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RESEARCH ARTICLE

Effects of temperature shocks on economic growth and welfare in Asia

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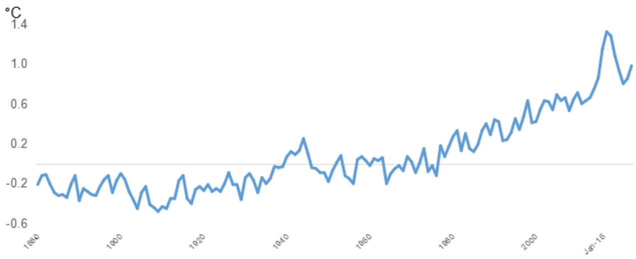
Abstract: Using the Burke, Hsiang, and Miguel (2015)[1] framework, we examine the nonlinear response effect of economic growth to historic temperature and precipitation fluctuations. We confirm that aside from the significant effect of rising temperature on agricultural production, industrial production and investment endeavors also serve as other potential channels through which temperature significantly affects overall economic productivity. We find the overall economic productivity of developing Asia to be at least 10% lower by 2100 relative to business as usual. We also empirically analyze policy measures and factors that could help countries mitigate consumption volatility driven by climate change-related events. Consistent with several micro-level findings, financial inclusiveness helps households mitigate consumption volatility amid temperature change. Likewise, government plays a critical role in moderating the negative impact of rising temperature in both output and consumption.

Keywords: climate change, consumption volatility, global warming, developing Asia, JEL Classification

1 Introduction

At the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21 or Paris Climate Conference) in December 2015, 195 countries adopted the universal, legally binding global climate deal that sets out a global action plan of keeping the increase in global average temperature to "well below 2°C above pre-industrial levels," while "pursuing efforts to limit the temperature increase to 1.5°C"[2]. To provide consistent estimates for efforts in keeping global warming below agreed-upon thresholds, Climate Central[3] estimated the global average temperature anomaly and found that the first 3 months of 2016 reached the 1.5°C warming threshold from pre-industrial levels, even pointing out February 2016 as the warmest month with the increase reaching 1.55°C. Many scientists have explained that the limit of 2°C should not be surpassed because exceeding it will result in most severe effects of global warming such as floods, droughts, and rising sea levels.

The recent National Aeronautics and Space Administration (NASA) data show that the increases in mean global temperature have occurred at greater rates. Starting 1980, the temperature rises and over the last 20 years, it warmed by an additional 0.4°C in 2000 and increased further to 0.9°C in 2015 (Figure 1).



Note: Data for 1880-2015 are December average temperature. Source: National Aeronautics and Space Administration (NASA). GISS Surface Temperature Analysis (GISTEMP). http://data.giss.nasa.gov/gistemp

Figure 1 Global mean temperature anomaly (base period: 1951-1980)[4]

How can a 1°C temperature anomaly adversely affect the planet? The Climate Stabilization Targets report identified and quantified the physical climate changes per degree of warming[5]. A 1°C temperature anomaly can increase or decrease the level of precipitation by 5%-10% across many regions and the amount of rain falling during the heaviest precipitation events increases by 3%-10%. Moreover, per degree of warming, the annual average Arctic sea ice extent will be reduced by about 15%. Meanwhile, oceans continue to become more acidic, the risk of "very hot" summers will increase (the National Research Council defined "very hot" in their report as the hottest

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5% of summers from the 1971-2000 average), and the global mean sea level will rise by 0.5-1.0 meters by 2100.

Climate change is not only an environmental problem but also a socioeconomic one. Too much heat or cold can influence human behavior and efficiency, and, worst of all, even mortality (documented by several researchers, *e.g*. Anttila-Hughes and Hsiang (2013)[6]; Curriero *et al*. (2002)[7]; Kilbourne (1997)[8]; Kovats and Hajat (2008)[9]; McMichael and *et al*. (2008)[10]; Wendt, van Loon, and Lichtenbelt (2007)[11]). Furthermore, there are a number of well-documented micro-econometric studies that provide evidence that extreme weather has adverse effects on agricultural yields and on workers' productivity. These have consequences on household welfare that may translate into increased poverty incidence.

The relationship between temperature and aggregate economic activity has traditionally been quantified by examining the historical relationship between fluctuations in a country's temperature and variations in its economic performance in cross-sections of countries. Nordhaus[12] uses gross domestic product (GDP) per grid cell level and finds a relationship between average annual temperature and output (per grid cell) that is robust and single-peaked. Beyond investigating the magnitude and locus of any effects, Dell, Jones, and Olken[13] use the panel's distributed lag structure to inform whether temperature affects aggregate economic activity in developing countries by influencing the level of outputs or the growth rate of output, for example, by affecting investment or the institutions that influence productivity growth. They conclude that the increase in temperature correlates with a slowing of economic growth in developing economies but has no significant correlation in developed countries. They also document that in poor countries, a 1°C rise in temperature in a given year reduces economic growth by about 1.3 percentage points in the same year, with agriculture, industry, and political instability as significant channels. These findings have implications for long-standing debates about the role of climate in economic development and the possibility of substantial negative impacts of higher temperatures on poor countries that suggest that future climate change may substantially widen income gaps between rich and poor countries.

Recently, Burke, Hsiang, and Miguel[1] presented a new analysis of the relationship between historical temperature fluctuations and macroeconomic growth arguing that, in contrast to past studies, aggregate macroeconomic productivity is nonlinear, with productivity peaking at an annual average temperature of 13°C and declining strongly at higher temperatures (Meta-analyses by Seppanen *et al*.[14], Hancock *et al*.[15], and Hsiang[16] support the non-linear relationship of temperature and economic growth). They considered a model (hereinafter referred to as BHM framework) aggregating the non-linear micro evidence reflected in macroeconomic responses over longer periods of time. Their results show that business as usual emissions throughout the 21st century will reduce per capita GDP by 23% and widen global income inequality relative to scenarios without climate change (the RCP 8.5 scenario was used as the business-as-usual scenario, which reflects no explicit climate policy). Countries with an average yearly temperature greater than 13°C (55°F) will have lower economic growth as temperatures rise. For cooler countries, warming will be an economic boon. This non-linear response creates a massive redistribution of future growth, away from hot regions and toward cool regions. Based on the analysis, rich and poor countries respond similarly at any temperature, but the impact of warming is nonetheless much greater on poor countries, because they are mostly in regions that are already warm.

