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CLIMATE CHANGE FOR SUSTAINABLE LAND MANAGEMENT IN CENTRAL ASIA

2- Observed Climate Change and Attribution

Evidence of a Warming World

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1. SUMMARY OF KEY IDEAS

This document explains why climate change is now considered an observed physical reality rather than a future possibility.

It reviews the instrumental temperature record, explains how scientists measure long-term change, and shows why global warming cannot be reduced to short-term weather variability.

It then examines precipitation, droughts and extreme events, emphasizing that warming intensifies the hydrological cycle in uneven ways.

A separate section introduces attribution science and the independent fingerprints that identify human greenhouse gas emissions as the dominant cause of recent warming.

Finally, the document focuses on Central Asia, where glacier retreat, heat stress and water insecurity make the regional consequences of climate change especially important.

2. LEARNING OBJECTIVES

By the end of this article, the student will be able to:

- Explain how global temperature records are assembled from land stations, ships, buoys and satellites.
- Distinguish between average climate change, precipitation change, drought and extreme events.
- Describe the logic of climate attribution and identify the main fingerprints of anthropogenic forcing.
- Evaluate why Central Asia is especially vulnerable to warming, glacier retreat and water stress.

3. INTRODUCTION

The phrase **"Evidence of a warming world**", refers to a large body of mutually reinforcing observations gathered from the atmosphere, oceans, land surface, cryosphere and biosphere. No single measurement proves climate change on its own. Instead, confidence arises because many independent records point in the same direction: the planet has warmed, the hydrological cycle has changed, glaciers and snow cover have declined in many regions, ocean heat content has risen, and the spatial pattern of change matches what physics predicts from greenhouse gas forcing.

Weather varies from day to day; however, climate is the statistical description of those conditions over decades. A cold winter, a wet month or a damaging flood can occur even in a stable climate. Climate change becomes scientifically visible only when long records reveal persistent shifts in averages, extremes and probabilities. This is why climate scientists rely on large observational networks, quality control procedures, homogenization methods and uncertainty analysis rather than isolated methods.

The discussion that follows is organised around four questions. First, how do scientists know that the Earth is warming? Second, what changes are being observed in precipitation, droughts and extremes?

Third, how do we know that humans, rather than solar or volcanic factors, are the principal driver of modern climate change? Fourth, what do these global findings mean for Central Asia, a region where aridity, glacier dependence and land degradation make climatic change particularly consequential?

Table 1. Core indicators used to observe climate change and the way they are measured.

Indicator	Primary measurement basis	Why it matters	Main caution
Surface temperature	Land stations plus sea surface observations from ships and buoys; increasingly cross checked with satellite data	Provides the clearest long-term signal of planetary warming	Coverage and methods change through time, so homogenization is essential
Precipitation	Rain gauges, radar, satellites and reanalysis procedures	Shows how the hydrological cycle is intensifying or shifting	Spatial coverage is uneven and regional trends are more mixed than temperature
Drought	Indices based on rainfall, soil moisture, streamflow, evapotranspiration and heat	Captures water stress relevant to ecosystems and society	Different drought definitions can give different answers
Greenhouse gases	Direct atmospheric measurements and ice core context	Links observed warming to a physical forcing mechanism	Short records alone do not explain impacts without temperature and energy balance evidence

4. GLOBAL TEMPERATURE RECORDS AND HOW WE MEASURE THEM

4.1. Surface stations, ships, buoys and satellites

The modern global temperature record is constructed from millions of individual observations. Over land, the basic inputs come from meteorological stations, including long-running national weather stations and Antarctic research stations. Over the oceans, where fixed land stations are absent, sea surface temperatures are measured by ships and drifting or moored buoys. In major analyses such as National Aeronautics and Space Administration (NASA) GISTEMP, these land and ocean observations are merged into a global estimate of temperature change[1].

