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Opportunity amid crisis: how climate risks drive digital governance — a dual perspective from public safety and low-carbon development

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As global climate risks intensify, government governance systems are confronted with unprecedented pressures for transformation and new strategic opportunities. Through the dual perspectives of public safety and low-carbon development, this study systematically explores how climate risks can enhance national digital governance capacity. By constructing a panel dataset encompassing 191 countries from 2003 to 2024, it is confirmed that physical climate risks and transition risks significantly contribute to the optimization of digital governance. Moreover, efficient government services and political stability strengthen the positive impact of physical risks on digital governance, while high-carbon economic systems and fiscal debt pressures mitigate the positive impact of transition risks. The findings indicate that climate risk is not merely a threatening external factor; in countries with institutional resilience and fiscal and budgetary capabilities, it can be leveraged as a strategic opportunity to promote digital governance. This paper not only offers an integrated analytical framework for examining the interactive relationship between climate risk and digital governance but also provides theoretical and policy-relevant insights for countries formulating differentiated digital economy strategies in the context of enhancing the resilience of global climate governance.

KEYWORDS

climate risk, crisis-driven reform, digital governance, low-carbon development, public safety

1 Introduction

Climate change has increasingly emerged as a systemic governance challenge rather than a purely environmental concern (Husted and de Sousa-Filho, 2017; Işık et al., 2025). The escalating frequency and intensity of extreme weather events, along with the economic and social disruptions caused by climate transition policies, have exerted continuous external pressures on national governance systems (IPCC, 2021). These pressures not only impact public health, economic stability, and fiscal sustainability but also challenge the governments' ability to coordinate policies, provide public services, and manage risks effectively (OECD, 2020; Kahn et al., 2021; Schulte et al., 2023). In this context, climate risk is a crucial external shock that may reshape the path of government capacity development.

Simultaneously, digital governance has become a key mechanism for governments to enhance administrative efficiency. Digital technologies allow governments to improve early-

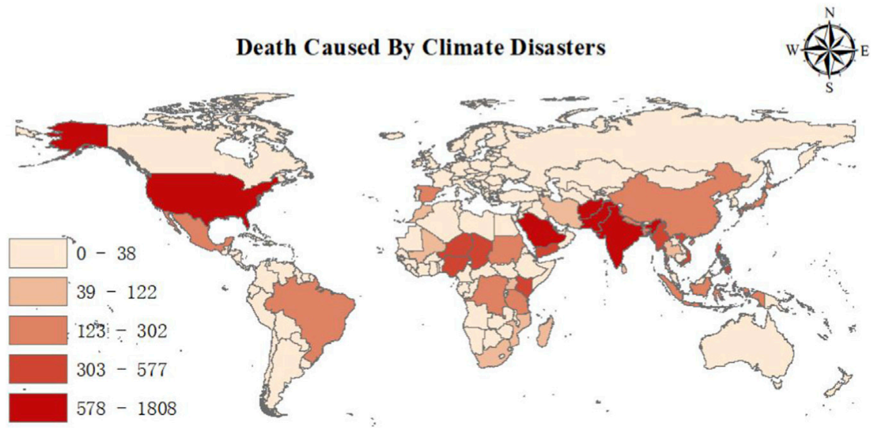

FIGURE 1
Number of Deaths from Climate-Related Disasters by Country in 2024. Note: The study sample comprises 191 countries. Among the 193 United Nations member states, El Salvador (ISO code: SLV) and the Federated States of Micronesia (ISO code: FSM) are not included owing to lack of data.

warning systems, integrate fragmented policy domains, and expand the scope and responsiveness of public services (Argyroudis et al., 2022). While digital transformation is often regarded as a result of technological progress or institutional reform, it may also be driven by external pressures that force governments to adapt their governance structures (Haug et al., 2023). Climate risk, by intensifying the demands for coordination, information processing, and rapid response, offers a particularly prominent context in which such adaptation may take place (Ariyachandra and Wedawatta, 2023; Crow et al., 2018).

Existing studies have predominantly explored climate risk and digital governance as distinct research areas. The literature on climate risk has mainly concentrated on macroeconomic outcomes, public health implications, or environmental policy responses. In contrast, research on digital governance has emphasized technological preparedness, institutional quality, or administrative reforms. Consequently, there is limited empirical evidence regarding whether and how climate risks act as external drivers of a nation's digital governance capacity. In particular, several questions remain inadequately explored. Regarding climate risks, does their impact on digital governance stem from passive adaptation under public-security pressures or from an active strategic orientation towards low-carbon growth? Is the effect of this drive merely a short-term response to stress, or does it represent a medium- or long-term strategic adjustment? More importantly, does the ability to turn adversity into advantage depend on internal factors such as a nation's institutional context and macroeconomic environment?

This paper places the global challenge of climate change within the realm of digital governance, aiming to empirically investigate how the climate-change risks act as a fundamental external impetus for the digital transformation of governments. Simultaneously, it seeks to examine the processes and boundary conditions of this adaptation. Utilizing panel data from 191 countries spanning from 2003 to 2024, we explore whether, and in what manner, climate-change risks elevate the level of national digital governance. The empirical results yield three significant findings. First, climate risks, classified as both physical and transition risks, significantly impact the level of digital governance, with transition risks having a more pronounced influence. Second, the mechanistic analysis reveals that the efficiency of public services and the stability of the political environment exacerbate physical risks and increase the significance of governance advancements. However, a carbon-intensive economic structure, combined with the fiscal pressure of national debt, mutually lead to a reduction in the effects of transition risks. In conclusion, we demonstrate that the risk arising from climate change is not merely an external threat. Under certain conditions, it can be transformed into an adaptive strategic advantage, significantly facilitating the development of government digital governance.

This research makes several key contributions. From a conceptual perspective, this study systematically classifies climate risks into physical risks and transition risks and integrates both into an analytical framework of government digital governance capacity. By focusing on the holistic impact of climate risks on national digital governance, it broadens the theoretical foundation at the intersection of climate governance and digital governance.

In terms of mechanism identification, this research not only confirms the significant positive influence of climate risks on digital governance but also delves deeper into the underlying pathways through which this effect operates. Specifically, it examines the mediating role of institutional capacity and fiscal resilience, analyzing how these factors tranform climate pressures into digital governance outcomes.

From a policy-oriented standpoint, this study adopts an opportunity-in-crisis lens to propose actionable pathways for governments to respond to climate pressures through strengthened digital governance systems. It emphasizes the importance of differentiated strategies tailored to national contexts, such as varying institutional readiness and fiscal constraints, and provides actionable recommendations on how to advance digital transformation while enhancing climate resilience.

