FINANCING CLIMATE RESILIENCE: ESTIMATING INDIA'S DAMAGE COSTS

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439
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Table of Contents

Abstract i

Acknowledgement ii

1. Introduction 1

2. Policy Relevance 2

3. Research Objectives 3

4. Methodology 4

4.1 Exposure Indices 4

4.1.1 Rainfall Variability Index 5

4.1.2 Flood Exposure Index 6

4.1.3 Drought Exposure Index 6

4.1.4 Heat Stress Index 7

4.1.5 Sea Level Rise Exposure Index 7

4.2 Estimation of Impact Pathways 8

4.2.1 Systematic Literature Review 8

4.2.2 Impact Pathways Coefficients 9

4.2.3 Estimation of Change in Climate Parameters 11

4.3 Damage Costs 12

5. Results and Discussions 14

5.1 Exposure Indices 14

5.2 Economic Impact of Climate Change 15

5.2.1 Heat Stress 17

5.2.2 Sea Level Rise 20

5.2.3 Water Stress 20

5.3 Climate-Induced Damage: Costs for India 23

6. Conclusion 26

7. Way Forward 27

8. Policy Recommendations 28

References 31

List of Figures

Figure 1: Multi-Step Framework to estimate EICC 4
Figure 2: Climate Stressors and Transmission Pathways 10
Figure 3: Methodology for Estimating the Damage Costs 13
Figure 4: Climate Risk Transmission Pathways and Associated GDP Impact (2022-23) 24
Figure 5: EICC as a Share of GDP: By Sector 26

List of Tables

Table 1: Climate Stressors Data Sources - Exposure Indices 5
Table 2: Exposure Indices for Different Climate Stresses 15
Table 3: Expected Loss Due to Climate Stressors: Across all Impact Pathways 16

Abstract

The rapid pace of development and urbanization has exerted mounting pressure on natural resources and increased global warming by altering the planet's radiative forcing, thereby intensifying the frequency and severity of climate-induced events. These events have caused significant socio-economic consequences. Several studies have indicated the immediate, direct economic consequences of climate risks; however, it is imperative to study the indirect and non-economic damages, including lives lost, biodiversity loss, and community displacements, as they also entail insurmountable economic losses. Subsequently, these losses and damages ultimately impede national output. This aggregate economic loss is commonly known as the economic impact of climate change (EICC). The study examined the economy-wide losses through marketable and non-marketable mechanisms and estimated the aggregated EICC at the national level. The analysis revealed that the country is most vulnerable to rainfall variability, followed by floods. Meanwhile, escalating climate risks adversely affect the outputs of electricity, water supply, and other utility sectors, closely followed by the service sector, which recorded a significant decline in output.

At the national level, the EICC was represented as 7.38 per cent of the GDP in 2022-23, underscoring the cost of inaction. This estimate captured annual adaptation-relevant damage costs as a share of GDP and projected them to reach 15.42 per cent in 2050, highlighting the financial resources required to mitigate future climate impacts. From a sectoral lens, Electricity, water supply, and other utility services emerged as the most vulnerable, with losses amounting to 3.49 per cent of GDP, followed by the service sector at 2.10 per cent of GDP. By 2050, these impacts are projected to intensify significantly, with the services sector's losses rising to approximately 6 per cent of GDP, followed by agriculture and allied sectors at 5.25%. Heat stress emerged as a major climate stress with significant economic impacts. This paper underscores the need for urgent, targeted investments in climate-resilient infrastructure and sector-specific adaptation strategies to mitigate future impacts.

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Financing Climate Resilience: Estimating India's Damage Costs

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1. Introduction

The macroeconomic implications of climate change are profound and far-reaching, defying conventional assumptions about economic growth and convergence in development. The G20 Finance Ministers and Central Bank Governors acknowledged this urgency, calling for deeper policy engagement on climate-induced macroeconomic risks to support strong, sustainable, and inclusive growth.

Climate change impacts are becoming starkly visible, particularly in developing regions such as Asia and the Pacific, which are warming at a rate faster than the global average. In 2023, these regions experienced their second-highest recorded mean land temperature, 1.87°C above the 1961–1990 average temperature (World Meteorological Organization, 2024), along with a surge in climate-related disasters ranging from floods and storms to heatwaves and droughts. These events are becoming more frequent and intense, placing immense pressure on already resource-constrained economies.

Developing and emerging economies face a disproportionate share of climate-induced losses. Between 2010 and 2019, six of the ten most climate-affected economies were in Asia, with the region regularly experiencing annual economic losses exceeding 1 per cent of Gross Domestic Product (GDP) (ADB, 2016, 2017; David Eckstein et al., 2021). Under high-emissions scenarios, projected losses for South Asia may reach 8.8 per cent of GDP by 2100, with India facing economic impacts of up to 24 per cent of GDP by 2070 and over 35 per cent by 2100, as per Campagnolo et al. (2023).

The transmission mechanisms through which climate change affects the macroeconomy are varied and often non-linear: declining crop productivity yields, disruptions to trade and migration patterns, impact on public health, loss of natural capital, and recurrent fiscal liabilities from disaster response and adaptation expenditures. These channels create compounding risks that undermine long-term growth potential and resiliency building. Stern (2007) review estimated that including monetised non-market impacts on health and environment raises the climate change cost from about 5% to 11% global GDP. However, these aggregate estimates often mask the deeper and localized economic shocks faced by vulnerable regions, particularly in low- and middle-income countries with low adaptive capacity.

Alongside warming trends, climate risks extend beyond extreme disaster events to more systemic disruptions in capital accumulation, labour productivity, industrial output, and water security. Many of these risks have long-term effects, such as the gradual loss of arable land or salinization of freshwater sources, which may not

immediately impact GDP, but significantly weaken economic resilience over time. Dell et al. (2014a) emphasized that quantifying these effects is critical to understanding how climate variability shapes long-run economic growth. This underscores the urgent need for a comprehensive outlook to assess economic risks due to climate change, accounting for a full spectrum of impacts beyond temperature anomalies, including sea-level rise, precipitation variability, and its cascading socio-economic disruptions. Furthermore, these stresses can converge into systemic shocks, overwhelming institutional capacity and undermining both macroeconomic stability and human development.

In this context, adaptation is therefore a sectoral concern and imperative to understand macroeconomic shocks. As highlighted in India's Second Biennial Update Report (MoEF&CC, 2018), adaptation technologies, particularly in agriculture, forestry, health, and water, remain significantly underutilised and underfunded. Scaling up these interventions, particularly through locally tailored and ecosystem-based approaches, is crucial for building long-term resilience.

The 28th UN Climate Conference (COP28) and the fifth meeting of the Parties to the Paris Agreement (CMA5) in 2023 marked a significant milestone with the operationalization of the Loss and Damage (L&D) Fund. This development strengthened international financial mechanisms to address both the economic and non-economic impacts of climate change, particularly for vulnerable countries. Thus, it reflects a growing consensus to move beyond mitigation and place greater emphasis on strategies that enhance economic resilience and social protection amid escalating climate risks.

Against this backdrop, this working paper aimed to understand the macroeconomic implications of climate-induced damages, focusing on the estimated economic losses as a percentage of India's national GDP. Based on the results, the working paper aims to outline the policy recommendations on integrating climate risks into macroeconomic planning and governance frameworks. The insights from the study underscore the urgency of risk-informed economic planning to enhance climate resilience and ensure long-term development sustainability.

2. Policy Relevance

The United Nations Environment Programme (2023a) highlighted a widening disconnect between the rising adaptation needs of developing countries and the shortage of adaptation finance. It is estimated that the developing nations would need USD 215 billion annually to meet their adaptation goals for this decade. However, public adaptation finance from multilateral and bilateral sources fell by 15 per cent in 2021, amounting to just USD 21 billion. Consequently, the adaptation finance gap has widened significantly, now estimated at USD 194–366 billion per year.

Climate change now poses a direct and systemic threat to economic stability, development progress, and fiscal resilience. In India, these impacts are already visible with rising temperatures, erratic rainfall, intensifying floods and droughts, cyclones,

wildfires, and sea-level rise, which are disrupting key sectors such as agriculture, infrastructure, health, and livelihoods. The damages transmitted through interlinked pathways compound over time, weakening the overall economy and exacerbating regional vulnerabilities.

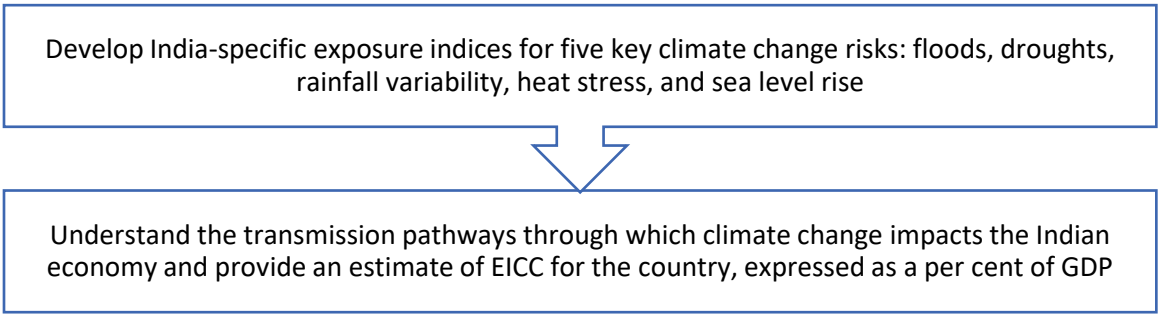
Despite these escalating threats, climate change remains insufficiently integrated into macroeconomic and fiscal policymaking. Most existing policy frameworks often rely on historical trends, future climate impacts and overlook emerging economy-wide risks. Without robust, forward-looking assessments and future projections of climate-related damages, governments risk misallocation of adaptation resources, misinterpretation of climate-driven inflationary pressures, and undermining both fiscal stability and long-term development objectives. This study intended to address this critical policy gap by systematically quantifying climate risks and translating them into sector-wise economic losses. In doing so, it provided a foundation to mainstream climate change into public finance, promoting resilient investments, and informed national development strategies.