Following the BHM framework, we examine the non-linear response effects of economic growth to historical temperature and precipitation fluctuations of 168 countries over the period 19602014, predicting that the estimated effects of warming by 2100 could lead to huge, global-scale macroeconomic impacts (We updated the dataset prepared by Burke, Hsiang, and Miguel[1] in their recent study of the global non-linear effect of temperature on economic production). We confirm that temperature change has significant economic impacts on global and regional agricultural production. Furthermore, our results show that the economic impacts of temperature change go beyond the agriculture sector, and that there are significant impacts on industrial production and investments that serve as channels through which temperature significantly and non-linearly affects aggregate economic growth. We also estimate the potential economic damage and benefits under different scenarios.

Recognizing the adverse impacts of temperature change on the economic growth trajectory of countries across different levels of economic development, we empirically analyze policy measures and factors that help countries mitigate consumption volatility driven by climate change-related events. Moreover, we survey several adaptation measures that could potentially help households against the effects of rising temperature.

The remainder of the paper is structured as follows. Section II discusses the main features of the dataset. Section III presents the framework and the empirical approaches used in the analysis. This is followed by estimated reductions and gains under future warming scenarios expressed in changes in per capita GDP in section IV. Section V provides empirical analysis on how to deal with consumption risks and volatilities as well as household's adaptive capacity mechanism. Section VI discusses policy recommendations and section VII concludes.

2 Data

Climate variables such as temperature and precipitation are updated and sourced from the University of Delaware reconstruction assembled by Matsuura and Willmott[17], which contains 0.5-degree gridded monthly average temperature and total precipitation data for all land areas in 1900-2014, as interpolated from station data. The annual temperature and precipitation data per country were derived using the 2000 population data from the Gridded Population of the World series, as weights. The growth rates of per capita GDP, agriculture gross value added (GVA), industry GVA, and services GVA, as well as gross fixed capital formation, all expressed at constant 2005 US dollars, are from the World Bank's 2015 World Development Indicators (WDI). As is defined in the WDI, the industry sector comprises the manufacturing, construction, mining, electricity, water, and gas industries.

To derive the expected economic damage or loss (measured as the fractional loss in annual economic output relative to an economy without climate policy) arising from higher temperature, we use the country-level projected temperature rise from selected Representative Concentration Pathway (RCP) scenarios. RCPs provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations, energy use, population, air pollutants and land use, and the consequent radiative forcing and temperature anomalies. Likewise, for comparison, we also applied temperature projections used in one of the existing integrated assessment models (IAMs), the WITCH (or the World Induced Technical Change Hybrid) model. The counter factual overall economic situation to which we will evaluate all climate scenarios will come from the per capita GDP growth trajectory of Shared Socio-economic Pathways (SSPs) developed by the research team from the Organisation for Economic and Co-operation and Development (OECD). The WITCH model also used SSP growth scenario to represent their counter factual (Reis *et al*., forthcoming). The details on the selection and application of growth and temperature projections are discussed in section III.

The indicators for selected mechanisms to mitigate consumption volatility were gathered from the following sources:

(1)Share of total capital flows to GDP, which measures the degree of financial openness of countries, is sourced from the WDI.

(2)Financial inclusion variables are derived from the Financial Inclusion (Global Findex) database, which is a new set of indicators that measure how adults in 148 economies save, borrow, make payments, and manage risks[18].

(3)Governance readiness index, which captures the institutional factors that enhance application of investment for adaptation against climate change, is reported by the Notre Dame Global Adaptation Index (the ND-GAIN Country Index, a project of the University of Notre Dame Global Adaptation Index (ND-GAIN), summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience. It aims to help businesses and the public sector better prioritize investments for a more efficient response to the immediate global challenges ahead).

(4)Total trade (exports plus imports) ratio to GDP is available from the WDI to reflect trade openness.

(5)Level of financial development of countries, measured as the ratio of private credit to GDP, is also available from the WDI.

3 Framework and empirical approach

We follow the same framework applied by Burke, Hsiang, and Miguel[1] to arrive at a global nonlinear response function of economic production on temperature:

$$Y(\overline{T}) = \sum_i Y_i(\overline{T}) = \sum_i \int_{-\infty}^{\infty} \int_i (T) \cdot g_i(T - \overline{T}) dT \tag{1}$$

It predicts a smooth concave function reflecting gradual but increasing losses on total economic output Y($\overline{T}$) as the average temperature $\overline{T}$ rises and a country warms on average. Crops and labor respond to momentary temperature in a highly nonlinear fashion and is well approximated by a piecewise-linear function. The productivity of basic units in the economy is either at or slightly increasing at lower temperatures, and then declines steeply with temperatures above a critical temperature threshold[1].

This framework enables macro-level data to mimic the response on temperature observed in high-frequency micro-level data such as crop yields, among others. Likewise, it is also important to note that, using the above framework, the absence of a strong response of output to temperature from rich countries in a macro-level analysis is set aside, which makes climate change an issue for all countries regardless of the level of economic development.

We apply the same empirical approach of the BHM framework to Equation (1) to get

$$\Delta Y_{it} = h(T_{it}) + \lambda_1 P_{it} + \lambda_2 P_{it}^2 + \mu_i + \nu_t + \theta_{i2} t^2 + \varepsilon_{it} \tag{2}$$

where ΔY_{it} refers to the change in the natural log of

GDP per capita of country i at time t, is the annual average temperature (in °C) of country *i* at time *t*, P_{it} is the annual total precipitation (expressed in millimetres) in country *i* at time *t*. $\mu_i + \nu_t + \theta_i t + \theta_{i2} t^2$ are country, year, and quadratic country-time trend fixed effects.

The global nonlinear response function is constructed from the individual response functions of selected countries at different points in the global temperature distribution. This approach then assumes a global function *h*(.) on which all individual countries lie. This assumption is tested by Burke, Hsiang, and Miguel[1] by closely examining if *h*(.) is different across different subsamples (*i.e.*, by income groups, time, and dependence on agriculture).

3.1 Projected damage or loss from warming

We use the historical response function to estimate the potential economic damage of higher temperature (under selected warming scenarios). Per capita income under different warming scenarios is computed as

$$GDP\ per\ capita_{it}^{scenario} = GDP\ per\ capita_{it-1}^{scenario} \times (1 + \eta_{it} + \delta_{it}) \quad (3)$$

where η_{it} refers to the baseline growth rate that represents the counterfactual. We follow the growth trajectory described as the middle-of-the-road scenario of the SSPs, also known as SSP2. O'Neill *et al.*[19] defined SSPs as reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale. Under SSP2, the world follows a path in which social, economic, and technological trends do not shift markedly from the historical pattern[19]. The projected country-level per capita GDP growth rates are available at 5-year intervals (Linear interpolation is done to calculate the annual projected growth rates).

