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DRIVERS OF CLIMATE CHANGE: INTERACTIONS BETWEEN NATURAL FORCING AND ANTHROPOGENIC INFLUENCES

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ABSTRACT

The Earth's climate system is governed by complex interactions among the ocean, atmosphere, geosphere, cryosphere, and biosphere, driven primarily by solar radiation. Variations in both external forcing and internal dynamics of these components lead to significant changes in climatic conditions across multiple temporal scales. Natural drivers such as orbital variations (Milankovitch cycles), tectonic processes, volcanic activity, and ocean–atmosphere interactions (e.g., ENSO and NAO) have historically shaped global climate patterns. In addition, atmospheric composition, particularly greenhouse gases and aerosols, plays a crucial role in regulating the Earth's energy balance. In recent decades, anthropogenic activities—including fossil fuel combustion, land-use change, industrialization, and urbanization—have emerged as dominant forces altering the climate system through enhanced radiative forcing. These human-induced changes are superimposed on natural variability, intensifying global warming and influencing ecological systems, agriculture, and biodiversity. Understanding the interplay between natural processes and anthropogenic pressures is essential for accurately assessing current climate trends and predicting future scenarios. This study highlights the need for a comprehensive approach to identify and evaluate the diverse agents of climate change in order to support effective mitigation and adaptation strategies.

KEYWORDS: CLIMATE CHANGE, NATURAL FORCING, ANTHROPOGENIC ACTIVITIES, GREENHOUSE GASES, AEROSOLS, MILANKOVITCH CYCLES, ENSO, RADIATIVE FORCING, GLOBAL WARMING, ENVIRONMENTAL CHANGE.

INTRODUCTION:

The Earth's climate system is governed by the complex interactions among its major components, namely the ocean, atmosphere, geosphere, cryosphere, and biosphere. Although the system is primarily driven by incoming solar radiation, variations within and between these components, along with fluctuations in solar energy, can significantly alter climatic conditions. Such influences are collectively referred to as climatic forcings, which involve changes in the balance between energy inputs and outputs, ultimately leading to modifications in climate.

Climate change operates across a wide range of temporal scales and is influenced by multiple natural processes. On geological timescales, long-term mechanisms such as tectonic activity and variations in the Earth's orbital parameters—commonly explained by the Milankovitch cycle—play a critical role. These orbital variations are widely accepted as the primary drivers of glacial and interglacial cycles. Tectonic movements, through their impact on continental distribution, topography, and ocean basin configuration, have also significantly shaped global climate patterns. In contrast, shorter-term geological processes, such as volcanic eruptions, can induce abrupt climatic changes by injecting large quantities of ash and aerosols into the atmosphere, thereby reflecting solar radiation and creating a transient cooling effect often described as a "global soot veil."

In addition to these external drivers, the climate system exhibits inherent internal variability. Ocean–atmosphere interactions, such as the Interdecadal Pacific Oscillation, El Niño–Southern Oscillation (ENSO), and North Atlantic Oscillation (NAO), operate on interannual to decadal timescales and exert strong influences on global and regional climates. For instance, ENSO events, characterized by weakened upwelling in the eastern equatorial Pacific, lead to significant alterations in sea surface temperatures and atmospheric circulation patterns, thereby affecting precipitation regimes and ecosystem dynamics across vast regions.

Climate change is thus the result of the interplay among multiple systems and variables, necessitating an integrated approach for its understanding. Natural climate variability has occurred throughout Earth's history, including abrupt events comparable in magnitude to contemporary environmental changes. However, in recent decades, anthropogenic activities have emerged as a dominant force influencing the climate system. Human-induced factors such as industrialization, fossil fuel combustion, land-use change, and urbanization have intensified radiative forcing, thereby accelerating climate change.

These anthropogenic influences are superimposed upon natural variability, leading to complex and often unpredictable outcomes. Climate change, in turn, has profound implications for natural vegetation, agriculture, and ecosystem stability. The increasing recognition of the scale, intensity, and persistence of human impacts has driven significant scientific interest in understanding the patterns and causes of recent climate change. Importantly, future climatic trends will depend on the interaction between natural processes and human-induced changes, which may either amplify or partially offset each other (Beniston, 2000).

Therefore, a comprehensive understanding of both natural and anthropogenic drivers is essential for accurately assessing current climate dynamics and for predicting future climate scenarios

Natural Forcing: *Natural climatic variability over geological timescales is primarily governed by periodic changes in the Earth's orbital parameters, as described by the* Milankovitch theory*. This framework proposes that cyclical variations in eccentricity, axial tilt (obliquity), and precession drive long-term climatic fluctuations, including glacial–interglacial cycles, by altering the distribution and intensity of incoming solar radiation (Agarwal, 2004; IPCC, 2021; Britannica, 2026) .*

Among these parameters, axial tilt (obliquity) plays a crucial role in regulating seasonal contrasts, particularly at middle and high latitudes. Variations in obliquity influence the magnitude of temperature differences between summer and winter. Lower tilt results in reduced seasonal variability, whereas higher tilt enhances seasonal contrasts, producing warmer summers and colder winters. These changes directly affect snow accumulation and ablation processes, with warmer summers promoting increased melting and evaporation of accumulated snow, thereby contributing to the retreat of glaciers under stable environmental conditions (IPCC, 2021).

