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The effect of climate risk on the human development index using the panel time-varying interactive fixed effects

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ABSTRACT

This study examines the effect of the Climate Risk Index (CRI) on the Human Development Index (HDI) using the innovative panel Time-Varying Interactive Fixed Effect (TV-IFE) in the Gulf Cooperation Council (GCC) during the period 2005–2024. The effects of climate risk on human development intensified drastically after 2020, having been insignificant from 2005 to 2010. Fragility increased during the subsequent decade, from 2010 to 2020, amid rising temperatures and water scarcity. This study also considers the effect of Information and Communications Technology (ICT) and PM2.5 air pollution. ICT has a positive impact, indicating an essential role in enhancing education, healthcare, and the HDI. The PM 2.5 variable has increasingly contributed to HDI outcomes in the GCC since 2020. These findings underscore the need for new policy implications in addressing climate vulnerability and enhancing human development.

1. Introduction

Climate risk is one of the most pressing challenges of the 21st century, with far-reaching impacts on economic growth, health, social stability, and environmental sustainability. With rising global temperatures, frequent extreme weather events, and depleted natural resources at an alarming rate, the negative impact of climate change threatens to undo decades of human development progress (Fletcher et al., 2024; Ma et al., 2025). The Human Development Index (HDI), one of the most widely used measures of development, summarizes three fundamental dimensions: health, education, and wealth (Nations U, 2024). These dimensions are vulnerable to global climate shocks, making it imperative to investigate how climate change impacts the HDI. In this context, HDI plays a significant role in human development policy, serving as one of the primary instruments used to evaluate human well-being across nations. It does not explicitly account for the environmental risks that influence development outcomes. Increasing global temperatures, frequent natural disasters, and deteriorating air quality directly undermine health conditions.

Additionally, increasing global temperatures and changing climate patterns lead to disease outbreaks, increased pressure on healthcare systems, and a higher number of deaths from heatwaves, malnutrition, and pollution-related illnesses (Frasch et al., 2025; Wang et al., 2025a). Such health challenges disproportionately affect vulnerable populations, particularly in developing countries, by exacerbating disparities in access to healthcare and the quality of medical services. At the same time, climate-induced shocks to agriculture and labor market participation threaten economic stability; moreover, the loss of access to education due to climate displacement and extreme weather events compounds inequality (Chen et al., 2024a; Zhao et al., 2024). Considering the influence of HDI in global policymaking, HDI should be closely evaluated when climate variability alters the pathways of human development progress.

This analysis is rooted in several interrelated theoretical frameworks that illuminate the impact of climate risk on human development. First, the Human Development Theory, as articulated by the United Nations Development Programme (UNDP, 1990), is developed not around income growth but rather as the creation of greater freedoms and capabilities for people to lead healthy and better lives through education and measurement, facilitating better policy advocacy. This conceptualization forms the basis for the HDI, as it highlights the quality of life, as opposed to solely focusing on economic aggregates (Sen, 1999). Second, the Vulnerability–Resilience Framework (Turner et al., 2003; Adger, 2006) in the climate change literature also posits that human development outcomes are contingent not only on the extent of exposure to climate-related shocks (e.g., temperature extremes, water scarcity, and air pollution) and the institutional capacity to ameliorate their deleterious impacts. Third, by revisiting Ecological Economics Theory (Daly

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and Farley, 2011; Costanza et al., 1997), our research acknowledges that economic growth has to be measured within the limits of ecology. Ongoing climate risks, including extreme heat, drought, and pollution, erode the biophysical basis of development, particularly in environmentally stressed and resource-intensive areas. The GCC's exposure to carbon intensity also underscores the challenge posed by the tension between growth models and sustainability. Fourth, the Capabilities Approach proposed by Nussbaum (2001) offers a normative framework for understanding how climate change limits individuals' freedom and opportunities by impinging on access to health, education, and a decent standard of living. Ultimately, this study is motivated by the pressing societal need to bridge the silos between environmental and socio-economic research (Ikram et al., 2023; Ulucak and Erdogan, 2022; Radulescu et al., 2025). Economic development models usually focus on growth and industrialization, frequently overlooking the ecological constraints that limit long-term prosperity (Nordhaus, 2019).

Based on the above background, the primary objective of this study is to assess how climate risk influences human development, considering the roles of particulate matter (PM2.5) air pollution and Information and Communication Technology (ICT) in the Gulf Cooperation Council (GCC). Moreover, this research employs the innovative panel Time-Varying Interactive Fixed Effect (TV-IFE) model, which captures smooth structural changes and accounts for the methodological features of the CSD absent in first- and second-generation panel data models. By combining this novel technique with the context of climate-fragile, resource-intensive GCC economies, the study provides new insights into the temporal evolution of climate impacts on development outcomes.

This choice focuses on the GCC countries (Qatar, Saudi Arabia, the United Arab Emirates, Oman, Kuwait, and Bahrain), which exhibit economies highly exposed to climate-related risks, including extreme temperatures, water scarcity, desertification, and air pollution, making them particularly vulnerable to environmental shocks. However, despite high levels of HDI, the rising frequency of climatic change threatens sustainable development. For example, temperatures in the GCC have increased at a staggering rate, with average summer temperatures exceeding 45 °C (113 °F) in many areas, and future projections indicate they could exceed 50 °C (122 °F) by the end of the century (Anwer, 2023). Such extreme heat heightens the risk of heat strokes and cardiovascular diseases. It also decreases labor productivity, especially in outdoor sectors such as construction and oil extraction, which are critical to the region's GDP (Curtis, 2009). The problem is exacerbated by water scarcity. Countries such as Saudi Arabia, the UAE, and Kuwait, which experience annual precipitation below 100 mm, heavily rely on desalination, an expensive and energy-intensive process (Fia et al., 2024; Moossa et al., 2022). Raising climate risk increases evaporation rates, adding pressure to already limited freshwater supplies. This, in turn, impacts food security, public health, and urban sustainability (Saboori et al., 2023).

Another rising concern is deteriorating air quality. The impact of desertification and unsustainable land use has led to more frequent sandstorms, resulting in higher concentrations of particulate matter (PM2.5). Studies have linked poor-quality air to an increase in asthma, lung infections, and other lung diseases, particularly in cities like Riyadh and Doha. It also impacts education. As heatwaves increase, school closures multiply, and students struggle to concentrate in extreme heat, even in air-conditioned settings (Khan et al., 2022).