3. Research Objectives

Variability in climatic conditions exacerbates socio-economic vulnerabilities, destabilizing the economy and straining financial resources due to mounting losses from severe climate impacts. Quantifying these damages is essential to formulate localized adaptation strategies and safeguard long-term macroeconomic stability. While several studies have attempted to quantify climate-related damages, they offer limited insight into the broader sectoral implications and their aggregate impact on the national GDP. This gap underscores the need to understand the direct and indirect economic losses across sectors, highlighting the urgency for a standardized framework to estimate these losses and lessen the quagmire of complexity.

Building on this narrative, the study aimed to examine the impact of five key climate stresses, such as rainfall variability, floods, droughts, sea level rise, and heat stress, on the Indian economy. These impacts were mapped through sectoral pathways and weighted by exposure indices, which captured the degree to which individuals, communities, and ecosystems are vulnerable to climate-related risks. The resulting Economic Impact of Climate Change (EICC) was expressed as a percentage of national GDP at 2022-23 current prices and projected for 2050.

Broadly, the objectives of the study were to



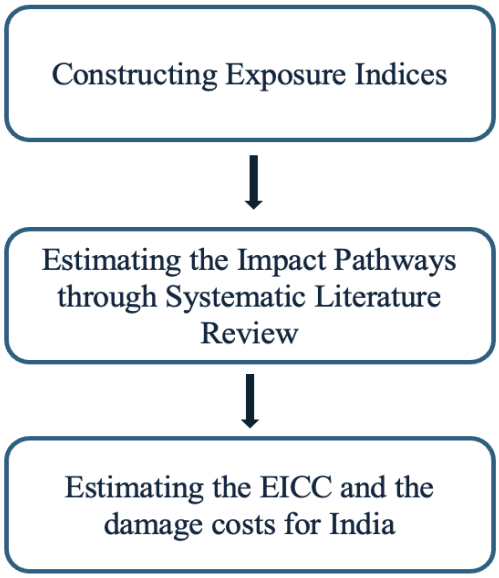
Source: Authors' Construction

Together, these objectives aimed to generate robust, policy-relevant evidence to guide climate-resilient planning, inform sectoral adaptation strategies, and support the integration of climate risk into India's long-term economic and fiscal frameworks.

4. Methodology

As indicated in the research objectives, the study evaluated the economic impact of climate-related damages, focusing on five key climate stresses: heat stress, water stress (including rainfall variability, floods, and droughts), and sea-level rise. The methodology followed the empirical framework established by Nicholson et al. (2023), adapted for the Indian context. As discussed above, the primary objective was to project the EICC as a percentage of GDP for 2050, considering India's economy and need for adaptation finance. To achieve this, an exposure index was calculated to quantify India's vulnerability to each climate stress. This index was then used to scale damage functions, which predicted the maximum sectoral EICC by capturing both direct and indirect economic losses. Finally, the projected EICC was applied across each impact pathway relative to sectoral GDP values to estimate the resultant growth effects.

Figure 1: Multi-Step Framework to estimate EICC



Source: Authors' Construction

4.1 Exposure Indices

The first component of the study aimed to build upon existing evidence to develop India-specific exposure indices for the five identified climate stresses. By focusing on these specific risks, the study provided a comprehensive understanding of the vulnerabilities faced by different regions within India, enabling policymakers to formulate more targeted adaptation strategies and resilience-building measures for the area's most at risk. Exposure to climate change refers to the degree to which individuals, communities, and ecosystems

are vulnerable to climate-related risks, including extreme weather events, shifts in temperature and precipitation patterns, and long-term changes in environmental conditions. Evidence of changing exposure is derived from recent climate-related events, such as floods, droughts, and heatwaves, as well as from climate modelling projections. These sources provide insights into how various regions are being impacted by climate change and how these impacts have evolved. The country's exposure index was determined using the sources of evidence as shown in Table 1.

Table 1: Climate Stressors Data Sources - Exposure Indices

Climate Stressors	Variable Used	Dataset	Spatial Resolution	Temporal Resolution
Rainfall Variability	Annual Rainfall	**IMD[1]**	**Metrological Subdivision**	**Annual**
Flood	Flood-affected area and population affected	**CWC[2]**	**State-wise**	**Annual**
Drought	Precipitation used to calculate SPI	**IMD[3]**	**Metrological Subdivision**	**Annual**
Heat Stress	Daily maximum temperature and no. of heat days	**IMD[4]**	**State-wise**	**Daily**
Sea-Level Rise	Sea-level elevation and population exposure	**IPCC[5]**	**Nationally aggregated**	**Annual**

Source 1: Authors' Construction

4.1.1 Rainfall Variability Index

Rainfall variability refers to fluctuations in the amount of rainfall received in a specific area over a certain period. In this study, the Rainfall Variability Index (RVI) measures interannual variability in annual rainfall relative to its long-term mean. Higher RVI values indicate larger year-to-year deviations from mean annual rainfall, while lower values indicate comparatively stable annual rainfall conditions. The RVI does not measure the frequency, intensity or duration of extreme rainfall events, which require a separate assessment based on daily rainfall.

The methodology to calculate the RVI for a region involved two main steps: first, calculating the variability for each state (sub-division) individually, and then aggregating these values into a national-level index. To calculate the variability for each state (sub-division), the Coefficient of Variation (CV) of the annual rainfall over the period from 1985 to 2015 (time considered for this study) was computed. The CV is a normalized measure that compares the standard deviation of

[1] **India Meteorological Department (IMD)**. *Climate data services portal*. Government of India. Retrieved from https://cdsp.imdpune.gov.in/

[2] **Central Water Commission (CWC)**. *Flood forecasting and water information system*. Ministry of Jal Shakti, Government of India. Retrieved from https://indiawris.gov.in/wris/

[3] **India Meteorological Department (IMD)**. *Climate data services portal*. Government of India. Retrieved from https://cdsp.imdpune.gov.in/

[4] **India Meteorological Department (IMD)**. *Climate data services portal*. Government of India. Retrieved from https://cdsp.imdpune.gov.in/

[5] **Intergovernmental Panel on Climate Change (IPCC)**. (2022). *Sixth Assessment Report (AR6): Impacts, adaptation and vulnerability*. Retrieved from https://www.ipcc.ch/report/ar6/wg2/

annual rainfall to the mean annual rainfall. Once the CV for each state (sub-division) was determined, the next step was to calculate a weighted average of these values at the national level. This accounted for differences in state sizes and their contribution to the total national rainfall. The weight for each state was proportional to its share of total rainfall in the country. The final RVI is then obtained by summing the weighted variabilities for each state. This index provided a comprehensive understanding of the overall rainfall variability across the country, incorporating both the size and rainfall distribution of each state.

4.1.2 Flood Exposure Index

The Flood Exposure Index (FEI) is a composite measure of exposure to flood hazards. It combines two complementary dimensions: the proportion of a region's total area affected by flooding, which represents the physical extent of flood exposure, and the proportion of its population directly affected by flooding, which represents human exposure. The population component does not capture the general population or population density of a region.

The flood-affected area and affected-population ratios were normalised to ensure comparability across regions and years. Equal weights of 0.5 were assigned to the two normalised components as a transparent baseline in the absence of an empirically established basis for prioritising physical extent over human exposure, or vice versa. The resulting index should therefore be interpreted as a balanced composite measure of physical and human flood exposure, rather than as a measure of flood-hazard severity or socio-economic vulnerability alone.

4.1.3 Drought Exposure Index

Drought is a prolonged period of below-average precipitation that can lead to significant water shortages, crop failures, and ecological stress. The Drought Exposure Index (DEI) is a quantitative measure used to assess the degree to which different regions are exposed to drought conditions over time. This index is particularly valuable for identifying areas where drought poses recurring or intensifying risks to agriculture, water security, and livelihoods. In this study, drought exposure was assessed using the Standardized Precipitation Index (SPI), a widely accepted metric that quantifies precipitation anomalies over a minimum of a 30-year timescale. The SPI standardizes rainfall deviations relative to the long-term mean, allowing for comparison across regions with different climatic characteristics. Negative SPI values indicate dry conditions, with more negative values reflecting greater drought severity.

To ensure consistency and comparability across spatial units, the SPI values were normalised, creating a uniform scale of drought exposure. This normalisation allowed regions with different precipitation patterns to be meaningfully compared. The final DEI was derived directly from these normalised SPI values, with lower index scores indicating more frequent or severe drought conditions. The DEI provided a measure of drought exposure across regions, supporting climate risk assessment and resource planning efforts, particularly in drought-prone and agriculturally sensitive areas.

4.1.4 Heat Stress Index

Heat stress represents the direct consequences of rising temperatures, impacting human health, labour capacity, and ecosystem resilience. The Heat Stress Index (HSI) is a composite indicator developed to quantify regional exposure to extreme heat events. It captures both the frequency and intensity of high-temperature conditions, offering a comprehensive picture of heat-related climate stress.

Two primary variables were used to construct the HSI: the number of heat days (defined as days when maximum temperatures exceed a critical threshold, 30°C for hilly areas and 40°C for plains) and the daily maximum temperature (Tmax) over the study period. These components reflected the dual nature of heat stress how often it occurs and how intense it is.

To create a balanced and comparable index, both variables were first normalized to account for regional climatic differences. Equal weights of 0.5 were assigned to each variable, under the assumption that both frequency (heat days) and magnitude (Tmax) contribute equally to heat stress. The weighted average of these normalized values was then calculated to generate the final Heat Stress Index.

Higher HSI values indicated greater exposure to extreme heat, highlighting regions where heat stress is a growing concern. The index served as a valuable tool for guiding adaptation strategies, such as public health preparedness and infrastructure resilience planning in the face of increasing heat extremes.

4.1.5 Sea Level Rise Exposure Index

SLR poses an increasing threat to coastal regions, leading to heightened risks of flooding, shoreline erosion, and saltwater intrusion. The Sea Level Rise Exposure Index (SLREI) is a quantitative measure used to assess the degree to which different coastal areas are exposed to these impacts. This index is particularly valuable for identifying locations where SLR presents significant or growing risks to communities, infrastructure, and ecosystems.