2 Literature review

2.1 Evolution of national governance and climate risk

The development of national governance is often triggered by external crises, through which governments adapt their governance structures continuously to be able to cope with complex challenges. Historically, crises have often acted as important catalysts in governmental reformation and innovation (Boin and 't Hart, 2022), generating a transformation from traditional bureaucratic models to more flexible and efficient paradigms for digital governance (Sarker et al., 2018). Early writings on digital governance were substantially focused on the technological aspect, underlining the instrumental value of information and communication technologies (ICTs), foremost as a means of attaining greater administrative efficiency and optimizing public service delivery (Cordella and Bonina, 2012). For example, discussions in e-governance were overwhelmingly focused on office automation and information exchange between governmental agencies (Bigdeli et al., 2013).

As we have entered the risk society, however, several systemic crises, such as the 2008 global financial crisis and the COVID-19 pandemic have fundamentally refocused the theme of digital governance. The meaning of digital governance has gradually changed from a utility-oriented manner of technology utilization to a strategic governance framework that has as its objective the management of systemic risks. Han et al. (2023) state that digital government is not merely a new and upgraded form of informatized government, but rather a change in the paradigmatic viewpoint on governance, where its aim is in part to optimize and enhance resilience and adaptability to challenges of state institutions through the instrumentality of data-supported decision-making.

In this context, climate risk, as a form of systemic risk, has promoted the strategic transformation of digital governance. The global, cascading, and uncertain situation (Scheffran and Battaglini, 2011) characterizes the risks of climate change that can create correlated crises such as energy supply shortages, food insecurity, and social instability (Barakat et al., 2023). These can represent an unprecedented challenge for traditional, fragmented forms of governmental governance. These realities highlight the need for governments to form integrated and intelligent digital governance systems that can provide early warning systems, rapid responses, and dynamic modification of policy.

The gravity of these problems is captured in the statement made by Erkut (2020) that digital governance is not so much a matter of using digital means but modifying the means of governance to be able to adapt systemically. Through a system of empowerment of big data, artificial intelligence, and other technologies of a new order, it could markedly increase the powers of governments in the face of complex or multidimensional crises. Thus, various crises represent the impact of continued extension and deepening of digital governance across the conceptual, technological, and institutional orders, which leads to the following hypothesis being offered with these views.

Hypothesis 1. *Climate risks drive national governments to enhance their levels of digital governance.*

2.2 The dual challenges of climate risk

Climate risk is presently steadily evolving from being solely an environmental issue to being a promoter of transformational change in governance systems, whereby changes occur in natural systems and socio-economic impacts. According to the IPCC report, climate change has caused 127 key risks to become widespread, which in many cases can no longer be simply reversed. The emphasis on global warming has also increased the number of extreme events such as heat waves and floods. This much more severe risk environment is significant because it relates in many respects not just to the basis for human survival but also because it poses serious challenges to existing governance systems. Albris et al. (2020) recommend risk management that embraces hazard, exposure, and vulnerability, thereby imposing new challenges for the design and implementation of digital governance systems (Albris et al., 2020).

2.2.1 Passive adaptation driven by public safety demands

Physical Risks (PR) are the threats, losses, and damages caused by extreme weather events and natural disasters (floods, droughts, and wildfires). The physical risks resulting from climate change are a direct threat to public safety and public health systems, which necessitate the implementation of reactive adaptive solutions by governments. In this process, digital governance becomes an important tool for improving emergency response and crisis management capacities (Chuard et al., 2022). The nature of physical risks, given their suddenness and destructive effect, highlights the limitations of traditional governance models with respect to the accuracy of early warning systems, the ability and effectiveness of resource allocation and communication, and cross-sectoral collaboration. This, in turn, creates pressure for governments to implement digital technologies to broaden their risk prevention and control systems (Balogun et al., 2020). According to Garcia and Fearnley (2012), the need to monitor more closely and put better early warning systems in place is made necessary by the increasing frequency of natural disasters, where digital technologies such as remote sensing and big data analytics have pervasive applications in relation to forecasting and assessing meteorological hazards. Extreme weather events create not only immediate physical catastrophes in terms of human casualties, but also noticeable secondary impacts, which cause additional health risks in the form of the exacerbation of cardiovascular disease through heat waves, the spread of waterborne diseases following floods, and the increase in mental health conditions (Karthick et al., 2023).

The passive adaptation of digital governance to physical risks is mainly expressed in terms of the technological empowerment given by digital governance throughout the whole cycle of disaster management. In the pre-disaster prevention phase of the disaster management cycle, technologies such as digital twin systems are employed to create virtual models of cities, which can simulate the possible effects of climate-related hazards and optimize the layout of their infrastructures and disaster prevention plans (Ariyachandra and Wedawatta, 2023). In the disaster-response phase, mobile internet, social media, and IoT devices are able to create real-time reports regarding disasters, thereby facilitating the effective allocation of funds and resources (Gaire et al., 2020). The post-disaster recovery phase sees the application of technologies such as blockchain to ensure the open and transparent distribution of funds for aid, while big data analytics are employed to ensure effective damage assessment and reconstruction decision-making (Shah et al., 2019). These applications show how, in contexts where there is pressure from physical risks, digital governance has moved from being an optative choice to a necessary investment, thus forcing governments to make use of technological upgrades to compensate for deficiencies in governance that necessitate such adaptations.

Notwithstanding, the limitation of this model of adaptive response is significant. Its principal characteristic is a stress response, especially an adaptation influenced by momentary political pressures or budgetary limits, and this prevents the establishment of stable institutional mechanisms. Abdullahi and Abdullahi (2023) argue that without a strategic plan being laid, there is a likelihood that digital technology schemes will remain piecemeal and fail to improve systemic, established governance resilience. On the other hand, it is clear that the driving effect of physical risk varies by country. Developed countries, taking into consideration their more evolved technical structures, are in a position to implement digital responses quickly, whereas in developing countries, the existence of an "adaptation divide" can be seen to result from a lack of either digital or institutional infrastructure (Ndubuisi et al., 2021). It is thus clear that the push given to digital governance enhancement made necessary as a result of the incidence of physical risk serves not only to examine the readiness of a government in the application of technology, but also the resilience of established governance systems inherent in governments.

Hypothesis 2a. *Climate-related physical risks compel national governments to enhance their level of digital governance.*