In response, GCC governments have adopted bold climate adaptation measures, promoting renewable energy, green finance, and other environmental policies to mitigate climate-related risks. For instance, the Saudi Arabia Vision 2030 and the United Arab Emirates Net Zero 2050 strategy have a strong commitment toward sustainable growth (e.g., the Saudi Green Initiative plans to meet 50 % renewable energy by 2030, and the UAE Energy Strategy 2050 aims at 44 % clean energy by the middle of the century (UNO, 2021). However, for these gains to last, human development must be more fully aligned with sustainable and climate-resilient economic progress. Investing in climate-resilient infrastructure is paramount; Dubai's $163 billion Clean Energy Strategy focuses on solar parks and desalination projects. Saudi Arabia's Red Sea Project aims to develop a carbon-neutral, revenue-generating tourism sector (Administration, 2024). Qatar's Lusail Smart City is a $45 billion development that emphasizes renewable energy, AI-based urban planning, and water-efficient technologies to create a sustainable and resilient urban habitat (Griggs, 2022). Investing equally in more substantial healthcare and education systems is essential, given that climate change worsens heat-related illnesses, such as heat stroke and water scarcity issues. In the UAE, the Ministry of Health and Prevention has launched initiatives to strengthen public health resilience. At the same time, Bahrain and Oman have also promoted climate risk awareness by embedding climate risk management into their education curricula to raise awareness among future generations. Furthermore, investing in sustainable industries can contribute to economic diversification and mitigate climate risks. This is evident in the UAE's $100 billion green industrial fund, which aims to stimulate investment in sectors such as renewable hydrogen and sustainable manufacturing. Additionally, Saudi Arabia's $500 billion NEOM city project emphasizes zero-carbon urban development through AI and innovative technologies (The Organisation for Economic Co-operation and Development, 2024).

Our study makes the following contributions to the literature. Firstly, this study makes a meaningful advancement over previous studies by analyzing the impact of climate risk on an all-encompassing HDI, whereas prior investigations have primarily focused on individual components of HDI, such as the consequences of climate change for health (Hamilton, 2011; Taylor et al., 2016), education (Hamilton, 2011), and income distribution (Taylor et al., 2016; Rezai et al., 2018). As the first GCC-relevant study of its kind, this work provides a key point of reference to support global action in understanding and optimizing climate risk management.

Secondly, the study by X. Wang et al. (2025b) on time-varying panel data models with interactive fixed effects (IFE) represents a significant methodological innovation. Unlike first- and second-generation panel data models, which impose the assumption of time-invariance and fixed effects, this technique evolves smoothly over time in this framework, making the approach highly relevant to the dynamic analysis of impacts. By contrast, Wang et al. (2025b) employs a bias-corrected local least squares estimator, which facilitates more accurate estimation of time-varying relationships —a crucial step toward disentangling how patterns of climate adaptation and economic transformation drive heterogeneous human development trajectories over time. In addition, one of the main limitations of prior panel techniques is the assumption of independence between countries (Cross-Sectional Dependence (CSD)). This model bridges the gap by allowing for standard regional shocks, such as rising temperatures, water shortages, and climate policy changes, that affect multiple countries but with varying intensities. Moreover, the existing literature assumes critical structural changes, such as abrupt policy shifts, despite acknowledging that economic and environmental changes are typically gradual processes. The time-varying panel model, which enables smooth structural changes, renders it more suitable than the present approach for studying long-term trends in climate-related human development challenges. Lastly, this new model enhances the precision of existing quantitative research in the streaming literature and provides a flexible framework for future inquiries that examine the dynamics linking variables rather than relying on first- and second-panel generations.

Thirdly, this study plays a substantial role in addressing four UN Sustainable Development Goals (SDGs) related to climate risk issues, providing a holistic assessment context that aligns with global efforts for sustainable development. This research contributes to international initiatives aimed at realizing the Sustainable Development Goals (SDGs), particularly in poverty alleviation, education, and climate action, informing strategies and future development of inclusiveness and sustainability.

This study is structured as follows: Section 2 describes the methods used for the data collection. Section 3 describes the empirical results. Lastly, Section 4 presents conclusions and policy implications.

2. Literature review

Extensive studies have investigated the impact of HDI on climate risk, highlighting its contribution to sustainability (Mbiankeu Nguea et al., 2024; Opoku et al., 2022; Çakar et al., 2021). Some research suggests that a higher HDI is associated with greater industrialization, increased energy consumption, and higher greenhouse gas emissions, which contribute to the acceleration of climate change (Rahman et al., 2021; Nuta et al., 2025). Conversely, some studies suggest that advanced economies may be better equipped with environmental policies, green technologies, and mitigation strategies that can help diminish climate vulnerability (Yirong, 2022; Boujedra and Jebli, 2025). While much research has focused on how HDI affects climate change, there have been relatively few studies examining the feedback effect of climate risk on HDI. The authors (Elkouk et al., 2022; Malpede and Percoco, 2024) explored the role of climate-induced stressors, including droughts, temperature changes, and soil aridity, in reducing the values of components of the HDI, such as life expectancy and educational quality. In more detail, drawing on panel data from 2000 to 2020, Malpede and Percoco (2024) examined the impact of rising temperatures, precipitation, and desertification on human development in 1564 regions worldwide. Using spatial econometric techniques, they show that temperature and soil aridity increases are negatively correlated with life expectancy and education as components of the HDI. They conclude that the damaging impacts of high evaporation on HDI are markedly more substantial in areas with low adaptive capacity, particularly in low-income regions. Elkouk et al. (2022) examined human development and global drought risk, with a focus on socio-economic inequality. Using climate change scenarios through 2050, the funding shows that high-emission scenarios increase vulnerability by 81 % in Sub-Saharan Africa and Southeast Asia. Yilanci et al. (2023) provide us with a fascinating study of economic development, urbanization, and human capital in the context of environmental sustainability, focusing on forest resource management in Turkey. Their results suggest that the adverse effects of wealth and urbanization on environmental quality can be partially mitigated by human capital through increased awareness and the adoption of sustainable behaviors. While their analysis, however, focuses on forest sustainability rather than human development directly, the underlying processes, such as the importance of education and structural features, are nonetheless germane to how countries might shore up their resilience to climate risks. This highlights the importance of considering multiple dimensions, such as the HDI, in the context of broader socio-economic and environmental factors. Baloch et al. (Baloch and Danish, 2022) studied the nexus between pollution and human development in developing economies. They employ state-of-the-art panel econometric methodologies to assess the role of environmental pressures, including CO_2 emissions, energy consumption, and ecological footprint, on human development. The findings suggest a strong and significant negative relationship between HDI and environmental degradation, indicating that the declining quality of the environment contributes to lower levels of education, life expectancy, and economic potential. The authors contend that these processes are magnified, particularly in countries with weak institutional structures and inadequate environmental governance.