In this study, exposure to SLR was assessed using a set of key indicators, including long-term sea level trends, coastal elevation, and population density. These indicators represented physical vulnerability as well as potential socio-economic consequences. To ensure consistency and comparability across spatial units, indicator values were normalised for comparison across regions with varying characteristics. Following normalisation, each indicator was weighted according to its relative importance in contributing to SLR exposure. The final SLREI was derived by combining these weighted indicator scores into a single composite value. Higher index values reflected greater exposure to SLR and its associated hazards.

The SLREI provided a standardized measure of coastal exposure, supporting efforts to map vulnerability, inform adaptation strategies, and prioritize interventions.

Given that different climate risks affect sectors and regions in varied ways, developing a comprehensive methodology that simultaneously accounts for all risks

prevalent in India is a challenge. Nonetheless, the critical need to understand these impacts has led this study to focus initially on the key climate stresses outlined above, to estimate adaptation-related costs. This targeted approach was justified by the widespread prevalence of these stresses and their substantial influence across multiple economic sectors.

Building on the exposure indices calculated, the next component of the study now involved identifying and quantifying the impact pathways through which these climate stresses translate into economic damages.

4.2 Estimation of Impact Pathways

4.2.1 Systematic Literature Review

The second component of the study focused on delineating the impact pathways through which the identified climate stresses influence economic outcomes across sectors and regions. Impact pathways refer to the mechanisms or channels through which climate risks are translated into tangible socio-economic implications and damages, giving rise to sectoral inequities and loss in productivities (Nicholson et al., 2023). In other words, impact pathways acts as a bridge between climate hazards, their respective associated damages, and ultimate impact on sectoral GDP. To observe the damages, the process involved quantifying the relationships between climate variables and sector-specific economic performance by estimating damage coefficients. A clear understanding of these pathways is essential for translating exposure to climate risks into quantifiable economic impacts, thereby enabling accurate estimation of the Economic Impact of Climate Change (EICC) and supporting the development of targeted adaptation strategies.

To identify appropriate impact pathway coefficients, a comprehensive systematic literature review was undertaken. The objective of this review was to identify and synthesize empirical studies that quantify the relationship between climate stresses and economic outcomes across various sectors using robust econometric methods. Following the review, studies were carefully selected based on their relevance and alignment with the study's objectives, ensuring the integration of the most pertinent and robust literature evidence.

The literature review process was conducted in two main stages. First, clearly defined inclusion and exclusion criteria were established to guide the identification of relevant literature. Second, a targeted search was conducted using stress-specific keywords across multiple sources, including peer-reviewed journals, technical reports, government documents, and institutional publications. This approach ensured comprehensive coverage of both academic and applied research relevant to the Indian context.

The inclusion criteria were as follows:

- Studies employing robust econometric or statistical methods to quantify the relationship between climate stresses and economic impacts. E.g., temperature, rainfall variability, SLR on

sectors such as agriculture, industry, health, forestry, electricity, services, etc.

- Research studies that provide sectoral or regional breakdowns of climate impacts, as sectoral specificity is crucial for this analysis.

The exclusion criteria included:

- Studies lacking quantitative data or coefficients.
- Research studies focusing on non-economic impacts (e.g., social or environmental consequences) without clear economic linkages.
- Studies focused on regions outside of India, unless methodologies could be directly applied to the Indian context.

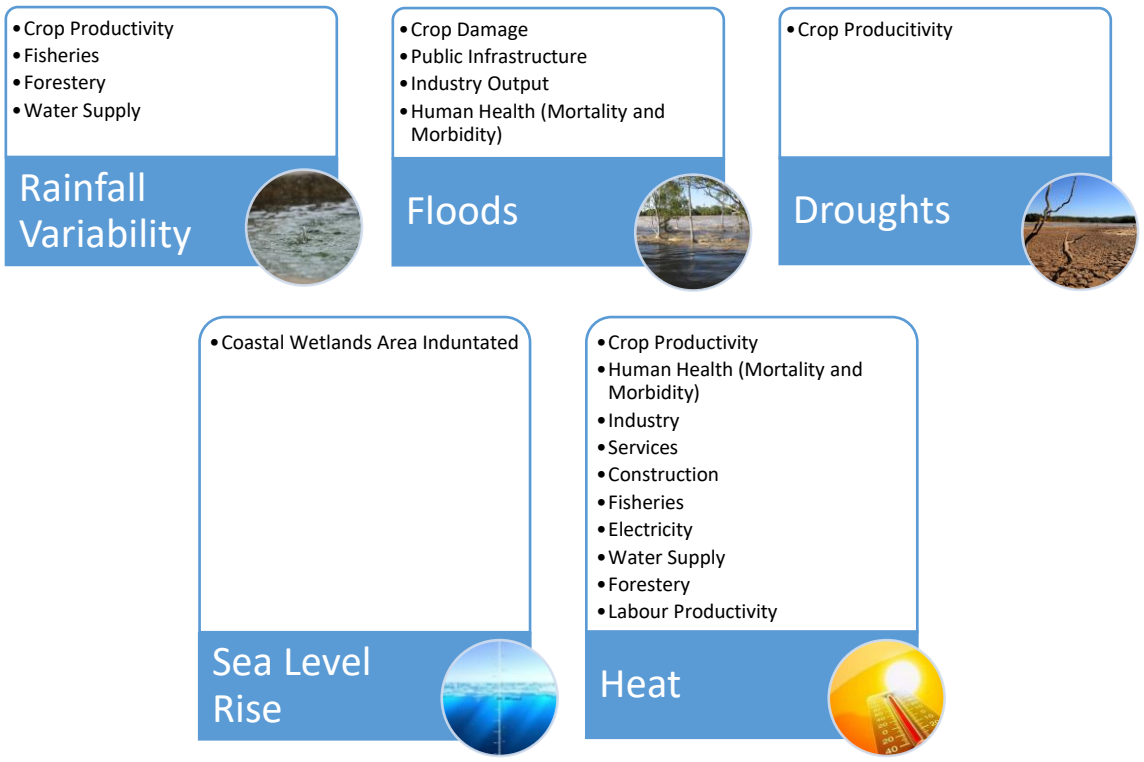
For instance, while searching relevant literature for the impact of floods on crop productivity, we used keywords such as "impacts of floods on crops/crop productivity", "floods and agriculture GDP affected". Similarly, to examine the effects of heat on human health, we used search terms like "impact of temperature on health," "temperature and hospitalization," "heat stress and mortality risk," and "impact of heat on disease incidence." Apart from the impact pathways, we included generic keywords such as "econometric analysis" and "regression" across all reviewed studies.

Following the identification of relevant literature and impact pathways, key data points were systematically extracted from the regression results of the selected studies, with a particular focus on those providing marginal effect estimates derived from robust econometric modelling. This emphasis on marginal estimates allowed for a consistent and standardized representation of damage coefficients across all impact pathways and climate stresses. By focusing on marginal changes such as the economic effect of a 1°C increase in temperature or a 10 per cent deviation in rainfall, the coefficients were standardized, enabling comparability and coherent integration across diverse studies and climate variables.

4.2.2 Impact Pathways Coefficients

As discussed above, the systematic literature review helped in identifying the 14 major impact pathways that were considered for the analysis and estimation of EICC, which is the estimated loss due to climate change. The ability of these pathways to capture the sectoral vulnerabilities formed the basis for the identification and selection. They involved sectors most vulnerable to climate change, such as labour productivity, crop productivity, water supply, electricity losses, and others. Figure 1 below presents the impact pathways for each stressor considered in this study:

Figure 2: Climate Stressors and Transmission Pathways



Source: Authors' Construction

Using the strategy defined in section 2.A., the values for each impact pathway were extracted in percentage terms following the identification and selection of studies that employed regression analysis. This ensured comparability by maintaining a consistent functional form across the derived coefficients. The coefficients used in the study were sourced at the national level, in alignment with the scope of the analysis.

To support the analysis, coefficients that did not reflect monetary damages and national economy-wide effect were suitably scaled using multipliers. These scaled damage coefficients then were assessed to determine the impact sectoral productivities. For instance, to analyse the impact of floods through the industry pathway, the coefficient extracted from the literature was reported in terms of output losses at the national (India) level and, therefore, did not require any scaling. However, for the human lives pathway under the same climate stress, the coefficient estimated the effect of flood magnitude[6] on human casualties rather than economy-wide damages. To translate this into an economy-wide impact, the coefficient was scaled by multiplying it with the exposed population, calculated as Population (crore) × percentage of flood-prone inundated area.

Despite arduous efforts, obtaining coefficients for certain impact pathways proved to be challenging. To make the analysis robust, certain coefficients for

[6] Flood magnitude is defined as a product of area affected by flood, severity of the flood, and flood duration (days).

impact pathways, including forests and water supply, were estimated using three-stage least squares (3SLS) regressions[7]. The steps involve estimating the parameters and the fitted values for the endogenous regressors. These are further used to compute residuals and construct the error covariance matrix across equations. Lastly, Generalized Least Squares (GLS) is used to obtain efficient estimates[8]. This method assumes that the model is identified, and errors are homoscedastic and serially correlated. This approach was adopted as climate shocks affect multiple impact pathways that are simultaneously determined and interdependent. By accounting for endogeneity and cross-equation error correlations, this method provided consistent and more efficient estimates of the structural relationships.

For this analysis, the following structure of the equations was modelled and used to estimate the marginal effects of maximum temperature and precipitation on impact pathways.

$$\textbf{Sectoral Expenditure}_{it} = \alpha_0 + \boldsymbol{\alpha}\mathbf{v}_{it} + \sigma_i + \mathcal{E}_{it} \quad \text{(Eq. 1)}$$

$$\textbf{Impact Pathway}_{it} = \beta_0 + \beta_1 \textbf{Sectoral Expenditure}_{it} + \beta\pi_{it} + \sigma_i + \mu_{it} \quad \text{(Eq. 2)}$$

where *i* represents states and *t* represents time (or here, years)

The vector $\mathbf{v}_{it}$ used in the first equation represented an array of explanatory variables spanning State Domestic Product (SDP), Gross Value Added (GVA) of major sectors of the economy, fiscal deficit, state debt, among others. While total adaptation-relevant expenditure formed the dependent variable in the first equation, the second equation involved the impact pathway as the dependent variable. The factors impacting the variable significantly, such as maximum temperature, average annual rainfall, and other socio-economic variables such as population, GVA of agriculture, and the like, were used as explanatory variables.