2.2.2 Proactive layout in the low-carbon development pathway

In contrast to the passive adjustment to physical risks undertaken, Transition Risk (TR) arises from the economic and social adjustments required for low-carbon transitions, such as the implementation of stricter environmental policies. Blasberg et al. (2021) argue that sudden changes in climate policy are the key drivers and sources of transition risk. Transition risks tend to induce active strategic planning on the part of governments. Within this framework, digital governance is increasingly regarded as a strategic tool designed to secure advantages flowing from the low-carbon transition and generate co-benefits in public health (Zhou et al., 2025). The transition risks involved arise under the dual agenda of global carbon neutrality, which operates by way of policy change, technical innovation, and market redeployment, such as carbon tariffs and upgrades of energy systems. These changes present problems for industrial redeployment but tend to open opportunities for "green" growth and health co-benefits. To reap benefits from these changes, governments actively promote their digital governance projects, taking advantage of digitalization to enable the green transition. The digital governance projects that are proactive are normally systemic and sustainable (Zhao et al., 2022). The development of sustainable and renewable energy is often accompanied by the digitalization of energy systems, the construction of smart grids, and the expansion of data-driven regulatory frameworks, which objectively strengthens the government's digital governance capabilities in information collection, policy feedback, and public service provision (Zheng et al., 2023). The European Union, for example, embraces the "Green Digital Alliance" project, in which digitalization and greening are embraced as the dual pillars of its recovery strategy to fund, on the part of member states, investments in digital infrastructure and support carbon neutrality (Santarius et al., 2023). Equally, China's "East–West Computing Resources Transmission Project" (Dongshu Xisuan) concentrates data center deployment to take place in an efficient manner that can reconcile growth in the digital economy with energy efficiency goals (Xie et al., 2024). These are examples of cases in which digital governance, brought about by transition risks, has moved beyond emergency response to become part of the mainstream of national development for the longer term, embracing the aim of steering comprehensive economic and social transformation towards sustainability through digitalization. The global transition to a low-carbon economy brings with it very significant health co-benefits. The reduction of fossil fuel consumption leads not only to reductions in carbon emissions but also has benefits for air quality, reducing respiratory diseases linked to air pollution (Tran et al., 2023).

The effectiveness of proactive strategic planning, however, is dependent on several factors. On the one hand, it requires governments to develop strong strategic foresight to anticipate transition risks and to develop coordinated policies early on. As Morgan (2022) demonstrates, the institutional framework needs to be strong in order to integrate digital technologies into green finance and prevent the systemic risks that now exist. On the other hand, transition risks can lead to problems of equity in socio-economic development, such as employment restructuring and digital exclusion, thereby pointing to the need for inclusive forms of digital governance design to prevent any widening of the digital divide (Carley and Konisky, 2020).

Overall, the bulk of the transition risk leads to motivation on the part of governments to actively engage in the furtherance of digital forms of governance through the generation of a common developmental vision. The ultimate effectiveness of this proactive response to transition risks, however, depends upon the overall resilience and adaptability of the domestic systems of governance.

Hypothesis 2b. Climate transition risks guide national governments to enhance their level of digital governance.

2.3 Boundary conditions for turning crisis into opportunity

It is important to clarify that the process of transforming climate risks from crisis to opportunity in terms of moving towards digital governance is not simple but is a function of the institutional capacity of the nation-state as well as the macro-economy (Ni et al., 2022). Institutional capacity refers to government efficiency, stability of policies, and conditions for organizational coordination (Salvador and Sancho, 2023). According to Gong X. et al. (2020), the process of digital transformation of government reconstructs the relations between the state, market, and society through the dual regenerative mechanisms of technology and empowerment of institutions. Its effectiveness, however, depends largely on the government's planning and implementation capacity. In this context, Ziatdinov et al. (2024) stated that the process of building a digital government involves a self-revolution in terms of the system of governance, which negates the current power relations. Unless sufficient institutional support is present, the efforts of such digital governance would be merely symbolic and not transformative. Also, Wang et al. (2024) points out how digital government helps in terms of increasing evidence-based decision-making and precision of social governance, but such a move only follows after considerable reforms in the regulation and process of the exercise of political power. Hence, it is that stability in policy becomes a major enabling factor for the continuity of such innovation in the realm of digital government.

On another note, macroeconomic conditions, particularly fiscal space and resource allocation, influence the efficiency of turning crises into opportunities (Zhang et al., 2023). Meng et al. (2023) use a Dynamic Stochastic General Equilibrium (DSGE) model to show that tough climate policies can increase financial instability, implying that the policy intensity must correspond to fiscal resilience so as to avoid recessions. Ullah et al. (2025) argues that digital financial policies and green bond markets have emerged as important catalysts for sustainable climate transitions if the fundamentals of the macroeconomy hold firm. In this light, optimal resource allocation can mitigate the fiscal burden implied by the reforms needed for digital governance.

Overall, the quality of a country's institutional capacity and macroeconomic conditions together provide the boundary conditions for converting crisis into opportunity. This suggests that only those countries with efficient governments, stable policies, and sufficient fiscal space can start to exploit the full potential of digital governance in responding to climate risks, which is the true seizing of opportunity amid crises.

Hypothesis 3. The positive impact of climate risks on national digital governance is moderated by institutional resilience and macroeconomic conditions.

3 Research design

3.1 Baseline empirical model

This study employs a fixed-effects panel regression model to estimate the impact of climate risks on national digital governance capacity. The baseline model is specified as follows:

$$DG_{i,t} = \alpha + \beta_1 ClimateRisk_{i,t-1} + \beta_m \sum Controls + \mu_t + \varepsilon_{it}$$

In this model, $DG_{i,t}$ denotes the level of digital governance in country i in year t. The key explanatory variable $ClimateRisk_{i,t-1}$ comprises two dimensions: physical risks (PR_{it}) and transition risks (TR_{it}). Controls represents a vector of time-varying control variables that may affect digital governance performance. The variable μ_t captures year-fixed effects to control for common temporal shocks, and ε_{it} is the idiosyncratic error term.

Considering the lagged transmission effects of climate risk, to avoid potential endogeneity caused by reverse causality, all the explanatory variables are lagged by one period. Moreover, year-fixed effects are inserted in order to control for unobservable time-varying factors. ε_{it} means the random disturbance term. To address potential endogeneity from reverse causality, all explanatory variables are lagged by one period. The reported standard errors are clustered at the country level to account for within-country serial correlation and heteroskedasticity, ensuring robust statistical inference.

3.2 Variable specification and data description

3.2.1 Explanatory variables

The key explanatory variable in this study is climate risk, which is divided into physical risk and transition risk, depending on its manifestation and source. Following Chen et al. (2021) and Wen et al. (2023), we will assess the magnitude of physical risks by the number of deaths due to climate-related disasters. The information on climate disasters is obtained from the Emergency Events Database (EM-DAT), Center for Research on the Epidemiology of Disasters (CRED), Université Catholique de Louvain, Belgium. EM-DAT, which has about 21,000 disaster events occurring globally, has shared data since the year 1900, covering the geographical location of each affected country or region, start and end dates of events, associated secondary hazards, causes, and human and economic losses of the said disasters. For example, the number of deaths from climate-related disasters by country in 2024 is shown in Figure 1. The EM-DAT dataset has also classified natural disasters caused by environmental factors into (1) meteorological disasters, (2) climatological disasters, and (3) hydrological disasters, based on their causes and characteristics. This study considers natural disasters related to climate elements resulting in wildfires and droughts as climatological disasters, floods as hydrological disasters, and extreme temperatures and storms as meteorological disasters. The total number of deaths from these climate-related disasters is aggregated at the national level. For countries and years with no reported disasters, the corresponding values are set to zero (indicating no events).