Previous research has also explored the health risks associated with climate change, focusing on the effects of climate change on disease burden. Bray et al. (2012) identified global cancer transitions and the influence of climate-related socio-economic transitions using epidemiological projections and demographic modeling from 2008 to 2030. They found that increased rates of non-communicable diseases stem from rising temperatures and pollution and particularly hit populations in low- and middle-income countries, where healthcare access is restricted. Van den Bergh and Botzen (van den Bergh and Botzen, 2018) argue that GDP-focused climate policies overlook the long-term social welfare losses associated with climate risk, and they therefore, propose the HDI as a more suitable welfare proxy for assessing climate policies. Likewise, Hickel (2020) presents the SDI, an ecologically sustainable alternative to Human Development from 2000 to 2019.

3. Data and methodology

3.1. Data

This study examines the effect of the Climate Risk Index (CRI) on the Human Development Index (HDI), considering the role of GDP, PM2.5 air pollution (PM), Information and Communication Technologies (ICT), Government Effectiveness (GE), and Inflation (INF) (See Equation (1)). For the robustness test, we will use Surface Temperature as a proxy variable in place of climate, as specified in Equation (2). This study selected GCC countries: the United Arab Emirates, Qatar, Bahrain, Oman, Kuwait, and Saudi Arabia. Due to data constraints, the study was conducted from 2005 to 2024 using a balanced panel. Following the logic of this research, the model developed as follows:

$$HDI_{it} = \psi_0 + \psi_1 CRI_{it} + \psi_2 GDP_{it} + \psi_3 PM_{it} + \psi_4 ICT + \psi_5 GE_{it} + \psi_6 INF_{it} + \varepsilon_t \quad (1)$$

$$HDI_{it} = \psi_0 + \psi_1 STC_{it} + \psi_2 GDP_{it} + \psi_3 PM_{it} + \psi_4 ICT + \psi_5 GE_{it} + \psi_6 INF_{it} + \varepsilon_t \quad (2)$$

Where ψ_0 is slop intercept, ψ_i Reveals slope coefficients of explanatory variables. While ε_{it} is the white noise error term.

The HDI, obtained from the United Nations, provides one of the most definitive measures of socio-economic development, with a scale ranging from 0 to 1 that quantifies national progress across education, healthcare, and living standards. It is essential to note that increasingly high HDI values generally indicate the extent to which countries have enhanced their capacity to establish institutions and achieve high HDI performance. Extensive studies have explored its interaction with environmental research (Proulx et al., 2024; Chen et al., 2024b). This study utilizes the climate risk index introduced by Greenwatch (Huang et al., 2018; Ozkan et al., 2022). The index measures annual and long-term climate risks resulting from weather-related disasters, such as storms and flooding, basing its score on four key indicators: total and per capita deaths, economic losses in US dollars, and losses as a percentage of GDP. To enable empirical analysis, annual and long-term indices are inverted, with lower induced risk scores corresponding to higher risk levels (Ozkan et al., 2022).

Surface temperature change (STC) is an important parameter that can robustly measure CRI, sourced from the World Development Indicators (WDI), indicating differences from a historical temperature baseline (Armour et al., 2024). Higher temperatures directly affect climate variability, energy needs, and public health, which is of particular concern for GCC states, where extreme heat exacerbates water shortages and demands on infrastructure. All these factors contribute to human well-being by providing access to clean water, housing, healthcare systems, and other essential characteristics that form the HDI (Pande et al., 2024; Duan et al., 2025). Furthermore, GDP per capita, as reported by the World Bank's World Development Indicators (WDI), is an essential driver of environmental sustainability and economic resilience. The link between GDP per capita and human development is straightforward: wealthier societies can provide advanced healthcare, education, and infrastructure that promote human development. On the other hand, unbridled economic growth, without policies that promote sustainability, can lead to pollution and environmental deterioration, result in the depletion of natural resources, and harm public health and quality of life (Xu et al., 2024) (see Table 1).

The following variable considers the role of PM2.5 air pollution, sourced from the World Development Indicators, and is crucial for assessing environmental health risks (Meo et al., 2024). Delicate particulate matter contributes to respiratory diseases through industrial emissions and high-density inhalable particles (HDI) (Wen et al., 2024). The GCC is one of the most carbon-intensive regions globally due to its reliance on fossil fuel extraction and petrochemical industries; therefore, tackling air pollution is critical to reducing the HDI. Similarly, ICT plays a role in climate mitigation. The expansion of ICT leads to increased HDI, influencing it through technological innovation, increased educational availability, and economic inclusion. The deployment of ICT infrastructure promotes digital literacy, increases access to quality education, and enhances the development of a skilled workforce, thereby facilitating the formation of human capital (Chishti et al., 2025; Zhang et al., 2022; Bahr et al., 2024). Governance quality, as captured by the Government Effectiveness Index, is another important determinant of climate risk mitigation sourced from the World Development Indicators (WDI). Effective governance is crucial for delivering high-quality public services, robust institutional frameworks, and well-executed development policies. Strong governance is characterized by high levels of investment in areas such as healthcare, education, and infrastructure, all of which contribute positively to human development (Razzaq et al., 2023; Adegboye et al., 2021). On the contrary, weak governance results in policy inefficiencies, poor service provision, and slow social and economic progress. Inflation, calculated as an annual percentage change in consumer prices (WDI), significantly impacts the HDI by influencing the cost of goods and services people purchase, individuals' spending power, and government expenditures on public welfare programs. The persistence of high inflation can erode real incomes, reducing the affordability of essential services, such as health and education, and negatively affecting human development (Yolanda, 2017; Ogujiuba et al., 2024). Table 2 provides a brief account, including abbreviations and summary statistics, for these variables. Fig. 1 depicts the data trend.

Table 1
Synthesis Table of previous research on HDI and climate risk.

