

*Article*

# Does Governance-Based Adaptation Capacity Reduce Human Exposure to Disasters? Evidence from Disaster-Exposed OECD Economies

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**Abstract:** This study examines whether governance-based adaptation capacity reduces human exposure to natural disasters in 14 disaster-exposed OECD countries over the period 2000–2024. Using a two-way fixed-effects framework with Driscoll–Kraay standard errors, the analysis evaluates the joint roles of temperature anomalies, disaster frequency, and governance capacity in shaping the disaster-affected population. The results show that temperature anomalies have a nonlinear effect on human exposure, while disaster frequency increases disaster-affected population across all model specifications. By contrast, governance-based adaptation capacity reduces baseline exposure. In the preferred specification, the coefficient of governance capacity is negative (−0.983), whereas the interaction between disaster frequency and governance capacity is positive (0.071), indicating that institutional capacity lowers baseline vulnerability but does not fully offset the effect of repeated hazard occurrence. These findings suggest that governance-based adaptation plays a protective role, yet its effectiveness remains conditional on the scale and frequency of climate-related hazards. The results underline the importance of strengthening institutional capacity as part of broader disaster risk reduction and adaptation strategies.

**Keywords:** Climate Change; Natural Disasters; Human Exposure; Adaptation Capacity; Governance; Disaster Frequency; OECD Countries

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## 1. Introduction

Climate change has increasingly altered the frequency, intensity, and spatial distribution of natural disasters over recent decades, and this transformation has placed renewed pressure on societies' ability to cope with environmental risks. Although the physical mechanisms behind climate extremes are now relatively well understood, their human consequences remain highly uneven across countries. While some economies experience limited human losses despite recurrent hazards, others face persistent vulnerability even under comparable climatic conditions, which has been widely documented in the disaster governance literature [1, 2]. At the same time, natural disasters no longer represent isolated shocks restricted to low-income or institutionally weak economies. Even advanced OECD countries have witnessed large-scale human impacts from heatwaves, floods, wildfires, and storms in recent years, as illustrated by recent pan-European and global flood assessments [3-5]. Rising temperatures, together with increasing disaster frequency, have amplified the scale of risk faced by densely populated and highly urbanized regions. Hence, disaster

vulnerability has become not only a development issue but also a structural challenge for high-income economies with complex governance systems.

Within this broader transformation, adaptation has emerged as a central policy instrument alongside mitigation. While mitigation efforts aim to slow the accumulation of climate risks, adaptation seeks to reduce the damages generated by unavoidable climate impacts. Yet the effectiveness of adaptation is neither automatic nor uniform. It depends critically on the quality of governance, the coherence of public institutions, and the capacity of states to translate resources into effective risk-reduction mechanisms. Early-warning systems, land-use planning, resilient infrastructure, emergency response coordination, and public communication all operate through institutional channels, and their risk-reducing role has been emphasized in both disaster risk reduction and climate adaptation research [6, 7]. Consequently, adaptation cannot be evaluated solely as a technical investment decision; it is inherently embedded in governance structures.

Despite this recognition, empirical evidence on how governance-based adaptation capacity shapes human exposure to disasters remains fragmented. A substantial part of the existing literature either concentrates on developing countries or focuses on direct mortality outcomes instead of broader measures of human exposure [8-10]. Moreover, most cross-country studies consider climate variables and disaster occurrences as primary drivers, while the moderating role of institutional adaptation capacity is often treated as secondary or indirectly proxied through income levels or development status. This leaves an important gap in understanding how adaptation operates within relatively high-income, institutionally heterogeneous settings such as the OECD.

Against this background, the present study examines how temperature anomalies, disaster frequency, and governance-based adaptation capacity jointly determine human exposure to natural disasters in a group of disaster-exposed OECD economies over the period 2000–2024. Rather than focusing exclusively on economic losses or mortality, the analysis employs disaster-affected population per million inhabitants as the core outcome variable, thereby capturing the realized human dimension of climate-related risks. This perspective allows the study to move beyond abstract vulnerability indices and to assess directly how climatic stress translates into human exposure.

The study is guided by a theoretical framework in which environmental damage arises from the interaction between hazard intensity, exposure, and adaptive capacity. In this structure, adaptation operates through institutional capital that mitigates the welfare consequences of pollution and climate-related shocks, yet with diminishing marginal returns. This theoretical insight motivates an empirical specification in which temperature anomalies generate nonlinear damage effects, disaster frequency reflects hazard intensity, and governance capacity captures the institutional dimension of adaptation. The interaction between governance capacity and disaster frequency is introduced to test whether stronger institutions merely reduce baseline vulnerability or also alter the transmission of hazard intensity into human losses, as suggested by recent institutional disaster studies [1, 2, 10].

Empirically, the analysis relies on a balanced panel of 14 disaster-exposed OECD countries and employs two-way fixed-effects models with Driscoll–Kraay standard errors. This approach explicitly accounts for cross-sectional dependence, heteroskedasticity, and temporal correlation, which are common features of climate–economy data. By integrating nonlinear temperature effects and interaction terms into a unified panel framework, the study provides a comprehensive assessment of how climatic stress and institutional adaptation interact in shaping disaster outcomes.

The contribution of this paper is threefold. First, it offers new empirical evidence on the

nonlinear effects of temperature anomalies on human disaster exposure within advanced economies. Second, it explicitly quantifies the direct and moderating roles of governance-based adaptation capacity, rather than treating institutional quality merely as a background control. Third, by focusing on disaster-affected population instead of fatalities alone, it broadens the empirical understanding of how climate risks translate into human vulnerability.

In this context, this study aims to clarify whether governance-embedded adaptation can effectively reduce human exposure to disasters under rising climatic stress, and whether institutional capacity reshapes the sensitivity of disaster outcomes to increasing hazard intensity. By doing so, it seeks to contribute to the growing policy debate on how adaptation strategies should be designed and prioritized in an era of intensifying climate risks. Accordingly, the empirical analysis is guided by two testable expectations. First, stronger governance-based adaptation capacity is expected to reduce the baseline level of disaster-affected population. Second, the effect of disaster frequency on human exposure is expected to vary systematically with the level of governance-based adaptation capacity.

## **2. Literature Review**

A growing body of empirical research shows that higher adaptive capacity is generally associated with lower disaster vulnerability and reduced human impacts, although the magnitude of this relationship varies across socio-economic and institutional contexts. Household-level and settlement-based evidence further indicates that adaptive capacity strengthens resilience and lowers vulnerability, particularly among disadvantaged and spatially fragile populations. Access to livelihood options, information, and institutional support enables households to absorb climatic shocks more effectively [11-13, 53, 54]. At the same time, these studies also underline that adaptation benefits remain unevenly distributed across societies.