Following the approach of Ciccarelli and Marotta (2024) and Gu and Hale (2023), this study measures climate transition risk by the number of climate-related policies issued by each country. Climate policies include those policies intended to reduce the emissions of greenhouse gasses, improve energy efficiency, assist in the introduction of clean energy technologies, and promote adaptation to the effects of climate change. This includes, but is not limited to, carbon taxes or carbon emission trade systems, subsidies for renewable energy, and energy efficiency standards. The data on climate policies are obtained from the International Energy Agency (IEA) Policy Database, which provides detailed information on government initiatives aimed at the reduction of emissions, improving energy efficiency, and advancing clean energy technologies. For example, the number of climate transition policies issued by country in 2024 is shown in Figure 2. Under the framework of the green transformation process, the adoption of

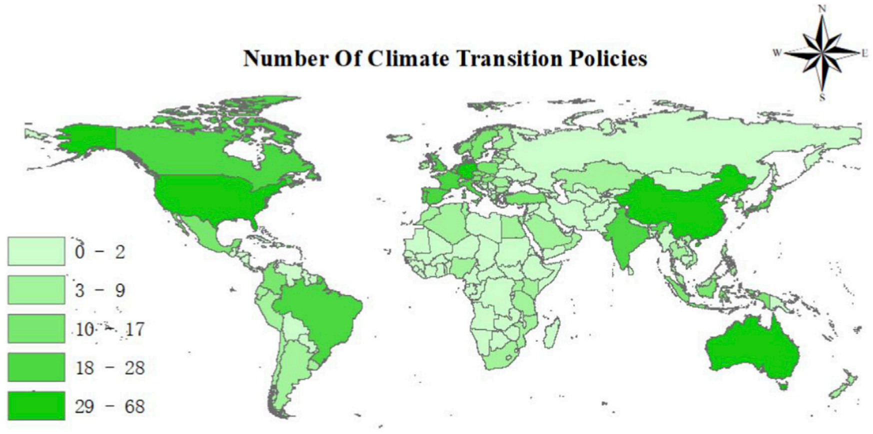

FIGURE 2
Number of climate transition policies issued by country in 2024.

climate policies provides the additional costs from compliance thereof and operating costs imposed on enterprises. However, it does provide the necessary instruments of policy and the strategic approach to be followed, which are essential to effect the transformation in energy, environmental management, and urban governance.

3.2.2 Dependent variable

The dependent variable in this study is digital governance (DG), and the United Nations E-Government Development Index (EGDI) is used as the core indicator for measuring a country's level of digital governance. The EGDI data are sourced from the *United Nations E-Government Survey* regularly published by the Division for Public Institutions and Digital Government of the United Nations Department of Economic and Social Affairs (UN DESA). The EGDI is a comprehensive index composed of three equally weighted sub-indices: the Human Capital Index, the Online Service Index, and the Telecommunication Infrastructure Index. The Human Capital Index primarily reflects a country's population's skills and capabilities in digital governance based on indicators such as years of schooling, literacy rates, and school enrollment rates. The Online Service Index measures the government's online service provision level in areas such as information dissemination, transaction processing, and interactive participation, based on functional assessments of government websites and digital public service platforms. The Telecommunication Infrastructure Index comprehensively considers internet usage, fixed and mobile communication penetration rates, and broadband access to reflect the infrastructure conditions supporting digital governance. This index has high authority and comparability in international comparative studies and can comprehensively characterize a country's digital governance capabilities.

It should be noted that the UN e-Government Survey released initial data in 2003, 2004, and 2005, and since 2008 has changed to releasing systematic assessment data every 2 years. Therefore, to maintain the continuity of the sample period from 2003 to 2024 and to ensure the comparability of data from different years, this paper uses linear interpolation to extend the EGDI for missing years and the period from 2021 to 2024.

To further ensure the robustness of the results, this paper introduces the e-participation index (E-part) on top of the EGDI. The e-participation index (E-part) is sourced from the *United Nations E-Government Survey* published by the United Nations Department of Economic and Social Affairs (UN DESA). The index is compiled by the Division for Public Institutions and Digital Government and measures the extent to which governments use online tools to facilitate information provision, public consultation, and citizen participation in decision-making processes. This index can more directly reflect the dimensions of interactivity and public participation in digital governance and thus serves as a substitute indicator for verification.

3.2.3 Control variables

Building on existing research into the determinants of national digital governance (Horobeţ et al., 2023; Haug et al., 2023; Li and Yan, 2024), we employ a set of control variables to achieve full model specification. The measurement indicators and their respective data sources are summarized in Tables 1, 2.

As shown in Table 2, the mean value of the explained variable DG is 0.49, and its standard deviation is 0.23. This indicates that there are certain disparities in the digital governance levels among countries, yet the overall distribution remains relatively concentrated. Among the explanatory variables, PR has a low mean value (1.45) but a large standard deviation (2.06), with a maximum value of 11.84. This suggests that some countries face heightened climate-related physical risks. The distribution of TR shows similar characteristics, with a mean of 0.64, a standard deviation of 0.89, and a maximum value of 4.73, reflecting significant variations in the number of climate policies enacted across countries.

4 Empirical results

4.1 Baseline regression results

Table 3 presents the baseline regression results that examine the impact of climate risk on digital governance (DG) of the

TABLE 1 Definitions and data sources of control variables.

Variable name	Abbreviation	Measurement indicator	Data source
Economic structure	ES	Service sector (% of GDP)	World bank, *World Development Indicators (WDI)*
Financial development	FD	Domestic credit to the private sector (% of GDP)	World bank, *WDI*
R&D intensity	RD	Research and development expenditure (% of GDP)	World bank, *WDI*
Level of investment	INV	Gross fixed capital formation (% of GDP)	World bank, *WDI*
Urbanization rate	UR	Urban population as a percentage of total population	World bank, *WDI*
Climate exposure	CE	Annual climate risk index score published by Germanwatch	*Global Climate Risk Index* (Germanwatch reports)
Logged per capita income	PCI	Natural logarithm of Gross national income (GNI) *per capita*	World bank, *WDI*
Institutional quality	IQ	Average of "government effectiveness" and "rule of law" indicators	World bank, *Worldwide Governance Indicators (WGI)*
Industrial intelligentization scale	IIS	Ratio of value added in the service sector to that in the industrial sector	The author's calculation is based on world bank *WDI* data

TABLE 2 Descriptive statistics of main variables.

Variable	Observations	Mean	SD	Min	Max
DG	4,202	0.4926	0.2294	0.0000	0.9847
PR	4,202	1.4494	2.0644	0.0000	11.8377
TR	4,202	0.6382	0.8926	0.0000	4.7274
ES	4,202	26.7204	30.1447	2.0050	329.077
FD	4,202	50.9759	43.2546	0.4980	304.575
RD	4,202	0.4298	0.8651	0.0000	6.0000
INV	4,202	23.1261	7.7253	1.2250	78.001
UR	4,202	57.3512	23.2151	8.9080	100.000
CE	4,202	12.9982	8.9851	0.0759	81.5665
PCI	4,202	8.5844	1.4422	5.5326	12.3683
IQ	4,202	−0.3999	5.3878	−14.4572	11.6813
IIS	4,202	2.3632	2.8213	−20.808	97.006

government. Columns (1) and (2) consider the separate effects of Climate Physical Risk (CPR) and Climate Transition Risk (CTR), respectively, whereas column (3) considers both forms of risks for joint estimation. The effective sample size in the regression analysis is 3,909. This is smaller than the full dataset (4,202 observations) for two main reasons. First, the inclusion of lagged explanatory variables leads to the automatic exclusion of the first-period observation for each cross-sectional unit. Second, a small number of observations were removed due to missing data on government digital governance indicators.

