Assessing the economic impacts of future fluvial flooding in six countries under climate change and socio-economic development

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SUPPLEMENTARY MATERIAL

SM1.1 Literature on risks of fluvial flooding in our study countries

Since the beginning of 2010, the sum of total damage of fluvial flooding has been 2.8 billion US$ for Brazil, 74.4 billion US$ for China, 2.2 million US$ for Ethiopia and 22.5 billion US$ for India, corresponding to 23, 58, 4 and 36 flood events respectively (EM-DAT 2020). The total damage from fluvial flooding is not available in the EM-DAT database for Egypt and Ghana but there were 2 and 5 flooding events in Egypt and Ghana respectively during this period.

A global analysis showed that large direct economic losses of fluvial floods will be observed in China and India, among other countries (Willner et al. 2018). In China production losses were estimated to be 214 billion US$ in 1996-2015 increasing to 389 billion US$ in 2016-2035 (*ibid.*). You and Ringler (2010) modelled the impacts of climate change on three major factors which affect the Ethiopian economy, including flooding, under the SRES emissions scenarios. Results showed the occurrence of flooding events will increase and cause substantial economic losses in both the agricultural and non-agricultural sectors.

Although few country-level studies exist, there are some city or river basin level studies that project future impacts within the six countries. Ranger et al. (2011) estimated the direct total economic losses for floods of different return periods in Mumbai. A 1 in 50-year flood in the future is estimated to cause 210-550 million US$ of damage, excluding infrastructure. A 1 in 100-year flood is projected to cause damage of 490-1350 million US$ and a 1 in 200-year flood damage of 510-1420 million US$. When the damage to infrastructure is included, these costs increase. Asumadu-Sarkodie et al. (2015) modelled the damage of flooding for each river basin within Greater Accra City, Ghana, under the SRES emissions scenarios using the AQUEDUCT model. This research only considered 2011-2020 and did not project flood economic damages further into the future. A 1 in 10-year flood is projected to cause 98.5 million US$ in urban damage without flood protection. A 1 in 100-year flood is projected to cause 162.9 million US$ in urban damage without flood protection.

Hu et al. (2019) used an input output model to estimate the potential macroeconomic impact of fluvial flooding on the manufacturing sector in China, based on historical floods exceeding 1 in 100-year return periods between 2003 and 2010. The study reported a 12.3% direct loss in annual total output, with further indirect losses of 2.3% of annual total output at the macro-level.

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SM1.2 Estimation of indirect damages

The method for estimating indirect damage from fluvial floods is based on the existing Flood Footprint model presented in Mendoza-Tinoco et al. (2020). The model is run at a monthly time-step. Here we first consider the CC+SE experiment, where socio-economic growth is incorporated. The economy is initially in equilibrium, with total supply and demand balanced as follows[1]:

$$x_i^0 + im_i^0 = \sum_{j=1}^{n} a_{i,j} * x_j^0 + fd_i^0 \quad [1]$$

$$fd_i^0 = hc_i^0 + gc_i^0 + inv_i^0 + ex_i^0 \quad [2]$$

Where x_i^0, im_i^0, fd_i^0 are the output, imports and final demand of products in sector i in the pre-flood equilibrium (month before flooding $t = 0$)[2]. $a_{i,j}$ reflects the i th row and j th column element of the input coefficient matrix, which refers to the intermediate demand for product i to produce one unit of product j. n represents the number of industrial sectors. Thus, the left-hand side of equation 1 represents the total supply of product i, while the right-hand side denotes its total demand.

Final demand consists of: 1) household consumption (hc_i^0), divided into basic demand (bd_i^0) and other consumption (ohc_i^0): $hc_i^0 = bd_i^0 + ohc_i^0$; 2) governmental expenditure (gc_i^0); 3) fixed capital formation or investment (inv_i^0); and 4) exports (ex_i^0).

Inherent in IO modelling, the productive factors are invested in fixed proportions during the production process. That means the output of each sector is determined by the minimum of capital and labour input. In addition, for the long run analysis, a labour-augmenting technical progress is assumed to simulate endogenous economic growth. This is a standard approach in macroeconomics with an observation that most economies tend to have a labour-biased growth (Acemoglu, 2003). The input-output relation with technical change is described as below:

$$x_i^0 = \min\left(\frac{z^0 * l_i^0}{u_i}, \frac{k_i^0}{v_i}\right) \quad [3]$$

Where l_i^0 and k_i^0 denote the employment of labour and capital in sector i before flooding respectively, u_i and v_i are the technical labour and capital coefficients showing the amount of labour and capital required to produce one unit of product in sector i. As the economic structure is assumed to be stable during the time window of each experiment, the values of $a_{i,j}$ (in equation 1), u_i and v_i are kept constant over each 30 years involved. We only consider technical shift through the effects of z^t, which represents the labour-augmenting technical change, varying with time. The value of z^t is assumed to be the same across all the industrial sectors and is measured by the percentage increase in

[1] In this paper, we use bold capital letters to represent matrices (e.g. $\mathbf{I}$ and $\mathbf{A}$), italic bold lowercase letters for vectors (e.g. $\boldsymbol{x}$), and italic lowercase letters for scalars (e.g. n). Vectors are column vectors by default, and the transposition is denoted by an apostrophe (e.g. $\boldsymbol{x}'$). The conversion from a vector to a diagonal matrix is expressed as italic bold lowercase letters with a circumflex (e.g. $\hat{\boldsymbol{\alpha}}$).