A crucial point is that scientists generally analyse temperature anomalies rather than absolute temperatures. An anomaly is the difference between an observed temperature and a local average for a chosen reference period. This approach reduces the problem caused by the fact that a tropical coast, a desert plateau and a polar station have very different normal temperatures. While their absolute values are incomparable, departures from each location's normal conditions can be meaningfully averaged over large areas. NASA explicitly notes that GISTEMP v4 combines meteorological station data with ERSST v5 ocean data to estimate global temperature change rather than a single absolute temperature field[1].

Satellite data are also important, but they play a complementary role. Satellites do not simply place thermometers in space; instead, they measure radiances that must be converted into temperature estimates for different atmospheric layers. For that reason, the surface instrumental record and satellite records are not identical products. Their agreement on long-term warming is scientifically valuable precisely because the measurements are independent and based on different observing systems.

Rather than showing Earth's absolute temperature, Figure 1 shows how much warmer or cooler each year was in between 1951–1980 average, compared to 1981-2025 average, which is why the values are expressed as temperature anomalies[2]. That makes it easier to compare very different places across the planet and combine them into one global record[3]. In practice, this record is built from millions of observations: air temperatures measured at land-based meteorological stations are combined with sea-surface temperatures measured by ships and buoys, and datasets such as NASA's GISTEMP merge those land and ocean measurements into a single estimate of global temperature change[2,3]. The blue line shows the year-to-year ups and downs, while the red is the 5-year mean which is smoothing the short-term variability and makes the broader pattern easier to see[2]. As presented in Figure 1, that broader pattern is clear: despite natural fluctuations from one year to the next, the long-term trend is strongly upward, with the sharpest sustained warming occurring from the late twentieth century into the present[2].

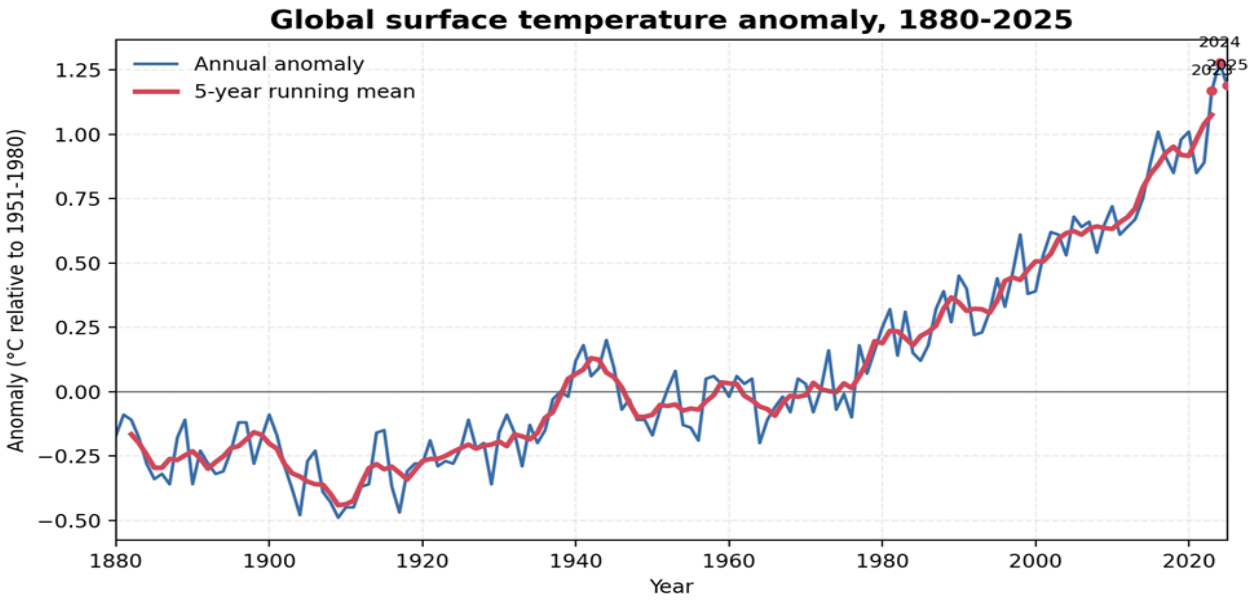


Figure 1. Global annual surface temperature anomalies relative to 1951-1980, based on NASA GISTEMP v4 data through 2025. The smoothed curve highlights the long-term trend[1].