The results suggest that, in the separate regressions in the second column, the coefficient of CPR is 0.006, positive and significant at the 1% level. This shows that an increase in physical climate risk is accompanied by better improvement in the performance of digital governance. In column (2), the TR has a coefficient of 0.034, which is also positive and significant at the 1% level, showing that stronger national climate policy efforts have a positive effect on the development of digital governance. In the joint regression (column 3), the direction and significance of both coefficients remain stable. The coefficient of TR still remains 0.0318, significant at the 1% level, while the coefficient of CPR slightly declines to 0.0023 but remains significant at the 5% level. Both forms of climate risk have independent positive effects on digital governance, with the transition risk having a relatively stronger effect.

4.2 Robustness tests

4.2.1 Considering the lagged effects of the core explanatory variables

In robustness testing, we examines the lag effects of explanatory variables. First, there are inherent lags between policy transmission and governance system adjustments. The impact of climate risks on digital governance needs to be gradually manifested through policy responses and resource allocation, and incorporating lag terms helps to accurately capture its dynamic transmission pathways. Second, using lag variables can mitigate the endogeneity bias caused by reverse causality to some extent. For example, improved digital governance levels may influence disaster monitoring and reporting mechanisms. Finally, by testing multi-period lag effects, we can distinguish whether climate risks drive short-term responses or systemic reforms with lasting impact, thereby revealing the long-term mechanisms through which risks catalyze governance transformation.

As shown in Table 4, the explanatory variables were lagged by 2, 3, and 4 periods. The coefficients for both physical and transition risks remain positive and statistically significant across all these lag specifications. This confirms that their positive impact on government digital governance is persistent, demonstrating a medium-to long-term effect rather than a short-term fluctuation. This significantly strengthens the credibility of our baseline findings.

TABLE 3 Baseline regression results

DG	(1)	(2)	(3)
	Independent effect of PR	Independent effect of TR	Combined effect
Physical risk (PR)	0.0060***		0.0023**
	(0.0008)		(0.0009)
Transition risk (TR)		0.0341***	0.0318***
		(0.0024)	(0.0026)
ES	−0.0002***	−0.0001**	−0.0001*
	(0.0001)	(0.0001)	(0.0001)
FD	0.0006***	0.0005***	0.0005***
	(0.0001)	(0.0001)	(0.0001)
RD	0.0280***	0.0207***	0.0207***
	(0.0026)	(0.0026)	(0.0026)
INV	0.0011***	0.0010***	0.0010***
	(0.0002)	(0.0002)	(0.0002)
UR	0.0001	0.0000	0.0001
	(0.0001)	(0.0001)	(0.0001)
CE	0.0033***	0.0033***	0.0032***
	(0.0002)	(0.0002)	(0.0002)
PCI	0.0742***	0.0720***	0.0724***
	(0.0024)	(0.0024)	(0.0024)
IQ	0.0073***	0.0063***	0.0064***
	(0.0006)	(0.0006)	(0.0006)
IIS	−0.0010	−0.0005	−0.0006
	(0.0009)	(0.0009)	(0.0009)
Constant	−0.2451***	−0.2247***	−0.2303***
	(0.0183)	(0.0179)	(0.0180)
Time FE	YES	YES	YES
Observations	3,909	3,909	3,909
R^2	0.805	0.812	0.813

*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the country level are reported in parentheses. The same applies to the following tables.

4.2.2 Considering the impact of the COVID-19 pandemic

Because the various resources for governance and requirements for policies of different countries may have suffered extreme magnitudes of alteration during the extraordinary shock of COVID-19, we accordingly re-estimated our model, eliminating the sample of 2020–2021, in order not to be disturbed by this extreme exogenous shock. As it appears in columns (1) to (3) of Table 5, the coefficients of both climate physical risk (PR) and transition risk (TR) remain significantly positive at the 1% level and consistent in sign with the coefficients stated above. From this, we conclude that the promoting effect of climate risk on digital governance still obtains under ordinary circumstances and is not influenced by the extraordinary cases presented by the consequences of the pandemic years.

4.2.3 Replacing the dependent variable

In order to avoid some of the shortcomings of a single measure, citizen e-participation (E-part), which reveals the interactive characteristics of digital governance, is used instead as a dependent variable in this study. This measure is concerned with measuring the extent of use of digital outlets by governments for the involvement of citizens in decision-making, which would reveal the "interactivity" and "democratic" aspects of such digital governance.

TABLE 4 Test of lagged effects of explanatory variables.

DG	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	PR lags 2 periods	PR lags 3 periods	PR lags 4 periods	TR lags 2 periods	TR lags 3 periods	TR lags 4 periods	Combined effect lags 2 periods	Combined effect lags 3 periods	Combined effect lags 4 periods
L2_PR	0.0060***						0.0025***		
	(0.0009)						(0.0009)		
L3_PR		0.0056***						0.0024***	
		(0.0009)						(0.0009)	
L4_PR			0.0054***						0.0022**
			(0.0009)						(0.0009)
L2_TR				0.0337***			0.0314***		
				(0.0025)			(0.0026)		
L3_TR					0.0342***			0.0322***	
					(0.0026)			(0.0027)	
L4_TR						0.0338***			0.0320***
						(0.0026)			(0.0027)
Constant	−0.2528***	−0.2594***	−0.2683***	−0.2327***	−0.2415***	−0.2490***	−0.2388***	−0.2476***	−0.2544***
	(0.0186)	(0.0188)	(0.0191)	(0.0181)	(0.0183)	(0.0186)	(0.0183)	(0.0185)	(0.0188)
Controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	3,723	3,537	3,351	3,723	3,537	3,351	3,723	3,537	3,351
R^2	0.808	0.811	0.814	0.815	0.818	0.822	0.815	0.819	0.822

*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

TABLE 5 Considering the impact of the COVID-19 pandemic and replacing the dependent variable.