Capturing transmissions of climate change-induced vulnerabilities through identified pathways involves deliberate steps. The steps included interlinking the long-term effects of climate change with impact pathway sensitivities and translating the collective impact into economic damages. This was achieved by utilising suitable economic values and changes in climate parameters, which are discussed in detail in the subsequent sections.

4.2.3 Estimation of Change in Climate Parameters

The potential EICC is expected to increase over time as climate change intensifies. Thus, deviation in climate parameters adds as a key variable to determine the expected losses. The assessment of climatic changes was conducted through a comprehensive two-phase analytical framework that examines both current observed trends and future projected scenarios. This dual-scenario approach provided a robust evaluation of climate dynamics across

[7] This approach is particularly suitable for systems comprising various equations simultaneously, as it exploits error correlation across equations (Kakwani, 1968). Zellner & Theil (1962) extended the Two-Stage Least Squares (2SLS) method to systems of simultaneous equations. It combines the advantages of multivariate regression and 2SLS by estimating all structural equations jointly while accounting for potential correlation among their error terms.

[8] Over the years, 3SLS has been widely used to determine the relationship between the outcome and expenditure variables (Buck & Hakim, 1982; Diakodimitriou et al., 2025).

different timescales, enabling a more complete understanding of both recent changes and potential future conditions.

For the current scenario analysis, a rigorous methodology was adopted to identify recent climatic trends. The process began by establishing a 5-year moving average centred on the reference year 2000 (spanning 1998-2002) as the climatic baseline. Contemporary conditions were then represented by a corresponding 5-year average centred on 2024 (2022-2026). The absolute changes in key climate variables, including temperature, precipitation, and evapotranspiration, were calculated as the differentials between these periods. This methodological approach served to minimise the effects of interannual variability while effectively capturing meaningful decadal-scale trends.

The projected climate change variable values were referred to in the Assessment of Climate Change over the Indian Region, a report by the Ministry of Earth Sciences (MoES), Government of India, 2020. The projections were made by the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models based on multiple standardized forcing scenarios called Representative Concentration Pathways (RCPs). Each scenario is a time series of emissions and concentrations for the full suite of GHGs, aerosols, and chemically active gases, as well as LULC changes through the twenty-first century, and is characterized by the resulting Radiative Forcing in the year 2100. The values were scaled down to the year 2050 for the RCP 4.5 projection scenario.

This approach ensured that the detected changes represent climatically meaningful signals rather than stochastic variability, while the ensemble methodology effectively addressed inherent uncertainties in climate projections. The parallel analysis of current and projected conditions provided valuable opportunities to evaluate whether observed trends align with model expectations, offering important validation of the projection scenarios and enhancing confidence in future climate assessment.

4.3 Damage Costs

Drawing on the framework employed by Nicholson et al. (2023), which was suitably adapted, impact pathway coefficients were multiplied by appropriate economic values as the final step of the methodology. These values were sourced from publicly available databases, such as sectoral GVA or government-sanctioned compensation rates for deaths related to extreme weather events, to estimate the sectoral damages for each climate stress. The corresponding GVA values were considered, as sensitivity to most climate risks is closely linked to the sectoral composition of GDP. To align climate impact pathways with relevant economic sectors, each pathway was systematically mapped to corresponding sectors using the Ministry of Statistics and Programme Implementation's (MOSPI) Supply Use Table (SUT)[9] sector product classification. Once the relevant sectors were identified and mapped, the sectoral

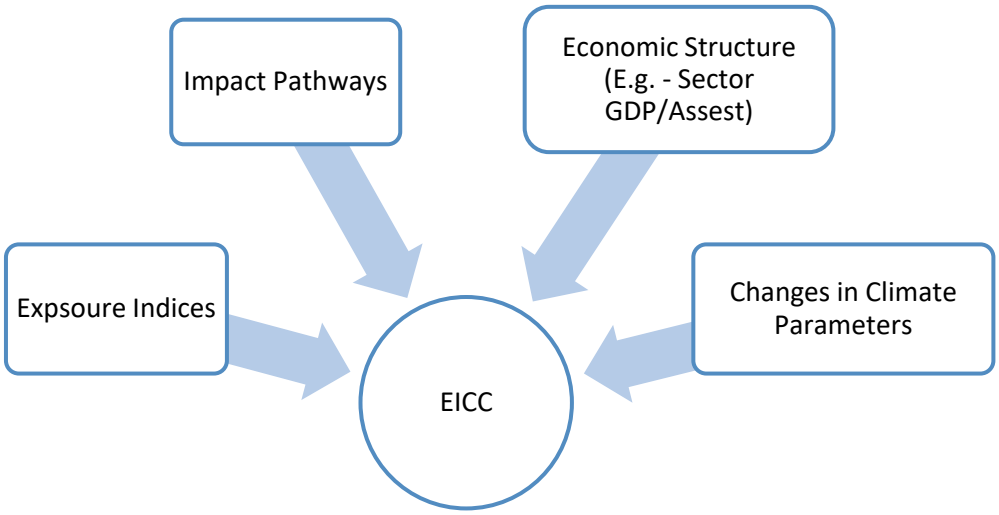
[9] Available at: https://mospi.gov.in/publication/supply-use-tables. Accessed on 15th April 2025.

GVA at current prices for the year 2022-23, as per the national accounts, was taken into account. However, for non-marketed services such as biodiversity and forests, the economic values of the respective ecosystem services were extracted from the literature to account for their economic contribution to the national GDP.

These were further combined with exposure indices to capture both the direct and indirect impact of climate stresses on the most affected sectors and the associated ripple effects across the economy. Additionally, average change in climate parameters was incorporated to reflect the effect of long-term shifts in temperature, precipitation, and related variables in driving sectoral damages, as elaborated in the previous subsection. This enabled the estimation of sector-specific economic losses attributable to each climate stressor at the current prices. The resulting values were used to calculate economic losses as a share of the country's GDP, thereby predicting the maximum EICC.

Future economic losses were estimated by incorporating projected changes in climate parameters from 2024 to 2050. Further, to reflect the true future cost of adaptation, sectoral GVAs, values of ecosystem services, and GDP were also projected till 2050, which was then used to determine the economic loss as a percentage of GDP. The procedure remained the same: the coefficients were weighted by exposure indices and applied to projected sectoral GVAs to estimate expected losses in 2050. These losses were then multiplied by the projected climate variables to determine the aggregate EICC as a percentage of projected GDP. Overall, this framework provides (see Figure 2) a comprehensive glimpse of the extent of loss and damage that climate change could inflict in the absence of adaptation-relevant interventions.

Figure 3: Methodology for Estimating the Damage Costs



Source: Authors' Construction

In sum, EICC refers to the estimated total economic losses arising from climate-related stressors, where physical and sectoral impacts are first quantified using changes in climate parameters, climate-stress specific exposure indices, and impact pathway coefficients that capture the transmission and sensitivity of climate shocks. These impacts are then scaled into monetary terms using sectoral economic values, including GVA. The resulting aggregate economic loss is subsequently expressed as a percentage of GDP to reflect the relative macroeconomic burden. By capturing both direct damages and indirect ripple effects across sectors, EICC represents the maximum potential economic cost under current and projected climate scenarios, accounting for future changes in climate conditions, economic structure, and adaptation needs.

5. Results and Discussions

The analysis began with identifying the climate-specific exposure indices that quantify spatial and sectoral vulnerability to the five key stressors. These indices served as scaling factors, applied to empirically derived impact coefficients from peer-reviewed literature, to translate physical climate risks into economic losses. The outcome was a consolidated metric, i.e., EICC, which aggregated sectoral damages across 14 impact pathways and expressed the total loss as a percentage of GDP. This captured the current and projected macroeconomic cost of climate change under observed and modelled climatic deviations. Building on the EICC, the analysis estimated India's damage costs due to adaptation, reflecting the level of investment needed to prevent, mitigate, or offset these losses.

5.1 Exposure Indices

Exposure indices were developed for five critical climate stressors: rainfall variability, floods, droughts, heat stress, and sea level rise. These indices provided a quantitative framework for assessing regional vulnerabilities, enabling policymakers to prioritise areas that are most at risk and design tailored adaptation strategies for climate resilience.

Rainfall variability recorded the highest exposure-index value of 0.663, reflecting relatively large interannual deviations in annual rainfall over the period 1985–2015. Such variability increases uncertainty for rainfall-dependent sectors, particularly agriculture and water supply, although the index should not be interpreted as a measure of extreme rainfall events. Flood Exposure, with an index of 0.630, represented a substantial level of vulnerability. This index is calculated by combining two essential components: the extent of flood-affected areas and the number of people exposed to flood risks. Regions with high population densities in flood-prone zones face disproportionately high risks, underscoring the urgency for investment in flood management infrastructure and disaster risk reduction measures. The dual focus on land area and population exposure highlighted the need for targeted interventions in flood-prone regions, with a focus on early-warning systems, flood defences, and community preparedness.

Drought Exposure, with an index of 0.604, indicated growing vulnerability to prolonged dry periods. The Standardized Precipitation Index (SPI) was used to quantify the severity and frequency of rainfall deficits. These

indices signalled significant risks to water security and agricultural productivity, particularly in arid and semi-arid regions. Areas most at risk of drought require enhanced water conservation strategies, resilient crop varieties, and improved irrigation systems to mitigate the socio-economic impacts of water scarcity.