4.2. Why anomalies, baselines and quality control matter

Long-term climate records require careful adjustment and verification before analysis. Over time, stations may be relocated, instruments replaced, observing times modified, or surrounding environments altered due to urbanisation and land-use change. If such discontinuities are ignored, the record may show artificial jumps that are not climatic. Climate data centres therefore apply homogenization methods to identify break points, compare records with neighbouring stations, and correct non climatic influences. These procedures do not generate warming trends; they remove false signals so that the remaining trend better reflects the physical climate.

Independent analyses carried out by NASA, National Oceanic and Atmospheric Administration (NOAA), the UK Met Office and other groups differ slightly in details such as spatial interpolation and baseline periods, yet they converge on the same broad conclusion: recent decades are the warmest in the instrumental era. The NOAA concluded that each of the last four decades has been successively warmer than any decade since 1850 and estimated that global surface temperature in 2011-2020 was about 1.09 degrees Celsius above 1850-1900[4]. More recent updates showed that 2024 remained the hottest year in NASA's series, while 2025 still ranked among the three warmest years in major global datasets [1,5]

This convergence across observing systems is one of the strongest arguments in climate science. If warming was an artefact of instrument bias, dataset choice or selective station use, it would be expected that the different analyses would diverge strongly. Instead, they agree on the central fact of sustained global warming, even though they are produced by different agencies using different methods.