[2] Here it is assumed that each sector produces only one uniform product. Apart from industrial sectors, the residential sector is also damaged by flooding events. Unless specifically mentioned, 'sectors' in this section only refer to industrial sectors.

GDP per capita relative to the pre-flood level, so for $t=0$, we have $z^0=1$. However, for different experiments, $a_{i,j}$, u_i and v_i may take different values if different IOTs are used.

Following a flood event supply and demand become imbalanced with the economy no longer in equilibrium. On the supply side, direct flood damage to industrial capital and labor reduce the production capacity of affected sectors. Equations 4 and 5 show the industrial capital available for production in each month following flooding.

$$\alpha_i^t = \frac{\Delta k_i^t}{k_i^t} \quad [4]$$

$$k_i^t = (1-\alpha_i^t)*(k_i^{t-1} + \sum_j ra_{j,i}^{t-1}) \quad [5]$$

Here α_i^t is the proportion of damaged capital in sector i during month t. Δk_i^t is the direct damage to the capital stock (as estimated in section 2.3). k_i^t is the available capital of sector i at the beginning of month t. Available capital comprises the remaining capital following a flood plus any recovered capital during the last month. ra_{ji}^t is the element of an $n*n$ recovery matrix $\mathbf{RA}^t$, which denotes the investment from sector j to restore capital in sector i in month t.

Due to the linear relationship between input factors and industrial output[3], capital production capacity, xk_i^t, is proportional to available capital, k_i^t, in each month, relative to the pre-flood level:

$$xk_i^t = {k_i^t}/{k_i^0} * x_i^0 \quad [6]$$

Damaged physical capital includes industrial and residential capital. The amount of residential capital at the beginning of each month, k_{res}^t, is calculated in the same manner as for industrial capital. However, damages to residential capital have no effects on production capacity, as it is not involved in the production processes[4].

$$k_{res}^t = (1-\alpha_{res}^t)*(k_{res}^{t-1} + \sum_j ra_{j,res}^{t-1}) \quad [7]$$

Where the subscript 'res' refers to the residential sector. Similarly, labour availability can change in the aftermath of a flood reflecting casualties and transport disruptions which may delay or impede travel to work. Labour availability in the aftermath of a flood is determined in the model by: labour affected by floods and labour recovery from the previous month. Labour recovery is considered only exogenously due to data limitations.

Labour availability is formulated as below:

$$l^t = \left[(1+r_n)*l^{t-1} + \sum_k lr_k^{t-1} - \sum_k ld_k^t\right] * {wh^t}/{wh^0} \quad [8]$$

[3] This is because we assume a Leontief production technique as in the standard Input-Output theory.

[4] However, damages to residential capital have indirect effects on the production process, as its recovery results in a non-negligible part of the total reconstruction demand, competing with industrial capital for reconstruction resources.

Where l^t represents the total supply of labour in the economy in month t, and r_n denotes the natural growth rate of population. ld_k^t denotes the three types of labour unable to attend work due to casualties, namely the dead, the heavily injured and the slightly injured, $k = 1, 2, 3$. lr_k^{t-1} corresponds to the recovery of each affected labour type during the previous month. Apart from casualties, other labour may be delayed for work due to transport disruptions. wh^t and wh^0 denote total working hours during month t and the month before flooding, respectively, which are related to the traffic conditions. As we consider labour recovery exogenously, a few assumptions are made here: 1) labour affected by transport disruptions are delayed for work for one hour per day during the first period after the floods; 2) all floods begin to subside within 6 months, which means that the working hours increase linearly to the pre-flood level in 6 months; 3) slightly injured labour comes back to work after half a month; 4) 23% of the heavily injured labour recovers health in each month after the floods. These assumptions are made due to data limitations.

We assume that the labour force flows freely across different industrial sectors, so that during each month the labour production capacity in each sector experiences the same percentage change as the total labour supply. Therefore, the labour production capacity, xl_i^t, is calculated as below:

$$xl_i^t = \frac{z^t * l^t}{l^0} * x_i^0 \quad [9]$$

The available production capacity of sector i in month t, $xcap_i^t$, is determined by the minimum capacity of labor and capital in that month, as shown below:

$$xcap_i^t = \min(xk_i^t, xl_i^t) \quad [10]$$

Where 'min' means the minimum value between xk_i^t and xl_i^t.