Heat Stress, with an index of 0.474, indicated exposure to extreme heat events, which are expected to increase in frequency and intensity. While the estimated score was moderate, projections suggest that heat stress will become a more pressing issue in the coming decades. The implications of heat stress are wide-ranging, affecting public health, labour productivity, and ecosystem health. Policy responses should include measures to address urban heat islands, strengthen public health systems, and improve infrastructure to withstand higher temperatures.

Sea Level Rise stood at 0.477, highlighting emerging risks for India's coastal regions. This index integrated indicators such as coastal elevation, population density, and long-term sea level trends to assess exposure. Coastal communities face significant risks from flooding, erosion, and saltwater intrusion, which threaten infrastructure, agricultural productivity, and human livelihoods. Immediate action is needed to enhance coastal zone management, safeguard critical infrastructure, and develop climate adaptation strategies that focus on resilience for coastal communities.

Table 2: Exposure Indices for Different Climate Stresses

Rainfall Variability Index (RVI)	Flood Exposure Index (FEI)	Drought Exposure Index (DEI)	Heat Stress Index (HSI)	Sea Level Rise Exposure Index (SLREI)
0.663	0.630	0.604	0.474	0.477

Source: Authors' Construction

Collectively, these exposure indices, as shown in Table 2, provided a comprehensive view of the regions that are most vulnerable to climate change impacts. The findings emphasised the need for region-specific, proactive measures to mitigate the risks associated with each climate stressor.

5.2 Economic Impact of Climate Change

This section elaborates on the quantification of the economic impact of the five major climate stressors on the Indian economy. Each stressor is evaluated through distinct sectoral impact pathways (see Table 2), including infrastructure damage, agricultural productivity loss, industrial disruption, and ecosystem degradation. Coefficients were largely drawn from existing literature and were correspondingly weighted using India-specific exposure indices. The analysis revealed the economic cost of each climate risk as a percentage of national GDP. The results offer a consolidated picture of the macroeconomic damages associated with each climate stressor, underscoring the urgent need to embed climate risk into fiscal planning and development policy.

Table 3: Expected Loss Due to Climate Stressors: Across all Impact Pathways

Climate Stressors	Impact Pathways	Paper	Regional	Key Parameters (Value)	Key Parameters (Unit)
Rainfall	Crop Productivity	Kumar and Pritee (2013)	National	-0.000225	1 per cent change in rain
	Fisheries	Mohanty et al. (2017)	National	-0.089	1 mm change in rain
	Forest	Authors' Estimation	National	0.0014	1 mm change in rain
	Water Supply	Authors' Estimation	National	0.0003572	1 mm change in rain
Floods	Crop Damage	Parida and Chowdhury (2020)	National	-0.0018	1 per cent increase in crop area affected (Impact on crop GDP)
	Public Property	Bahinipati and Patnaik (2020)	National	0.2508	0.0001 unit (Million ha) increase in average area affected by flood
	Industry	Hossain (2020)	National	-0.0094	1 per cent increase in flood exposure
	Human Lives	Parida (2020)	National	0.00141	An increase in flood magnitude (flood magnitude defined as - Area affected by flood in sq km × Severity × Duration in Days)
		Kaur et al. (2020)	Global	0.301	1 per cent rise in floods
Drought	Crop Productivity	Birthal et al. (2018)	National	-0.131	1 SD increase in mean rainfall deficit
Sea Level Rise	Coastal Wetland Area Inundated	Roson and Sartori (2016)		-0.84	1 m rise in SLR leads to loss in sq km
Heat	Health	Bont et al. (2024)	Few Indian cities	0.095	1 degree celsius rise in temp
		Moors et al. (2013)	Northern India	0.056	1 degree celsius rise in temp
	Electricity Losses	Kumar and Maiti (2024)	National	-0.12	1 degree celsius rise in temp
	Water Supply	Authors' Estimation	National	-0.1522283	1 degree celsius rise in temp
	Fisheries	Habibullah et al. (2021)	Global	0.010701	1 per cent rise in temp
	Forest	Authors' Estimation	National	-0.000264	1 degree celsius rise in temp
	Biodiversity		Global	0.014328	1 per cent rise in temp
	Crop Productivity	Birthal et al. (2014)	National	-0.0131	1 degree celsius rise in temp
	Industry	Colmer (2021)	National	-0.0256	1 degree celsius rise in temp
		Colmer (2021)	National	-0.113	1 degree celsius rise in temp
		Kumar and Maiti (2024)	National	-0.0202	1 degree celsius rise in temp
	Labour Productivity	Dua and Garg (2024)	National	-0.025	1 degree celsius rise in temp

Source: Authors' Construction

5.2.1 Heat Stress

Rising global temperatures and the increasing frequency and intensity of extreme heat events pose significant challenges to economic performance worldwide (Bilal & Känzig, 2024; Kahn et al., 2021; Olivier Blanchard et al., 2022). One of the most critical transmission channels through which heat stress affects the economy is through its adverse impact on labour productivity. Elevated temperatures reduce both the cognitive and physical functioning of workers, thereby diminishing output, especially in heat-exposed sectors (Picchio & Van Ours, 2024; Thompson et al., 2024).

Heat stress also imposes broader economic burdens through its indirect effects, disrupting energy infrastructure, diverting investment toward adaptation measures, increasing production costs, and affecting supply chains (Pankratz et al., 2023; Ponticelli et al., 2023). Since productivity growth is a key determinant of long-run economic growth and living standards (Solow, 1956), the compounding effect of climate-induced heat stress has serious implications for macroeconomic stability and development planning. Building on these insights, we now move on to focus on quantifying the economic damages associated with heat stress in India. It draws from this growing body of literature to estimate the sector-specific impacts of rising temperatures, particularly in labour-intensive and heat-sensitive sectors, along with ecosystem services.

Given the limited availability of literature assessing the direct impact of change in temperature on water supply and forest cover, the present study analysed the damages using three stages least squares (3SLS) regression. The results indicated that with an increase of 1 degree in temperature, the water supply was reduced by approximately 15 per cent. To contextualize this impact, the coefficient was scaled by the share of surface water availability, currently at 61 per cent (CPHEEO, 2023), reflecting the significance of surface water as a critical input for both residential and industrial consumption. Similarly, a temperature rise led to an estimated 0.026 per cent reduction in forest cover, also derived using the 3SLS method. This finding was consistent with the analysis of Kumar & Maiti (2024), who demonstrated that declining forest cover impairs ecosystem services and poses serious consequences for economic development. These include reduced biodiversity conservation, diminished carbon sequestration capacity, and compromised water purification functions—all of which have downstream effects on various economic activities. To capture the broader implications of the forest loss, the estimated impact was further adjusted using a suitable multiplier that reflected the national share of forest cover, thereby capturing the sector-wide contribution of forest-related services to overall output.

As for fisheries, Habibullah et al. (2022), using worldwide data, found that a 1 per cent decline in temperature could negatively impact fish by 1.07 per cent. In contrast, another study reported a decline in fisheries productivity by 5 per cent with an increase in temperature by 4^0C in the northeast coast of India (Das et al., 2020). While the impact

differed significantly between the two studies, it is important to note that the present study focused on marginal effects. Therefore, the higher temperature shock reported in the regional study was not incorporated. Consequently, to examine the economic impact and exhibit national representativeness, a multiplier was applied to translate the ecological impact on the sectoral output. This was achieved through an ordinary least squares (OLS) estimation, analysing the relationship between the fish stock and GVA of the fishing and aquaculture sector. For biodiversity, the coefficient from Habibullah et al. (2021) states that a 1 per cent increase in temperature results in a 1.43 per cent decline in biodiversity species. To estimate the economic damages associated with biodiversity services, the coefficients were scaled using India's total plant and animal species and then converted into monetary terms using the existing valuation of ecosystem services from Pandey et al. (2024). The estimated EICC for biodiversity was 0.11 per cent.

Furthermore, (Birthal et al., 2014) found a negative impact of 1.31 per cent on crop productivity associated with a temperature rise. This coefficient was scaled using the share of cropped land in India to reflect the temperature sensitivity of agricultural output nationwide. This coefficient varied modestly from that of Roson & Martina Sartori (2016), who employed a reduced form of the agricultural response function calibrated for the GTAP 9 countries. Their analysis revealed that a rise in temperature leads to a 2.17 per cent variation in agricultural output for India. The divergence in coefficients arose from the use of climate variables under the RCP 8.5 scenario for each country, which represents a high-emissions trajectory with the most pronounced climatic changes. As a result, the deduced coefficient represented the impact under extreme warming conditions.

As stated, rising temperatures implicitly affect the productivity of the industrial sector through adverse impacts on labour productivity. Colmer (2021), using a difference-in-difference approach, reported that a 1 °C rise in temperature reduces manufacturing and service GDPs by 2.5 per cent and 11.3 per cent, respectively. Similar findings are reported by Kumar & Maiti (2024) and Somanathan et al. (2021), who observed a negative and economically significant impact on manufacturing, construction, and other services sectors. The sectoral growth of the construction sector varied by 2.02 per cent in response to changes in temperature (Kumar & Maiti, 2024). These effects are largely attributed to a decline in total factor productivity (TFP) of labour due to health effects of extreme temperatures, such as fatigue, impaired concentration, and increased health risks, reducing workers' efficiency. Adverse working conditions pose a threat to TFP by 2.3-2.7 per cent in the manufacturing and service sectors, as indicated by Dua & Garg (2024). The coefficient is closely aligned with the estimation of Roson & Sartori (2016), who reported that a degree rise in temperature reduces labour productivity by 2.47 per cent. To establish a link between labour productivity and the significant contribution of the factor of production to output, the range was suitably apportioned against a multiplier, revealing the intricate

relationship between labour productivity and output.