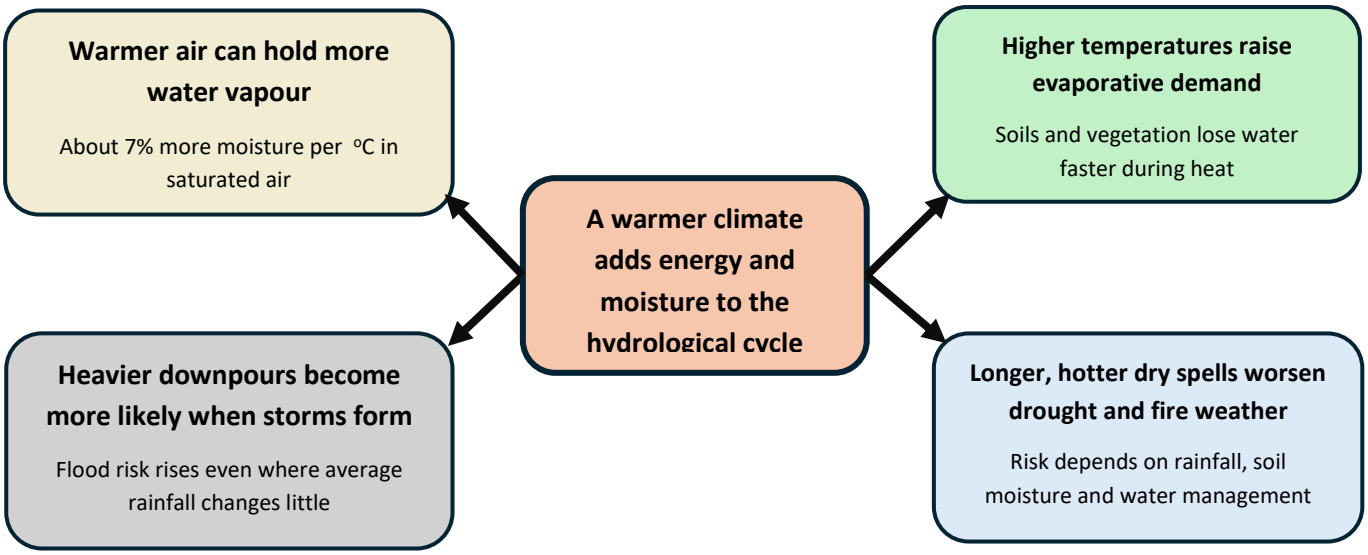
5. CHANGES IN PRECIPITATION, DROUGHTS AND EXTREME EVENTS

5.1. What the observed records shows

Temperature is not the only climate indicator that has changed. A warmer atmosphere can hold more water vapour, and this intensifies the hydrological cycle. In physical terms, saturation water vapour increases by roughly 7% per degree Celsius of warming, which means that when storms develop in favourable conditions, they can produce heavier rainfall than in a cooler atmosphere. Therefore, the Intergovernmental Panel on Climate Change (IPCC) assessed that globally averaged precipitation over land has likely increased since 1950, with a faster rate of increase since the 1980s, and that human influence likely contributed to the observed pattern of precipitation change since the mid-20th century[4].

At the same time, the observational picture is more complex than for temperature. Average precipitation can increase in one season and decrease in another; one region may become wetter overall while still while experiencing more severe flash floods; and a location can suffer drought even without a large fall in annual rainfall if higher temperatures sharply increase evaporation. For this reason, precipitation trends are more variable and usually assessed with more caution than temperature trends.

Extreme events are especially important because societies are affected not only by changes in averages but also by changes in probability. The IPCC Synthesis Report concluded that human influence has increased the frequency and intensity of hot extremes in virtually all inhabited regions and has likely increased the chance of compound events such as concurrent heatwaves and droughts on the global scale [4,6].In practice, this means that now the same rainfall deficit often occurs under hotter background conditions, making water stress more damaging for soils, crops and ecosystems.



Schematic 1. Conceptual pathways linking warming to both heavier rainfall and more severe drought risk[4,6].

5.2. Why drought is more difficult to define than rainfall

Drought is not a single variable but a family of related factors. Meteorological drought refers mainly to a rainfall deficit. Agricultural drought concerns soil moisture available to crops. Hydrological drought refers to reduced river flow, reservoir storage or groundwater. A region may therefore show different drought trends depending on which variable is examined and over what time scale. This is one reason why climate scientists use several drought indices rather than a single universal measure.

Recent assessments emphasize that heat is becoming a more important drought amplifier. Even where precipitation trends are modest or uncertain, high evaporative demand during hot periods can dry soils more rapidly, shorten the recovery time between dry spells and increase wildfire risk. This is particularly relevant for arid and semi-arid landscapes, where a relatively small decline in effective moisture can have major environmental and economic consequences.

Global reports for 2024 illustrate the uneven nature of the hydrological cycle. The World Meteorological Organization (WMO) reported drier than average conditions in some world regions and wetter than average conditions in others, while noting that large parts of East and Central Asia experienced above normal precipitation totals in 2024 [7] . Such contrasts are not contradictory; they are exactly what one expects in a changing climate where circulation, topography, land use and background warming interact.

6. ATTRIBUTION: HOW WE KNOW HUMANS ARE DRIVING CLIMATE CHANGE

6.1. Detection and attribution

Detection and attribution are related but distinct scientific tasks. Detection asks whether an observed change is statistically distinguishable from the background variability of the climate system. Attribution then asks what combination of causes best explains that detected change. Modern climate attribution does not rely on a single piece of evidence. It combines observations, physical theory and climate model experiments in which the climate is simulated with different forcings switched on or off.

The IPCC's assessment language is deliberately careful, and its conclusion is unusually strong: it is unequivocal that human influence has warmed the atmosphere, ocean and land[4]. In the same assessment, the likely range of total human caused warming from 1850-1900 to 2010-2019 was estimated at 0.8 to 1.3 degrees Celsius, with a best estimate of 1.07 degrees Celsius. Natural drivers alone were assessed as contributing between -0.1 and +0.1 degrees Celsius, which is far too small to explain the observed warming[4].