Therefore, the final output of each sector in month t, x_i^t, should be non-negative and no larger than the available capacity.

$$0 \le x_i^t \le xcap_i^t \quad [11]$$

The importing capacity, $imcap_i^t$, is assumed to be constrained by the surviving capacity of the transport sector, $xcap_{tran}^t$, that is, if the remaining capacity of the transport sector '*tran*' is declined by $x\%$ in month t, then the imports will contract by the same percentage relative to the pre-flood level, im_i^0.

$$imcap_i^t = \frac{xcap_{tran}^t}{x_{tran}^0} * im_i^0 \quad [12]$$

Therefore, similar with the output constraint, the actual imports in month t, im_i^t, should be non-negative and no larger than the importing capacity.

$$0 \le im_i^t \le imcap_i^t \quad [13]$$

On the demand side, a new kind of final demand to support the reconstruction and replacement of damaged physical capital arises after flooding. The final use of products in sectors that are involved in the reconstruction process increases. The formation of demand from the reconstruction of industrial capital is defined as below:

$$rd_{i,j}^{t} = \max\left\{\left[(1+r_s)*k_j^{t-1} - k_j^{t} - \sum_{m=1}^{t-1} rasto_j^{m}\right]*d_i, 0\right\} \qquad [14]$$

Where $rd_{i,j}^{t}$ is the element of an $n*n$ reconstruction demand matrix $\mathbf{RD}^{t}$, which denotes the investment that is needed for sector i to support the capital reconstruction of industrial sector j. 'Max' means the maximum. r_s is the targeted growth rate of capital stock. $\sum_{m=1}^{t-1} rasto_j^{m}$ is the accumulative capital under construction before month t. Capital under construction does not contribute to productivity increase until it is fully recovered. Therefore, the demand for capital reconstruction in sector j comes from the gap between the capital target, $(1+r_s)*k_j^{t-1}$, and the actual amount of capital in month t, k_j^{t}, subtracting the capital already under construction, $\sum_{m=1}^{t-1} rasto_j^{m}$. Then a proportion of this demand is allocated to sector i, according to the contribution of sector i to capital reconstruction.

If sector i is involved in capital reconstruction (e.g., machinery, equipment, vehicle, and construction), $0 < d_i \le 1$; otherwise, $d_i = 0$. The sum of d_i, $\sum_{i=1}^{n} d_i = 1$.

Similarly, the reconstruction demand of the residential sector for products in sector i in month t, $rd_{i,res}^{t}$ is defined as below:

$$rd_{i,res}^{t} = \max\left\{\left[(1+r_s)*k_{res}^{t-1} - k_{res}^{t} - \sum_{m=1}^{t-1} rasto_{res}^{m}\right]*d_i, 0\right\} \qquad [15]$$

Finally, the total reconstruction demand for sector i, $frec_i^{t}$, is the sum of investment required by all other industrial and residential sectors to support their reconstruction activities.

$$frec_i^{t} = rd_{i,res}^{t} + \sum_{j=1}^{n} rd_{i,j}^{t} \qquad [16]$$

On the other hand, it has been noted that strategic adaptive behavior in the aftermath of floods would drive people to ensure their continued consumption of basic commodities, such as food, clothes and medical services (Mendoza-Tinoco et al., 2017). The coexistence of reconstruction and basic demand delimits the boundary of final demand. That is, the final use of products in sector i in month t, fd_i^{t}, after satisfying its intermediate demand, should be at least larger than the basic demand, bd_i^{t}, but do not exceed the aggregate demand of all other final users (including the reconstruction use).

$$bd_i^{t} \le fd_i^{t} \le (1+r_g)^{t} * fd_i^{0} + frec_i^{t} \qquad [17]$$

Where $fd_i^t = x_i^t + im_i^t - \sum_{j=1}^{n} a_{i,j} * x_j^t$ according to equation 1, r_g is the targeted growth rate of national GDP. Here we simply assume that the growth rate of final demand equals that of GDP. Basic demand, bd_i^t, is usually a fraction (5% in this analysis) of the domestic final demand in month t, $\left(1+r_g\right)^t * \left(fd_i^0 - ex_i^0 \right)$.

Given disruptions to both the supply and demand sides, industrial sectors choose their optimal production, $x_i^{t,*}$, and imports, $im_i^{t,*}$, under production, import and consumption constraints, to maximize the total economic supply each month during the post-flood recovery. The optimization problem is as below:

$$\begin{aligned} \max \quad & \sum_{i=1}^{n} \left(x_i^t + im_i^t \right) \\ s.t. \quad & 0 \le x_i^t \le xcap_i^t \\ & 0 \le im_i^t \le imcap_i^t \\ & bd_i^t \le x_i^t + im_i^t - \sum_{j=1}^{n} a_{i,j} * x_j^t \le (1+r_g)^t * fd_i^0 + frec_i^t \end{aligned} \qquad [18]$$

Solving the above problem gives us the optimal production, $x_i^{t,*}$, and imports, $im_i^{t,*}$, in each month, which in turn determines the amount of final demand, $fd_i^{t,*}$, that could be actually satisfied.

$$fd_i^{t,*} = x_i^{t,*} + im_i^{t,*} - \sum_j a_{i,j} * x_i^{t,*} \qquad [19]$$

The remaining final products, after satisfying the basic demand, are then proportionally allocated to the reconstruction demand and other categories of final demand, as below:

$$rd_{i,j}^{t,*} = (fd_i^{t,*} - bd_i^t) * \frac{rd_{i,j}^t}{(1+r_g)^t * (fd_i^0 - bd_i^0) + rd_{i,res}^t + \sum_{j=1}^{n} rd_{i,j}^t} \qquad [20]$$

$$rd_{i,res}^{t,*} = (fd_i^{t,*} - bd_i^t) * \frac{rd_{i,res}^t}{(1+r_g)^t * (fd_i^0 - bd_i^0) + rd_{i,res}^t + \sum_{j=1}^{n} rd_{i,j}^t} \qquad [21]$$

$$fd_{i,k}^{t,*} = (fd_i^{t,*} - bd_i^t) * \frac{(1+r_g)^t * fd_{i,k}^0}{(1+r_g)^t * (fd_i^0 - bd_i^0) + rd_{i,res}^t + \sum_{j=1}^{n} rd_{i,j}^t} \qquad [22]$$

Where $rd_{i,j}^{t,*}$, $rd_{i,res}^{t,*}$ and $fd_{i,k}^{t,*}$ are the reconstruction demand of the industrial sector j, the reconstruction demand of the residential sector and the k th category of final use (i.e., household consumption, governmental expenditure, fixed capital formation and exports) that are actually realized by products in sector i given the optimal production and import.