At the community level, ecosystem-based and community-based adaptation strategies emerge as key mechanisms through which adaptive capacity reduces disaster risk. Empirical evidence shows that locally tailored risk-reduction measures, green infrastructure, and ecosystem-based interventions significantly reduce exposure and sensitivity to hazards when they are embedded in effective local governance structures [14-16, 57]. However, where coordination across governance levels is weak, the protective effects of these measures remain limited.

Recent studies further demonstrate that adaptive capacity is not solely determined by income or education. Instead, behavioral and cognitive factors such as risk perception, prior disaster experience, and social trust strongly shape whether available capacity is translated into actual adaptation behavior [17, 18]. This evidence points to a persistent capacity–action gap, whereby existing capacity does not automatically generate effective adaptation unless it is mediated by social and institutional mechanisms [18, 19].

Alongside these micro-level mechanisms, a substantial strand of the literature emphasizes the central role of governance and institutions in shaping disaster vulnerability. Cross-country evidence consistently shows that stronger state capacity and higher institutional quality are associated with lower disaster-related mortality and fewer affected individuals, particularly in the case of predictable hazards such as floods and storms [1, 9, 20]. Moreover, government effectiveness, regulatory quality, rule of law, and control of corruption are found to be systematically linked to lower human losses, whereas weak institutions and corruption amplify exposure and vulnerability [21-23, 55].

Formal disaster risk governance frameworks also play a decisive role in transforming institutional capacity into effective risk reduction. Countries with comprehensive disaster risk laws, inclusive policy processes, and strong multi-level coordination mechanisms tend to experience fewer human losses following extreme events [24-26]. At the local scale, participatory governance, effective resource allocation, and inter-agency coordination further enhance community resilience and reduce human vulnerability [27-29].

A closely related literature focuses explicitly on the role of institutions in reducing disaster-related human losses. Early cross-country studies show that higher institutional quality is associated with significantly fewer disaster fatalities [8, 30], while more recent global assessments confirm that improvements in disaster risk management governance systematically reduce mortality and exposure [9, 10]. These institutional effects are particularly pronounced in democratic settings with high accountability, although democracy alone is insufficient where institutional effectiveness remains weak [2, 31].

Climate adaptation policies constitute another critical channel through which human exposure to disasters can be reduced. Empirical evidence shows that ecosystem-based adaptation, early-warning systems, and structural flood-protection measures significantly lower disaster-affected population levels when they are integrated into broader risk-reduction frameworks [3-7]. In addition, community-based and decentralized adaptation strategies enhance resilience when they are supported by inclusive governance and long-term policy commitment [32-34].

Nevertheless, the literature also highlights important limitations. The effectiveness of both institutional capacity and adaptation policies varies substantially across regions, hazard types, and development levels. Fragmented governance structures, limited financial resources, and short-term planning horizons frequently undermine the long-term benefits of adaptation investments [33, 35, 36, 56]. Similar patterns are also reported in global city-level analyses of post-disaster adaptation responses [37]. Moreover, some hard-infrastructure measures may entail adverse long-run consequences when they are not aligned with broader spatial planning and risk-management strategies [3, 33]. This spatial dimension is particularly important in shaping the long-term interaction between resilience, vulnerability, and adaptation in metropolitan areas [38]. European case-study evidence further shows that disaster risk reduction and climate adaptation are most effective when they are systematically integrated into urban and territorial planning frameworks [39]. Local flood case studies further indicate that weak institutional coordination and fragmented governance structures translate root socio-economic causes into persistent urban risk conditions [40].

Taken together, this literature establishes that adaptive capacity, governance quality, and institutional strength jointly shape human exposure to disasters. While adaptive capacity and climate adaptation policies can significantly reduce disaster impacts, their effectiveness critically depends on the institutional and governance environment in which they operate. This integrated perspective provides the conceptual foundation for empirically examining how governance-based adaptation capacity moderates the effects of temperature anomalies and disaster frequency on disaster-affected population, as undertaken in the present study.

### **3. Theoretical Model**

To examine the joint dynamics of climate-related disaster exposure and adaptation capacity, we develop a continuous-time social planner framework. The model is based on a stylized production

economy in which human disaster losses are shaped by climatic stress, hazard frequency, and governance-based adaptive capacity. For analytical simplicity, labor input is normalized, and output is represented by a capital-focused Cobb–Douglas production function:

$$Q(t) = AK(t)^\alpha, \quad A > 0, \quad \alpha \in (0,1). \quad (1)$$

In Equation (1),  $Q(t)$  represents total output,  $K(t)$  the physical capital stock,  $A$  the constant technology level, and  $\alpha$  the contribution of capital to output.

The produced output is allocated among consumption  $C(t)$ , capital investment  $I_K(t)$ , adaptation investment  $I_D(t)$ , and abatement spending  $B(t)$ . This resource constraint can be written as in Equation (2):

$$Q(t) = C(t) + I_K(t) + I_D(t) + B(t). \quad (2)$$

The dynamics of the capital stock are determined in the standard manner, with investments increasing capital and depreciation reducing it:

$$\dot{K}(t) = I_K(t) - \mu_K K(t). \quad (3)$$

In Equation (3),  $\mu_K$  is the constant depreciation rate of physical capital. Similarly, in Equation (4), adaptation capital  $D(t)$ , increases with investments and depreciates over time:

$$\dot{D}(t) = I_D(t) - \mu_D D(t). \quad (4)$$

In Equation (4),  $\mu_D$  is the depreciation rate of adaptation capital. Adaptation capital  $D(t)$ , increases with investments and decreases at the depreciation rate  $\mu_D$ . The primary element representing environmental quality is the pollution stock. The law of motion for the pollution stock has a structure where production-related emissions and natural decay operate together. Therefore, the dynamics of the pollution stock are expressed as in Equation (5):

$$\dot{P}(t) = -\delta_p P(t) + \gamma \frac{Q(t)}{1 + B(t)}. \quad (5)$$

In Equation (5),  $\delta_p$  indicates the natural decay rate, and  $\gamma$  represents the pollution intensity dependent on the production scale. According to the equation, as abatement spending  $B(t)$  increases, the pressure on the pollution stock decreases, thus leading to a lower equilibrium pollution level.

In the welfare function, individuals derive utility from consumption and suffer damage from pollution. This damage is mitigated thanks to adaptation investments. The instantaneous flow of social welfare can be defined as in Equation (6):

$$U(C(t), P(t), D(t)) = \ln C(t) - \eta(D(t)) \frac{P(t)^{1+\theta}}{1+\theta}, \quad \theta > 0. \quad (6)$$

In Equation (6),  $\ln C(t)$  represents the logarithmic utility derived from consumption, and  $\theta$  denotes society's sensitivity to environmental damage. The damage term is defined as  $\frac{P(t)^{1+\theta}}{1+\theta}$ , and the intensity of this damage is multiplied by the adaptation function  $\eta(D(t))$ .