Authors	Focus of Study	Key Findings
Malpede & Percoco (Malpede and Percoco, 2024)	Impact of temperature and aridity on HDI	Temperature & aridity reduce life expectancy & education
Yirong (Yirong, 2022)	Policy readiness reduces vulnerability	High HDI countries adopt better environmental policies
Elkouk et al. (Elkouk et al., 2022)	Climate-induced stress on HDI via drought risk	Droughts reduce HDI components in vulnerable regions
Yilanci et al. (Yilanci et al., 2023)	Urbanization, affluence, and human capital's effect on forest sustainability	Human capital mitigates urbanization's negative ecological impact
Boujedra & Jebli (Boujedra and Jebli, 2025)	Green technology and policy impact	Advanced economies reduce climate risk with technology
Çakar et al. (Çakar et al., 2021)	HDI's and sustainability linkage	HDI supports sustainability transitions
Mbiankeu Nguea & Kaffo Fotio (Mbiankeu Nguea et al., 2024)	HDI's role in climate resilience	Human development helps reduce climate vulnerability
Opoku et al. (Opoku et al., 2022)	HDI's environmental linkages	HDI improvements contribute to environmental outcomes
Van den Bergh & Botzen (van den Bergh and Botzen, 2018)	HDI vs. GDP as a climate policy metric	HDI better reflects welfare losses from climate change
Hickel (Name et al., 2021)	Proposal of Sustainable Development Index (SDI)	SDI integrates ecological sustainability into development metrics

Table 2
Variables and sources.

Variable	Variable	Explanation	Source
Climate risk index	CRI	Index (Ln)	Greenwatch
Human Development Index	HDI	The index between 0 and 1	United Nations
Surface Temperature change	STC	Temperature change concerning a baseline climatology	WDI
GDP per capita	GDP	GDP Per capita (Ln)	WDI
PM2.5 air pollution	PM	mean annual exposure (micrograms per cubic meter)	WDI
Information and Communication Technologies	TEC	Mobile cellular subscriptions (per 100 people/Ln)	WDI
Government Effectiveness	GE	Index from −2.5 to 2.5	WDI
Inflation (life-cost)	INF	consumer prices (annual %)	WDI

3.2. Methodology

The time-varying interactive fixed effects (TV-IFE) model was recently developed by X. Wang et al. (This selection is motivated by both the nature of the data and the limitations of conventional panel econometric methods. It can accommodate Cross-Sectional Dependence (CSD), structural breaks, and dynamic heterogeneous coefficients, making it a potent tool in panel econometrics. This technique contributes to the literature by incorporating time-varying interactive fixed effects to account for unobserved standard shocks and the heterogeneous reactions of CSD. This offers greater estimation accuracy among globalized and interconnected markets. TV-IFE models contrast with traditional models, which assume structural changes with time-invariant coefficients and fixed factor loadings. In contrast, the TV-IFE model allows both coefficients and unobserved common factors to vary smoothly over time, making it ideal for analyzing dynamic processes such as climate risk and development (Wang et al., 2025b). Moreover, this period encompasses significant structural shifts (e.g., Vision, 2030-driven measures, the post-COVID industrial response, and an ongoing sentimental climate) that are more appropriately captured by a model that allows for gradual structural changes rather than sudden breaks or rigid behavior. Finally, the TV-IFE method is more robust against endogeneity and omitted variable bias by including in the model some unobservable factors that would otherwise lead to omitted variable bias, a crucial strength in macro-panel analysis where environmental and institutional variables are employed. As an illustration, it utilizes the LLS and principal component methods for rapid estimation of dynamic parameters. It can also capture nonlinear dynamics and is helpful in energy economics, climate finance, and financial risk modeling. Accounting for evolving policies allows for more accurate real-time assessments, including carbon pricing, climate risk, and financial regulations.

As mentioned, the TV-IFE model is motivated by prior foundational research in panel econometrics focusing on the sufficient treatment of CSD. The CSD (test identifies the disparity between countries using (Pesaran, 2006; Pesaran, 2004; Breusch and Pagan, 1980) tests. For an unbalanced panel, the Pesaran CD test can be applied to assess the degree of common stochastic trends (CST). One simple test for CSD in panel data is the Breusch-Pagan Lagrange multiplier (LM) test. A different approach is presented in the Pesaran-scaled LM test, which is more robust, allowing for CSD in an unbalanced panel. For example, Pesaran (Chudik and Pesaran, 2015) made early contributions with the Common Correlated Effects (CCE) estimator, which incorporates unobserved common factors to address the common structural disturbance (CSD). However, this approach presupposed fixed factor loadings and was, therefore, unable to capture time-variant ones. We formulate the

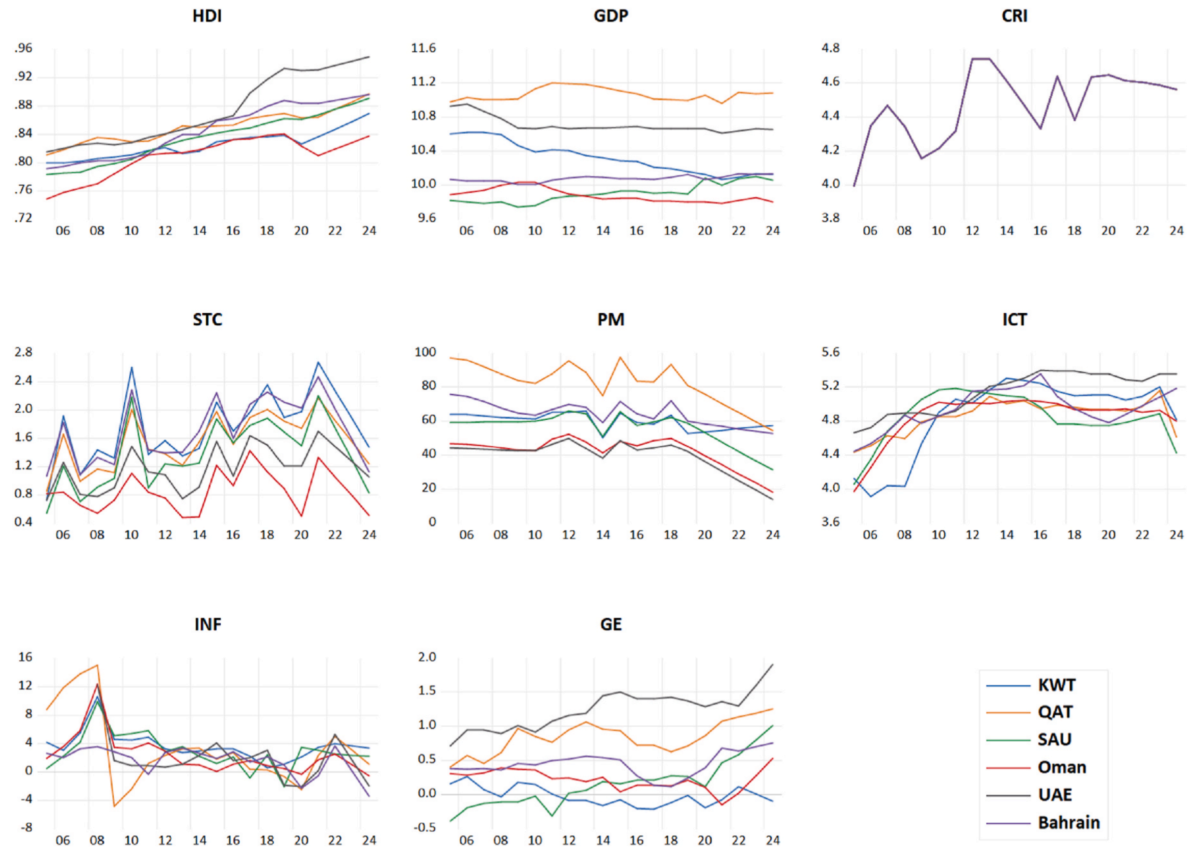

Fig. 1. Data trend of the surveyed variables.