On realization of reconstruction demand, damaged capital becomes under construction. This stage usually last 1-7 months for various types of capital according to their physical characteristics and empirical evidence. Damaged capital is fully recovered and put into production after its construction is completed. Therefore, in month t, the recovered capital in the industrial sector i and in the residential sector by investment from all other industrial sectors, $\sum_{j=1}^{n} ra_{j,i}^{t}$ and $\sum_{j=1}^{n} ra_{j,res}^{t}$, are calculated as below:

$$\sum_{j=1}^{n} ra_{j,i}^{t} = \sum_{m=1}^{7}\left[p(m) * \sum_{j=1}^{n} rd_{j,i}^{t-m+1,*} \right] \quad [23]$$

$$\sum_{j=1}^{n} ra_{j,res}^{t} = \sum_{m=1}^{7}\left[p(m) * \sum_{j=1}^{n} rd_{j,res}^{t-m+1,*} \right] \quad [24]$$

Where $ra_{j,i}^{t}$ and $ra_{j,res}^{t}$ stand for the recovered capital in the industrial sector j and the residential sector by investment from sector i in month t. $p(m)$ is the proportion of capital that completes its construction in m months, where $m = 1, 2, ..., 7$ and $\sum_{m=1}^{7} p(m) = 1$.

Therefore, the accumulative amount of industrial and residential capital under construction before month t are expressed as:

$$\sum_{m=1}^{t} rasto_{i}^{m} = \sum_{s=1}^{7}\left\{ \left[1 - \sum_{h=1}^{s} p(h) \right] * \sum_{j=1}^{n} rd_{j,i}^{t-s+1,*} \right\} \quad [25]$$

$$\sum_{m=1}^{t} rasto_{res}^{m} = \sum_{s=1}^{7}\left\{ \left[1 - \sum_{h=1}^{s} p(h) \right] * \sum_{j=1}^{n} rd_{j,res}^{t-s+1,*} \right\} \quad [26]$$

The recovered capital in sector i in month t, $\sum_{j=1}^{n} ra_{j,i}^{t}$, will increase the capital availability for the next month, k_{i}^{t+1}, and boost capital production capacity, xk_{i}^{t+1}, as in equations 5 and 6. On the other hand, labor recovery, $\sum_{k} lr_{k}^{t}$, is exogenously determined as mentioned above, as well as labor availability, l^{t+1}, and labor production capacity, xl_{i}^{t+1}, as in equations 8 and 9. This iterative process continues until the total supply and demand of the economy are in equilibrium and the economic output recovers to the targeted growth trajectory.

Finally, the total indirect economic damage is calculated as the loss of monthly GDP compared to its potential.

$$va_{i}^{t,*} = x_{i}^{t,*} - \sum_{j=1}^{n} a_{j,i} * x_{i}^{t,*} \quad [27]$$

$$IndirectDamage = \sum_{t}\left[\left(1 + r_{g}\right)^{t} * \sum_{i=1}^{n} va_{i}^{0} - \sum_{i=1}^{n} va_{i}^{t,*} \right] \quad [28]$$

Here $va_{i}^{t,*}$ refers to the value added of sector i in month t, which is the extra value of final products created above intermediate input. Summation of value added in all sectors, $\sum_{i=1}^{n} va_{i}^{t,*}$, constitutes the national GDP for month t. Then the total indirect damage is the accumulative losses of GDP over all months.

The above method reflects the method for the CC+SE experiment, whereby the economy can recover to a target level above the pre-flood level, based on the exogenous growth trajectory. In the CC only experiment economic recovery is constrained to the pre-flood level. Constraints on physical capital, labour, output and imports are set so that they cannot grow larger than the pre-flood level. In this case r_g and r_s are set to zero, and z^t is constant at 1, which indicates no economic growth.