A commonly adopted specification for adaptation efficiency with diminishing returns is given in Equation (7), consistent with the damage–adaptation framework proposed by Hritonenko and Yatsenko [41]:

$$\eta(D) = \frac{1}{1 + D}. \quad (7)$$

The function given in Equation (7) has three key properties: (i) if there is no adaptation ( $D = 0$ ), it does not reduce damage, (ii) as  $D$  increases, it reduces damage, (iii) the marginal effect

gradually decreases. Thus, the diminishing returns property of adaptation is mathematically ensured.

In the steady-state analysis, it is assumed that stock variables do not change over time. In this case, setting the derivative of the capital stock to zero yields the equality  $I_K^* = \mu_K K^*$ . That is; to maintain the equilibrium capital level, investment must exactly offset depreciation. Similarly, for the adaptation capital to be maintained in equilibrium, the condition  $I_D^* = \mu_D D^*$  must hold. The steady-state value of the pollution stock can be found by setting (Eq. 5) to zero:

$$P^* = \frac{\gamma}{\delta_p} \cdot \frac{Q^*}{1 + B^*} \tag{8}$$

Equation (8) shows that as production increases, pollution rises, but at the same production level, increasing abatement spending reduces pollution.

The damage term in the welfare function takes the following form in the steady state, given by Equation (9):

$$Damage^* = \frac{1}{1 + D^*} \cdot \frac{(P^*)^{1+\theta}}{1 + \theta} \tag{9}$$

Equation (9) shows that adaptation reduces damage, but the rate of decrease diminishes over time due to the declining marginal effect. Furthermore, it is evident that abatement spending also indirectly reduces damage because it pulls  $P^*$  down.

The optimal level of adaptation investment can be characterized by equating marginal benefit and marginal cost. Taking the derivative of the welfare function with respect to  $D$ , the marginal benefit is obtained as in Equation (10):

$$\frac{\delta U}{\delta D} = -\eta'(D) \cdot \frac{P^{1+\theta}}{1 + \theta} = \frac{1}{(1 + D)^2} \cdot \frac{P^{1+\theta}}{1 + \theta} \tag{10}$$

In Equation (10), the expression is positive and shrinks rapidly as  $D$  grows. That is, the marginal benefit of adaptation has a diminishing structure. This benefit, when equated to the shadow value of a unit of output measured through the resource constraint, reveals the optimal adaptation level. Considering Equation (10), the planner prefers to make more adaptation investment at high pollution levels because the marginal benefit of adaptation will be greater. However, since the benefit declines rapidly as  $D$  increases, beyond a point, the return on additional adaptation spending does not cover its cost.

A similar condition holds for abatement decisions. The marginal benefit of an increase in  $B$  is the gain obtained by reducing the pollution flow. This benefit, when equated to the marginal cost from the resource constraint, determines the optimal abatement level. Thus, in the system, adaptation and abatement emerge as two complementary tools: abatement reduces pollution at the source, while adaptation mitigates the damage caused by pollution

In terms of empirical application, the model has a directly testable structure. The damage function (Eq. 9) can be associated with an observed damage variable (e.g., disaster-induced economic losses or mortality rates). The expected damage can be written between the exposure indicator  $H_{it}$  and the adaptation level  $D_{it}$  in the form of Equation (11):

$$E[Damage_{it}|H_{it}, D_{it}] = \Lambda(H_{it}) \cdot \frac{1}{1 + D_{it}} \tag{11}$$

In Equation (12),  $\beta_0$  denotes the constant term;  $\beta_1$  captures the effect of exposure intensity (e.g., disaster intensity or temperature anomaly);  $\beta_2$  reflects the effect of adaptation capacity;  $W'_{it}$  represents a vector of control variables, such as per capita income and population;  $\gamma$  is the associated

coefficient vector; and  $\varepsilon_{it}$  denotes the error term. Theoretically,  $\beta_2 > 0$  is expected, implying that greater adaptation capacity reduces realized damage.

This theoretical framework jointly considers two main policy instruments for reducing environmental damage:  $B$ , which lowers pollution at the source, and  $D$ , which mitigates the damage caused by environmental stress. The diminishing returns to adaptation provide a coherent basis for both optimal policy analysis and empirical testing. In this framework,  $H_{it}$  denotes the underlying hazard or climate-related stress factor, while  $D_{it}$  captures adaptation capacity. In the empirical analysis, these theoretical concepts are proxied by measures such as temperature anomalies and disaster frequency on the hazard side, and governance-based adaptive capacity on the adaptation side.

In reduced-form empirical specifications where adaptation capacity enters directly rather than through the term  $-\beta_2 \ln(1 + D_{it})$ , its estimated coefficient may appear with a negative sign. This remains fully consistent with the theoretical prediction that greater adaptation capacity reduces realized damage.

#### **4. Methodology and Data**

This section presents the empirical strategy used to examine how temperature anomalies, disaster frequency, and governance-based adaptation capacity shape disaster-affected population in disaster-exposed OECD countries. It first outlines the econometric methodology, data structure, variable construction, model specification, and diagnostic procedures that guide the empirical analysis.

##### *4.1. Methodology*

This study adopts a macro-panel empirical framework to examine how climate-related hazards and governance-based adaptation capacity jointly shape realized human exposure to disasters across countries. This approach is preferred because it relies on directly observable variation in disaster outcomes, temperature anomalies, hazard frequency, and institutional capacity over time. In contrast to survey-based or stated-preference approaches, it allows the analysis to assess how institutional differences are associated with observed human impacts under actual hazard conditions in a comparable cross-country setting.

Given the structure of the data, panel estimation provides an appropriate empirical setting for this purpose, since it exploits both the cross-country and time-series dimensions of disaster exposure. While climate anomalies evolve over time, governance capacity and socio-economic characteristics also display persistent cross-country variation. Therefore, a panel-data framework is well suited to capture the interaction between climatic stress, hazard occurrence, and adaptation-related institutional conditions.

The dependent variable is defined as the inverse hyperbolic sine (IHS) transformation of disaster-affected population per million inhabitants. This variable reflects not only the physical occurrence of disasters but also their realized human impact. Temperature anomalies represent the primary climatic indicator in the model. Since temperature series contain both positive and negative values, they are transformed using the inverse hyperbolic sine (IHS) function. In this way, negative observations are preserved while a log-type interpretation of the coefficients is maintained. Moreover, this transformation reduces the influence of extreme values and improves the statistical stability of

the estimations.