	(1)	(2)	(3)	(4)	(5)	(6)
	Independent effect of PR	Independent effect of TR	Combined effect	Independent effect of PR	Independent effect of TR	Combined effect
PR	0.0068***		0.0029***	0.0169***		0.0077***
	(0.0009)		(0.0009)	(0.0014)		(0.0014)
TR		0.0361***	0.0330***		0.0863***	0.0787***
		(0.0027)	(0.0028)		(0.0038)	(0.0040)
Constant	−0.2427***	−0.2217***	−0.2286***	−0.0176	0.0379	0.0190
	(0.0198)	(0.0194)	(0.0195)	(0.0296)	(0.0282)	(0.0283)
Controls	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Observations	3,351	3,351	3,351	3,909	3,909	3,909
R^2	0.798	0.805	0.806	0.693	0.718	0.720

*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

TABLE 6 Results of the instrumental variable (IV) estimation.

DG	(1)	(2)	(3)	(4)
	PR: First Stage	PR: Second Stage	TR: First Stage	TR: Second Stage
Peer_PR	0.3427***			
	(0.0551)			
PR		0.0584***		
		(0.0120)		
Peer_TR			0.2988***	
			(0.0438)	
TR				0.3584***
				(0.0537)
Constant	2.5281***	−0.4638***	−0.1812*	−0.1629***
	(0.3345)	(0.0407)	(0.1047)	(0.0444)
Controls	YES	YES	YES	YES
Time FE	YES	YES	YES	YES
F statistic	38.69		46.52	
Kleibergen-Paap rk LM statistic		52.207		45.5 84
Cragg-Donald F statistic		38.685		62.646
Observations	3,909	3,909	3,909	3,909

*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

TABLE 7 Interaction analysis results: the role of public security.

DG	(1)	(2)
	Moderating effect of political stability	Moderating effect of government effectiveness
PR	0.0055***	0.0050***
	(0.0009)	(0.0008)
Political stability	−0.0432***	
	(0.0034)	
PR* political stability	0.0048***	
	(0.0008)	
Government effectiveness		0.0786***
		(0.0051)
PR*Government effectiveness		0.0017**
		(0.0008)
Constant	−0.2557***	−0.0917***
	(0.0180)	(0.0202)
Controls	YES	YES
Time FE	YES	YES
Observations	3,909	3,909
R^2	0.813	0.817

*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

The results in Table 5 Columns (4) to (6) suggest that when e-participation of citizens is used as the dependent variable, the coefficients of the two important explanatory variables remain significant and in the same direction, and thus serve to confirm the robustness of the results of the regression made at the basic level.

4.2.4 Addressing endogeneity

To deal with potential endogeneity of the climate risk variables, this study systematically designs several different sets of instrumental variables (IVs) in order to ensure the consistency and robustness of the estimation results.

Following the approaches of Acemoglu et al. (2016), Colacito et al. (2019) and von Hinke et al. (2019), we construct the instrument as the average climate risk of other countries within the same UN geographical region (Asia, Africa, Europe, the Americas, and Oceania). This strategy leverages the spatial spillover of climate risks across neighboring countries while purging local, domestic confounders. The validity of this instrument rests on two conditions. Relevance is satisfied because physical climate risk exhibits strong spatial correlation; countries within a region share similar climate systems and are often exposed to coordinated transboundary extreme events (e.g., monsoons, droughts), making the regional average a strong predictor of local risk. Exogeneity is maintained as the instrument, by construction, excludes any country's own institutional, economic, or policy factors. Moreover, reverse causality is unlikely since a country's digital governance level cannot objectively influence the climate risks of other nations. Accordingly, an analogous instrument is constructed for climate transition risk to ensure model equivalence and comparability.

The diagnostic tests confirm the validity of our instruments. As is shown in Table 6, the first-stage F-statistics for all the models exceed the Stock-Yogo critical value for weak identification (16.38 at the 10% level), indicating that there is no weak instrument problem present. The p-value associated with each of the overidentifying restrictions tests is larger than 0.05, validating the assumption that the instruments are exogenous. After accounting for the potential endogeneity of the explanatory variables, the coefficients of physical risk and transition risk remain significantly positive, consistent with the baseline regression results.

5 Further analysis

In examining how climate risks affect national digital governance, the impacts are largely moderated by each country's internal institutional and macroeconomic situation. This study proposes to examine the differing mechanisms that underlie these effects through the introduction of two key categories of moderating variables

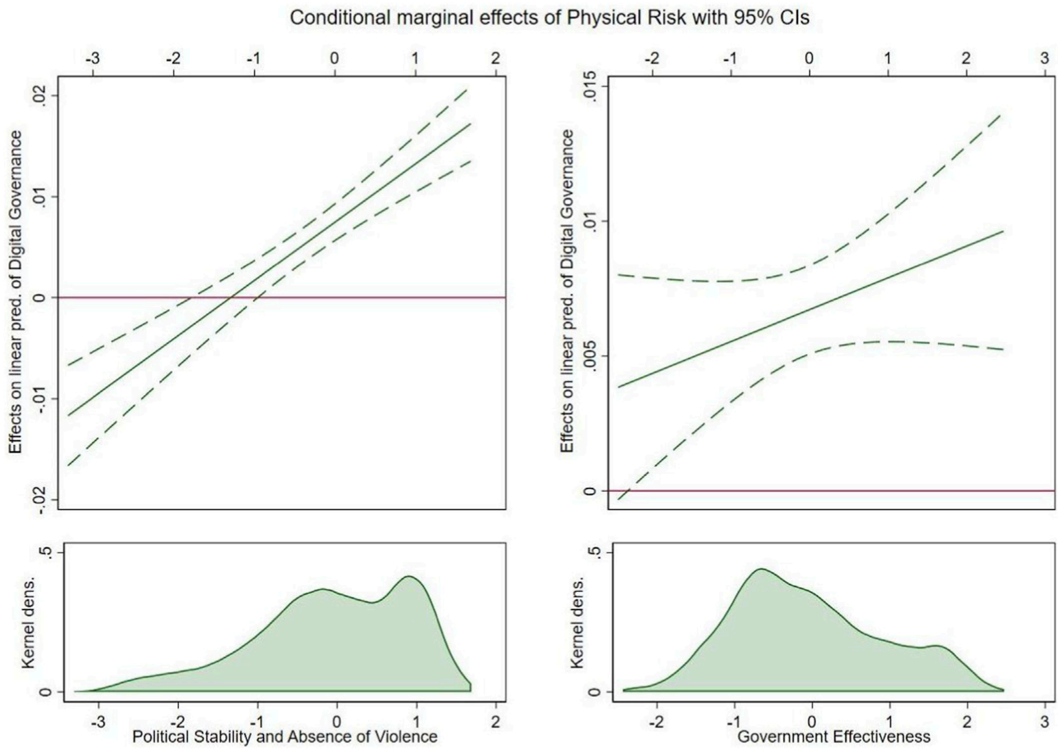

FIGURE 3
Conditional marginal effects of interaction terms for physical risk.

related to climate physical risks and climate transition risks, as described below.