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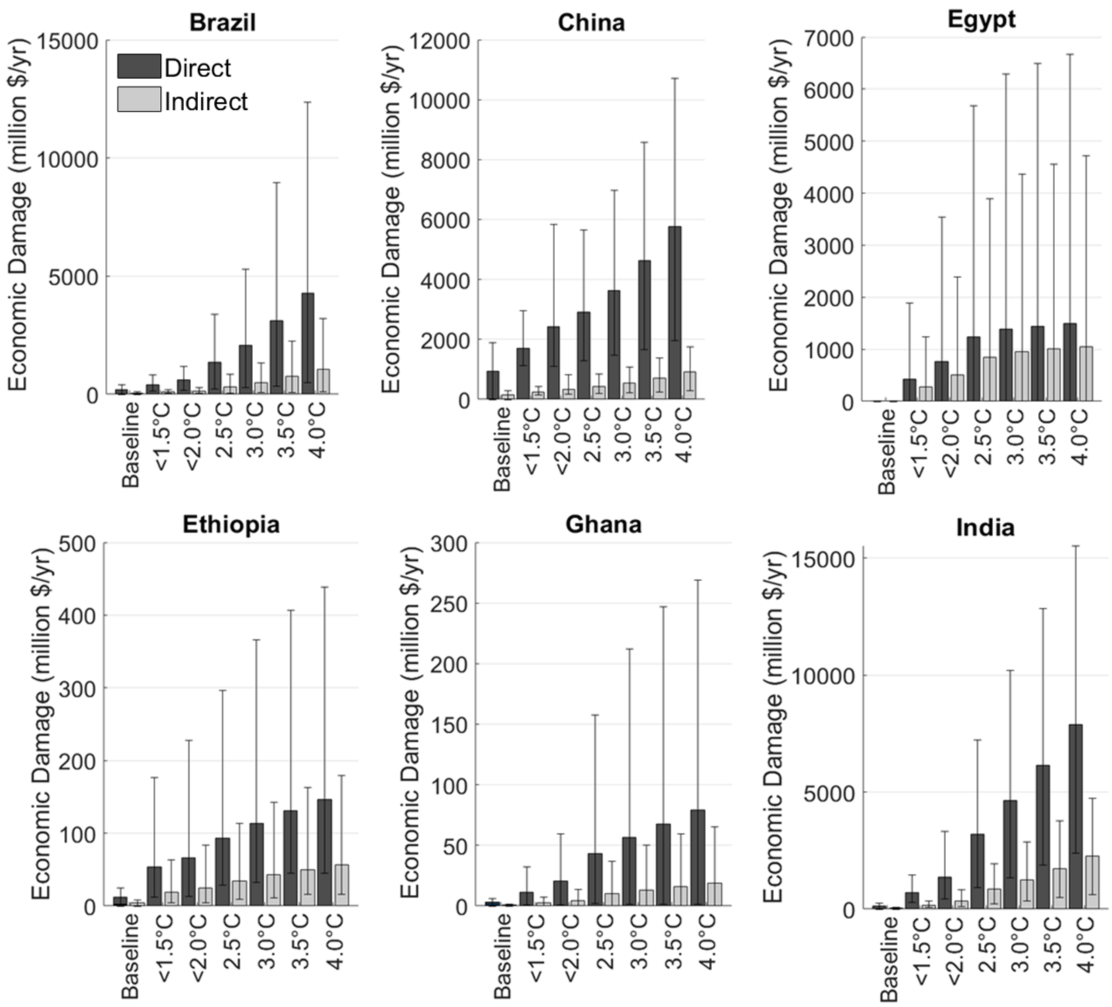

Figure S1: Direct and indirect fluvial flood damages for the baseline and six warming scenarios in the six countries expressed in million US$/yr for the CC experiment. Bars represent the model ensemble average, with whiskers indicating the ensemble maximum and minimum. Note the different scale of the y-axis.