δ_{it} refers to the predicted growth loss/gain resulting from higher temperature in year *t*. It is derived from the following equation applying the pooled historical response function *h(T)*:

$$\delta_{it} = h(T_{it}^{+}) - h(\overline{T}_i) \quad (4)$$

where $\overline{T}_i$ is the average temperature in country *i* from 1980 to 2014 and T^{+}_{it} is the projected temperature for the years 2015 up to 2100. We use projections simulated by the fifth phase of the Coupled Model Intercomparison Project (CMIP5) driven by the concentration or emission scenarios, consistent with the different RCPs (CMIP5 promotes a standard set of model simulations in order to evaluate how realistic the models are in simulating the recent past, provides projections of future climate change on two time scales, near term (out to about 2035) and long term (out to 2100 and beyond), and quantifies some key feedbacks such as those involving clouds and the carbon cycle[20]). RCPs provide time-dependent projections of atmospheric GHG concentrations[21]. It is built upon different assumptions on emissions trajectories and concentrations, energy use, population, air pollutants and land use, and the consequent radiative forcing and temperature anomalies. Our choice of warming scenarios is anchored on the adoption of the universal and legally binding global climate deal set out at COP21 in December 2015. The agreement aims to significantly reduce the risks associated with climate change. In line with this, we chose RCP2.6 which depicts meeting the COP21 target and RCP8.5 which depicts the extreme projected temperature rise should the world fail to meet the target.

van Vuuren *et al.*[22] explain that "the emissions pathway under RCP2.6 leads to very low GHG concentration levels. It is a so-called 'peak' scenario: its radiative forcing level first reaches a value around 3.1 W/m^2 mid-century, returning to 2.6 W/m^2 by 2100. In order to reach such radiative forcing levels, GHG emissions (and indirectly emissions of air pollutants) are reduced substantially over time." Using the original baseline, *i.e.*, 19862005, countries are expected to experience a moderate rise in temperature ranging from 0.6°C to 1.6°C. Meanwhile, Riahi *et al.*[23] describes RCP8.5 as the baseline scenario with no explicit climate policy, characterizing the highest GHG emissions among four RCP scenarios. It combines assumptions of high population and relatively slow income growth with modest rates of technological change and energy improvements that lead to high energy demand in the long term. Country-level temperature change under this scenario is projected to range from 2.7°C to 5.8°C.

We also run our simulation using the temperature projections used in the WITCH model[24], which is computed using the climate model, MAGICC (See http://www.cgd.ucar.edu/cas/wigley/magicc Model for the Assessment of Greenhouse Gas Induced Climate Change) that determines changes in, among others, global mean surface air temperature resulting from anthropogenic emissions. The scenarios were based on the pledges of each country, known as intended nationally determined contributions (INDCs), under the Paris Agreement to reduce its GHG emission. Through the INDCs, the international community is informed on the countries' climate change efforts to determine whether the world can achieve the long-term goals of the Paris Agreement. The INDC scenario assumes perfect implementation of the Cancun (until 2020) and INDC (until 2030) emission pledges. We use the four scenarios for temperature projections: (i) Business as usual, (ii) INDC, (iii) INDC to 2°C, and (iv) Optimal 2°C. The business as usual scenario is the baseline or reference scenario. The INDC to 2°C scenario assumes a global carbon tax after 2030, consistent with attaining the 2°C climate goal. Lastly, the Optimal 2°C scenario allows more stringent emissions reductions prior to 2030[24].

Meanwhile, Burke, Hsiang, and Miguel[1] defines $\overline{T}_i$ as the average temperature in country *i* in the base period, 1980-2010 in their case. To partially address the inherent stationarity assumption of the h(.) function in Equation (2), we consider a case in which optimizing economic agents have strong incentives to use all available current information in forming their best possible expectations of the future temperature following the rational expectations approach[25]. Considering this, we adjust δ_{it} in Equation (4) by changing $\overline{T}_i$ in such a way that is expected to change as new information (*i.e.*, temperature data) becomes available. We replace $\overline{T}_i$ with the medium term (*i.e.*, 6 years) rolling average that incorporates projected annual temperature. This method will tend to reduce the level of sensitivity of aggregate economic growth with temperature rise.

Estimated loss (in percent) is thus derived from the following equation:

$$Loss_{it}^{scenario} = \left[\left(\frac{GDP\ per\ capita_{it}^{scenario}}{GDP\ per\ capita_{it}^{business\ as\ usual}} \right) - 1 \right] \times 100 \tag{5}$$

3.2 Estimated benefits of climate actions

We also explore to determine the potential benefits of climate actions, particularly the adoption of the Paris Agreement to limit the global average temperature rise to well below 2°C above pre-industrial levels and, if possible, to as low as 1.5°C. By 2050, carbon emissions from developing Asia are expected to be 50% lower (relative to a no climate policy scenario) resulting from the progressive implementation of INDCs. We use the loss estimates in Equation (5) arising from individual temperature rise projections. The climate action benefit is derived from the difference between estimated loss under extreme temperature rise projections (RCP8.5) and the projections that indicate successfully meeting the COP21 target (RCP2.6), *i.e.*

$$Climate\ action\ benefit_{it} = Loss_{it}^{RCP8.5} - Loss_{it}^{RCP2.6} \tag{6}$$

We also estimate the climate action benefit using WITCH temperature projections. We computed the difference in loss estimates from no climate policy (business as usual) scenario with scenarios depicting climate actions, *i.e.*, implementation of the INDCs and increasing mitigation at a constant rate after 2030 (INDC scenario), moving from the INDCs to emissions pathways that limit warming to 2°C (INDC to 2°C) and the optimal path of early action that would achieve the 2°C target (Optimal 2°C).