5.1 The moderating role of public security

This research uses two moderator variables among the physical risks of climate: government effectiveness and political stability and the absence of violence. Drawing on the studies of Agheli and Taghvaee (2022) and Gong Y. et al. (2020), political stability and government governance capacity are recognized as important institutional factors influencing environmental governance performance and the ability to respond to climate-related risks. The first one expresses the competence of a country, that is, its capacity for distributing public resources and implementing policies, while the second varies depending on the degree to which the political and social environment is capable of producing security and stability, which guarantees long-term investments in effective governance assignment. Data on government effectiveness and political stability and absence of violence are obtained from the Worldwide Governance Indicators (WGI) compiled by the World Bank.

A highly effective government can enhance emergency response, optimize resource deployment, improve social resiliency, and thereby lessen external shocks and perhaps transform crisis circumstances into advanced opportunities for digital governance reform. A stable political environment, in turn, provides sustained institutional assurance to long-term, capital-intensive digital governance initiatives, reducing policy uncertainty and enhancing the adaptive capacities of governance systems to climate shocks.

The empirical results in Table 7 provide evidence for the moderating mechanisms outlined above. The interaction variables of climate physical risk (PR) with the two moderating variables of government effectiveness and political stability are both significantly positive. Thus, across countries that display higher government effectiveness and political stability, the positive impacts of physical climate risk on digital governance are enhanced.

As shown in Figure 3, the marginal impact of climate physical risk on digital governance grows as government effectiveness and political stability improve. Specifically, an effective government can quickly allocate fiscal and administrative resources to the development of digital infrastructure. Meanwhile, political stability offers the institutional development of credible commitments and policy continuity required for the advancement of such long - term governance investments.

5.2 The moderating role of low-carbon development

About climate transition risks, this study further examines how a country's low-carbon transition pressure and fiscal regulatory capacity moderate the relationship between transition risks and the development of digital governance. Here, two variables are

TABLE 8 Interaction analysis results on low-carbon development.

	(1)	(2)
	Emission pressure	Fiscal pressure
TR	0.0434***	0.0433***
	(0.0046)	(0.0044)
Carbon dioxide emissions	0.0334***	
	(0.0013)	
TR*Carbon dioxide emissions	−0.0090***	
	(0.0008)	
Central government debt		0.0002***
		(0.0001)
TR*Central government debt		−0.0002***
		(0.0001)
Constant	−0.0617***	−0.2871***
	(0.0178)	(0.0279)
Controls	YES	YES
Time FE	YES	YES
Observations	3,347	1808
R^2	0.865	0.815

*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

selected as moderator variables: carbon dioxide emissions (CO_2 emissions) and central government debt (central government debt). According to Hambel and Van Der Ploeg (2025) and Kling et al. (2025), a country's carbon emissions reflect the pressure for emission reduction under a high-carbon economic structure, while central government debt captures its fiscal sustainability and capacity for policy adjustment. Data on CO_2 emissions are obtained from the World Bank's World Development Indicators (WDI), and data on central government debt are sourced from the International Monetary Fund (IMF) and the World Bank.

The regression analyzes in Table 8 provide substantiation for the aforementioned claims. In column (1), the interaction term (TR) by CO_2 emissions is significantly negative at the 1% level, which implies that high levels of emissions weaken the positive effect that transition risks have on digital governance. This implies that a high-carbon structure may limit the power of digital governance to facilitate the green transition. In column (2), similarly, the interaction term for transition risk and central government debt gives significant negative results, which indicates that higher levels of public sector debt weaken the positive effect that transition risks have for digital governance. This indicates the importance of fiscal space afforded for the purposes of digital transformation.

As reflected in Figure 4, as emissions of CO_2 and the debt of the central government rise, the marginal influence of transition risk on digital governance weakens. In particular, in conditions of high emissions and high debt, there is less possibility that the transition risks will work as momentum for improvements in the governance of digitalization. By contrast, in environments characterized by a clear low-carbon orientation and great sustainability of public finances, climate risks still provide a better impulse to help realize the synergistic evolution of digitalization and transformation of a green nature in national governance systems.

6 Conclusions and recommendations

6.1 Main findings

This research addresses the central question of how climate risks influence digital governance, with a focus on public security and low-carbon development. Using panel data from 191 countries covering 2003–2024, the study systematically examines the effects of physical climate risks and climate transition risks on governmental digital governance capacity.

The results demonstrate that climate risk is not merely an environmental challenge but also a critical external driver of digital transformation within national governance systems. Both physical and transition risks significantly enhance digital governance performance, with transition risks exerting a stronger effect.

Further mechanism analyzes reveal that the positive relationship between climate risks and digital governance is contingent upon a country's institutional quality and macroeconomic conditions. In the public security dimension, effective governance and political stability amplify the positive impact of physical risks on digital governance. In the low-carbon development dimension, however, a high-carbon economic structure and substantial government debt weaken the positive influence of transition risks, underscoring the constraining role of fiscal and structural rigidity.

Overall, the findings indicate that the translation of climate risks into digital governance outcomes depends on the interplay between external climatic pressures and domestic governance capacities. Only countries with robust institutions and adequate fiscal space can transform climate-induced crises into opportunities for effective governance innovation.

6.2 Limitations and further discussion

While this paper empirically distinguishes and quantifies climate physical risks and climate transition risks and verifies their significant impact on national digital governance, the limitations of relevant proxy variables still demand careful consideration.

Although the climate risk indicators employed in this paper enjoy high acceptability in the existing literature, their cross-border comparability may still be influenced by factors such as disparities in data sources, inconsistent statistical standards, and varying national disaster reporting capabilities. Particularly in sample countries with substantial differences in development levels and institutional governance capabilities, climate risk observations may, to some extent, simultaneously reflect national governance and statistical capabilities.

Additionally, the physical and transition risk indicators are hard to completely seperate from broader development-level or institutional capacity factors during construction. For instance,

