations will shift to drier classes by 2171–2200 (Shahsavan et al., 2024). This demonstrates that the window for preventive action is rapidly closing. Structural barriers include centralized governance, limited fiscal capacity, lack of municipal climate data and analytical capacity, and competing priorities. Addressing these requires national-level mandates, capacity-building, and financial incentives for local climate action. Furthermore, the weakening of Mediterranean systems and Caspian basin precipitation decline highlight the need for transboundary cooperation on climate risk management, as these phenomena are driven by large-scale atmospheric circulation changes that transcend national borders.

While this review has primarily focused on the physical dimensions of climate tipping points, it is important to acknowledge that climate hazards do not automatically translate into crises. A crisis emerges when a physical hazard intersects with social structures, institutional weaknesses, and existing inequalities. In the Iranian context, for example, the projected increase in heatwaves and climatic zone degradation will disproportionately affect vulnerable populations—including rural communities dependent on rain-fed agriculture, low-income urban households with limited access to cooling infrastructure, and regions with weak governance and inadequate early warning systems. The absence of formal Climate Action Plans (CAPs) in Iranian cities is a clear indicator of institutional vulnerability that exacerbates the impacts of physical hazards. Similarly, climate-induced migration, while mentioned in the introduction, is not merely a demographic shift; it is a complex socio-economic process driven by loss of livelihoods, regional inequalities, and the failure of adaptive capacity. Future research should prioritize the integration of social vulnerability indices, governance frameworks, and equity considerations into tipping point analyses to provide a more holistic understanding of climate risks and to inform just and effective adaptation policies.

5. Conclusion

This comprehensive review has examined the observed and projected climate tipping points and abrupt changes in Iran, revealing a multidimensional crisis driven by global warming that is unfolding at an alarming pace. Iran's warming rate, approximately twice the global average, combined with decreasing precipitation and increasing evapotranspiration, is pushing multiple natural and socio-economic systems toward critical and often irreversible thresholds. The key tipping points and abrupt changes identified include: (i) heatwave intensification, with durations projected to surge from ~5 days to 98–175 days under SSP5-8.5 by 2171–2200—a 25- to 30-fold increase; (ii) nationwide climatic zone collapse, with 100% of stations shifting to drier classifications by the early 22nd century under SSP5-8.5, and dry to semi-dry zones expanding from 64% to 92%; (iii) Zagros climate collapse, where rapid warming (2.2°C observed, ~8.5°C projected) and altered precipitation patterns are driving irreversible ecosystem degradation; (iv) weakening of Mediterranean low-pressure systems, reducing winter and spring rainfall over western Iran; and (v) Caspian basin precipitation decline, with projected reductions up to 59.6% by 2070–2099.

Alongside above negative changes, an emerging positive emerging trend —increased tropical cyclones in the Arabian Sea—offers localized water resource opportunities if managed through rainwater harvesting and aquifer recharge, though it also brings flash flood risks requiring integrated disaster preparedness.

The findings underscore that Iran's metropolitan areas are at the forefront of these changes. Tehran emerges as the most vulnerable city due to the convergence of extreme heatwave intensification, severe water scarcity, and hazardous air quality. Other cities face region-specific threats: Ahvaz with extreme heat (>50°C), Mashhad with highest temperature increases and loss of snowpack, Kermanshah with flood risk, and Isfahan and Yazd with irreversible desertification. The Caspian region faces declining autumn and summer rainfall, threatening its agricultural base and unique Hyrcanian forests.

A critical finding is the absence of formal Climate Action Plans (CAPs) in Iranian cities, despite observed climate shifts already affecting 27% of long-record stations and projections showing that even under the optimistic scenario, 97% of stations will shift to drier classes by 2171–2200. This demonstrates that the window for preventive action is rapidly closing. Structural barriers—centralized governance, limited fiscal capacity, lack of municipal climate data, and competing priorities—must be addressed through national-level mandates, capacity-building, and financial incentives for local climate action. Furthermore, the weakening of Mediterranean systems and Caspian basin precipitation decline highlight the need for transboundary cooperation on climate risk management.