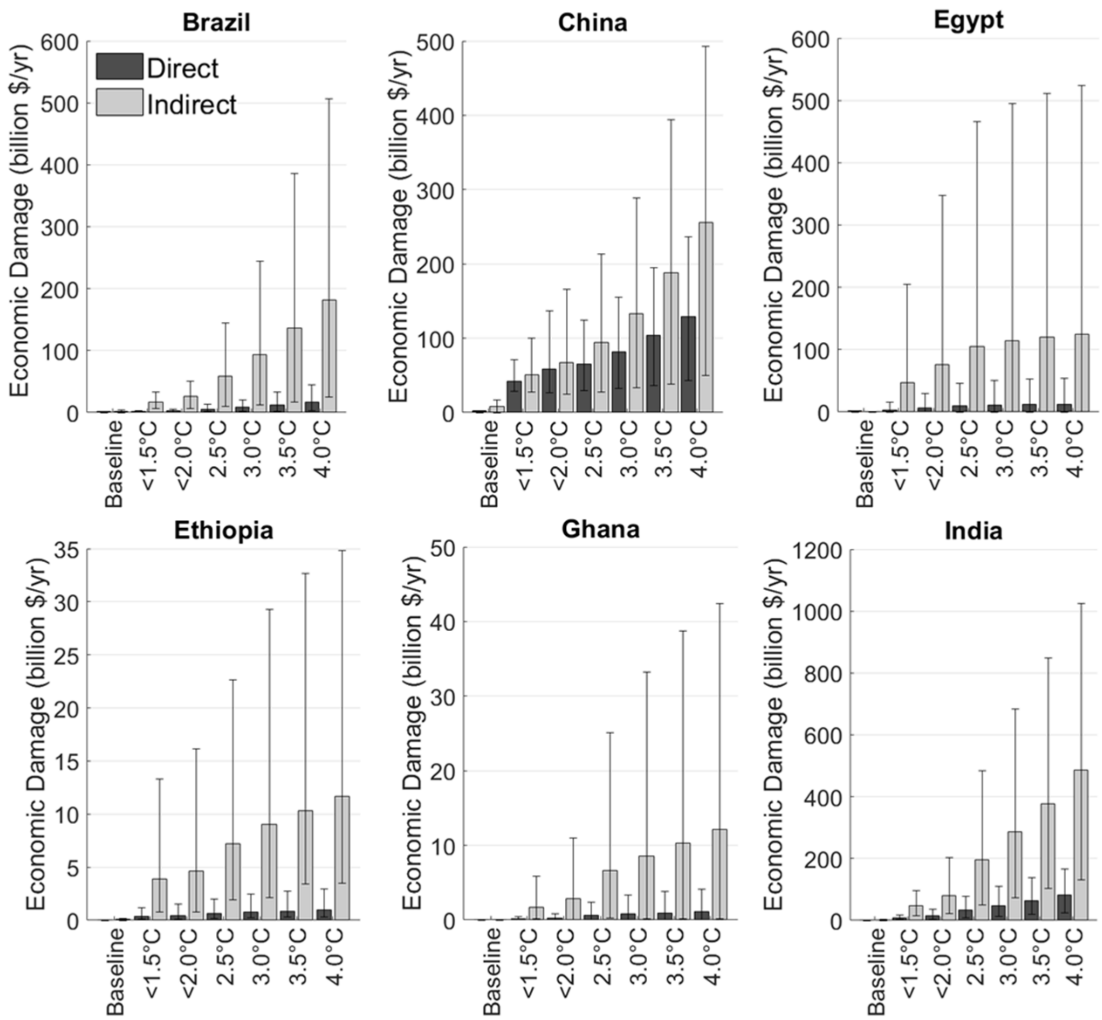

Figure S2: Direct and indirect fluvial flood damages for the baseline and six warming scenarios in the six countries expressed in billion US$/yr for the CC+SE experiment. Bars represent the model ensemble average, with whiskers indicating the ensemble maximum and minimum. Note the different scale of the y-axis.

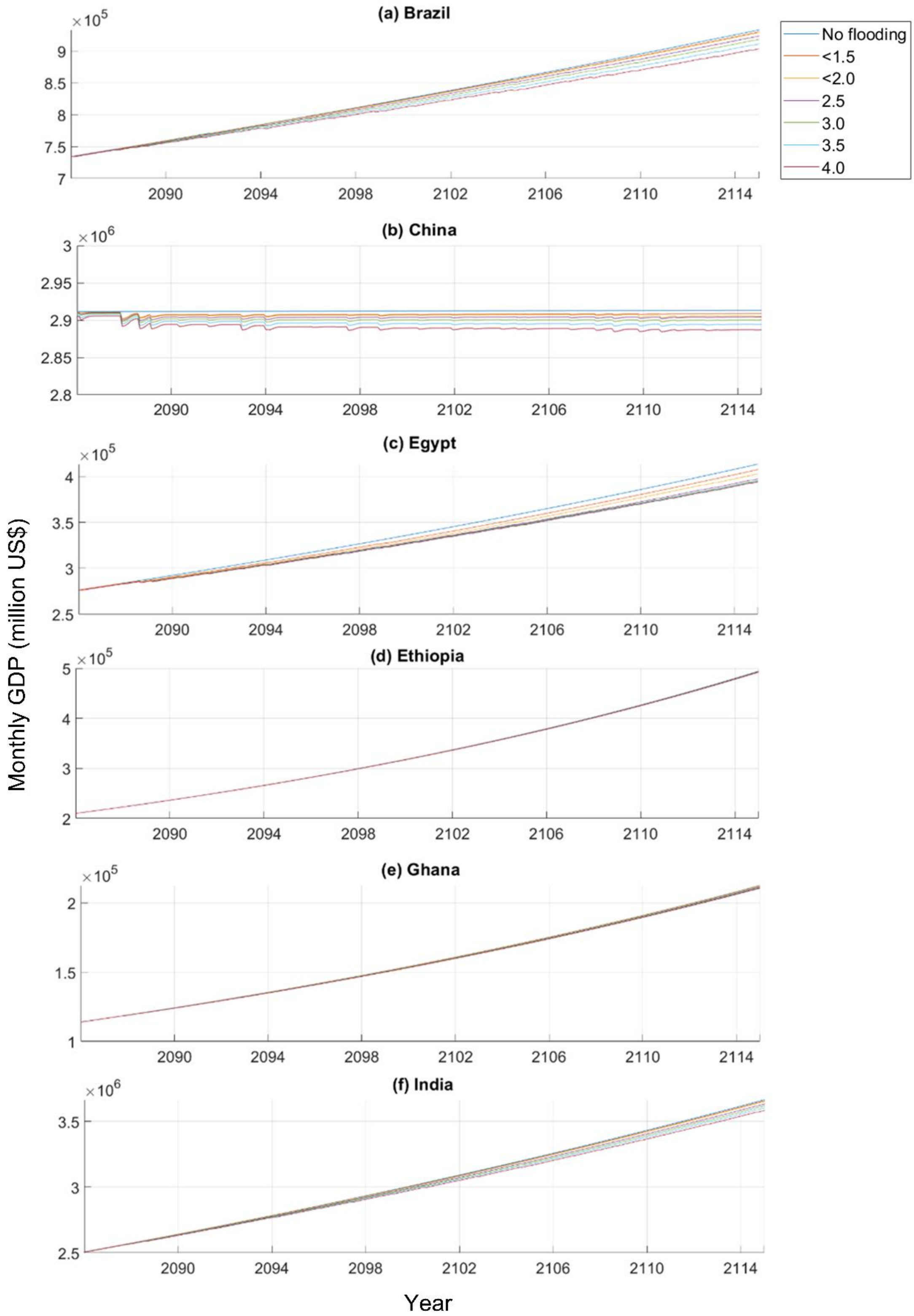

Figure S3: Monthly GDP (million US$) growth projections for each of the six countries under the climate scenarios. Results are shown for the CC+SE model experiments (based on exogenous growth data between 2086-2115). Please note the different scale of y-axis for each panel.