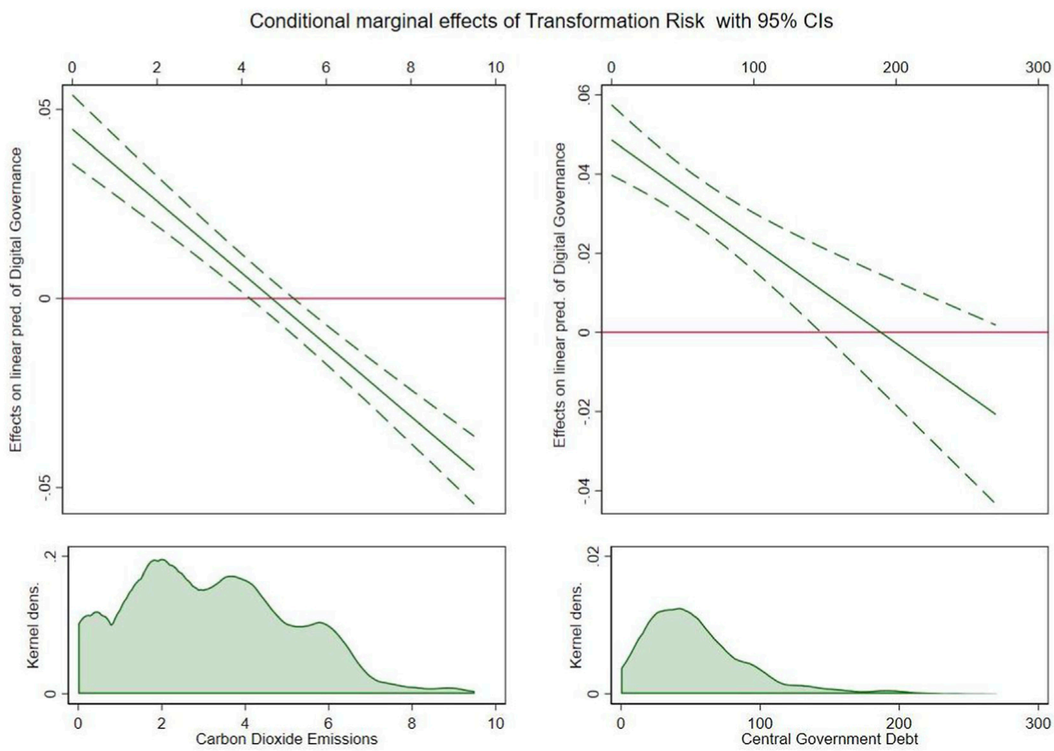

FIGURE 4
Conditional marginal effects of transition risk interaction variables.

fiscal capacity, institutional quality, and industrial structure may affect a country's actual losses in response to climate shocks and shape its digital governance capabilities. This potential overlap implies that although this paper has mitigated endogeneity issues through control and instrumental variable methods, it cannot entirely eliminate the overlap between climate risk indicators and national comprehensive development characteristics.

Future research could advance in several key directions. One priority is the development of internationally comparable measurement methods that isolate "pure" climate impacts, for instance, by constructing risk indicators using objective data like satellite remote sensing. Another vital direction involves conducting case studies or micro-level analyses to reveal how climate risks influence digital governance through specific policy processes and socio-economic mechanisms. Finally, scholars should examine the heterogeneity in risk transformation pathways across nations at different developmental stages, paying particular attention to how institutionally weaker countries overcome resource and capacity constraints to establish foundational conditions for digital governance during crises.

6.3 Policy implications

This paper proposes the following policy implications, aiming to offer actionable approaches for enhancing digital governance for countries, particularly those at different stages of development and confronted with diverse climate risks.

6.3.1 Implementing differentiated digital governance strategies

The study reveals that physical risks and transition risks drive digital governance mechanisms differently, therefore targeted policy design is required.

For countries frequently affected by extreme weather events, governments should prioritize strengthening public safety and emergency management systems. Specifically, investments should focus on climate disaster early-warning systems, real-time monitoring networks, and cross-departmental emergency command platforms. By leveraging digital twin, IoT, and big data technologies, capabilities for pre-disaster simulation, in-disaster response, and post-disaster assessment can be enhanced. Such investments should not be regarded as temporary expenditures but rather integrated into national long-term security strategies, with legislative safeguards ensuring continuous operation and iterative upgrades.

For nations undergoing critical phases of low-carbon transition or facing stringent climate policy pressures, governments should position digital governance as a strategic catalyst for green growth and structural transformation. Policy priorities must shift towards establishing incentive frameworks that drive digital transformation in high-carbon sectors such as energy, transportation, and construction. This may include motivating enterprises to adopt smart grids and intelligent energy management systems through tax incentives and green credit mechanisms. Concurrently, it is crucial to actively develop the digital-green synergistic industries. For example, big data can be used to optimize renewable energy dispatch and blockchain technology can be employed to track carbon footprints.

6.3.2 Building institutional resilience

The research confirms that government efficiency and political stability significantly enhance the positive impact of physical risks on digital governance. Therefore, enhancing institutional resilience is essential to convert climate pressures into governance opportunities.

Governments should focus on improving digital literacy and collaboration capabilities in the public sector through systematic training and organizational reforms. They should break down departmental data silos and establish regular data-sharing and policy coordination mechanisms across environmental, emergency response, health, and economic domains.

Strategic planning and top-level design for digital governance projects must be strengthened to avoid fragmentation caused by crisis-driven reactive responses. It is recommended to establish high-level digital governance promotion agencies responsible for developing a long-term roadmap and overseeing its implementation, ensuring the deep integration of digital transformation with climate adaptation and mitigation goals.

At the legal and regulatory level, efforts should be accelerated to improve legislation related to data security, privacy protection, and digital rights. This will provide stable institutional expectations for the deep application of digital technologies and enhance public trust. Simultaneously, a dynamic evaluation and adjustment mechanism for digital governance projects should be established to ensure their flexibility in adapting to changes in the climate-risk patterns.

6.3.3 Optimizing fiscal resource allocation

This study demonstrates that a high-carbon economic structure and excessive government debt significantly undermine the momentum for digital governance driven by transformation risks. Therefore, overcoming fiscal constraints is crucial to unlocking the potential of digital transformation.

Governments should innovate financing mechanisms in the climate-digital synergy domain. By issuing green sovereign bonds and establishing transition finance instruments, they can channel targeted funds into digital infrastructure and green technology R&D. At the same time, they should clearly allocate cross-sector investments for climate adaptation and digital transformation within fiscal expenditures, establish a performance-based budget allocation model to enhance the efficiency of fund utilization.

For heavily indebted countries, the international community and multilateral development banks should provide concessional financing and technical assistance that combines climate resilience with digital inclusion, helping them bridge the "digital divide" and "adaptation gap". Meanwhile, countries should implement reforms such as carbon pricing and phasing out inefficient fossil-fuel subsidies to increase fiscal revenue and channel private capital into green digital projects.

6.3.4 Promoting inclusive and equitable digital transformation

Climate risks and digital transformation may exacerbate social inequalities. Policy-making must uphold the principles of fairness and justice, designing an inclusive digital governance framework. Specific measures include expanding broadband coverage and digital device access in rural and marginalized communities, offering digital skills training to vulnerable groups, and ensuring their access to climate early-warning systems and digital public services.

During the transition of high-carbon industries, complementary labor retraining programs and social security measures should be implemented to mitigate the employment impacts, allowing workers to integrate into the emerging green digital economy.

6.3.5 Strengthening global and regional cooperation

Climate risks and digital governance are both cross-border issues. Countries should actively participate in the dialogue and formulation of global digital governance and climate governance rules, promoting the establishment of mutually recognized data standards, crisis coordination response protocols, and green digital technology transfer mechanisms.

Regional organizations can take the lead in building public platforms to facilitate experience sharing and joint R&D among member states in areas such as climate risk monitoring and digital solutions for low-carbon technologies. They should particularly assist developing countries in enhancing their relevant capacity-building efforts.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JZ: Methodology, Supervision, Validation, Writing – review and editing, Funding acquisition, Resources, Project administration. ZH: Visualization, Data curation, Conceptualization, Project administration, Formal Analysis, Writing – original draft, Software.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2026.1740695/full#supplementary-material

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