In conclusion, climate tipping points in Iran are no longer hypothetical future scenarios but emerging realities with observable and measurable effects. The convergence of multiple negative tipping points and abrupt changes—compounded by positive tipping points and abrupt change that require proactive management—demands a paradigm shift in national and urban planning. Integrated adaptation strategies, grounded in robust scientific evidence and supported by early warning systems, sustainable water and energy management, agricultural transformation, and climate-resilient urban design, are essential to safeguard livelihoods, ecosystems, and long-term national resilience. Addressing climate tipping points in Iran requires not only physical adaptation measures but also a fundamental shift in governance, social equity, and institutional capacity. Without integrating social vulnerability and justice into climate policy, even the most ambitious adaptation strategies will fall short of protecting the most vulnerable communities. The time for action is now; every fraction of a degree of warming avoided and every year of delayed adaptation will determine the habitability and sustainability of Iran's cities and ecosystems for generations to come.

Authors' Contribution

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Data Availability Statement

This study is a review article and does not involve the generation or analysis of new primary data. All data and information used are derived from publicly available published literature, reports, and datasets, which have been cited in the reference list. Any further inquiries regarding the sources of specific data discussed in this article can be directed to the corresponding author.

Declaration of AI Use

The authors used AI-based language tools to improve the language, clarity, and readability of the manuscript. All scientific content, interpretations, and conclusions are solely the responsibility of the authors.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

References

1. Alizadeh-Choobari, O., & Najafi, M. S. (2017). *Trends and changes in air temperature and precipitation over different regions of Iran*. *Journal of the Earth and Space Physics*, 43(3), 569–584. https://doi.org/10.22059/jesphys.2017.60300
2. Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., … & Lenton, T. M. (2022). *Exceeding 1.5°C global warming could trigger multiple climate tipping points*. *Science*, 377(6611), eabn7950. https://doi.org/10.1126/science.abn7950
3. Babaeian, I., Fahiminezhad, E., Baaghideh, M., Karimiyan, M., Modiriyan, R., & Bayatani, F. (2017). *Future climate projection of the southern Caspian basin under global warming, case study: HadCM3 model*. *Journal of Natural Environmental Hazards*, 6(14), 17–34. https://doi.org/10.22111/jneh.2017.3334
4. Babaeian, I., Giuliani, G., Karimian, M., Modirian, R. (2024). *Projected precipitation and temperature changes in the Middle East—West Asia using RegCM4.7 under SSP scenarios*. *Theoretical and Applied Climatology*, 155(6), 4453–4463.
5. Babaeian, I., Karimian, M., Modirian, R., & Mirzaei, E. (2019). *Future climate change projection over Iran using CMIP5 data during 2020–2100*. *Nivar*, 43(104–105), 67–77. https://doi.org/10.30467/nivar.2019.142745.1103
6. Babaeian, I., Khazanedari, L., Modirian, R., Karimian, M., Kouzegaran, S., Malbusi, S., & Babaeian, A. (2026). *Observed heat wave assessment over Iran and its future projections through 2200 under SSP scenarios*. *Journal of the Earth and Space Physics*, 50(2). https://doi.org/10.22059/jesphys.2026.412290.1007765
7. CHRS (Center for Hydrometeorology and Remote Sensing). (2019). *An assessment of unprecedented extreme precipitation events over Iran: From satellite perspective*. University of California, Irvine. https://chrs.web.uci.edu/articles/iran_rainfall_05062019.php
8. Danehchin, F. (2024). *Designing a climate index for precipitation over the southern coasts of the Caspian Sea*. Master's thesis, Ferdowsi University of Mashhad, Iran.
9. Earth.Org. (2023). *Tipping points of climate change*. https://earth.org/tipping-points-of-climate-change/
10. ESA (European Space Agency). (2023). *Understanding climate tipping points*. https://www.esa.int/Applications/Observing_the_Earth/Space_for_our_climate/Understanding_climate_tipping_points
11. Igini, M. (2023). *Tipping points of climate change*. Earth.Org. https://earth.org/tipping-points-of-climate-change/
12. IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, et al., Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896
13. Jahangirpour, D., & Bakhshoodeh, M. (2020). *The impact of climate change on rural migration in Iran: Application of panel VAR approach*. *Environmental Researches*, 11(21), 133–142.
14. Khorsandi, M., Ghalkhani, H., & Bateni, M. M. (2023). *Trend analysis of precipitation and air temperature in water basins of Iran*. *Journal of Agricultural Meteorology*, 11(2), 51–69. https://doi.org/10.22125/agmj.2023.368274.1142
15. Kouzegaran, S., Mousavi Baygi, M., & Babaeian, I. (2020). *Modeling of the saffron yield in Central Khorasan region based on meteorological extreme events*. *Theoretical and Applied Climatology*, 139, 1207–1217. https://doi.org/10.1007/s00704-019-03028-y
16. Lenton, T. M., Armstrong McKay, D. I., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F., … & Dyke, J. G. (Eds.). (2023). *The Global Tipping Points Report 2023*. University of Exeter.
17. Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). *Tipping elements in the Earth's climate system*. *Proceedings of the National Academy of Sciences*, 105(6), 1786–1793. https://doi.org/10.1073/pnas.0705414105
18. Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2012). *Tipping elements in the Earth's climate system*. *Philosophical Transactions of the Royal Society A:*