CCE model as follows:

$$Y_{it} = X_{it}\beta + \lambda_i^{'} F_i + \varepsilon_{it} \tag{3}$$

Where F_i are latent common factors and $\lambda_i^{'}$ is heterogeneous factor loadings. Although this framework helps model strong CSD, it is without time-varying coefficients. This idea was further developed by Bai (2009), who defined the Interactive Fixed Effects (IFE) model, which generalizes the standard additive fixed effects to relevant multiplicative structures. This model accounts for heterogeneous responses to common shocks but still assumes no time variation in factor loadings and regression coefficients, which may not be accurate in practice. Nearby, Pesaran et al. l (Chudik and Pesaran, 2015) developed the CCE framework by including weakly exogenous regressors, making it suitable for dynamic environments:

$$Y_{it} = X_{it}\beta + \lambda_i^{'} F_i + \Upsilon W_{it} + \varepsilon_{it} \tag{4}$$

where ΥW_{it} is weakly exogenous variables. However, this extension provided more flexibility, but it could not model time-variant coefficients. Additionally, Moon and Weidner (2017) developed methods for estimating panel models with unknown factors, thereby enhancing their robustness in high-dimensional applications.

To tackle this time-invariance constraint, the TV-IFE) the model was proposed, breaking new ground for panel econometrics. The TV-IFE model generalizes the IFE framework by allowing both factor loadings and regression coefficients to follow smooth trajectories over time, reflecting gradual structural evolution rather than stepwise changes. The formal representation of the TV-IFE model is.Where:

$$Y_{it} = X_{it}\beta + \lambda_i^{'} F_i + \varepsilon_{it} \ \ \mathrm{i} = 1, \ldots, \mathrm{N}; \ \mathrm{t} = 1, \ldots, \mathrm{T} \tag{5}$$

Y_{it} is the dependent variable for unit i at time t; X_{it} is a vector of observed regressors; β: is the vector of time-varying coefficients that evolve smoothly over time; $\lambda_i^{'}$ characterizes time-varying factor loadings, allowing for dynamic unit-specific reactions to common shocks; F_i are common time-varying factors and ε_{it} is the idiosyncratic error term. A local least squares (LLS) method is usually employed to minimize the following to estimate the time-varying coefficients and the factor loadings:

$$\sum_{t=0}^{T} \sum_{i=0}^{N} \left(Y_{it} = X_{it}\beta + \lambda_i^{'} F_i \right)^2 K_h\left(\frac{t-r}{T} \right) \tag{6}$$

4. Results and discussion

4.1. Descriptive statistics

This section examines the descriptive statistics for the CRI, GDP, PM2.5, ICT, GE, INF, and HDI. The skewness, kurtosis, and the Jarque-Bera normality tests shown in Table 3 suggest that most variables deviate from normality. More specifically, the descriptive analysis revealed that GCC countries have high human development, as evidenced by a mean of 0.840, indicating good socio-economic conditions and minimal variability, as indicated by the standard deviation of 0.039. The mean and standard deviation of GDP are 10.311 and 0.446, respectively. Pollution levels exhibit the most significant variability, with a standard deviation of 17.096, indicating inequalities in air quality among GCC countries. The ICT variable shows a negative skewness −1.179, indicating that most countries have reached high levels of ICT infrastructure while others remain behind. Additionally, HDI and GDP are right-skewed, whereas CRI and ICT are left-skewed, as determined by skewness and kurtosis analysis. The kurtosis for INF and ICT is approximately 6.636 and 4.540, respectively, indicating significantly high kurtosis and suggesting a heavy tail and a high rate of outliers. On the contrary, GE and PM provided nearly symmetric values. The Jarque-

Table 3
Descriptive statistics information.

	HDI	GDP	CRI	STC	PM	ICT	INF	GE
Mean	0,840	10,311	4477	1414	57,668	4921	2617	0,471
Median	0,835	10,122	4565	1385	58,623	4947	2327	0,366
Maximum	0,949	11,205	4743	2676	97,700	5400	15,050	1909
Minimum	0,748	9745	3994	0,473	13,705	3910	−4863	−0,39
Std. Dev.	0,039	0,446	0,196	0,511	17,096	0,315	3223	0,499
Skewness	0,524	0,602	−0,660	0,223	0,156	−1179	1408	0,636
Kurtosis	3398	1979	2640	2375	4228	4540	6636	2610
Jarque-Bera	6123	12,144	9115	2873	8726	38,663	103,083	8628
Probability	0,047	0,002	0,010	0,238	0,016	0,000	0,000	0,013

Bera JB test results reject the null hypothesis of normality for most variables, implying a higher likelihood of extreme fluctuations than a normal distribution. Additionally, the JB test statistics indicate that the values are significant, corroborating that the studied series exhibits a nonlinear pattern.

4.2. Correlations results

In this section, we analyze the correlation between HDI and CRI, GDP, STC, PM, ICT, INF, and GE (See Table 4). Governance effectiveness and ICT have a strong positive correlation with HDI, at 0.633 and 0.534, respectively, indicating the importance of institutions and their quality in their role towards human development in the GCC countries. Although GDP correlates positively with HDI at approximately 0.346, it highlights that economic growth is not a sufficient condition for sustainable human development. Interestingly, climate risk positively correlates with HDI (0.478), suggesting that the more developed GCC countries will experience stronger environmental risk from urbanization and industrial activity.) On the other hand, pollution and inflation negatively affect HDI, respectively −0.233 and −0.359.