The empirical strategy follows a stepwise specification design. In the first stage, a baseline model is estimated in order to capture the linear effect of temperature anomalies on disaster exposure. At the same time, disaster frequency, governance capacity, per capita income, and urban population are included as control variables. In the second stage, the squared temperature term is added to the model. Thus, the potential nonlinearity of climate-related damages, which is implied by the theoretical framework, can be formally tested. In the final stage, an interaction term between disaster frequency and governance capacity is introduced. Through this interaction, the moderating role of institutional capacity on disaster-related vulnerability is examined directly.

All models incorporate country fixed effects and time fixed effects. Country effects account for unobserved, time-invariant national characteristics such as geographical conditions, institutional traditions, and long-run development patterns. Time effects, on the other hand, control for global shocks and common trends that may simultaneously affect all countries, such as worldwide climate cycles or international economic fluctuations.

Before moving to the estimation phase, a comprehensive set of diagnostic tests is implemented. First, cross-sectional dependence is examined using different versions of the Pesaran CD [42]-[43] test. Since the results indicate the presence of cross-sectional dependence, second-generation panel unit-root tests are subsequently employed. Stationarity is assessed by means of the Pesaran CIPS [44] test and the Karavias–Tzavalis [45] test with structural breaks. In addition, slope homogeneity is evaluated using the Pesaran–Yamagata [46] delta test and Swamy’s test [47].

Model selection is carried out using likelihood ratio tests, the Lagrange Multiplier test, and the Hausman test. While pooled and random-effects alternatives are initially considered, the test results consistently support the use of the fixed-effects specification. Nonetheless, the presence of heteroskedasticity and potential serial correlation remains a concern. Therefore, all fixed-effects models are estimated using Driscoll–Kraay [48] standard errors. This estimator is preferred because it produces consistent inference in the presence of heteroskedasticity, autocorrelation, and cross-sectional dependence at the same time. All empirical analyses, including variable transformations, principal component analysis, diagnostic tests, and fixed-effects estimations, were conducted in Stata 14.2.

#### *4.2. Data and Variables*

The empirical analysis is based on a panel of 14 disaster-exposed OECD countries, namely Australia, Canada, Chile, France, Germany, Greece, Italy, Japan, Korea, Mexico, New Zealand, Spain, Türkiye, and the United States. The sample covers the period 2000–2024. These countries are selected according to two explicit criteria. First, they are OECD members with continuous and reliable macroeconomic, institutional, and climate data over the sample period. Second, the EM-DAT database reports a sufficiently high frequency and intensity of natural disasters for these countries, together with non-negligible human losses. Thus, OECD economies with almost zero disaster impacts in most years are deliberately excluded in order to avoid excessive zero observations that could distort the estimation results.

Table 1 reports the list of variables, their corresponding indicators, and the notations used throughout the empirical analysis

**Table 1.** Variables and Indicators.

Variable group	Description of indicators	Notation
Disaster Losses	Disaster-affected population per million inhabitants (IHS transformed)	ihSA
Hazard Indicators	Annual land-surface temperature anomalies (°C) (IHS transformed)	ihST
	Squared temperature anomaly (IHS transformed)	(ihST) <sup>2</sup>
	Number of disaster events per year (hazard frequency) (log)	lnD
Adaptation Capacity	Governance capacity index based on PCA from the six WGI dimensions (IHS transformed)	ihSG
Interaction Term	Disaster frequency × governance quality	lnD × ihSG
Control Variables	GDP per capita (constant 2015 USD) (log)	lnY
	Total urban population (log)	lnP

Note: A and D are obtained from the EM-DAT International Disaster Database. T is based on modified Copernicus Climate Change Service data processed by Our World in Data. G is constructed by the authors using principal component analysis (PCA) based on the six Worldwide Governance Indicators (WGI) dimensions. DG is computed by the authors as the interaction between D and G. Y and P are obtained from the World Bank World Development Indicators (WDI).

As shown in Table 1, the dependent variable is the disaster-affected population per million inhabitants (A), which reflects the realized human exposure to natural disasters. This variable is obtained from the EM-DAT International Disaster Database. Since its distribution is highly skewed and contains zero values, it is transformed using the inverse hyperbolic sine (IHS) function in the regression analysis.

Temperature anomaly (T) represents the main climatic indicator and is measured as the annual land-surface temperature anomaly in degrees Celsius. These data are based on modified Copernicus Climate Change Service records processed by Our World in Data. Because temperature anomalies take both positive and negative values, they are transformed using the inverse hyperbolic sine (IHS) function in the estimations. In addition, the squared temperature anomaly term (T<sup>2</sup>) is included in order to capture potential nonlinear climatic effects, which are central to the theoretical damage function.

Disaster frequency (D) is measured as the annual number of disaster events and is also obtained from EM-DAT. This variable reflects the intensity of hazard exposure faced by each country. Governance capacity (G), which serves as a proxy for adaptation capacity, is constructed by the authors using principal component analysis (PCA) based on the six dimensions of the Worldwide Governance Indicators (WGI). These dimensions include voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption. The resulting composite index contains both positive and negative values, therefore it is transformed using the inverse hyperbolic sine (IHS) function.

In order to directly test the moderating role of institutional capacity, an interaction term between disaster frequency and governance capacity (DG) is constructed. This variable allows the impact of disaster frequency on disaster-affected population to vary with the level of adaptation capacity. Finally, two macroeconomic control variables are included in all models. GDP per capita (Y), measured in constant 2015 U.S. dollars, captures countries' income levels and development capacity, whereas total urban population (P) controls for demographic concentration effects. Both variables are obtained from the World Development Indicators (WDI) database and are used in logarithmic form.

After defining the variables, Table 2 presents descriptive statistics for the original,

untransformed series.

**Table 2.** Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
A	332	501139.8	4822478.6	0	85119183
T	332	0.0265	0.551	-1.389	1.955
D	330	5.545	6.205	1	43
G	317	0	2.322	-5.848	3.322
Y	331	31544.328	14807.449	5887.686	66682.615
P (million)	332	60.26	63.18	3.32	284.00

Note: Descriptive statistics are reported for the original (untransformed) variables. The regression models use log or inverse hyperbolic sine transformations of some of these variables.

Table 2 indicates substantial variation across countries and over time in terms of disaster exposure, temperature anomalies, disaster frequency, and governance capacity. In particular, the wide range observed in disaster-affected population and disaster frequency highlights the heterogeneous nature of disaster risk among the sampled OECD economies. Moreover, the dispersion in governance capacity confirms that institutional quality differs markedly even among high-income countries.

Following the descriptive overview, Table 3 reports the pairwise correlation matrix for the transformed variables used in the regressions.