Mathematical, Physical and Engineering Sciences, 370(1962), 1166–1184. https://doi.org/10.1098/rsta.2011.0306

19. Lenton, T. M., Milkoreit, M., Willcock, S., Abrams, J. F., Armstrong McKay, D. I., Buxton, J. E., … & Wieners, C. (Eds.). (2025). *The Global Tipping Points Report 2025*. University of Exeter.
20. Lu, F., Lu, H., Gu, Y., et al. (2025). *Tipping point-induced abrupt shifts in East Asian hydroclimate since the Last Glacial Maximum*. *Nature Communications*, 16, 477. https://doi.org/10.1038/s41467-025-55888-w
21. Masoodian, S. A. (2004). *Temperature trends in Iran during the last half century*. *Geography and Development*, 2(3), 89–106. https://doi.org/10.22111/gdij.2004.3831
22. Meshari Eshq Abad, S., Babaeian, I., Nohahgar, A., & Arshadi, S. (2018). *Projection of flood-prone areas in the Shandiz sub-basin for the 2030s under global warming using climate-hydrological modeling*. In: *Proceedings of the 2nd National Conference on Iranian Meteorology and Hydrology*.
23. Najah, A., van der Merwe, R., & Al Shehhi, M. R. (2025). *Review of tropical cyclones impacting the Western Arabian Sea and Oman*. *Journal of Operational Oceanography*, 18(1), 21–39. https://doi.org/10.1080/1755876X.2024.2444753
24. Rasouli, A. A., Babaeian, I., Ghaemi, H., & ZawarReza, P. (2012). *Time series analysis of sea-level pressure of the synoptic pattern centers affecting seasonal precipitation of Iran*. *Geography and Development*, 10(27), 77–88.
25. RIMAS (Research Institute for Meteorology and Atmospheric Science). (2026). *Investigating the future climate conditions of Mashhad with emphasis on applied aspects in urban management* (Project No. 136665/1403/22). Mashhad Municipality.
26. Saeed, A. (2022). *Heat waves assessment and their future projections over Pakistan*. Global Change Impact Studies Centre.
27. Samant, R., & Prange, M. (2023). *Climate-driven 21st century Caspian Sea level decline estimated from CMIP6 projections*. *Communications Earth & Environment*, 4, 357. https://doi.org/10.1038/s43247-023-01017-8
28. Shahsavan Gharehghouni, M. (2024). *Projection of climatic zones of Iran until the 22nd century according to SSP scenarios*. Master's thesis, Ferdowsi University of Mashhad, Iran.
29. Shahsavan Gharehghouni, M., Doostan, R., & Babaeian, I. (2024). *Observed changes in the climate zones of Iran from mid-20th century onwards (1961–2022)*. *Physical Geography Research*, 56(1), 123–138. https://doi.org/10.22059/jphgr.2024.371399.1007805
30. Steffen, W., Crutzen, P., & McNeill, J. (2025). *Earth System Dynamics and Tipping Points*. Springer. https://link.springer.com/book/10.1007/978-3-031-50762-5
31. Tandon, A., McSweeney, R., & Keating, C. (2025). *Tipping points: Window to avoid irreversible climate impacts is rapidly closing*. Carbon Brief.org
32. WMO (World Meteorological Organization). (2019). *March–April 2019 unprecedented severe rainfall in Iran*. https://wmo.int/media/news-from-members/march-april-2019-unprecedented-severe-rainfall-iran-ir-of-iran-meteorological-organizationirimo
33. WMO (World Meteorological Organization). (2023). *Guidelines on the definition and characterization of extreme weather and climate events (WMO-No. 1310)*. World Meteorological Organization.
34. Zare, M. (2024). *Climate crisis and migration: Over 50 to 70 million Iranians displaced*. AsrIran. https://asriran.com/004Tbs