This happens because climate science is sometimes misunderstood as an argument from correlation alone. In fact, attribution is stronger than correlation. Scientists observe rising greenhouse gas concentrations, quantify their radiative forcing, compare observed patterns with physically expected fingerprints, and test whether natural only simulations can reproduce the changes. They cannot. When human greenhouse gases are included, the observed warming is reproduced far more successfully.

A further line of evidence comes from climate model experiments that compare the observed temperature record with simulations driven by different causes like in Figure 2. The instrumental record of global surface temperature change since 1850 is set against modelled responses to greenhouse gases, aerosols and other human influences, natural forcings alone, and the combined effect of human and natural drivers. The importance of the comparison is that it tests causation rather than simply describing a trend: it asks which set of forcings can reproduce the timing and magnitude of the warming that was observed. The answer is clear. Simulations that include human influence closely track the observed rise in temperature, whereas simulations driven by natural forcings alone do not reproduce the modern warming trend. This is why such figures are central to attribution science: they show in a direct and quantitative way that recent global warming is explained primarily by anthropogenic influences, especially greenhouse gas emissions.

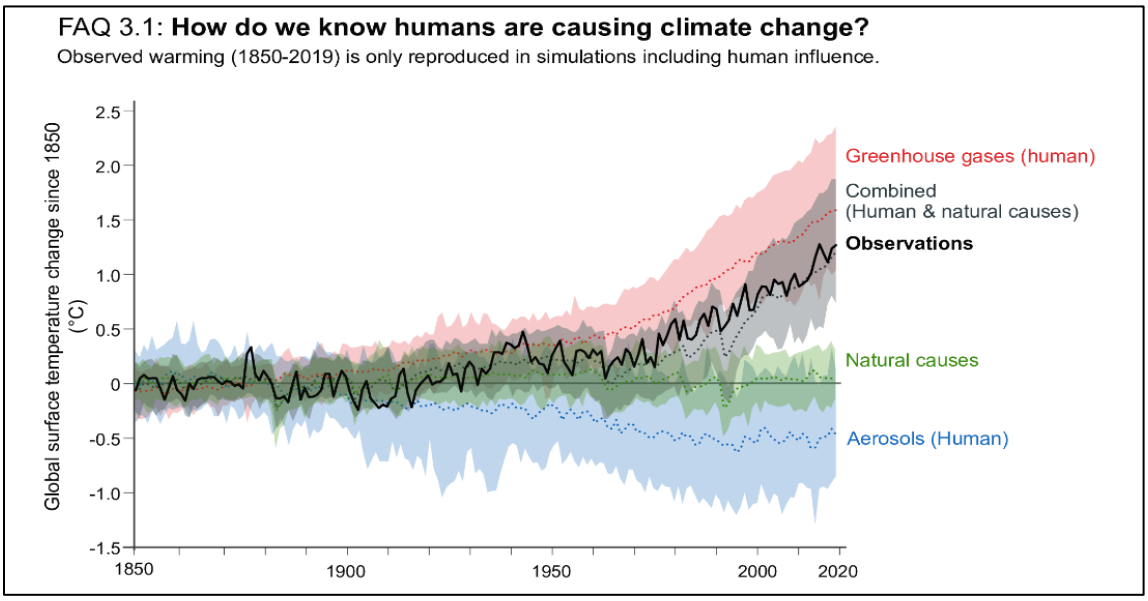


Figure 2. Attribution of recent global warming using climate model simulations and observations. Natural forcings alone do not reproduce the observed warming trend, whereas simulations that include human influences closely match the instrumental record[4].