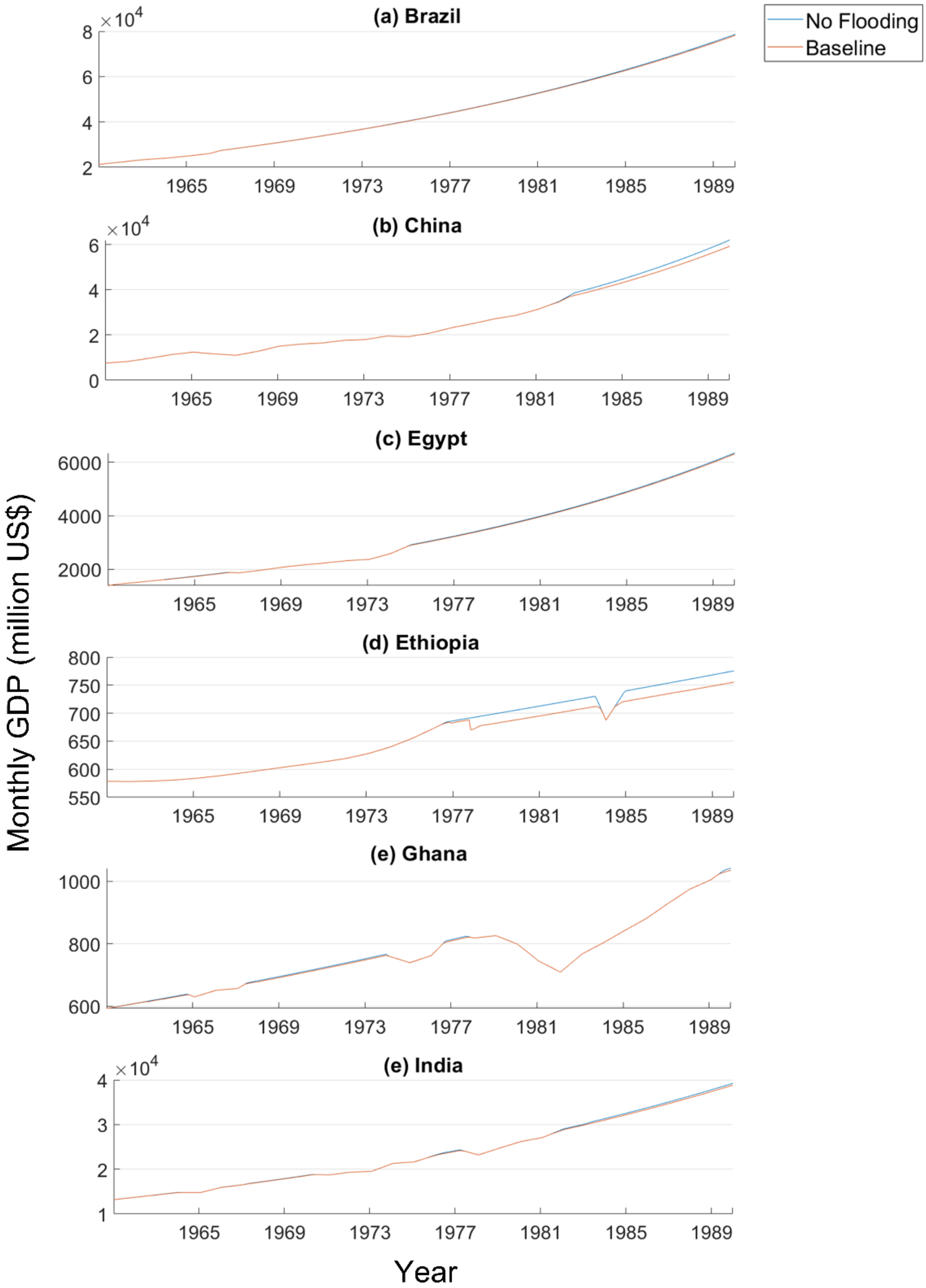

Figure S4: Monthly GDP (million US$) growth projections for each of the six countries under the baseline scenario. Results are shown for the CC+SE model experiments (based on exogenous growth data between 1961-1990). Please note the different scale of y-axis for each panel.