**Table 3.** Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) ihsA	1.000							
(2) ihsT	-0.088	1.000						
(3) ihsT2	-0.075	0.470	1.000					
(4) lnD	0.208	0.115	0.007	1.000				
(5) ihsG	-0.145	-0.115	-0.005	-0.257	1.000			
(6) lnD×ihsG	0.027	-0.153	-0.063	-0.294	0.607	1.000		
(7) lnY	-0.104	-0.031	-0.050	0.028	-0.067	-0.112	1.000	
(8) lnP	0.063	0.121	0.075	0.681	-0.437	-0.211	-0.124	1.000

The results in Table 3 reveal that most correlation coefficients remain at moderate levels. While disaster frequency and urban population display a relatively higher correlation, no coefficient approaches a level that would indicate a serious multicollinearity problem. Therefore, the correlation structure suggests that the estimated models are unlikely to suffer from severe collinearity bias, and the individual effects of the explanatory variables can be identified with sufficient precision.

#### 4.3. Empirical Model Specification

This section translates the theoretical disaster–adaptation framework into a set of testable panel-data specifications. Consistent with the theoretical model, realized human exposure to disasters is specified as a nonlinear function of climate-related hazard conditions, with temperature anomalies and disaster frequency capturing the hazard dimension, and governance-based adaptation capacity capturing the institutional adaptation dimension. The empirical strategy proceeds in a stepwise manner to identify (i) the baseline climatic effect, (ii) possible nonlinearities in temperature impacts, and (iii) the moderating role of governance-based adaptation capacity in shaping disaster-related human losses.

The dependent variable is the inverse hyperbolic sine (IHS) transformation of disaster-affected population per million inhabitants ( $A_{it}$ ), which captures realized human exposure in country  $i$  and year  $t$ . Temperature anomalies enter the model through their inverse hyperbolic sine transformation to accommodate negative values and potential nonlinearities. Disaster frequency ( $D_{it}$ ), governance-based adaptation capacity ( $G_{it}$ ), real income per capita ( $Y_{it}$ ), and population size ( $P_{it}$ ) are included as explanatory variables consistent with the theoretical framework.

To operationalize these mechanisms, three nested empirical specifications are estimated. All models incorporate country fixed effects ( $\alpha_i$ ) to account for time-invariant heterogeneity and time fixed effects ( $\gamma_t$ ) to control for common global shocks.

Model 1 - Baseline linear specification:

$$ihsA_{it} = \alpha_i + \gamma_t + \beta_1(ihsT_{it}) + \beta_2 \ln D_{it} + \beta_3 ihsG_{it} + \beta_4 \ln Y_{it} + \beta_5 \ln P_{it} + \varepsilon_{it} \quad (13)$$

Model (1) in Equation 13 captures the average linear effect of temperature anomalies on disaster exposure while conditioning on disaster intensity, governance quality, and macroeconomic controls. Higher hazard intensity is expected to increase disaster exposure, whereas stronger institutional capacity is expected to mitigate vulnerability.

Model 2 - Nonlinear temperature effects:

$$ihsA_{it} = \alpha_i + \gamma_t + \beta_1(ihsT_{it}) + \beta_2(ihsT_{it}^2) + \beta_3 \ln D_{it} + \beta_4 ihsG_{it} + \beta_5 \ln Y_{it} + \beta_6 \ln P_{it} + \varepsilon_{it} \quad (14)$$

Model (2) in Equation 14 allows for nonlinear temperature effects by augmenting the baseline specification with the squared temperature term. This formulation is consistent with the nonlinear damage function emphasized in the theoretical model.

Model 3 - Moderating role of adaptation:

$$ihsA_{it} = \alpha_i + \gamma_t + \beta_1(ihsT_{it}) + \beta_2(ihsT_{it}^2) + \beta_3 \ln D_{it} + \beta_4 ihsG_{it} + \beta_5(\ln D_{it} \times ihsG_{it}) + \beta_6 \ln Y_{it} + \beta_7 \ln P_{it} + \varepsilon_{it} \quad (15)$$

Model (3) in Equation (15) introduces the interaction between disaster frequency and governance quality in order to examine whether institutional capacity moderates the effect of disaster occurrence on human exposure to disasters. A positive interaction coefficient would indicate that the effect of disaster exposure on affected population varies systematically with institutional quality. In this regard, the conditional marginal effect of disaster exposure is given by:  $\partial ihsA_{it} / \partial \ln D_{it} = \beta_3 + \beta_5 ihsG_{it}$

A statistically significant interaction term indicates that the impact of disaster intensity on affected population depends on the level of adaptation capacity, consistent with the central prediction of the theoretical model.

#### 4.4. Panel Diagnostics and Model Selection

Before proceeding to the estimation stage, a series of diagnostic tests is conducted in order to determine the appropriate econometric framework and to ensure the reliability of the inference. Since macro-panel data are often characterized by cross-country interdependence and heterogeneous slope coefficients, these features are explicitly examined prior to model estimation.

Table 4 reports the results of the cross-sectional dependence tests based on several versions of the Pesaran CD statistic.

The test outcomes consistently indicate the presence of cross-sectional dependence for most of the variables, including disaster exposure, temperature anomalies, governance capacity, and the macroeconomic controls. Moreover, the CD statistics for the regression residuals are also statistically

significant. This finding suggests that shocks affecting one country are likely to spill over to others, which is not surprising given the global nature of climate-related risks and economic linkages. Therefore, the assumption of cross-sectional independence is rejected, and the use of second-generation panel methods becomes necessary in the subsequent stages of the analysis.

**Table 4.** CD Test.

Variables	CD	CDw	CDw+	CD*
ihsA	0.540 (0.588)	4.890 (0.000)	105.670 (0.000)	-2.120 (0.034)
ihsT	26.540 (0.000)	1.920 (0.055)	254.810 (0.000)	-0.450 (0.652)
ihsT2	22.380 (0.000)	3.400 (0.001)	220.980 (0.000)	1.140 (0.252)
lnD	1.330 (0.183)	-0.050 (0.963)	116.670 (0.000)	-1.280 (0.202)
ihsG	11.420 (0.000)	-0.090 (0.930)	281.360 (0.000)	-3.370 (0.001)
lnD×ihsG	-0.220 (0.822)	0.070 (0.942)	25.780 (0.000)	-2.710 (0.007)
lnY	32.650 (0.000)	-2.520 (0.012)	316.120 (0.000)	4.680 (0.000)
lnP	44.980 (0.000)	-3.330 (0.001)	425.720 (0.000)	12.670 (0.000)
residual	10.84 (0.000)	2.60 (0.009)	174.79 (0.000)	-0.78 (0.437)

Note: p-values in parentheses. CD: Pesaran [42, 43]; CDw: Juodis and Reese [49]; CDw+: CDw with power enhancement from Fan et al. [50]; CD\*: Pesaran and Xie [51] with 4 PCs.

