Climate change and economic growth: An intertemporal general equilibrium analysis for Egypt

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Abstract:
This study develops a multisectoral intertemporal general equilibrium model with forward-looking agents, population growth and technical progress to analyse the long-run growth prospects for Egypt in a changing climate. Based on a review of existing estimates of climate change impacts on agricultural productivity, labor productivity and the potential losses due to sea-level rise for the country, the model is used to simulate the effects of climate change on aggregate consumption, investment and welfare up to 2050. Available cost estimates for adaptation investments are employed to explore adaptation strategies.
The simulation analysis suggests that in the absence of policy-led adaptation investments, real GDP towards the middle of the century will be nearly 10 percent lower than in a hypothetical baseline without climate change. A combination of adaptation measures, that include coastal protection investments for vulnerable sections along the low-lying Nile delta, support for changes in crop management practices and investments to raise irrigation efficiency, could reduce the GDP loss in 2050 to around 4 percent.

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1. Introduction

Due to the high concentration of economic activity along the low-lying coastal zone of the Nile delta and its dependence on Nile river streamflow, Egypt's economy is highly exposed to adverse climate change. Adaptation planning requires a forward-looking assessment of climate change impacts on economic performance at economy-wide and sectoral level and a cost-benefit assessment of conceivable adaptation investments.

This study develops a multisectoral intertemporal general equilibrium model with forward-looking agents, population growth and technical progress to analyse the long-run growth prospects of Egypt in a changing climate. Based on a review of existing estimates of climate change impacts on agricultural productivity, labor productivity and the potential losses due to sea-level rise for the country, the model is used to simulate the effects of climate change on aggregate consumption, investment and welfare up to 2050. Available cost estimates for adaptation investments are employed to explore adaptation strategies.

On the methodological side, the present study overcomes a basic limitation of existing country-level recursive-dynamic computable general equilibrium models[1] for climate change impact analysis by incorporating forward-looking expectations. In contrast to the standard recursive-dynamic approach, in which climate shocks hit agents in the model by surprise, the intertemporal approach pursued here takes account of endogenous anticipative adaptation responses to expected future climate change impacts. Moreover, it extends the existing family of discrete-time intertemporal computable general equilibrium models to which our model belongs by incorporating population growth and technical progress. On the empirical side, the model is calibrated to a social accounting matrix that reflects the observed current structure of the Egyptian economy, and the climate change impact and adaptation scenarios are informed by a close review of existing quantitative estimates for the size order of impacts and the costs of adaptation measures.

[1] Examples for recent country-level studies using recursive-dynamic CGE models include Arndt et al (2011,2012), Robinson et al (2012) and Thurlow et al (2012). For an early study of this type for Egypt see Strzepek and Yates (2000). Fankhauser and Tol (2005) and Lecocq and Shalizi (2007) provide systematic conceptual discussions of the channels through which climate change potentially affects aggregate economic growth in Solow-type growth models, Cass-Koopmans-type optimal growth models and endogeneous growth models. Babiker et al (2009) compare recursive-dynamic and intertemporal specifications in global climate change mitigation modeling.

The following section outlines the model and its numerical calibration. Section 3 specifies and motivates the climate change impact simulation scenarios. Section 4 presents simulation results in the absence of policy-led adaptation investments. Section 5 considers adaptation scenarios, section 6 reflects briefly on sensitivity and limitations of the analysis, and section 7 concludes.

2. The model

The determination of intertemporal saving and investment decisions in the model is essentially a multi-sector open-economy extension of neoclassical optimal growth theory in the Ramsey-Cass-Koopmans tradition, while intratemporal allocation decisions across sectors are determined by a standard static small open economy CGE model as described in full technical detail in Robinson et al (1999). The operational model design draws upon the contributions to intertemporal CGE analysis and its applications by Go (1994), Mercenier and Sampaio de Souza (1994), Diao and Somwaru (1997), Elshennawy (2011) and Roe et al. (2010), but extends this class of applied models by incorporating population growth and technical progress.

In line with its theoretical pedigree, the long-run steady-state growth rate of the model is governed by labor force growth and the rate of technical progress, while climate impacts that affect savings and investment entail *level* shifts in the time paths of GDP, consumption and other macroeconomic aggregates without affecting the long-run trend growth rate.