In addition to orbital forcing, internal climate variability—particularly ocean–atmosphere interactions—also plays a significant role. Phenomena such as the El Niño–Southern Oscillation (ENSO) represent one of the strongest sources of interannual climate variability, influencing global weather patterns, precipitation regimes, and ecosystem dynamics (Jin, 2025).

Thus, natural forcing mechanisms, including orbital variations and internal climate oscillations, constitute fundamental drivers of long-term and short-term climate variability and are essential for understanding the baseline upon which anthropogenic climate change is superimposed (Agarwal, 2004; IPCC, 2023)

Thus, orbital forcing constitutes a fundamental natural driver of long-term climate change and has played a critical role in shaping Earth's climatic history.

ATMOSPHERIC CHEMISTRY VARIATIONS

Green house gases (GHGs): The crux of the enhanced greenhouse effect is that human modificationofatmosphericconcentrationofthekeyradiationabsorbinggases–CO_2,CH_4, N_2O and various halocarbons –has resulted in a radiative forcing of the climate system. These gases have been released primarily as a result of industrial, transport and domestic activities and to a lesser extent from agricultural activities and land use changes (IPCC, 1996). Radiative forcings by GHGs is the primary cause of global warming. CO_2, CH_4, CO, NO_2, CFC sand O_3 have the greatest effect on our climate. Water vapour with high variability abundance (0.5 – 4%) also has strong influence on climate. These trace gases are known as GHGs or radiatively important trace species (RITS) (Hardy, 2003).

Green house gas concentrations in the earth's atmosphere have undergone natural changes over time and those changes have been closely followed by changes in climate. Warmer periods were associated with higher GHGs concentrations and cooler periods with lower GHGs concentrations. The main GHGs, their anthropogenic sources and their global warming potential are given in Table 1. Motor vehicle emissions are one of the major sources of GHGs. On clear warm days with a stable atmosphere vehicle combustion hydrocarbons and NO_2 undergo aphotochemical reaction to produce a hazy air pollution condition called smog with high concentration so fozone (Table 1). While lower atmosphere (the troposphere) is warming, the upper atmosphere (the stratosphere) is cooling. As GHGs concentrations increase theory predicts that more heat will be trapped in the troposphere instead of escaping to the stratosphere and space. A warmer troposphere will increase evaporation of water from the oceans leading to a general global average increase in atmospheric water vapour and rainfall (Hardy, 2003).

Aerosols: Aerosols are fine particulate matter suspended in the atmosphere that plays a significant role in modulating the Earth's radiative balance and climate system. These particles originate from both natural processes and anthropogenic activities, including fossil fuel combustion, industrial emissions, and biomass burning. Depending on their physical and chemical properties, aerosols can exert either cooling or warming effects on the climate.

Sulphate aerosols, primarily derived from sulphur emissions during the combustion of coal and oil, are highly reflective and scatter incoming solar radiation, thereby exerting a cooling effect on the Earth's surface. However, these aerosols also contribute to atmospheric acidity and are a major cause of acid rain, which has detrimental effects on ecosystems and infrastructure (Hardy, 2003; IPCC, 2021). In contrast, black carbon (soot), produced from incomplete combustion of fossil fuels such as diesel and coal, absorbs solar radiation and contributes to atmospheric warming. Black carbon is considered one of the most potent short-lived climate forcers due to its strong light-absorbing properties (IPCC, 2021).

In addition to their direct radiative effects, aerosols influence cloud formation and properties. They act as cloud condensation nuclei (CCN), increasing the number of cloud droplets and thereby enhancing cloud reflectivity (albedo) and lifetime. This indirect effect can lead to further cooling of the Earth's surface by increasing the reflection of solar radiation back into space (IPCC, 2021).

Industrial processes also contribute significantly to atmospheric composition. For instance, cement manufacturing is a major source of carbon dioxide (CO_2), released both through the calcination of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$) and the combustion of fossil fuels used in production. The cement industry accounts for approximately 5–8% of global anthropogenic CO_2 emissions, with roughly half originating from chemical processes and the remainder from energy use. It is estimated that nearly 900 kg of CO_2 is emitted for every 1000 kg of cement produced, highlighting its substantial contribution to greenhouse gas emissions and climate change (IPCC, 2021; Andrew, 2019).

Overall, aerosols represent a complex component of the climate system, exerting both warming and cooling influences through direct and indirect mechanisms, and interacting closely with anthropogenic emissions and atmospheric chemistry.

El Nino/ Southern Oscillation: The El Niño–Southern Oscillation (ENSO) is a major mode of natural climate variability arising from complex interactions between the ocean and atmosphere in the tropical Pacific region. It represents a coupled ocean–atmosphere phenomenon that significantly influences global and regional climate patterns on interannual timescales. ENSO events are characterized by anomalous sea surface temperature variations in the equatorial Pacific, which in turn alter atmospheric circulation, including trade winds and precipitation regimes (IPCC, 2021).