Following the detection of cross-sectional dependence, the assumption of slope homogeneity is examined. The results of the slope homogeneity tests are presented in Table 5.

**Table 5.** Slope Homogeneity.

Delta ( $\Delta$ )	Adj. ( $\Delta$ )	Swamy's ( $\chi^2$ ):
-3.068 ( $p = 0.002$ )	-3.454 ( $p=0.001$ )	70.26 ( $p=0.047$ )

Both the Pesaran–Yamagata [46] delta statistics and Swamy [47] test strongly reject the null hypothesis of homogeneous slope coefficients across countries. This outcome implies that the magnitude of the estimated relationships varies across the sample, even among OECD economies. Hence, treating all countries as structurally identical would be overly restrictive. The presence of slope heterogeneity further supports the use of fixed-effects estimators with robust standard errors that allow for cross-sectional dependence and parameter heterogeneity.

Together, the results reported in Tables 4 and 5 justify the subsequent use of second-generation unit-root tests and robust panel estimators. They also confirm that both cross-sectional dependence and parameter heterogeneity are important features of the data-generating process in this study, and therefore must be explicitly accounted for in the empirical analysis.

Following the evidence of cross-sectional dependence and slope heterogeneity, the time-series properties of the variables are examined using second-generation unit-root tests, which explicitly account for cross-sectional dependence.

Table 6 reports the results of the Pesaran CIPS [44] test and the Karavias and Tzavalis [45] test with one structural break.

The findings indicate that the majority of the variables are stationary at levels. In particular, the logarithm of disaster-affected population, the inverse hyperbolic sine transformation of temperature anomaly, its squared term, disaster frequency, and the interaction term are all found to be stationary at conventional significance levels. By contrast, governance capacity, GDP per capita, and urban population appear to be non-stationary in levels. However, these variables become stationary after first differencing.

**Table 6.** Unit-root test.

Variables	Pesaran (CIPS stat.)		Karavias and Tzavalis (minZ-stat.)	
	Level	1st diff.	Level	1st diff.
ihSA	-2.339***		-23.439***	
ihST	-4.880***		-15.601***	
ihST2	-3.330***		-4.943***	
lnD	-4.942***		-22.494***	
ihSG	0.593	-3.411***	-0.621	-6.007***
lnD×ihSG	-2.673***		-16.332***	
lnY	0.568	-2.154**	-0.089 ***	
lnP	1.858	-1.605**	-0.913	-9.631***

Note: Significance: \*\*\* p<0.01, \*\* p<0.05, \* p<0.1. First-difference results are reported only when the level series is non-stationary. The Karavias and Tzavalis unit root test is implemented with one structural break and bootstrap critical values based on 100 replications.

These results in Table 6 suggest that the variables exhibit a mixed order of integration, with a combination of I(0) and I(1) processes. Nevertheless, since no variable is integrated of order two or higher, the panel remains suitable for fixed-effects estimation with robust standard errors. Moreover, the stationarity of the dependent variable in levels further supports the validity of the subsequent regressions. The inclusion of structural breaks in the Karavias–Tzavalis [45] test also strengthens the robustness of the inference against potential regime shifts in climate and institutional dynamics.

Following the unit-root analysis, the panel-data specification is determined through relevant tests, with the results reported in Table 7.

**Table 7.** Panel effects and model selection tests

Panel effect tests	Individual Effect	Time Effect	Joint Effect
LR	$\chi^2= 50.60$ (0.000)	$\chi^2= 31.68$ (0.1069)	$\chi^2= 31.08$ (0.7422)
F	F= 43.44 (0.000)	F= 25.04 (0.3484)	F= 28.56 (0.8386)
Model Specification Tests			
LM	$\chi^2= 34.28$ (0.000)		
Hausman Test	$\chi^2 = 6.31$ (0.3894)		

Note: p-values in parentheses.

The likelihood ratio and F tests strongly support the presence of individual (country-specific) effects, whereas the null hypothesis of no individual effects is clearly rejected at conventional significance levels. By contrast, the tests for pure time effects and joint effects do not yield statistically significant results. These findings suggest that unobserved heterogeneity across countries plays a dominant role in shaping disaster exposure, whereas common time-specific shocks are less pronounced once country effects are controlled for.

To further discriminate between alternative panel estimators, the Lagrange Multiplier (LM) test and the Hausman test are employed. The LM test rejects the pooled OLS specification in favor of a panel-based estimator. Meanwhile, the Hausman test fails to reject the null hypothesis that the difference between the random-effects and fixed-effects estimators is not systematic. Nevertheless, given the previously documented cross-sectional dependence and slope heterogeneity, the fixed-effects specification is retained on methodological grounds. Although time effects are not strongly supported in isolation, year fixed effects are included to absorb common global shocks. Accordingly, all subsequent estimations are conducted within a two-way fixed-effects framework with Driscoll–Kraay standard errors.

After selecting the fixed-effects specification, a final set of model validity diagnostics is performed. The results of these tests are reported in Table 8.

**Table 8.** Model validity tests.

Modified Wald (H0: groupwise heteroskedasticity)	$\chi^2= 75.34 (0.000)$
Jochmans portmanteau test (H0: no autocorrelation of any order)	$\chi^2= 14.000 (0.4497)$
Mean VIF	1.77 < 5

Note: p-values in parentheses.

The Modified Wald test strongly rejects the null hypothesis of homoskedasticity, indicating the presence of groupwise heteroskedasticity across countries. However, the Jochmans portmanteau test [52] fails to reject the null hypothesis of no serial correlation, which suggests that autocorrelation is not a major concern in the estimated models. In addition, the mean variance inflation factor (VIF) is well below the commonly accepted threshold of five. This implies that multicollinearity does not pose a serious threat to the reliability of the coefficient estimates.

Taken together, the findings reported in Tables 4 through 8 indicate that the empirical setting is characterized by cross-sectional dependence, slope heterogeneity, and heteroskedasticity. Therefore, conventional standard errors would lead to biased inference. For this reason, all fixed-effects models are estimated using Driscoll–Kraay [48] standard errors, which remain consistent in the simultaneous presence of these econometric issues.

#### 4.5. Estimation Results

The estimation results obtained from the two-way fixed-effects models with Driscoll–Kraay [48] standard errors are reported in Table 9. Three specifications are estimated in a stepwise manner in order to assess the linear temperature effect, potential nonlinearities, and the moderating role of governance capacity.