For purposes of the present study, the model distinguishes six sectors of economic activity: agriculture, oil, industry, construction, electricity and services. Output is produced using intermediate inputs and primary factors of production which include labor and capital. To capture the impact of different policy scenarios on the labor market, two skill categories of labor are distinguished, production and nonproduction labor. For simplicity, the role of government is confined to tax collection. Tax revenue is redistributed to the household sector and government expenditure is treated as part of household consumption. The agents in the model are a representative household with infinite planning horizon, a representative firm in each of the production sectors, and the rest of the world, which is linked to the domestic economy via trade, transfer and capital flows. Markets are perfectly competitive. What follows is a description of the dynamic components of the model.

2.1. Consumption behavior

The representative household receives labor and dividend income from firms as well as net transfer income from the rest of the world and the re-transfer of tax revenue. The household chooses the path of consumption that maximizes the intertemporal utility function

(1) $$U_o = \sum_{t=0}^{\infty} N_t \ln\left(\frac{C_t}{N_t}\right)\frac{1}{(1+\rho)^t} = N_0 \sum_{t=0}^{\infty} ln\left(\frac{C_t}{N_t}\right)\left(\frac{1+n}{1+\rho}\right)^t$$

subject to the intertemporal budget constraint

(2) $$\sum_{t=0}^{\infty} R_t P_t C_t \leq \sum_{t=0}^{\infty} R_t[wp_t LP_t + wn_t LN_t + TR_t + TX_t] + W_0$$

and a no-Ponzi-game transversality condition, where C is an index of aggregate real consumption, N = LP + NP is household size with LP and NP denoting production and non-production labor respectively, n is the rate of population and labor force growth, ρ is the pure rate of time preference, P is the implicit consumer price index dual to C, wp and wn are the wage rates for production and non-production labor, TR denotes net transfer income from the rest of the world, TX is tax revenue, W_0 is initial financial net wealth of the household sector, which is equal to the total market value of the firms owned by the representative household minus the initial external debt owed to the rest of the world, and

(3) $$R_t = \prod_{s=0}^{t} 1/(1+r_s)$$

is the discount factor where r denotes the world interest rate.

The first-order conditions for the maximization of (1) subject to (2) and the transversality condition, which ensures that the given initial debt does not exceed the present value of future current account surpluses, take the form

(4) $$\frac{P_{t+1}C_{t+1}}{P_t C_t}\frac{1+\rho}{1+n} = 1 + r_t.$$

2.2. Investment behavior

In each model sector s, firms are aggregated into one representative firm which finances all of its investment through retained earnings and thus the number of equitiy shares issued remains constant. Managers seek to maximize the value of the firm. Assuming perfect capital markets, asset market equilibrium requires equal rates of returns (adjusted for risk) on all assets. This implies that firm’s equity must earn an expected rate of return equal to that of a safe asset like foreign bonds as reflected in the condition

(5) $$r = \frac{DIV_s}{V_s} + \frac{\Delta V_s}{V_s}$$

where DIV is dividends, V is the value of the firm, $\Delta V_s = V_{s,t} - V_{s,t-1}$ is the expected annual capital gain on firm equity and r is the interest rate on foreign bonds.

Solving the above difference equation (5) forward yields

(6) $$V_t = \sum_{v=t}^{\infty} R_t DIV_t \ .$$

The market value of the firm equals the discounted stream of future dividends. Dividends distributed to the household sector equal operating surplus minus investment expenditure:

(7) $$DIV_{S,t} = \ PVA_{S,t} f\left[bLP_{S,t}, bLN_{S,t,} K_{S,t}\right] - wp_t LP_{S,t} - wn_t LN_{S,t} - PI_{S,t} I_t - ADC_{S,t},$$

where, f (.) is the production function, K is capital, PI is the price per unit of investment I, PVA is the value added price (output price net of indirect production taxes and intermediate input unit costs) and ADC represents adjustment costs associated with the installation of new capital:

(8) $$ADC_{S,t} = PIA_{S,t} \varphi \frac{I_{S,t}^2}{K_{S,t}}$$

Due to the presence of these adjustment costs, the capital stock does not adjust instantaneously to its new optimal long-run level following exogenous shocks that affect the return to capital. Adjustment costs to investment are assumed to be internal to the firm. For any given level of the capital stock these costs are strictly increasing in investment and decreasing in the capital stock for any given level of investment. As a result, firms will find it optimal to increase the capital stock gradually over time in order to reach the optimal long run capital intensity. The adjustment cost function is assumed to be linear-homogeneous in investment and capital. Along with the assumption of constant returns to scale in production, the linear homogeneity of the adjustment cost function entails that Tobin's marginal q equals Tobin's average q (Hayashi, 1982). In the general equilibrium model, the real adjustment costs take the form of purchases of installation services, which are a Leontief composite of the construction and industry commodities, and PIA is the unit price of this composite.