Table 1 Regression results of 168 countries, 1960-2014

Variable	Coefficient	Robust SE	t	P>t
Temperature	0.0136***	0.0037	3.66	0.000
Temp. squared	-0.0005***	0.0001	-4.34	0.000
Precipitation	0.0124	0.0886	1.40	0.165
Precip. squared	-0.0041**	0.0021	-2.01	0.046
Statistic				
Observations		7,224		
R squared		0.2588		
Optimum temperature level		14.24		

Note: 1. GDP: gross domestic product; 2. Dependent variable: per capita GDP growth; 3. Source: Authors' estimates; 4. *** p<0.01, ** p<0.05, * p<0.1

4 Results: Potential loss and benefits

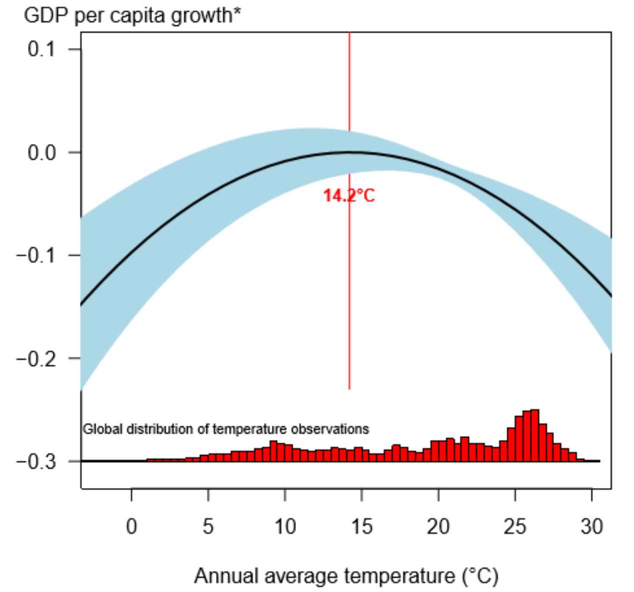
The non-linear effect of temperature on economic growth is similarly evidenced from the historical data that cover up to 2014 (Table 1 and Figure 2). Robustness checks can be found in Appendix 1. The coefficients of the quadratic temperature variables are statistically significant at all conventional levels.

Time-invariant factors (*e.g.*, history, culture, or topography), year fixed effects such as abrupt global events, as well as the quadratic country-specic time trends are incorporated in the model to produce more robust results. Precipitation variables are likewise included noting their correlation to temperature that may bias empirical estimates. As Auffhammer *et al.*[26] suggested, other climatic variables aside from precipitation such as relative humidity, solar radiation, and wind speed must be added to avoid the classic omitted variables problem.

Overall economic productivity, as Figure 2 shows, is estimated to decline when temperatures climb above an optimal average annual temperature of 14.2°C. Of the 31 developing Asian countries included in this study, two-thirds lie beyond the estimated critical temperature threshold (see Figure 3). This reflects the general vulnerability of the region in temperature variations.

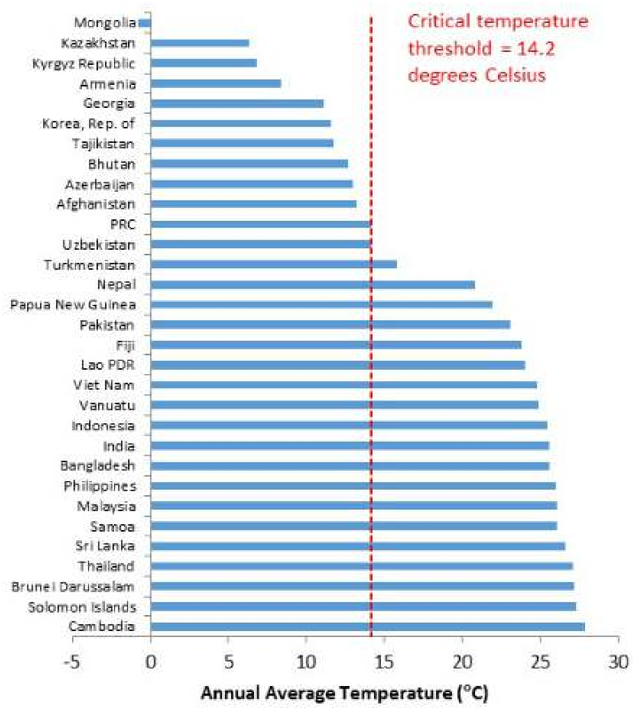
4.1 Channels: Agriculture, industry, and investments

Our application of the panel methodology to major economic sectors and investments will explore the extent to which temperature change affects overall economic growth. These other dimensions, if found significantly affected by temperature change, have important policy implications. Table 2 provides evidence of the significant effect of temperature change on the agriculture sector. We also note the significant nonlinear relationship of the sector's growth with average precipitation levels consis-



Note: 1. GDP = gross domestic product; 2. The blue area indicates the 90% confidence interval, clustered by country. The histogram shows the global distribution of temperature exposure (red); 3. Multiply by 100 to derive values in percent (%); 4. Source: Authors' estimates.

Figure 2 Nonlinear effects of annual average temperature on economic production



Note: 1. Lao PDR: Lao People's Democratic Republic; 2. PRC: People's Republic of China; 3. Source: Temperature data are from University of Delaware reconstruction assembled by Matsuura and Willmott, and authors' estimate.

Figure 3 Average temperature of developing Asian economies relative to estimated critical temperature threshold

Table 2 Regression results: Major economic sectors and investments

	Agriculture	Industry	Services	Investments
Temperature	0.0157*	0.0240**	0.0042	0.0260**
	(0.0082)	(0.0109)	(0.0077)	(0.0131)
Temp. squared	0.0007***	0.0007**	0.0001	0.0008*
	(0.0002)	(0.0003)	(0.0002)	(0.0005)
Precipitation	0.0886***	0.0105	0.0101	0.0341
	(0.0245)	(0.0191)	(0.0145)	(0.0305)
Precip. squared	0.01948***	0.00247	0.00100	0.00338
	(0.0060)	(0.0048)	(0.0030)	(0.0067)
Constant	2.18855***	0.27898*	0.05056	0.64157**
	(0.1514)	(0.1469)	(0.0909)	(0.2508)
Observations	5,373	5,315	5,147	4,760
R squared	0.104	0.232	0.209	0.173

Note: 1. Robust standard errors in parentheses; 2. Source: Authors' estimates; 3. *** p<0.01, ** p<0.05, * p<0.1

tent with the findings of Schlenker and Roberts[27] on an inverted U-shaped relationship between precipitation and specific crop yields in the United States (US).

Further, the earlier results show that the growth impacts of temperature change go beyond the agriculture sector. Industrial production and investments are found to be potential channels through which temperature change affects aggregate economic growth. The effect of temperature change on the industry sector could be either a first-order or a second-order effect. The former is in response to potential labor productivity losses arising from a warmer climate. The construction and mining sector, in particular, involves outdoor activities. Graff Zivin and Neidell[28,29] document a decline in labour supply during hot days in US industries heavily exposed to weather. We also note the second-order effect, *i.e.*, through the initial effect on agriculture that causes sensitivity of the industry sector to temperature.