The health-related consequences of extreme heat are a critical, yet often underrepresented dimension of climate-induced economic damages. Recent empirical evidence underscores the severity of this impact. Bont et al. (2024) found that a 1 per cent rise in mean temperature above the 97th percentile correlates with a 3.8 per cent increase in mortality. Building on this, the present analysis estimated heatwave-related deaths in India by applying a scaled mortality risk of 9.5 per cent per additional degree Celsius above a 40°C baseline threshold. This risk was monetised using India's total population, age-adjusted mortality ratios, official compensation rates for climate-related fatalities, the national heatwave exposure index, and observed temperature deviations. Other studies present both higher and lower coefficients of heat-related mortality, highlighting the variation in methodological frameworks and geographic focus. However, these studies often focused on seasonal windows or prolonged events, limiting their generalizability. In contrast, the methodology employed by Bont et al. (2024) focuses on consecutive two-day thresholds above the 97th percentile, capturing short-duration but high-intensity events with wider geographic coverage. This offers us a more conservative yet nationally representative estimate of the economic burden of heat-induced mortality. Broader estimates reinforced this urgency, such as Zhao et al. (2021), who reported that India accounted for 20.74 per cent of global heatwave-related deaths between 1990 and 2019. In another paper, Xu et al. (2020) projected that those annual fatalities could rise 25-fold by 2100 under a high-emissions scenario.

Similarly, estimates from the University of California, Berkeley (n.d.)[10] project 3,400 excess deaths across India from a single-day extreme heat event, further substantiating the urgency for targeted public health and adaptation investments.

While numerous studies have evaluated heat-related mortality, far fewer have focused on the morbidity impacts of temperature rise in India. To assess the health impacts of rising temperatures, we used the coefficient from Moors et al. (2013), which indicates that a 1°C increase in temperature leads to a 5.6 per cent rise in diarrhoea cases. By applying this percentage to the total number of diarrhoea cases in India and multiplying it by the Disability-Adjusted Life Year (DALY) rate per case, the health burden was converted into economic terms. A recent study by Dureja & Jain (2025) has attempted to link heat stress with hospitalisation rates in Andhra Pradesh. While directionally relevant, the study's limited geographic scope and the use of quarterly average temperature thresholds (≥27°C) limit its applicability to acute heat events and its generalizability across India's diverse climatic zones. Moreover, the methodology does not adequately capture short-duration, high-intensity heatwaves, one of the most damaging climate-health pathways in India. Together, these findings

[10] Available at https://www.downtoearth.org.in/climate-change/lost-in-the-heat-the-critical-miscalculation-in-indias-heatwave-mortality-data. Accessed on 15th June 2025.

highlight the need for comprehensive public health planning that incorporates both mortality and morbidity risks associated with rising temperatures. Scaling up investment in heat-resilient infrastructure, disease surveillance, early warning systems, and targeted adaptation strategies is not only a social imperative but also a macroeconomic necessity to mitigate escalating climate-health costs.

In addition to its direct effects on labour productivity and health as stated above, heatwaves also exert substantial pressure on energy supply. Kumar & Maiti (2024) estimated that a 1°C rise in temperature causes a 12 per cent reduction in electricity sector growth. This is corroborated by findings from Ember's Global Electricity Review (2024), which reported a 5 per cent rise in electricity demand in India in 2024, largely driven by increased cooling requirements during extreme heat events, highlighting the escalating pressure on power systems under intensifying climate conditions. To quantify the economic impact, the estimated decline in electricity sector growth was multiplied by the sectoral GVA and the associated heat exposure index.

5.2.2 Sea Level Rise

Sea level rise (SLR) poses an increasing threat to India's coastal ecosystems, primarily through the processes of inundation, shoreline erosion, and saltwater intrusion. According to Roson & Martina Sartori (2016), a 1-meter rise in sea level is associated with a 0.00084 per cent reduction in coastal wetlands. This figure, when weighted using India's SLR-specific exposure index and applied to regional economic damage estimates for South Asia (INR 115 crore as per Blankespoor et al. (2014)), yielded an estimated economic loss of approximately INR 4 crore for India. While less comprehensive, this estimate provides a standardized national reference point for ecosystem-related losses.

A World Bank study projects a 0.84 per cent loss in India's coastal wetlands under a 1-meter rise, suggesting far greater ecosystem vulnerability than national averages. By contrast, sub-national studies suggest much larger localized losses. For instance, Dwivedi & Sharma (2005) estimate up to 58 per cent wetland loss in West Bengal under future SLR scenarios, while Patil & Deo (2020) identify significant infrastructure risks at major western ports due to accelerated shoreline retreat. However, such studies remain spatially fragmented and focus primarily on ecosystem or asset exposure without estimating cascading macroeconomic effects. In sum, while our approach quantifies SLR impacts within a consistent national economic framework, the broader literature highlights localized severity and the urgent need for more integrated assessments. The absence of sector disaggregated econometric estimates on SLR's economic transmission remains a critical gap in India's climate risk evidence base.

5.2.3 Water Stress

As indicated by the existing studies, water stress has emerged as a critical challenge due to population-driven increases in demand, leading to a scarcity of surface water availability. Climate-induced

variations in rainfall have further intensified the issue, leading to both floods and droughts, and exposing regional and economic vulnerabilities. As previously discussed, variability in precipitation levels alone can reduce crop productivity, strain water supplies, degrade forest cover, and impact health, among other effects. Given the profound economic implications of water stress, the analysis was disaggregated to account for the effects of rainfall variability, floods, and droughts, assessing the individual contributions of each to the overall water-related risks.

5.2.3 (A) Floods

Floods represent one of the most economically disruptive natural hazards in India, which ranks among the most flood-prone countries globally. The transmission of economic impacts from flooding occurs through four principal channels: (i) damage to crops, (ii) destruction of public infrastructure, (iii) loss of human lives, and (iv) disruption of industrial output. To quantify these impacts, coefficients from the literature were used and were suitably scaled to national estimates based on certain multiplier values.

For instance, Bahinipati & Patnaik (2020) found that flood-affected areas experience a 25.08 per cent increase in public infrastructure damages for every one million hectares affected. Given the vastness of this scale, the estimate was proportionally adjusted to a 100-hectare basis to better align with national-scale assessments. Parida & Chowdhury (2021) found that floods lead to a 0.18 per cent decline in crop GDP. In terms of industrial output, Hossain (2020) reported a 0.094 per cent reduction in manufacturing productivity for a1 per cent increase in flood exposure. Furthermore, understanding the impact of floods on human health, we looked at the people affected due to floods, both by mortality and morbidity. Parida (2020) estimated a 0.14 per cent increase in fatalities for each unit rise in flood magnitude, which was later converted into monetary terms using government-sanctioned compensation rates and scaled by population exposed to flood-prone areas. For morbidity, Kaur et al. (2020) stated that a one per cent increase in the number of people affected by a flood increases the cases by 0.161 per cent. This coefficient was later multiplied by the malaria cases in India along with the DALY rate per person to convert it into economic value loss.

In cases where national-level data were not directly available, appropriate proxies were employed to scale impact coefficients consistently. The total economic loss attributable to floods was computed by multiplying these coefficients by the flood exposure index and observed changes in relevant climatic variables.

5.2.3 (B) Droughts

For droughts, the impact was captured via the agricultural productivity pathway. Birthal & Hazrana (2019) found a statistically significant -13.1 per cent decline in crop productivity (Rupees (Rs.) /hectare) with rainfall deficit. This value was extrapolated using India's total cropped land, estimating a total economic loss of approximately Rs. 210 crore due to drought-induced yield losses. In contrast, a 2006 study led by the

International Rice Research Institute (IRRI)[11] in collaboration with research institutions in Chhattisgarh, Jharkhand, and Odisha found that a single severe drought year resulted in farmer losses of nearly USD 400 million (approx. Rs. 1,800 crore) in just three states. This sharp contrast illustrates that while the Rs. 210 crore reflects a conservative model-based average impact across all cropped land, real-world losses in extreme drought years, especially in vulnerable, rainfed regions, can be significantly higher.

Given the centrality of agriculture to rural livelihoods and its high sensitivity to precipitation variability, the analysis currently focuses on crop productivity as the primary transmission channel for drought-related economic impacts. Although droughts also affect water availability, livestock, and informal employment, the lack of standardised and consistent national-level data on these dimensions limits their inclusion in the existing aggregate economic loss estimation.

5.2.3 (C) Rainfall Variability

To assess the direct and indirect impact of changes in rainfall, the study considered pathways including crop productivity, fisheries, forests, and water supply (see Table 2). For crop productivity, the impact on representative crops such as wheat and rice was examined. Kumar & Sharma (2013) reported that a 1 per cent increase in annual average rainfall (AARF) results in a decline of 0.0625 per cent in rice yields. Similarly, an impact of 0.01747 per cent was also associated with wheat yields, indicating the sensitivity of agricultural output to variability in rainfall. These findings aligned with the studies by Srivastava et al. (2010) and Birthal et al. (2014), both of whom document a decline in crop productivity due to climate change and its cascading impacts on food security. The quantified changes in yields, on average, are further multiplied by the minimum support price, as well as the cropped land, to capture the economic value of the pathway.

Further, Mohanty et al. (2017) reported a decline in fish stock by 8.9 per cent attributable to rainfall patterns. This decline was translated into economic losses by applying a coefficient derived from establishing a link between fish stock and GVA of fishing and aquaculture through a regression. In a global context, Jones et al. (2020) also found that an increase in the standard deviation of rainfall enhances the productivity of salmon by 6.6 per cent across south-central Alaska, demonstrating a strong link between rainfall and fish population dynamics.

For the third impact pathway, forests, a 3SLS regression was employed to estimate a coefficient of 0.0014, translating into a change in 1mm of rainfall leads to a change in forest cover by 0.14 per cent. This finding was consistent with existing literature. Maringer et al. (2021), Neumann et al. (2017), and Haughan et al. (2022) highlight a recurring relationship between regional and seasonal precipitation levels and forest cover loss, emphasizing that variability in precipitation poses a significant risk to future forest ecosystems, as adequate

[11] Available at https://www.downtoearth.org.in/climate-change/desertification-droughts-reduced-india-s-gdp-by-up-to-5-in-20-years--82794. Accessed on 15th June 2025.

precipitation is essential for maintaining sufficient soil moisture and sustaining a healthy forest cover. The impact was suitably adjusted using the share of forest cover in India to account for its contribution to the forest-related economic services.