The model incorporates labor-augmenting technical progress. The labor efficiency parameter b in (7) grows at the uniform exogenous rate g.

In each sector producers maximize the value of the firm subject to the capital accumulation constraint

(9) $K_{S,t+1} = (1-\delta_S)K_{S,t} + I_{S,t}$,

where δ is the rate of depreciation. Differentiating the Lagrangean for this optimization with respect to the control variable I yields

(10) $q_{S,t} = PI_{S,t} + 2PIA_{S,t}\varphi\frac{I_{S,t}}{K_{S,t}}$,

which determines the shadow price of capital. Condition (10) states that the firm invests until the cost of acquiring capital – which is equal to the price of a unit of investment plus marginal adjustment costs – is equal to the value of capital. Differentiating with respect to the state variable K yields the no arbitrage condition

(11) $PVA_{S,t}f_K + PIA_{S,t}\varphi\left(\frac{I_{S,t}}{K_{S,t}}\right)^2 + (1-\delta)q_{S,t} - (1+r)q_{S,t-1} = 0$.

According to Equation (11), the value of the marginal product of capital PVA f_K plus the marginal reduction in adjustment costs brought by the increase in capital plus the capital gains q_t - q_{t-1} minus depreciation δq must equal the amount foregone rq by choosing to accumulate this extra unit of capital. For simplicity, there is no differentiation between government and private investment in the model. $I_{S,t}$ is a Cobb-Douglas composite good over commodity groups demanded for investment purposes,

(12) $I_{S,t} = AK_S\prod_{S'} INVD_{S',S}^{\theta_{S',S}}$,

where $INVD_{S',S}$ is investment demand by sector S for goods of type S' and AK_S is a constant parameter. $PI_{S,t}$ is the investment price index dual to $I_{S,t}$.

2.3. Current account dynamics

The current account dynamics associated with the optimal consumption and investment path is described by

(13) $D_{t+1} - D_t = r_tD_t + TB_t + TROW_t$,

where TB_t is the trade balance surplus in t and TROW denotes exogenous net transfers from abroad. Letting Y denote aggregate GDP, $TB_t = Y_t - P_tC_t - \sum_S PI_{S,t}I_{S,t}$. The no-Ponzi-game condition invoked in the derivation of the optimal consumption path described by (4) entails that the initial debt inherited from the path constrains the future path of domestic absorption, so that $D_0 = PV(Y_t+TROW_t) - PV(P_tC_t) - PV(\sum_S PI_{S,t}I_{S,t})$, where PV(x) denotes the present value of a stream x_t discounted at rate r. In other words, the initial debt must be matched by a corresponding positive present value of future primary account surpluses.

2.4. Intratemporal general equilibrium

Embedded in this dynamic structure is a standard within-period general equilibrium model that determines intratemporal relative prices, the sectoral allocation of labor and the commodity composition of consumption, imports and exports.

Producers in the model are price takers in output and input markets and use constant returns to scale technologies described by constant elasticity of substitution (CES) value added functions and a Leontief fixed-coefficient technology for intermediate input requirements by commodity group. The decision of producers between production for domestic and foreign markets is governed by constant elasticity of transformation (CET) functions that distinguish between exported and domestic goods in each traded commodity group. Under the small-country assumption, Egypt faces perfectly elastic world demand for its exports at fixed world prices. The profit-maximizing equilibrium ratio of exports to domestic goods in any traded commodity group is determined by the relative prices for these two commodity types.

On the demand side, imported and domestic goods are treated as imperfect substitutes in both final and intermediate demand. In line with the small-country assumption, Egypt faces an infinitely elastic world supply at fixed world prices. The equilibrium ratio of imports to domestic goods is determined by the intratemporal felicity- and cost-minimizing decisions of domestic agents based on the relative tax-inclusive prices of imports and domestic goods.

2.5. Properties of the steady-state equilibrium growth path

Technically the dynamic system described by (1) to (13) can be reduced to a saddlepoint-stable system in the state variable K and co-state variable q. K_0 is predetermined while q_0 is a jump variable. In the absence of shocks to the exogenous parameters of the model, the system can be shown to converge to a steady-state equilibrium, in which q and the sectoral capital stocks per effective labor unit ($K_S/(b(LN+LP))$) are stationary, while aggregate income, consumption, investment and other macro aggregates grow at the steady-state growth rate $z = g + n + gn$, provided that (using asterisks to denote steady-state levels of variables) $r^* = \rho + g + \rho g$.