It is important to note that investments growth displays a significant non-linear relationship with temperature change. It is critical as investment is one of the major drivers of economic growth. Meanwhile, we did not find a significant response of the services sector to temperature change. Intuitively, the services sector is not directly exposed to weather as opposed to both the agriculture and industry sectors.

4.2 Estimated losses in aggregate economic productivity

Applying the estimated nonlinear response function of temperature and output, Table 3 presents the estimated reductions and gains under future warming scenarios as a percentage of the baseline per capita GDP.

Relative to the business as usual growth scenario under SSP2, an increase in temperature under RCP8.5 is projected to reduce the average global per capita income

Table 3 Estimated loss from a warmer climate (RCP Scenarios), 2100

Region/Scenarios	RCP 8.5	RCP 2.6
World	-4.4	-0.6
Developing Asia	-11.0	-2.4
Central Asia	2.5	1.0
East Asia	-2.9	-0.1
South Asia	-15.5	-3.4
Southeast Asia	-13.0	-3.4
The Pacific	-9.6	-2.2

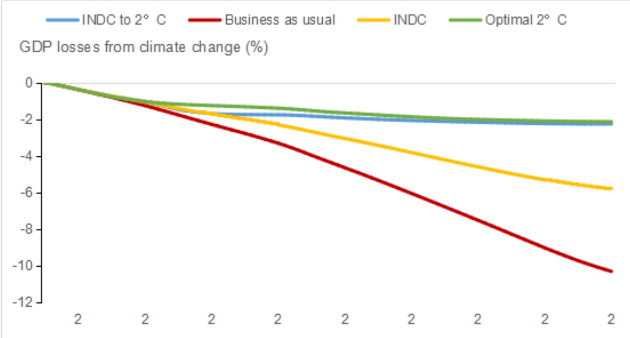
Note: GDP: gross domestic product; RCP: Representative Concentration Pathways; Source: Authors' estimates; % of baseline per capita GDP

level by 4.4% and average developing Asia per capita income by 11.0% in 2100 (Table 3). The world under the SSP2 scenario "follows a path in which social, economic, and technological trends do not shift markedly from historical patterns"[19]. Within the developing Asian region, the subregions are likewise affected differently depending on differences in average temperature. Central Asia is projected to fall in a positive growth territory after accounting for future warming, *i.e.*, per capita income is projected to be higher by 2.5% in 2100. East Asia is expected to have the least loss from higher temperature, with a lower per capita income by around 2.9% in 2100. South Asia, Southeast Asia, and the Pacific are projected to experience higher income losses arising from higher temperature. Under a scenario of a relatively lower temperature increase (RCP2.6), average global per capita income is expected to be 0.6% lower than the baseline in 2100. Developing Asia will experience lower economic loss by around 2.4% of the baseline per capita GDP in 2100.

Table 4 presents estimated losses associated from temperature projections of four scenarios of the WITCH model. The no climate policy scenario (business as usual) leads to 3.9°C of mean global warming by 2100, which is slightly less than RCP8.5. It leads to losses as high as 10% of per capita income for developing Asia by 2100. In contrast, the 2°C scenarios (INDC to 2°C and Optimal 2°C) will keep losses around 2% by 2100. The INDC scenario leads to losses about half way in between the no climate policy and the 2°C scenarios (Figure 4).

4.3 Estimated benefits from climate action

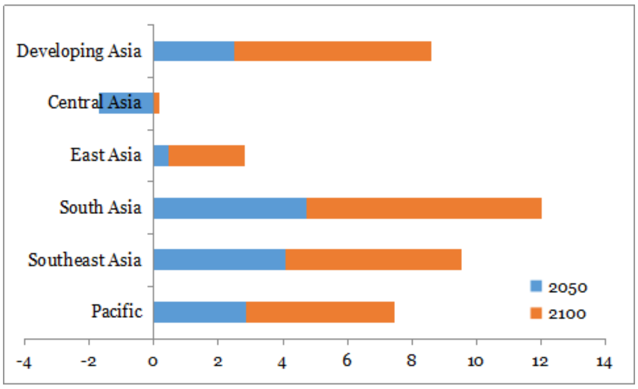
The successful implementation of the universal and legally binding global climate deal at COP21 where individual economies agreed to meet future commitments to limit global warming to well below 2°C will pose huge benefits for all. Risks associated with climate change will be reduced; expected losses will turn to be benefits. The developing Asian region, noting the substantial losses it might face from warming, has much to gain from



Note: GDP: gross domestic product; INDC: intended nationally determined contribution; Source: Authors' estimates

Figure 4 Economic losses from higher temperature in developing Asia

acting against climate change. There will be 3.7% gain on global average income by 2100 if concerted global efforts capped temperature rise to 1.5°C relative to the pre-industrial period. For the developing Asian region, Figure 5 shows that there will be 2.5% gain by 2050 and bigger benefits will accrue by 2100, *i.e.*, almost 10% of per capita GDP. South Asia (12%), followed by Southeast Asia (9.6%) and the Pacific (7.5%), will have huge benefits from climate actions.



Note: 1. RCP: Representative Concentration Pathways; 2. Source: Authors' estimates.

Figure 5 Potential benefits from climate action, 2050 and 2100 (RCP Scenarios)

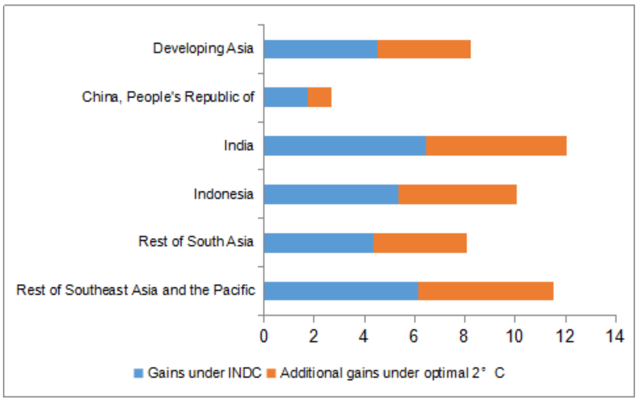
Meanwhile, Figure 6 presents the gains from climate policy using the WITCH model temperature projections. Potential benefits are estimated to reach 8% of per capita GDP in the 2°C scenarios (INDC to 2°C and Optimal 2°C) by 2100 and 4% of per capita GDP in the INDC scenario. The gains from reduced climate change accrue to the greatest extent in India, Indonesia, and the rest of Southeast Asia, and to a slightly lower degree in the rest of South Asia. The pattern of expected gains deviates from the patterns of INDC ambition, in that India, the rest of Southeast Asia, and South Asia have goals that are similar to the case without climate policy, even though