6.2. Fingerprints of anthropogenic forcing

Several fingerprints are especially instructive for students. First, greenhouse gas forcing, warms the lower atmosphere while tending to cool the stratosphere; this vertical pattern differs from what one would expect from increased solar output alone. Second, land generally warms faster than ocean because water has a higher heat capacity and mixes vertically. Third, nights often warm faster than days and winters faster than summers in many regions because greenhouse gases reduce outgoing long-wave radiation. Also, the oceans absorb most of the excess heat trapped by the climate system, which is why ocean heat content has risen strongly in recent decades[7].

There is also chemical evidence that the increase in atmospheric CO_2 is primarily due to fossil-fuel combustion. The isotopic composition of atmospheric carbon has shifted in a way that identifies the source of the added carbon. Carbon exists in different isotopic forms, especially carbon-12 and the heavier carbon-13, and scientists express their relative abundance using the $\delta^{13}C$ value of atmospheric CO_2. Since the industrial revolution, this value has declined from about -6.5‰ to around -8‰, showing that atmospheric CO_2 now contains relatively less carbon-13. This trend is consistent with the addition of carbon from fossil fuels, which are depleted in carbon-13 because they were formed from ancient organic matter. Their combustion therefore leaves a distinctive atmospheric signature, known as the Suess effect.

When these fingerprints are considered together, attribution becomes exceptionally strong. Rising greenhouse gases explain not only the fact of warming, but also its pattern across altitude, season, latitude, ocean heat content, glacier retreat and atmospheric chemistry. This is why attribution science is central to policy: if human activities are the dominant driver, then reducing emissions is not symbolic but causally relevant.

7. OBSERVED TRENDS IN CENTRAL ASIA

7.1. Mountains, glaciers and seasonal water supply

Central Asia combines strong continentality, widespread aridity and heavy dependence on mountain snow and glacier melt. This makes the region highly sensitive to climate variability and climate change. The broader Asian context is already clear: the WMO's State of the Climate in Asia 2024 reports that Asia is warming at nearly twice the global average and that glaciers in the Tian Shan suffered severe mass loss, increasing hazards and threatening long-term water security[7]. Although Asia is diverse, these findings are especially relevant to Central Asia because river systems in Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan are closely tied to high mountain cryospheric processes.

Peer-reviewed research likewise shows that the mountain water towers of Central Asia are undergoing substantial change. Studies describe the glacierized mountain systems of the region as critical water sources and show that their cryosphere and runoff patterns are already shifting. More recent work on heat extremes and glacierized landscapes also indicates that warming has intensified across much of Central Asia, while high-elevation areas are facing declining snow reserves and severe glacier loss[8].

A key hydrological consequence is seasonality. Enhanced glacier melt may temporarily increase water availability in some basins during the early phase of retreat, but once glacier volume has been substantially reduced, long-term summer runoff becomes more vulnerable. For agriculture and hydropower, this is a serious structural issue because irrigation demand is highest in the warm season when glacier-fed water becomes most valuable.