Lastly, using 3SLS regression, it was determined that a change in rainfall could lead to a change in water supply by 0.035 per cent. This was further supported by Yin et al. (2022), who showed that water storage deficits are highly vulnerable to rainfall anomalies. Reduced water availability affects agricultural yields, industrial output, and household consumption, leading to widespread economic repercussions. In this vein, the change in the resource was multiplied by the share of surface water available in India to account for the impact of rainfall variability at the national level.

The impacts transmitted through each pathway were aggregated to estimate sectoral losses. This was achieved by mapping the pathways to their corresponding sectors, based on the assumption that each pathway contributes primarily to the sectors identified in the previous section. The exercise resulted in the estimation of losses transmitted to sectors, namely agriculture, fishing, and aquaculture. For forestry, biodiversity, and water supply, the economic value of services was sourced from Pandey et al. (2024) and Ghosh & Bhowmick (2023), respectively. The results are discussed in detail in the subsequent section.

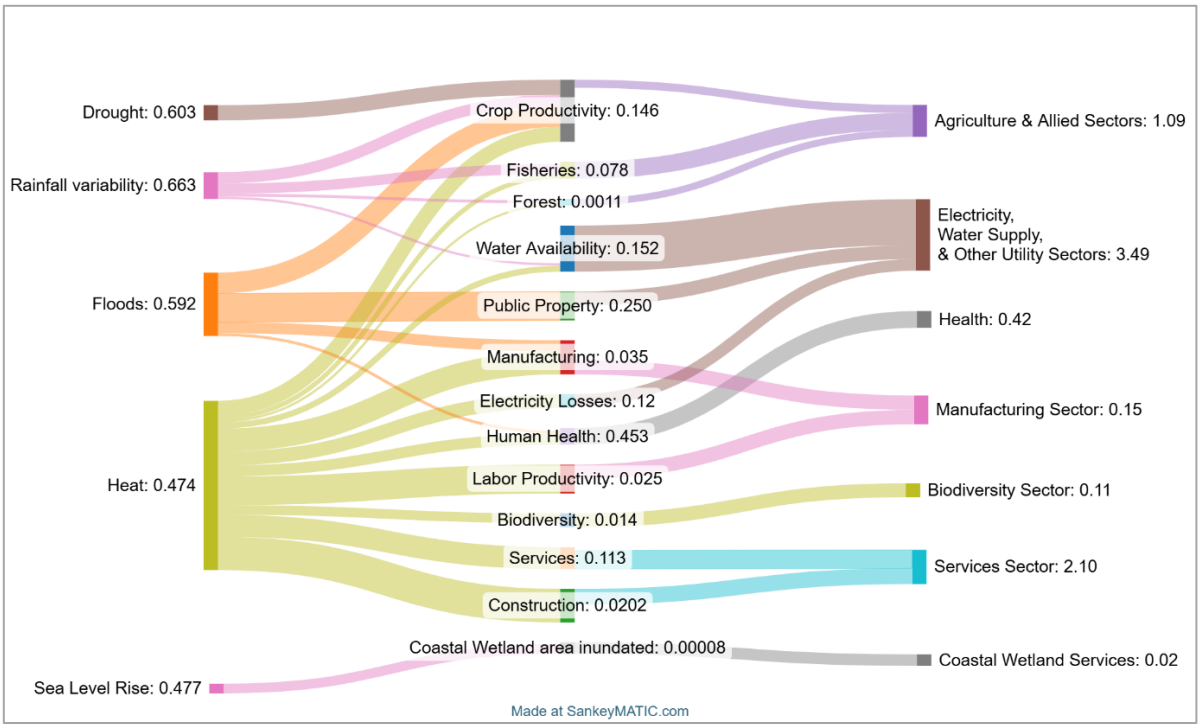
5.3 Climate-Induced Damage: Costs for India

Several econometric studies have established quantitative relationships between climatic variations and economic performance. By applying these empirical coefficients to observed and projected changes in key climate parameters, the present study estimated India's EICC across fourteen identified impact pathways (health is expressed as an aggregation of morbidity and mortality impact pathways). As depicted in Figures 3 & 4, the coefficients discussed previously led to significant sectoral losses. Electricity, water supply & other utility services emerged as the most vulnerable, with a loss amounting to 3.49 per cent of GDP. Our estimates revealed the service sector as the second most vulnerable to climate change, with a share of 2.10 per cent of GDP. Agriculture and allied sectors, health, and manufacturing were also observed to have been negatively impacted by 1.09 per cent, 0.42 per cent, and 0.15 per cent, respectively, due to climate change. This could be attributed to a decline in labour productivity due to climate-related illnesses and the number of working hours, factors serving as critical components for producing output. Additionally, sectors such as ecosystem services and biodiversity were found to be negatively impacted by 0.11 per cent. The results suggest that as climate change intensifies, sectoral vulnerabilities are likely to deepen, underscoring the need for targeted adaptation strategies and resilience-building policies across sectors.

Furthermore, in 2050, the service sector was found to be highly vulnerable to climate risks, with its share at 6 per cent of GDP, followed by agriculture and allied sectors at 5.25 per cent. The impact of climate change was observed to have significantly impacted other sectors as well. Electricity, water supply & other utility services, health, and manufacturing reported 3 per cent, 0.67 per cent, and 0.35 per cent, respectively, as GDP share affected. Ecosystem services such as biodiversity and coastal wetlands depicted a loss of 0.19 and 0.01 per cent, respectively.

When the sectoral economic losses were aggregated and expressed as a share of national output, the total economic damage was estimated at 7.38 per cent of GDP, or the corresponding adaptation financing requirement to offset these damages.

Figure 4[12]: Climate Risk Transmission Pathways and Associated GDP Impact (2022-23)



Source: Authors' Construction

Although the Economic Survey (2023–24)[13] reported that adaptation-relevant expenditure constituted approximately 5.6 per cent of GDP in 2021–22, it is evident through our analysis that this level of spending does not adequately reflect the magnitude of current or anticipated climate-related damages. With the increasing frequency and intensity of climate stresses, the finances needed to manage damage costs are expected to rise significantly. Based on our projected climate parameter trajectories, the adaptation financing requirement could rise to 15.42 per cent of GDP by 2050.

[12] Human health captures two impact pathways affected by rising temperatures and floods: morbidity and mortality.
[13] Available at https://www.indiabudget.gov.in/budget2024-25/economicsurvey/index.php. Accessed on 15th June 2025

By 2050, an estimated 12 per cent of GDP in lower- and lower-middle-income countries, including India, is projected to be at risk from climate hazard-related losses under a slow transition scenario, over four times higher than that of wealthier economies.[14] For countries like India, where economic vulnerability intersects with exposure to extreme climate events, the after-effect is particularly high.

Adaptation costs, when expressed as a share of GDP, are also disproportionately higher for lower-income countries. According to the United Nations Environment Programme's Adaptation Gap Report (2023), these costs could reach 3.5 per cent of GDP annually for the poorest economies, substantially more than the 0.7 per cent and 0.5 per cent required by lower-middle and upper-middle income countries, respectively. Yet, adaptation finance remains severely inadequate, especially in developing nations like India that are on the frontlines of climate impacts.

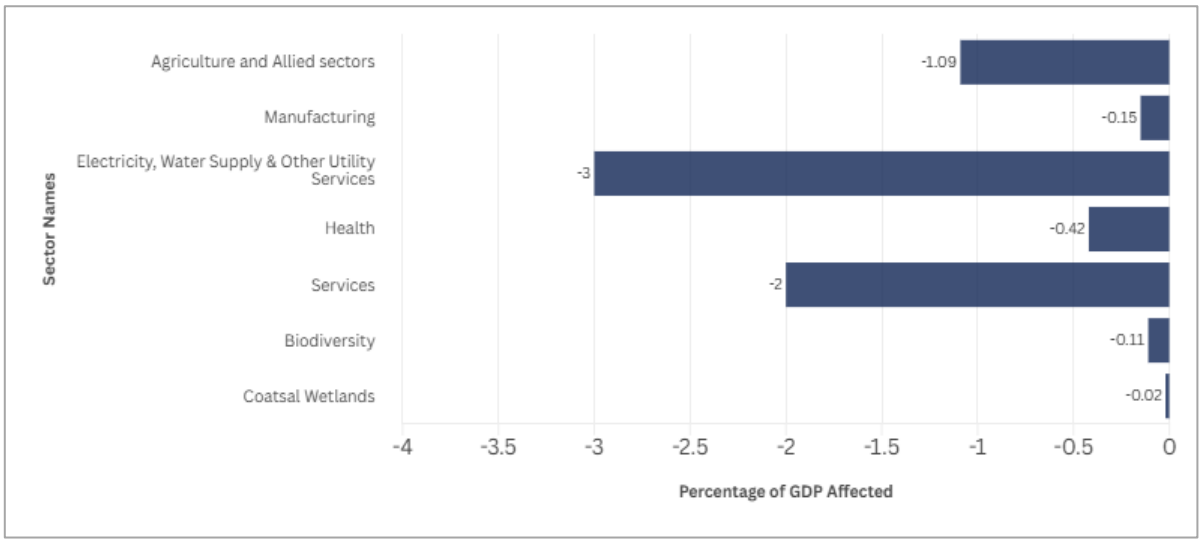
As of 2023, less than 9 per cent of global green bonds were issued outside developed economies. While climate finance flows to developing countries reached USD 89 billion in 2021 (OECD, 2015), this accounts for just 0.03 per cent of total global debt, and most still flows towards mitigation. Adaptation remains vastly underfunded. The adaptation needs for developing countries ranged between USD 215 billion and USD 387 billion annually this decade, or 0.6 per cent to 1.0 per cent of their GDP. For India, securing sufficient adaptation investment is not only a development imperative but also a macroeconomic necessity. Without it, the country faces escalating fiscal burdens, productivity shocks, and long-term growth constraints driven by climate-related disruptions.