**Table 9.** Two-way fixed effects with Driscoll–Kraay standard errors.

Variables	Model 1		Model 2		Model 3	
	Coef.	Std.Err.	Coef.	Std.Err.	Coef.	Std.Err.
ihsA						
ihsT	0.654*	0.367	-0.695*	0.368	-0.830**	0.367
ihsT2	–	–	0.662**	0.299	0.597***	0.312
lnD	0.107***	0.035	0.135**	0.055	0.120***	0.033
ihsG	-0.779***	0.252	-0.780***	0.251	-0.983***	0.357
lnD×ihsG	–	–	–	–	0.071**	0.025
lnY	-0.811***	0.225	-0.817***	0.238	-0.754***	0.254
lnP	5.371**	5.802	5.286**	2.457	5.790**	2.342
_cons	21.473***	5.802	21.460***	5.788	24.632***	5.598
R-squared	0.300		0.301		0.359	
Chi-square	20.976***		21.015***		32.750***	

Note: \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

In Model 1, the coefficient of temperature anomaly is positive and statistically significant at the 10 percent level. This result suggests that temperature deviations from long-run norms are associated with higher disaster-affected population, once disaster frequency, institutional capacity, and macroeconomic controls are taken into account. At the same time, disaster frequency exhibits a positive and highly significant effect on disaster-affected population. Thus, as the number of disaster

events increases, human exposure to disasters rises in a systematic manner. By contrast, governance capacity enters with a negative and statistically significant coefficient, which implies that stronger institutional capacity is associated with lower levels of disaster-affected population. This finding is consistent with the adaptation mechanism emphasized in the theoretical framework. Income per capita also displays a negative and significant coefficient, indicating that wealthier economies experience lower human exposure to disasters, *ceteris paribus*. Urban population, on the other hand, enters with a positive coefficient, which reflects the greater concentration of people in risk-prone areas.

In Model 2, the squared temperature term is introduced in order to test for nonlinear climatic effects. While the linear temperature term becomes negative and remains weakly significant, the squared term appears with a positive and statistically significant coefficient. This pattern points to a nonlinear, convex relationship between temperature anomalies and disaster-affected population. Accordingly, small temperature deviations may not immediately intensify human exposure, whereas larger anomalies lead to a disproportionately higher disaster impact. Disaster frequency and governance capacity preserve both their signs and statistical significance, which confirms the stability of their effects across alternative specifications. Similarly, the coefficients of income and urban population remain largely unchanged, which further strengthens the robustness of the baseline results.

In Model 3, the interaction term between disaster frequency and governance capacity is introduced to explicitly test whether governance-based adaptation capacity moderates the effect of hazard occurrence on realized human exposure. The interaction coefficient is positive and statistically significant at the 5 percent level. This result indicates that the marginal effect of disaster frequency on the disaster-affected population varies systematically with the level of governance capacity. At the same time, the direct effect of governance remains negative and significant, suggesting that, on average, stronger institutional capacity continues to reduce baseline human exposure to disasters. Nevertheless, the interaction term shows that this mitigating effect is not uniform across different hazard conditions; rather, the effect of disaster frequency on realized human exposure depends on the level of governance-based adaptation capacity.

Across all three models, the explanatory power improves gradually, with the R-squared increasing from 0.30 in Model 1 to 0.36 in Model 3. In addition, the joint significance of the regressors is confirmed by the chi-square statistics, which are significant at the one-percent level in all specifications. Hence, the inclusion of nonlinear temperature effects and the interaction term yields additional explanatory content beyond the linear benchmark model.

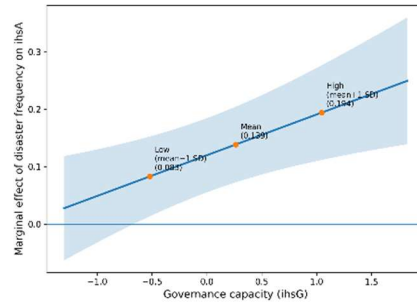
#### 4.6. Marginal Effect of Disaster Frequency Conditional on Adaptation Capacity

While the interaction term in Model 3 provides statistical evidence of moderation, its economic interpretation requires an explicit evaluation of marginal effects. Therefore, the conditional marginal effect of disaster frequency on the IHS-transformed disaster-affected population is computed at different levels of governance capacity. The marginal effect is derived from Model 3 and evaluated at three representative values of the adaptation capacity indicator, namely low (mean - 1 standard deviation), medium (mean), and high (mean + 1 standard deviation).

$$\frac{\partial ihsA_{it}}{\partial \ln D_{it}} = \beta_3 + \beta_5 \cdot ihsG_{it} = 0.120 + 0.071 \cdot ihsG_{it}$$

**Table 10.** Marginal effect of disaster frequency at different levels of adaptation capacity.

Adaptation Capacity Level	ihsG Value	Marginal Effect
Low (Mean - 1 SD)	-0.5204	0.0830
Medium (Mean)	0.2623	0.1386
High (Mean + 1 SD)	1.0450	0.1942



The numerical results of this exercise are reported in Table 10. At the low level of governance capacity, the marginal effect of disaster frequency is estimated at 0.0830, which indicates that an increase in the number of disaster events leads to a relatively modest rise in the disaster-affected population when institutional capacity is weak. At the mean level of governance, the marginal effect increases to 0.1386, which suggests that the sensitivity of disaster exposure to disaster frequency becomes stronger as institutional capacity improves. Finally, at the high level of governance capacity, the marginal effect rises further to 0.1942.

This pattern indicates that the marginal impact of disaster frequency on human exposure becomes larger as governance capacity increases. At first glance, this result may appear counterintuitive. However, it reflects the fact that countries with stronger institutions tend to have more comprehensive reporting systems, better disaster registration mechanisms, and more precise population impact assessments. Therefore, as disaster frequency rises, a greater share of affected individuals is formally recorded in high-governance settings. At the same time, this finding does not contradict the negative direct effect of governance observed in the regression results. On the contrary, while governance reduces the baseline level of disaster exposure, it also sharpens the responsiveness of measured disaster impacts to variations in disaster intensity. The accompanying graph supports this interpretation by illustrating that the marginal effect of disaster frequency increases monotonically with adaptation capacity, together with its confidence band.

Finally, the marginal effect analysis confirms that adaptation capacity does not eliminate the effect of disaster frequency; rather, it reshapes how strongly disaster events are translated into observed human losses. This result is fully consistent with the theoretical prediction that adaptation mitigates vulnerability but does not completely neutralize exposure to climate-related hazards.

## 5. Discussion

While temperature anomalies and disaster frequency emerge as the main drivers of human exposure to disasters, the findings also show that governance-based adaptation capacity shapes both the level of this exposure and the way in which hazard conditions are translated into observed human impacts. In this sense, disaster vulnerability in OECD countries depends not only on climate-related stress and hazard occurrence, but also on the institutional setting through which these shocks are mediated.