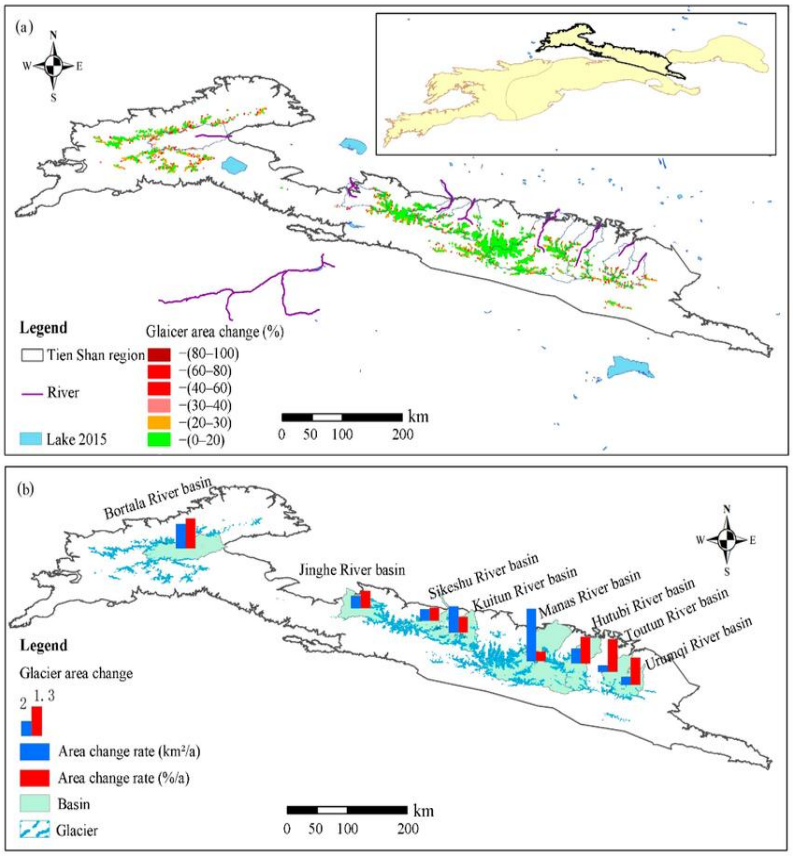


Figure 3. Observed glacier area change in the Tien Shan region and selected river basins. The figure shows widespread glacier retreat across this major mountain water source of Central Asia, with implications for the timing and long-term reliability of meltwater that supports irrigation, hydropower, and seasonal river flow[8].

7.2. Heat, drought and land-use pressure

Not all observed changes in Central Asia point in the same hydrological direction. Some areas show wetting tendencies in specific seasons or elevations, while others show stronger drying pressure, and recent years have alternated between drought, extreme heat, floods and landslides. This complexity should not be mistaken for a lack of evidence. Rather, it reflects the fact that climate change in dry continental interiors is mediated by topography, irrigation, snowpack, soil moisture feedback and atmospheric circulation.

For the region's societies, the most important message is that warming acts as a risk multiplier. Hotter summers increase evapotranspiration from crops and soils; degraded land surfaces reduce resilience to both drought and intense rainfall. Changing snow and glacier conditions alter the river water flow, and the availability when water is needed most. These pressures are especially difficult in transboundary basins, where upstream and downstream users depend on the same water towers but often have different seasonal demands.

The Aral Sea offers a cautionary example. Its shrinkage was caused primarily by decades of water diversion for irrigation, not by greenhouse warming alone. Nevertheless, it remains highly relevant in a climate-change document because it reveals how fragile dryland water systems become when land management, hydrology and environmental change are poorly aligned. Under a warmer climate, such governance failures can become even more damaging.

8. CONCLUSIONS

Climate change is now established as an observed physical reality based on multiple independent lines of evidence rather than any single dataset or indicator. Instrumental temperature records compiled from land stations, ships and buoys show a clear long-term warming trend, while additional observations from the oceans, cryosphere and atmosphere point in the same direction. Changes in precipitation, drought risk and extreme heat further show that climate change is not confined to temperature alone but is affecting the wider hydrological and ecological systems on which societies depend.

The case becomes stronger still when attribution is considered. Modern attribution science does not rest on correlation alone, but on the combination of observations, physical theory and model experiments. Natural factors by themselves cannot reproduce the full pattern and magnitude of observed recent warming, whereas simulations that include human influences match the instrumental record far more closely. Additional fingerprints, including the vertical structure of atmospheric warming, rising ocean heat content and the changing isotopic composition of atmospheric carbon, further identify anthropogenic greenhouse gas emissions as the dominant cause of recent climate change.

For Central Asia, these findings are especially significant. The region's dependence on glacier-fed river systems, irrigated agriculture and climate-sensitive dryland environments makes it particularly vulnerable to rising temperatures, glacier retreat and growing water stress. In this context, understanding the evidence for climate change is not simply a scientific exercise. It is essential for adaptation planning, regional cooperation and the long-term management of water, land and food systems.

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