Campagnolo et al. (2023) reinforced this by estimating that under a high-emissions scenario with climate shocks such as floods and sea level rise, India could face GDP losses of up to 13 per cent by 2050, rising to 24.7 per cent by 2070. While our study estimated a relatively higher GDP loss for India by 2050, the difference is mainly attributed to the methodology, as this study focuses on direct, sectoral-level damages via five climate stresses, whereas the Asian Development Bank's model incorporates global transmission effects through value chains, trade and investment, and competitiveness, which somehow softens the climatic impact.

Nevertheless, even under a moderate emissions trajectory, the results underscore the significant macroeconomic risks posed by climate change. Without accelerated adaptation and risk mitigation, these losses are likely to intensify, potentially converging with worst-case outcomes. Importantly, the burden will fall disproportionately on vulnerable populations, making the impacts not only substantial but also regressive.

[14] Available at https://www.spglobal.com/en/research-insights/special-reports/look-forward/investment-in-climate-adaptation-needs-have-high-returns-on-growth. Accessed on 15th June 2025.

Figure 5: EICC as a Share of GDP: By Sector



Source: Authors' Construction

Taken together, these findings underscore the critical need for a comprehensive, well-targeted, and forward-looking adaptation finance investment. Such a strategy must integrate climate risk into fiscal and development planning and prioritize interventions that enhance resilience among the most vulnerable populations. Inaction could result in compounding economic losses, deepening poverty, and heightened macroeconomic instability.

6. Conclusion

As climate change rapidly intensifies, its far-reaching and pronounced macroeconomic consequences exert considerable pressure on the national economy. In this context, the present study provided a comprehensive assessment of both economic and non-economic impacts of climate change, transmitted through distinct pathways, collectively resulting in sectoral economic losses. Subsequently, these sectoral losses aggregated to impact the national GDP. These losses raise a significant question about how much adaptation-relevant finance is required for India to mitigate and reduce the risks posed by climate change.

The EICC was quantified through identified impact pathways, incorporating vulnerabilities and sensitivities to climate stressors. The methodology drew inspiration from the framework developed by Nicholson et al. (2023), which was suitably modified and adapted in the present study. The impacts were largely drawn from existing literature, while a few were estimated using 3SLS regressions. These marginal impacts were subsequently scaled using suitable multipliers and exposure indices to the economy-wide effect. The outcomes were then applied to changes in climate variables to estimate both sectoral losses and EICC at the national level, expressed as a percentage of the GDP. The analysis examined the expected losses for the base year, i.e., 2022-23, and projected them for 2050.

The results revealed that rainfall variability and flood exposure present the highest

current climate risks, with drought and sea level rise also showing growing threats. These indices collectively highlighted the increasing climate vulnerability across India's diverse regions.

Following the estimation of expected losses by accounting for the effects from impact pathways, exposure indices, and variability in climate stresses, it was observed that electricity, gas, water supply, and other utility sectors emerged as the most affected. The losses stemmed from damages to public property, electricity losses, and a loss in water availability, among which water supply experienced the highest loss, closely followed by the service sector. Other sectors that observed a decline in GDP included biodiversity and coastal wetlands, indicating that climate-induced damages spill beyond economic sectors.

Meanwhile, in 2050, the projected economic losses were observed to have increased significantly. The service sector emerged as the most affected, while agriculture and allied sectors trailed behind with the second-highest decline in output share. Other sectors and services, such as manufacturing, health, biodiversity, and coastal wetlands, also experienced a decline in their output.

At the national level, the EICC was reported to be at a loss of 7.38 per cent of the GDP at current prices for 2022-23, while the projected loss in 2050 was estimated at 15.42 per cent of the GDP. The EICC as a percentage of GDP presents the country's climate-induced damage costs, providing crucial insight into the quantum of finance required to mitigate the climate change-induced damages, which are highly vulnerable to climate shocks in the present study.

Although the study examined the broader economic implications of climate stresses that may lead to severe economic damages, it is essential to acknowledge that the impact pathway coefficients were derived from existing relevant literature employing diverse methodologies. These coefficients were primarily derived from the studies conducted in earlier years using historical data relative to the base year considered in the present analysis. Thus, the estimates may not represent the current damages caused by climate change. Additionally, while the analysis focused on five stresses, further investigation is required to explore the impacts of other extreme events, such as cyclones, wildfires, and storms, and their associated economic implications transmitted through mechanisms other than those considered in the present analysis.

7. Way Forward

The study analysed the damages and losses caused by climate change, transmitted through impact pathways, leading to sectoral economic losses. It drew upon existing literature to assess the impacts of aforementioned stresses on selected pathways and estimate the EICC at the national level, projected till 2050. While this provided a valuable insight into the country’s climate-induced damage costs, further research is required to capture the broader picture of adaptation finance required to address the consequences of global warming-induced climate change. The effective rate of current adaptation-relevant spending stands at 78 per cent, highlighting

the substantial cost of inaction. With both private and public spending projected to increase in the coming years, climate change-induced economic losses are expected to decline, provided that adaptation-informed efforts are enhanced and improved. Looking ahead, as climate change-induced damages exacerbate, the gap between adaptation spending and the cost of inaction should decline through scaling up of adaptation measures, paving the way for a more climate-resilient economy.

The present study heavily relies on a systematic literature review and associated multipliers to represent the impact at the national level. However, this approach might not be ideal for capturing the full complexity of climate-related damages. In this regard, damage functions serve a crucial purpose by providing an accurate estimation of the impacts transmitted through different pathways. This can be achieved by establishing a relationship between climate parameters and their impact on economic variables through econometric methods to quantify the damages caused by climate change**.** The functions, in essence, include climatological parameters, regional sensitivity parameters to the climatological parameters, regional gross output, and socio-economic parameters as control variables to fully capture the complex interplay of various indicators. The estimation will likely reveal the sensitivity of certain socio-economic variables to climate change. In addition, future estimations may be made to capture the impacts of cyclones on socio-economic pathways, as the present study primarily focuses on only five stresses.

Furthermore, given India's vast diversity, both geographically and climatically, the impacts of climate change are expected to vary significantly across states. To account for the diverse physical traits of the country, estimation of damage functions at the state level would offer a more nuanced insight into the true extent of climate change impacts within the country, thereby enabling a more accurate assessment of damage costs. State-level analysis is essential, as the effects of climate stressors demand localised adaptation strategies and targeted technological interventions.

Following the estimation of damage costs, assessing the adaptation finance gap should be the next critical step. Future studies may consider analysing the current adaptation expenditure to identify this gap. This will help in identifying the potential sources of finance required to bridge the gap.

Lastly, climate change impacts do not necessarily translate into economic impacts alone. Although the present study incorporates the damages caused on non-economic sectors such as health, loss of life, and ecosystem services, further studies could examine other trends such as climate-induced migration, gender responsiveness to climate change, and the loss of cultural and traditional knowledge and heritage due to quick-onset events like floods and cyclones.

8. Policy Recommendations

The analysis reveals some key insights that can enable policymakers to design targeted policies and strategies to mobilize adaptation-relevant funds and mitigate the

far-reaching consequences of climate change. As climate change poses uncertainty and significant financial demands, proactive policy responses are critical to minimizing losses and damages. A few recommendations are outlined below to provide clear direction for potential policy reforms and enhancements in addressing the EICC

- The availability of granular and real-time data on climate stresses (such as floods, droughts, heatwaves, etc.) remains a significant challenge across many regions of India. Current climate risk assessments often lack comprehensive data, which hinders the accuracy of modelling and the effectiveness of policy interventions. There is a need to prioritise the development of robust data collection mechanisms to create a more accurate and up-to-date understanding of climate stress. This would enable targeted, evidence-based decision-making, particularly in areas that face the highest exposure to climate-related risks.
- There is an absence of detailed climate stress profiling and hazard-prone zone identification. Currently, many regions and sectors, including industrial zones and Special Economic Zones (SEZs), are not adequately assessed for their vulnerability to climate risks before development. This often leads to situations where, after significant investments have been made, it becomes evident that these zones are highly vulnerable to floods, heatwaves, or other climate-related impacts. The government should develop region-specific climate stress profiles and hazard maps to identify and mitigate these risks early on. By integrating this knowledge into urban planning, industrial development, and land-use policies, India can better protect investments and communities from future climate-related disruptions.
- Going forward, enhancing country-level as well as local assessment of the economic impact of climate change will require the use of national socio-economic data. At a broader level, a country-wide assessment of available data on economic indicators, public finance, and private finance could be a first step toward improving data quality and consistency. Consequently, a clear, concise, and transparent methodological framework is needed to estimate EICC. National authorities, along with academicians, could identify existing frameworks suitable for estimating EICC, pinpoint shortcomings that may hinder accurate calculations, and refine them further, resulting in the identification of accurate adaptation financing requirements.
- It is essential to engage local governments and communities as key stakeholders in climate-related studies to facilitate the integration of expert knowledge with indigenous and context-specific understandings of climate change and its impacts. Such collaboration captures locally grounded evidence, which is critical for formulating and implementing effective, context-sensitive adaptation strategies,

particularly in resource-constrained settings like India.

- Building institutional capacity is essential for implementing effective adaptation policies. Establishing climate cells within the sectoral ministries that track and monitor the implications of climate change through robust data is recommended. This would enable identification of financial needs, available financing, and potential sources of financing to ensure favourable outcomes.
- The study identifies the key impact pathways through which climate risks translate into economic losses. Expanding this framework to undertake an economy-wide analysis would enable the estimation of cumulative financing requirements for climate adaptation. Industrial associations, sectoral ministries, and governments at all levels can leverage these insights to design policies that strengthen sector-specific resilience. Targeted sectoral policies, integrated with adaptation measures, can safeguard livelihoods, reduce economic losses, prevent capital erosion, and promote long-term economic stability. It is imperative to place adaptation at the forefront of development planning and recognize that adaptation is complementary to development, rather than a standalone policy objective.
- To enhance financial resilience, developing and implementing innovative financing mechanisms to mitigate climate-induced damages is essential. Instruments such as parametric insurance, green bonds, and private finance, when coupled with increased public investment in adaptive capacity, can strengthen long-term economic resilience by reducing climate-related economic losses.

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