The positive association between disaster frequency and the disaster-affected population across all model specifications indicates that repeated hazard occurrence remains a major source of human vulnerability. This result is consistent with the theoretical expectation that more frequent shocks lead

to greater realized damage. At the same time, the strong statistical significance of this variable makes it clear that, even among high-income OECD countries, disaster risk remains substantial and continues to generate measurable human consequences. Similarly, the nonlinear effect of temperature anomalies suggests that climate-related damages become much stronger once temperature deviations pass certain levels. In other words, moderate temperature changes may generate limited additional exposure, whereas larger anomalies appear to produce a much sharper increase in the disaster-affected population. This convex pattern fits well with the theoretical damage function and supports the argument that climate change brings not only gradual but increasingly amplified risks for human systems.

The consistently negative coefficient of governance capacity points to the protective role of institutional adaptation. Countries with stronger governance structures, more effective regulatory systems, and higher administrative capacity tend to experience lower levels of human exposure to disasters, even under similar climatic and hazard conditions. This finding provides clear support for the adaptation channel emphasized in the theoretical framework. At the same time, the marginal effect analysis adds an important qualification. Although stronger governance reduces the overall level of disaster-affected population, the marginal effect of disaster frequency becomes larger as governance capacity improves. As shown in Table 10 and the accompanying graph, this marginal effect rises steadily from low to high levels of adaptation capacity. At first sight, this pattern may seem unexpected. However, a plausible explanation is that countries with stronger institutions also tend to have more complete reporting systems, better disaster registration mechanisms, and more accurate impact assessments. For this reason, when disaster frequency increases, a larger share of affected individuals may be formally identified and recorded in high-governance settings. Accordingly, this result should not be interpreted as contradicting the protective role of governance. Rather, it suggests that adaptation mainly works by lowering baseline vulnerability, even though it does not fully eliminate the responsiveness of observed disaster impacts to hazard occurrence.

The negative association between income per capita and disaster-affected population also supports the role of economic capacity in strengthening resilience, while the positive coefficient on urban population points to the vulnerability-increasing effect of demographic concentration. Taken together, these findings support the central expectations of the theoretical framework. Disaster frequency and temperature anomalies increase human exposure to disasters, whereas governance-based adaptation capacity reduces the baseline level of vulnerability. Even so, adaptation does not completely block the translation of hazard conditions into realized human impacts. Instead, it reshapes vulnerability in a manner that remains consistent with diminishing marginal returns to adaptation.

## **6. Conclusion**

This study examines how temperature anomalies, disaster frequency, and governance-based adaptation capacity jointly shape human exposure to natural disasters in a group of disaster-exposed OECD economies over the period 2000–2024. While the theoretical framework emphasizes the dual roles of mitigation and adaptation in reducing climate-related damages, the empirical analysis focuses on the adaptation channel and evaluates its effectiveness under varying levels of climate-related stress and hazard occurrence.

The empirical results indicate that disaster frequency remains a fundamental driver of human exposure to disasters, even among high-income countries. In addition, temperature anomalies exhibit a nonlinear effect on the disaster-affected population, implying that climate-related damages increase disproportionately once temperature deviations become sufficiently large. This finding suggests that climate risks do not evolve in a linear and predictable manner. Instead, extreme temperature conditions generate amplified human impacts, thereby strengthening the urgency of effective adaptation strategies.

Governance capacity emerges as a key protective factor throughout the analysis. Countries with stronger institutional structures, higher regulatory quality, and more effective public administration experience systematically lower levels of disaster-affected population. This result confirms that adaptation capacity, when embedded in sound governance frameworks, plays a central role in reducing baseline vulnerability to natural hazards. However, the marginal effect analysis also shows that governance does not completely insulate societies from the effects of rising disaster frequency. While institutions reduce the overall level of human exposure, they do not fully eliminate the responsiveness of observed human impacts to repeated hazard occurrence. Instead, adaptation reshapes vulnerability rather than eliminating it.

The findings also reveal that economic development contributes to resilience, since higher income per capita is associated with lower human exposure to disasters. Nevertheless, income alone does not substitute for institutional quality. Even in relatively wealthy economies, weak governance structures can limit the effectiveness of adaptation efforts. Moreover, the positive effect of urban population on disaster exposure suggests that demographic concentration continues to pose challenges for disaster risk management, particularly when urban expansion is not aligned with climate-resilient planning.

From a policy perspective, these results underline that investments in physical protection and early-warning systems must be complemented by sustained improvements in institutional quality. While financial resources are important, their effectiveness ultimately depends on governance arrangements that ensure efficient allocation, transparent implementation, and rapid emergency response. Therefore, adaptation policies should not be viewed solely as technical or infrastructural interventions; rather, they should be embedded in broader institutional reforms that enhance state capacity, regulatory effectiveness, and public trust.

More specifically, three policy implications follow from these findings. First, reducing baseline human exposure requires sustained improvements in governance quality, particularly in areas such as administrative effectiveness, coordination capacity, and implementation credibility. Second, adaptation policies should not rely solely on institutional strength in a narrow sense, since repeated hazard occurrence continues to translate into measurable human impacts even under stronger governance conditions. Third, adaptation planning should be integrated with broader disaster risk reduction strategies, including early-warning systems, risk monitoring, and urban resilience policies, in order to address both baseline vulnerability and the growing intensity of climate-related hazards.

## **7. Limitations and Future Research Directions**

While this study provides robust evidence on the roles of climate anomalies, disaster frequency, and governance-based adaptation capacity in shaping human exposure to disasters, several limitations should be noted.

First, the analysis uses disaster-affected population as the main outcome variable. Although this measure captures the human dimension of disaster impacts in a comparable way, it does not fully account for economic losses, infrastructure damage, or longer-term welfare effects. Future research may extend the analysis by using alternative damage indicators, including direct economic loss measures and sector-specific impact data.

Second, adaptation capacity is proxied by a composite governance index based on the WGI dimensions. This provides a broad measure of institutional quality, but it does not allow the effects of individual governance components to be identified separately. Future studies could examine which dimensions of governance—such as government effectiveness, regulatory quality, or rule of law—are most relevant for reducing disaster vulnerability.

Third, the sample is limited to disaster-exposed OECD countries. This improves comparability across countries but may limit the generalizability of the findings to lower-income or institutionally weaker settings. Future research could test the same framework in broader country samples or through comparative analyses across income groups.

These limitations do not alter the central conclusion of the study, but they point to useful directions for refining the measurement of disaster impacts and the institutional channels of adaptation.

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