4.3. Main results

In this section, the analysis findings on the effect of climate risk on HDI, considering the remaining explanatory variables, are reported and discussed, as shown in Table 5. The outcomes of the TV-IFE model reveal crucial insights into the factors affecting HDI in GCC countries, accounting for net-positive and net-negative effects over time. Note that the pseudo-R-squared value is 0.90, indicating that our model and explanatory variables account for approximately 90 % of the HDI variance, yielding a statistically significant result. Moreover, the value bandwidth of 0.3079 indicates that the model identifies smooth structural changes instead of sudden jumps and is better equipped to analyze changes in a dynamic relationship (see Table 6).

The effect of the climate risk index on HDI is also significant, albeit dynamic, with an average value of 0.07 and a maximum value of 0.206. This suggests that more developed GCC nations experience higher levels of climate-related risks; however, these risks are effectively managed through well-developed adaptation strategies. At the same time, the minimum effect of climate risk is approximately 0.0046, indicating a minimal impact. GDP per capita also has a positive (and significant) effect on HDI, with an average impact of 0.0185 and 0.0579 during periods of growth. This reaffirms that human development tends to improve with higher income levels due to better access to living standards, healthcare, and education (Elkouk et al., 2022; Armour et al., 2024). On the contrary, the minimum effect (−0.0325) indicates the adverse effects of economic downturns. In contrast, the impact of inflation is always negative and minimal on HDI, with an average effect of −0.0015, and this effect decreases further to −0.0092 during inflation-prone periods. This means that inflation erodes purchasing power and impacts the HDI index, confirming previous studies (Yolanda, 2017; Ogujiuba et al., 2024).

As the most significant factor among HDI's positive contributors, governance effectiveness accounts for an average effect of 0.015 and a maximum effect of 0.076. It underscores the fundamental importance of the quality of institutions, the effectiveness of policies, and the stability of governance as key drivers of human development. Nonetheless, governance also demonstrates a minimum relevance of −0.0314, indicating that in some periods, governance and reduced policy efficiencies had an adverse effect on HDI. Likewise, ICT has a significantly positive effect, with a mean of 0.0621 and a maximum value of 0.1142. ICT significantly improves education, healthcare, and economic

Table 5
The main results.

	GDP	CRI	PM	ICT	INF	GE
Min.	−0,0325	0,0046	−0,0001	0,0323	−0,0092	−0,0314
Median	0,0203	0,0288	0,0002	0,0575	−0,0004	0,0057
Mean	0,0186	0,0707	0,0002	0,0621	−0,0016	0,0155
Max.	0,0579	0,2065	0,0006	0,1142	0,0014	0,0759

Note. R-squared:0.9019; Bandwidth:0.3808.

Table 6
Robustness test results.

	GDP	STC	PM	ICT	INF	GE
Min.	0,0325	0,0005	−0,0014	0,0436	−0,0078	−0,0324
Median	0,0588	0,0148	−0,0002	0,0492	−0,0029	−0,0002
Mean	0,0544	0,0144	−0,0006	0,0597	−0,0029	−0,0068
Max.	0,0661	0,0314	−0,0001	0,1002	−0,0002	0,0074

Note. R-squared:0.8697; Bandwidth:0.38.

Table 4
Correlation matrix.

Correlation	HDI	GDP	CRI	STC	PM	ICT	INF	GE
HDI	1							
GDP	0,346	1						
CRI	0,478	−0,001	1					
STC	0,327	0,146	0,158	1				
PM	−0,233	0,431	−0,192	0,327	1			
ICT	0,534	0,040	0,464	0,216	−0,224	1		
INF	−0,359	0,089	−0,234	−0,152	0,213	−0,262	1	
GE	0,633	0,647	0,153	−0,046	−0,154	0,294	−0,19	1

opportunities, increasing the HDI. Even at its minimal impact (0.032), ICT remains a consistently powerful driver of human development (Ulucak et al., 2020). These observations are consistent with (Chishti et al., 2025; Zhang et al., 2022; Bahr et al., 2024) in selected developed and developing countries.

On the other hand, in low and steady inflation levels, it can be observed that the maximum impact of 0.0013 is slightly positive, indicating that some inflation levels do not have a detrimental effect on HDI. PM2.5 pollution, by comparison, has a negligible overall impact on HDI, with a mean effect of approximately 0.00018. A lower impact indicates about −0.00014. On the other hand, the upper bound of the effect (0.00056) suggests that increases in pollution control measures may have led to slight increases in HDI. The findings corroborate the results of Meo et al. (Adebayo et al., 2024), which confirm the crucial role of PM2.5 air pollution in affecting health risks (Meo et al., 2024).

Fig. 2 presents the effect of CRI on HDI, considering the remaining variables from 2005 to 2024. The climate risk's impact on the HDI continued to be severe in GCC countries from 2005 to 2024, especially from 2020 onward. Between 2005 and 2010, the impact of climate risk on the HDI was negligible, as the region's economies were still largely dependent on fossil fuel revenues at that time, which helped fund infrastructure development, public services, and human development. However, the impact of CRI on HDI gradually increased during that decade (2010–2020), which reflects the growing vulnerability of the GCC to climate-related threats, including rising temperatures, water scarcity, and extreme weather conditions. Ten years of global climate inaction despite a decade of global inaction on climate (through international agreements such as the Kyoto Protocol and the Paris Agreement), this period saw the introduction of measures to diversify economies and adopt sustainability strategies such as investing in renewable energy sources, environmental regulations; however, only limited impacts would offset climate vulnerabilities. This increase since 2020 came as the constraints that climate risk imposes on the stability of the economy, infrastructure, and quality of life are growing in the GCC countries. However, the worsening climate and pressure to abandon hydrocarbons globally have created new economic and social risks, making climate adaptation essential to continued human development in the region. While mega projects in the GCC, such as NEOM in Saudi Arabia and Masdar City in the UAE, highlight sustainability, traditional investments in climate adaptation may not be sufficient to offset the growing climate risks these projects aim to counteract.

The importance of GDP in determining HDI within the GCC has been notable. The HDI responded strongly positively to the high oil prices that drove economic acceleration from 2005 to 2010, with governments able to reinvest surpluses in education, healthcare, and infrastructure. However, between 2010 and 2020, the GDP's effect on HDI decreased as GCC economies focused on addressing oil price volatility, fiscal consolidation, and increased environmental awareness. By 2020, GDP had a negative impact on HDI. Climate risks, as well as increased global energy transition policies and a drive toward carbon neutrality, have put additional pressure on GCC economies, necessitating a transition to sustainable, diversified economic models. The impact of GDP in the post-2020 period is adverse, suggesting a need for human dependence on governance and climate adaptation strategies instead of economic development in that region.