Table 4 Estimated loss from a warmer climate (WITCH Model Projections), 2100

Region/Scenarios	Business as usual	INDC	INDC to 2°C	Optimal 2°C
World	-6.0	-3.2	-1.1	-1.1
Developing Asia	-10.3	-5.8	-2.3	-2.1
China, People's Republic of	-2.9	-1.2	-0.3	-0.3
India	-15.4	-9.0	-3.6	-3.4
Indonesia	-13.1	-7.8	-3.2	-3.1
Rest of South Asia	-10.0	-5.6	-2.1	-1.9
Rest of Southeast Asia and the Pacific	-14.8	-8.7	-3.5	-3.3

Note: GDP: gross domestic product; INDC: intended nationally determined contribution; WITCH: World Induced Technical Change Hybrid; Source: Authors' estimates; % of baseline per capita GDP

their economies will be highly affected by whether mitigation is ambitious. This suggests that it may be in the economic interests of those regions to help contribute to a higher level of global emissions reduction.



Note: 1. INDC: intended nationally determined contribution; 2. WITCH: World Induced Technical Change Hybrid; 3. Source: Authors' estimates.

Figure 6 Potential benefits from climate action, 2100 (WITCH model projections)

5 Temperature and welfare: Dealing with risks and volatilities

The increasing weather volatility associated with climate change leaves households' output or income more volatile. Output volatilities evident from climate change, particularly from temperature rise, will unnecessarily translate into adverse welfare impacts. Aside from widely acknowledged effects such as increased heat stress, sea level rise, and lower agricultural productivity, Hof[30] claimed that the impact of climate change extends to the welfare of populations across the world. Empirical evidence on the effect of temperature shocks on economic growth[1, 13, 31, 32] and not only on contemporary output-suggests negative welfare effects, which are estimated to be higher than expected.

To demonstrate the pass-through of risks and volatilities to household welfare, we performed both fixed effects and instrumental variable regressions of per capita GDP and per capita household final consumption expenditure (measured in both growth and volatility). Household consumption is one of the many measures of welfare, and the availability of the data over a long period of time serves our purpose. Table 5 shows how output volatility translates into volatility in household consumption.

The results confirm the significant association between consumption and output. It is worth noting, however, that when output is instrumented with the nonlinear function of temperature, the estimated coefficient turns out larger, which implies that changes in output resulting from temperature variations are translated into changes in consumption at a pass-through rate of 87%. In a similar vein, Colacito *et al.*[33] evaluate the dynamic impact of shocks relative to the volatility across countries and find that the pass-through of relative output shocks onto relative consumption volatility is significant, especially in smaller countries. Suffice it to say, via its effect on output and growth, the welfare of the population is negatively affected through a more volatile consumption pattern. It is then crucial to determine ways of how to reduce, if not eliminate, the volatility of consumption resulting from climate-driven output variations.

5.1 Channels: Agriculture, industry, and investments

One of the main objectives of this paper is to explore mechanisms or measures that could potentially moderate the effects of warming. More specifically, we focus on the effect of temperature on household consumption as the primary measure of welfare. Figure 7 illustrates the various pathways through which climate change threatens earth assets, and, consequently, general welfare through household consumption. Explicitly, consumption can only be affected by temperature variations indirectly through its effect on output or income. Nkegbe and Kuunibe[34] find that climate variability affects consumption of rural livelihoods through its impact on agricultural

Table 5 Output and consumption

Variable	Coefficient	Standard Error	t	P>t
Growth				
(a) Fixed effects regression per capita GDP growth	0.72***	0. 0207	34.74	0.000
(b) Instrumental variable regression per capita GDP growth	0.87***	0. 0341	25.41	0.000
Volatility (5-year moving standard deviation)				
(c) Fixed effects regression output growth volatility	0.73***	0.0233	31.43	0.000
(d) Instrumental variable regression output growth volatility	1.17***	0.0375	31.16	0.000

Note: 1. Instruments: temperature, temperature^2, precipitation, precipitation^2, year, country, and country-time trends; 2. GDP: gross domestic product; 3. Source: Authors' estimates; 4. *** p<0.01, ** p<0.05, * p<0.1

production and income, since farm yields are directly affected by weather elements. A recent study by Schlenker and Roberts[27] found that there are threshold temperatures during summer for corn, soybeans, and wheat, that, when exceeded, will cause yields to fall sharply. This output or income shock is translated into welfare impacts in the process of reallocation of resources by households.

5.1.1 Indirect link of temperature with welfare through output

Following Figure 7, we empirically determine which mechanisms could possibly moderate the negative impact of temperature shocks on output growth, and consequently on household consumption by adjusting Equation (2):

$$\begin{aligned}\Delta Y_{it} =& h(T_{it}) + \lambda_1 P_{it} + \lambda_2 P_{it}^2 + \\ & \phi\left\{\left[T_{it} + T_{it}^2 + P_{it} + P_{it}^2\right] \times I_{it}\right\} + \\ & \mu_i + \nu_t + \theta_i t + \theta_{i2} t^2 + \varepsilon_{it}\end{aligned} \quad (7)$$