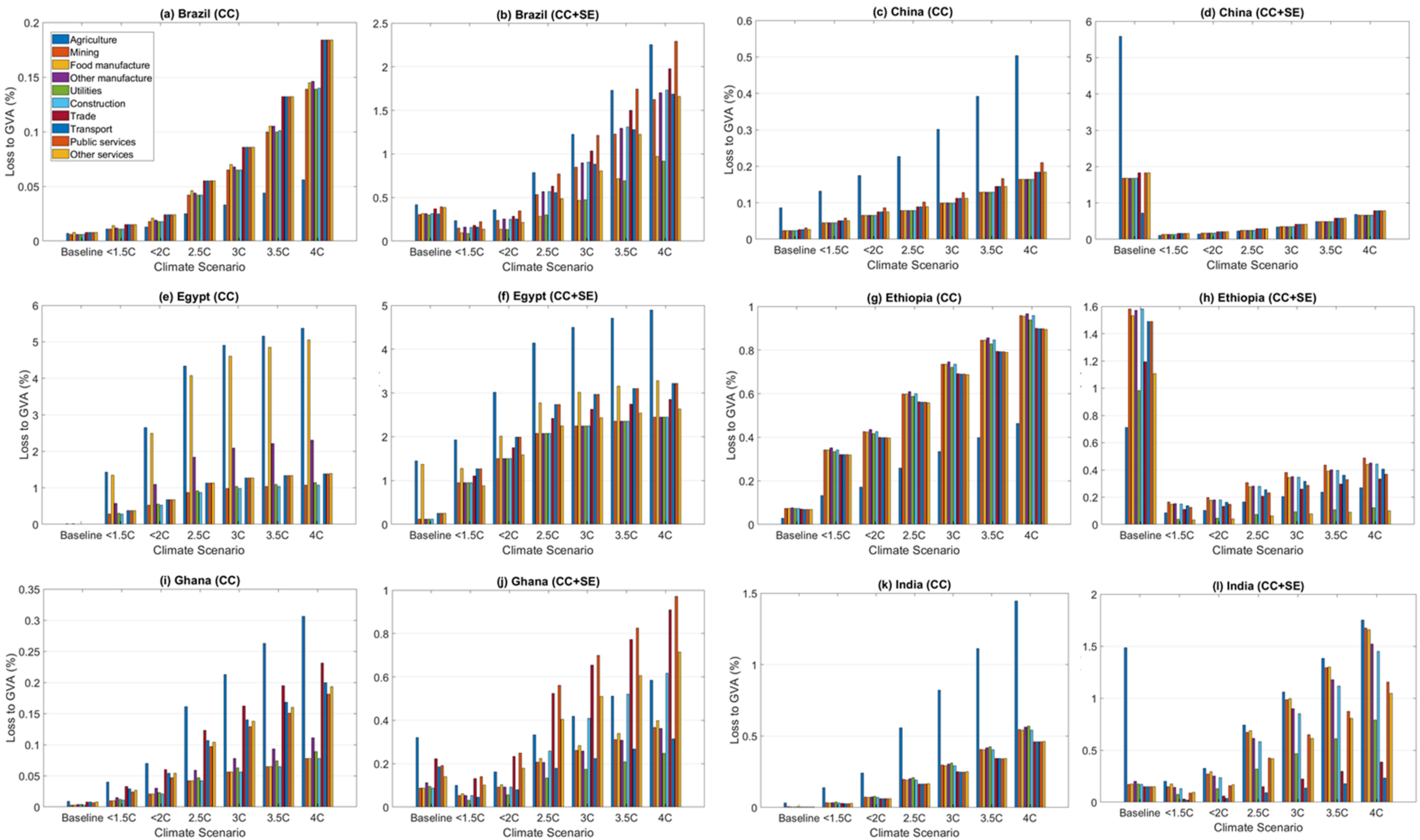

Figure S5: Average annual indirect economic loss of gross value added (GVA) in each economic sector for the baseline (1961-1990) and future warming scenarios (using SSP2 from 2086-2115) in the six countries. Results are shown for both the CC and CC+SE experiments.

	With socio-economic change (CC+SE)	Without socio-economic change (CC)
Population exposure	Scale down/up to the relevant years	Scale down to the average level between 1961-1990
Capital damage	Scale down/up to the relevant years	Scale down to the average level between 1961-1990
IO Tables	Baseline: earliest available version (e.g., 2005 for Ghana) Future: latest available version (e.g., 2015 for Ghana) (See Table S1 for full details)	Same IO Table as the baseline period
Land Cover	Baseline: 1992 Future: 2015	1992
GDP, labour, capital stock & other socio-economic indicators	Baseline: growing from 1961 using reported data Future: growing from 2086, according to SSP2 projections	Average between 1961-1990

Table S1: Overview of data used for "CC+SE" and "CC" experiments

			Final Sectors									
		IOT Year	**AGR**	**MIN**	**FDM**	**OTM**	**UTL**	**CON**	**TRD**	**TRA**	**PUB**	**OTS**
Ghana	Baseline	2005	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Future	2015	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ethiopia	Baseline	2005	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Future	2010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Egypt	Baseline	1996	✓	✓(oils)	✓	✓	✓(electricity)	✓	×	✓	✓	✓
	Future	2010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
India	Baseline	1993	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Future	2015	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
China	Baseline	1997	✓	✓	✓	✓	✓	✓	✓	✓	✓	×
	Future	2017	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Brazil	Baseline	2000	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Future	2015	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table S2: Year of IOTs used for each country under the baseline and future runs and coverage of sectoral data for: Agriculture (AGR), Mining (MIN), Food Manufacturing (FDM), Other Manufacturing (OTM), Utilities (UTL), Construction (CON), Trade (TRA), Transport (TRA), Public services (PUB) and Other Services (OTS)