Governance efficiency has effectively contributed to reducing the adverse impact of climate risk on the HDI in the GCC. Through better policy frameworks, institutional efficiency, and social welfare programs, governance reforms helped improve human development outcomes between 2005 and 2020. Governance, post-2020, is even more important than ever in addressing the growing challenges of climate risk and economic uncertainty. Countries such as the United Arab Emirates, Qatar, and Saudi Arabia have proactively developed climate policies, diversified their economies, and invested in green technologies. These governance responses have mitigated HDI declines in the face of intense climate stressors. Good governance, particularly in policy implementation, economic diversification, and environmental regulation, has emerged as a critical determinant of regional human development. Another area that positively impacted HDI levels in the GCC was ICT between 2005 and 2020. In this context, digitalization, smart cities, and e-government services were the key solutions to promote education, health, and economic participation during this period.

The most significant impact was observed from 2015 through 2018, with the rapid adoption of innovative infrastructure. However, most

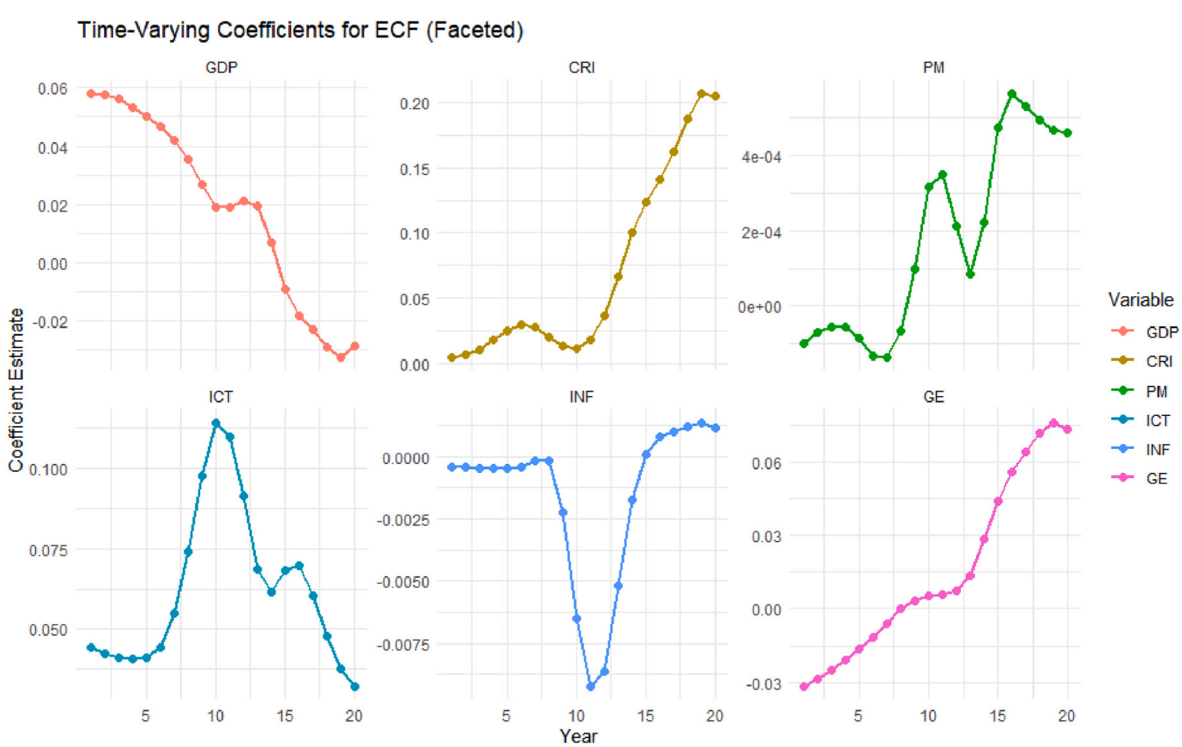

Fig. 2. Time-varying interactive fixed effects results.

notably, after 2020, the effect of ICT on HDI began to decline. This funding A strong focus on INF (has historically driven the HDIs in the GCC from 2005 to 2020 before sharply declining after 2015. PM2.5 interventions have played a growing role in shaping HDI outcomes in the GCC since 2020. Between 2005 and 2020, PM2.5 had a minimal impact on the HDI. Post-2020 marks a turning point for GCC countries in the context of climate risk's consequences for human development. Thus, CRI has emerged as a key structural challenge undermining HDI, eclipsing the traditional role of GDP. The increased emphasis on governance, policy markets, and climate-adaptive infrastructure is evidence of the growing irrelevance of GDP and the success of sustainable strategies. Climate adaptation policies should no longer be a backdoor approach that leads to a retreat from human development. GCC nations must also diversify their economies, moving away from their dependence on hydrocarbons and toward more sustainable and resilient economic models.

4.4. Robustness test

This section presents the robustness check outcome using Surface Temperature change rather than climate change, as shown in Table 5 and Equation (2). The findings strengthen the evidence that governance, ICT, and economic stability determine HDI, whereas increasing surface temperature plays a less significant yet still meaningful role in human development. GDP remains a significant driver of HDI, with a mean effect of 0.0544 and a maximum effect of 0.0661, confirming our earlier observations that economic growth ultimately promotes human development, albeit with varying impacts over time. The importance of ICT is supported by the findings, which indicate a mean value of 0.0597 and a maximum value of 0.1002, confirming that ICT has played a key role in enhancing education, health, and economic opportunities. Specifically, STC has a mean effect of 0.0144 (0.0073) and a maximum of 0.0314 (0.0226), indicating that surface temperature changes have a modest impact on HDI, albeit at a lower magnitude than climate risk in the previous analysis. On the downside, inflation has an equally significant negative impact on HDI, averaging −0.0029 and reaching as low as −0.0078, indicating that an increase in inflation lowers the standard of living and destabilizes the economy. GE has a mixed effect on human development, with a mean of −0.0068 and a minimum of −0.0324. For PM, the persistent weak negative coefficient on HDI remains, with an average of −0.0006, consistent with the observation that short-term exposure effects may not be evident. Still, long-term exposure has a significant impact on health and quality of life.

The robustness test showed that replacing climate risk with surface temperature change has a confirming effect on HDI, as shown in Fig. 3. In contrast to the previous plot, which was demonstrated with CRI, where CRI appeared to have an increasingly declining negative effect on HDI after 2020, STC has a more gradual and smoother effect, indicating that while development does respond to temperature rise, it does so over time, and at a relatively slower pace than climate-risk but confirm the same effect of CRI over the time.