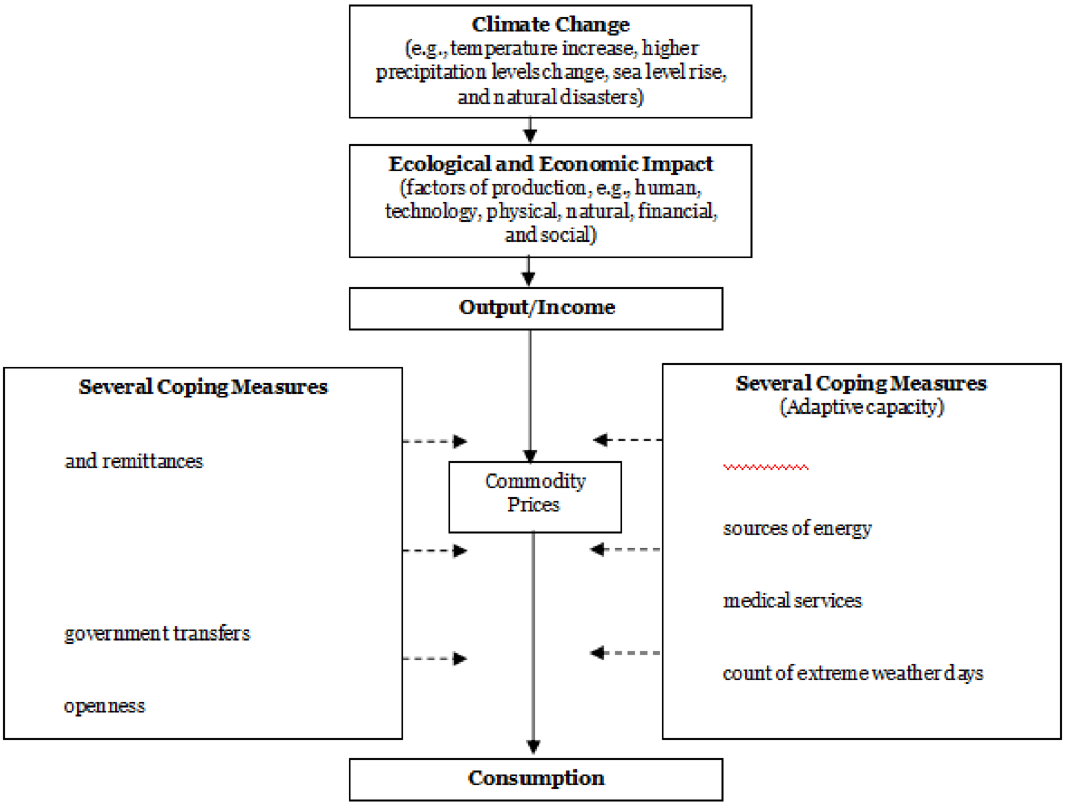
where I_{it} refers to several coping measures identified in the existing literature which are deemed essential to reduce, to varying degrees, the adverse effect of temperature shocks on output growth. The coefficient ϕ of the interaction terms will reflect how the identified factors will likely reduce the response of output growth to temperature shocks. We generate dummy variables classifying countries in the dataset relative to the global average of the following selected mechanisms:

(1) **Financial inclusion**. It is basically measured in terms of access to banks in general and credit availability in particular. Burgess *et al.*[35] find that credit availability facilitates consumption smoothing against weather shocks on income and output. Combes and Ebeke[36] find that remittances significantly reduce household consumption instability and the insurance role played by remittances is confirmed; remittances dampen the effect of various sources of consumption instability in developing countries (natural disasters, agricultural shocks, and discretionary fiscal policy). According to Mohapatra *et al.*[37], remittances rise when a recipient economy suffers natural disasters.

(2) **Availability of weather index-based insurance**. This is particularly crucial among countries heavily dependent on the agriculture sector, which is most directly affected by temperature shocks. Growth of the agriculture sector likely responds significantly to temperature variations. Greatrex, *et al.*[38] provides case studies of countries with insurance schemes managing risks from weather shocks. They observe the viability of scaling up index-based insurance especially for vulnerable smallholder farmers in the developing world such as in India, Ethiopia, Kenya, Rwanda, Tanzania, Senegal, and Mongolia. Magina[39] suggests that the government should increase the accessibility of financial products and services to farmers to promote agricultural development.

(3) **Access to foreign markets**. While there has been intense debate on the link between international trade and the emerging global environmental concern, the former is another potential mechanism through which the world as a whole will be able to moderate the welfare effects of higher temperature. Multilateral liberalization of renewable energy sources including the removal of fossil fuel subsidies is among the good examples of how trade negotiation efforts complement environmental objectives. The World Trade Organization negotiations on environmental goods and services could be used as a vehicle for broadening trade in cleaner technology options and thereby help developing countries reduce their GHG emissions and adapt to climate change[40]. Food security is one of the many areas that are deemed vulnerable to climate change, as well as one of the areas where international trade can be of significant use. Countries need to ensure access to important commodities to prevent shortage of supplies of relevant commodities and the consequences thereof. Likewise, international trade allows comparative advantages to be more fully exploited, especially when temperature shocks already change agricultural productivity. Restrictions on trade will worsen the effects of climate change by reducing the ability of producers and consumers to adjust[41].

(4) **Implementation of relevant policies and programs**. Governments should design programs that will potentially address volatilities in household consumption



Note: Source: Authors' illustration.

Figure 7 Conceptual flow of how to insulate consumption from climate-driven output volatility

arising from climate-induced output volatilities such as social protection and cash transfers. Vicarelli[42] finds that cash transfers partially smooth food consumption among rural households in Mexico after severe rainfall events. According to Baez, Kronick, and Mason[43], safety nets are another important component of a risk management strategy that enhances households' ability to adapt to both shocks and shifts.

A particular mechanism tends to moderate the negative impact of rising temperature if the coefficients before the interaction terms have the opposite signs of the temperature and precipitation variables. Negating signs attached to temperature and precipitation would lead to a smaller elasticity of output growth from temperature variations. This shows some signs of the potential of that particular measure to reduce the effect of temperature shocks on output growth. The following are our findings (see Appendix 2A for full regression results):

Financially inclusive countries are more able to mitigate the effects of a warmer climate. As shown in Appendix 2A under columns 26, the coefficients of the financial inclusion variables and their interaction terms reduce the coefficients of the nonlinear temperature and precipitation. We used indicators derived from the Financial Inclusion (Global Findex) Database, which is a new set of indicators that measure how adults in 148 economies save, borrow, make payments, and manage risk[18]. The results seem to concur with the observations in Burgess *et al.*[35] of the role of credit availability in facilitating consumption smoothing in rural India. Likewise, access to financial tools (*e.g.*, bank accounts and emergency funds) help households and firms adapt to climate change, prepare for natural shocks, and recover when affected[44]. Households are more able to cope with income losses associated with climate change and maintain consumption (*e.g.*, food as well as human capital expenditures) if they have protected savings and have ease of access on borrowings.

The ability of households to come up with emergency funds tends to reduce the negative impact of a hotter environment. Relatedly, another mechanism that is equally effective in moderating the effects of temperature shocks on the welfare of households is their ability to raise emergency funds. Using indicators also from Demirg-Kunt and Klapper[18], emergency funds will potentially mitigate output volatility arising from temperature shocks. Like the other financial inclusion variables, emergency funds will enable households to prepare as well as recover from damage associated with temperature rise effects.