The impacts of ENSO are far-reaching and extend to diverse geographical regions, including mountainous ecosystems. During El Niño events, the weakening of ocean upwelling in the eastern equatorial Pacific leads to warmer sea surface temperatures, which disrupt normal precipitation patterns. This often results in extreme climatic conditions such as droughts in some regions and excessive rainfall or flooding in others. Such variability can have profound ecological, hydrological, and socio-economic consequences, particularly in vulnerable mountainous and tropical regions (Beniston, 2000; IPCC, 2021).

Furthermore, there is growing scientific evidence suggesting that climate change may influence the frequency, intensity, and spatial characteristics of ENSO events. Although uncertainties remain, several studies indicate that global warming could amplify ENSO-related variability, potentially increasing the occurrence of extreme weather events associated with this phenomenon (IPCC, 2021).

Overall, ENSO represents a critical component of the climate system, linking oceanic and atmospheric processes and exerting significant control over global climate variability.

Volcanic Activity: *Volcanic activity represents an important natural forcing mechanism influencing the Earth's climate system. Episodic volcanic eruptions inject large quantities of ash, dust, and sulphate aerosols into the atmosphere, particularly into the stratosphere, where they can persist for extended periods. These particles reflect incoming solar radiation back into space, thereby reducing the amount of energy reaching the Earth's surface and resulting in short-term global cooling. Major volcanic eruptions, occurring several times per century, can induce measurable climatic effects lasting from months to a few years (IPCC, 2021).*

On much longer geological timescales, large-scale volcanic events such as Large Igneous Province (LIP) eruptions have the potential to alter global climate over millions of years. These massive outpourings of magma can release substantial quantities of greenhouse gases and aerosols, leading to profound climatic shifts and, in some cases, mass extinction events (Self et al., 2014). Thus, volcanic activity exerts both short-term cooling effects and long-term climatic influences, depending on the scale and duration of the eruption.

Anthropogenic Pressure: *Anthropogenic activities have emerged as dominant drivers of contemporary climate change through what are termed enhanced radiative forcings. Human-induced alterations in atmospheric composition and land surface processes have significantly modified global temperature, precipitation patterns, and other climatic variables. Activities such as fossil fuel combustion, industrialization, deforestation, and land-use change have disrupted biogeochemical cycles and ecosystem stability on a global scale (IPCC, 2023).*

Rapid urbanization and demographic shifts have further intensified environmental pressures, often resulting in unplanned settlements, increased vulnerability to natural disasters, and depletion of natural resources (Table 2). These impacts are driven by both proximate and underlying factors. Proximate drivers refer to direct human actions, such as land clearing, resource extraction, and industrial activities that immediately affect environmental systems. Underlying drivers, on the other hand, are linked to broader socio-economic and cultural factors, including population growth, consumption patterns, technological development, and policy frameworks (Steffen et al., 2001).

These drivers are interconnected through complex networks involving markets, institutions, infrastructure, and governance systems, forming a chain of causation that ultimately influences environmental change. Understanding the interaction between proximate and underlying drivers is essential for developing effective strategies to mitigate anthropogenic impacts and promote sustainable development.

TABLE 1: MAJOR GREENHOUSE GASES, THEIR ANTHROPOGENIC SOURCES AND GLOBAL WARMING POTENTIAL (100-YEAR TIME HORIZON)

Greenhouse Gas	Chemical Formula	Major Anthropogenic Sources	Global Warming Potential (GWP*)
Carbon dioxide	CO_2	Fossil fuel combustion, deforestation, cement production	1

Methane	CH_4	Fossil fuels, rice paddies, livestock, landfills	28–34
Nitrous oxide	N_2O	Agricultural fertilizers, industrial processes, combustion	265–298
Chlorofluorocarbons (CFC-12)	CCl_2F_2	Refrigerants, aerosols, foam production	6,200–7,100
Hydrochlorofluorocarbons (HCFC-22)	$CHClF_2$	Refrigerants	1,300–1,700
Perfluoromethane	CF_4	Aluminium production	~6,500
Sulfur hexafluoride	SF_6	Electrical insulation (dielectric fluid)	~23,500

Source: IPCC, 2021

TABLE 2: PROXIMATE AND UNDERLYING DRIVERS OF HUMAN TRANSFORMATION OF THE EARTH

Environmental Domain	Proximate Drivers (Direct Causes)	Underlying Drivers (Indirect Causes)
Land	Deforestation, agricultural expansion, tillage, irrigation, fertilizers, pesticides	Demand for food, fibre, ecosystem services
Atmosphere	Fossil fuel combustion, industrial emissions, biomass burning, land-use change	Demand for energy, transport, consumer goods
Water	Dams, extraction, irrigation, waste disposal, management practices	Demand for freshwater, agriculture, industry
Coastal/Marine	Coastal development, overfishing, aquaculture, sewage, land reclamation	Demand for food, livelihood, recreation
Biodiversity	Habitat loss, invasive species, overexploitation	Demand for food, safety, economic growth

Source: Adapted from Steffen et al. (2001), Global Change and the Earth System: A Planet Under Pressure.

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