GDP is more stable, meaning that economic growth can still correlate with HDI despite the temperature increase, and contrasts with the prior results of CRI. Governance Efficiency remains a stabilizing influence over time, reinforcing its effect on HDI. ICT exhibits a similar trend in both cases, peaking from 2015 to 2018 and declining thereafter, indicating diminishing returns from digitalization. Inflation is also less volatile in the STC model, indicating that increasing temperatures do not affect INF-driven progress to the same extent as wider climate risks.

5. Conclusion

This paper examines the impact of climate change on the HDI in the GCC nations. The results contribute to understanding the role of climate change on human well-being, indicating that climate has increased over time. The findings also indicate that economic growth, governance, and ICT development are key drivers of HDI; neglecting climate-related dimensions can eventually counteract human development progress. The findings indicate that inflation has a detrimental impact on the HDI, and that governance quality and technological innovation are crucial for sustaining progress. As climate challenges intensify, GCC governments must integrate climate adaptation policies into their broader, long-term human development strategies to prevent potential disruptions. There is a need to strengthen climate resilience policies by investing in green

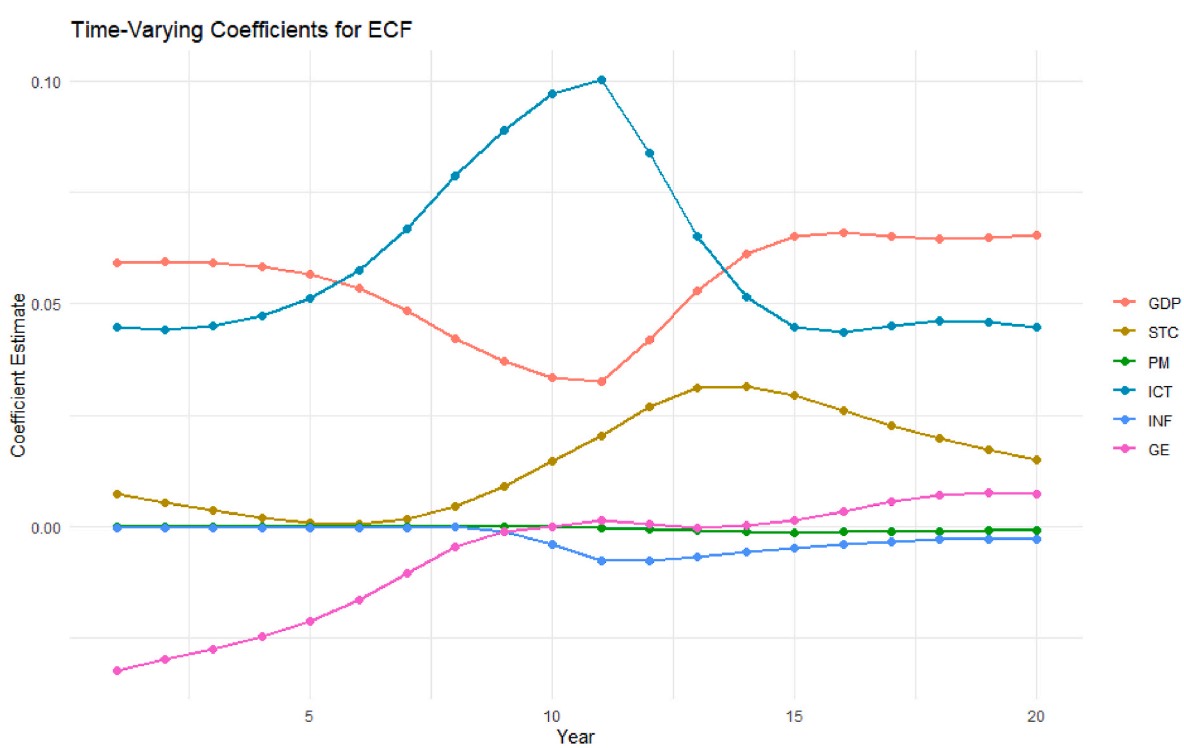

Fig. 3. Robustness test using time-varying interactive fixed effects.

infrastructure and renewable energy. Climate-smart cities and energy-efficient projects can help mitigate the adverse impacts of rising temperatures on public health and economic productivity. Moreover, climate risk assessments must be conducted within established governance frameworks to integrate climate risks into national policies effectively. Due to the significant positive impact of ICT on the HDI, policymakers need to prioritize digital affordability and accessibility, particularly in rural or underdeveloped areas. At the same time, ICT should be utilized for climate monitoring, early warning systems, telemedicine, and digital education to achieve co-benefits in development and resilience. GCC countries need stronger emissions standards for transport and industry, as well as cleaner public transportation and nature-based solutions, such as urban greening, to reduce exposure to particulate matter. There is a need for country-level interventions to incorporate these findings. Measuring against climate-resilient development, Saudi Arabia will need to integrate Vision 2030 and NEOM, as well as strengthen service delivery in areas affected by heat.

The UAE needs to integrate its Net Zero 2050 vision with inclusive digital health and education initiatives through smart city expansion and the control of PM2.5 emissions. Qatar should prioritize heat-resilient infrastructure and innovative healthcare in urban centers such as Lusail. To reduce rural vulnerability, Oman must enhance its local governance capacity, climate monitoring, and climate literacy. Bahrain will need to focus on mitigating inflation and reducing pollution through green subsidies and promoting clean transportation. It will have to leverage the potential of ICT to enhance service equity. Kuwait will need to invest its wealth of oil revenues in climate-adapted education and health systems and transform public governance to build resilience. Throughout the GCC, connecting national visions with adaptive, inclusive, and climate-sensitive HDI options is crucial for preserving future development amid growing climate pressures.

This study has some limitations. First, due to the availability of data, the analysis was limited to six GCC countries from 2005 to 2024, and the generalizability of these findings to other contexts and time scales may be compromised. Second, some variables, such as climate finance, demographic structure, institutional capacity, and migration flows, each of which potentially exerts a profound impact on human development, were not examined due to a lack of data. Third, reliance on integrated national-level indices, such as the Human Development Index, may obscure significant subnational differences in exposure, vulnerability, and adaptive capacity. Future research should fill these gaps by utilizing more disaggregated data, a broader selection of independent variables, and comparative analyses of GCC and non-GCC countries, advancing the overall understanding of the relationship between climate and development.

CRediT authorship contribution statement

Alanoud Al-Maadid: Writing – review & editing, Writing – original draft, Validation, Software, Data curation, Conceptualization. **Mohamed Sami Ben Ali:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Kamel Si Mohammed:** Writing – review & editing, Writing – original draft, Visualization, Validation.

Declaration of competing interest

The authors state and declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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