Moderating the effect of temperature on output volatility through agricultural insurance is less evident in macro-scale analysis. Appendix 2A, column 7 shows the insignificant negating effects of agricultural insurance against weather shocks on output. While several pilot studies on agricultural insurance suggest improved farmers' behavior toward farming investment decisions in countries like India and Ghana, Ramm and Steinmann[45], however, observe the effect of insurance on the total value of farm outputs to be lacking. They primarily attribute that observation to the inability of countries to expand agricultural insurance programs beyond pilot testing as well as to encourage the uptake of as many smallholder farmers, which is undermined by the following: (i) farmers underestimate the severity and frequency of risk, (ii) farmers' limited consumer education, (iii) farmers' lack of trust in insurance providers, and (iv) farmers' overreliance on traditional coping mechanisms such as selling assets or borrowing from relatives after a shock (Ramm and Steinmann 2014)[45].

Governments play a critical role to moderate the negative impact of rising temperature on output. Appendix 2A, columns 9 and 10 show how important quality institutions are in abating the economic impact of rising temperature. Good governance enables countries to improve the application of investments to adaptation (Notre Dame Global Adaptation Index). Meanwhile, transfers from the government are able to reduce the negative effects of temperature shocks. The availability of funds of affected households would facilitate their income and consumption smoothing[42].

5.1.2 Direct link of temperature with welfare

Aside from the output-consumption link through which temperature variations will affect welfare (emphasized in Figure 7 and preceding results), we also performed a separate empirical analysis that associates directly consumption and temperature:

$$\sigma_{it}^{c} = \alpha + \beta_1 T_{it}^{*} + \beta_2 P_{it} + \beta_3 I_{it} + \beta_4 (T_{it}^{*} \times I_{it}) + \mu_i + \nu_t + \theta_i t + \theta_{i2} t^2 + \varepsilon_{it} \quad (8)$$

where ${\sigma_{it}}^{c}$ refers to per capita consumption growth volatility (5-year moving standard deviation), ${T_{it}}^{*}$ is the temperature anomaly in country *i* at year *t*. The temperature anomaly is computed as the difference between the annual temperature observations and the reference period (we used the average temperature during 1960−1980). P_{it} is the precipitation level in country *i* at year *t*. Similar with the above exercises, I_{it} refers to several coping measures identified in the existing literature that are deemed essential to reduce, to varying degrees, the adverse effects of temperature shocks on output growth. We expect a positive sign for β_1 which means that as the temperature observed in country *i* at year *t* gets further away from the reference average temperature, the more volatile per capita consumption growth will become. Meanwhile, our coefficient of interest, β_4 will help us determine whether the selected mechanism will potentially insulate household consumption from temperature shocks. In addition, we also run separate regressions for countries in developing Asia and OECD.

Identified mechanisms are found statistically significant to reduce general consumption volatility, particularly the financial inclusion variables. Intuitively, as households have access to financial institutions to borrow, save, and put up emergency funds, they are more capable of smoothing their consumption as possible risks may arise. While the majority of the interaction terms β_4 displayed negative coefficient, which indicates that the mechanism identified has the potential to reduce consumption volatility arising from temperature rise, we did not find them statistically significant. Similar observations are found in both the developing Asia and OECD samples.

6 Conclusion

Our findings reflect the alarmingly high cost of inaction against rising temperature. Following the non-linear response framework of economic productivity to the historical temperatures of 168 countries over the period 1960−2014, we predict that the estimated impacts of 21st century warming could lead to huge, global-scale macroeconomic impacts extending beyond the agriculture sector, that is, it also affects off-farm sectors such as industrial activities and investments.

The projected higher temperature (worst scenario under RCP8.5) is estimated to reduce the average global per capita income level by 4.4% and average developing Asia per capita income by at least 10.0% by 2100 relative to business as usual growth. Developing Asian subregions will be affected differently based on differences in average temperature. Future warming in Central Asia will be favourable as its per capita income is projected to be 2.5% higher by 2100. The rest of the subregions will experience lower average per capita income due to temperature rise. East Asia's per capita income is projected to be around 2.9% lower by 2100. South Asia, Southeast Asia, and the Pacific are projected to experience higher income losses arising from a higher temperature of 15.5%, 13.0%, and 9.6%, respectively.

Noting substantial income losses that the region might face from future warming, there is much to gain from acting against climate change. We estimate a 3.7% gain on global average income by 2100 if concerted global efforts capped temperature rise to 1.5°C relative to the pre-industrial period. Huge potential economic benefit from climate action is expected in developing Asia. Climate action is poised to benefit the region, with gains reaching almost 10% of per capita GDP by 2100. South Asia (12%), Southeast Asia (9.6%), and the Pacific (7.5%) will enjoy higher economic benefits from climate actions.

In our effort to provide empirical evidence of which mechanisms potentially moderate the negative impact of rising temperature, we adjusted our main specification to include interaction terms of selected mechanisms. Using the indirect link of temperature and private consumption via per capita GDP growth, we find financial inclusion to be an essential element by which economies will be able to reduce the economic impact of warming. Households are more able to cope with income losses associated with climate change and maintain consumption (*e.g.*, food as well as human capital expenditures) if they have protected savings and ease of access to borrowings. The same could be said for households with the ability to come up with emergency funds.

We also emphasize the vital role governments will play before, during, and after extreme events that rising temperature may cause. Alongside improving the adaptive capacity or the ability to adapt to new or changing conditions, governments are expected to strengthen resilience of at-risk communities; intensify social protection measures, livelihoods development, basic infrastructure development, and disaster risk management; and improve households' access to physical assets, financial capital, and markets. Further, good governance enables countries to improve the application of investments to adaptation to moderate the negative impacts of rising temperature on output.

While we did not find significant results for trade, it is equally critical to ensure access to external capital markets for borrowings as well as access to foreign aid that could supplement beneficiary countries' ability to cope with weather-induced volatilities. Likewise, the absence of significant results in our macro-scale analysis does not discredit the role of agricultural insurance to abate income losses from temperature shocks. We also note other adaptation measures that should be made available to households greatly affected by rising temperature. Households should be assisted in several diversification strategies. Alongside cropland diversification, agriculture-dependent households in particular may choose to allocate their labor to nonfarm activities, including both wage labor and self-employment in household enterprises as well as deriving much of their income from off-farm activities. This mechanism would enable households to improve income security during extreme events associated with rising temperature.

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