The steady-state investment ratio in each sector is

(14) $\frac{I^*_{S,t}}{K^*_{S,t}} = \delta + z$.

The net foreign asset position along the steady-growth path evolves according to

(15) $(r^* - z)D^*_t = TB^*_t + TROW^*_t$.

The steady-state growth path market value of the firm in each sector obeys

(16) $(r^* - z)V^*_{S,t} = DIV^*_t$.

2.6. Data and calibration

The model is calibrated using the 2006/2007 Social Accounting Matrix (SAM) for Egypt. Assuming that the initial data represents an economy evolving along a steady state growth path, parameters are calibrated so that the model generates a path with a starting point that replicates the observed benchmark data set in the absence of anticipated future climate shocks. This dynamic baseline path serves as the benchmark for comparison for the climate change scenarios considered in the following sections.

Calibration of all parameters for the intratemporal part of the model follows the standard methods used in comparative-static CGE models. The dynamic calibration proceeds as follows. Based on the UN medium population growth projections for Egypt from 2010 to 2050, the average annual labor force growth rate is set to n = 0.07 and the growth rate of labor-augmenting technical progress is set to g = 0.025, hence the steady-state growth rate z = 0.0322. The rate of capital depreciation is set to δ = 0.04. Total dividend payments are calculated as the difference between the observed value of capital income (gross operating surplus) and the observed value of total investment in the SAM. In order for the model to replicate these observed magnitudes, the pure rate of time preference is set to ρ = 0.16, and the adjustment cost parameter is set to φ = 1. These settings jointly determine the initial real capital stock by sector (K_S), q_S and PI_S via the steady-state equilibrium conditions, and the parameters AK_S in (12) follow residually.

3. Simulation scenarios

Scenario S0 simulates the counterfactual steady-state equilibrium growth path in the absence of any climate change impacts and serves as the baseline for comparison with the climate change impact and adaptation scenarios.

Scenario S1 considers the economy-wide consequences of adverse climate change impacts on agricultural productivity. According to the 2007 SAM, the agricultural sector contributes 13.2 percent to Egypt's GDP at factor cost while it currently provides livelihoods for more than 30 percent of the population. Agricultural activity is largely confined to a small strip along the banks of the Nile river basin and the coastal zone of the Nile delta. More than 90 percent of Egypt's crop production is irrigated and the Nile supplies 95% of the country's total water needs (Agrawala et al, 2004). Precipitation over Egypt itself is low and does not significantly contribute to Nile streamflow, and hence future water supplies depend critically upon climate change impacts on rainfall and evapotranspiration - and adaptation responses to it - in the upstream East African Nile riparian regions. Since the completion of the Aswan Dam in 1972 which helps to cope with periodic upstream droughts, Egypt has been reasonably well adapted to current climate variability but remains vulnerable to multi-year droughts (Agrawala et al, 2004; Robinson et al, 2008).

Simulations towards 2100 with a hydrology model by Strzepek et al (2001) across different GCM scenarios suggest "modest" to "dramatic" reductions in Nile flow into Egypt in eight of the nine climate scenarios under consideration and reductions towards 2040 in all of the scenarios. A more recent hydrological study by Beyene et al. (2010) likewise concludes that Egyptian agricultural water supplies could be negatively impacted by climate change, especially in the second half of the 21st century.

Met Office (2011) and EEAA(2010) review existing studies of climate change impacts on crop yields for Egypt based on crop model simulations. For the country's main staple crops – maize, rice and wheat – these studies suggest yield reductions on the order of -11 to -19 percent by 2050 and by -20 to -36 percent by 2100. Livestock productivity is also expected to be adversely affected due to harmful heat stress and yield reductions for fodder crops under climate change (Met Office, 2011).

On the basis of these projections, scenario S1 assumes a gradual anticipated linear reduction in agricultural total factor productivity (TFP) over the period 2010 to 2100 by 0.25 percentage-points per year relative to the baseline, so that agricultural TFP is 10 percent below baseline in 2050 and 22.5 percent below baseline in 2100. The selection of yield reductions at the lower end of the spectrum of existing crop model projections makes allowance for a degree of autonomous adaptation responses by Egyptian farmers. It is worth emphasizing that due to the assumption of exogenous labour-augmenting progress in the agricultural sector as in other sectors, this scenario does *not* assume that agricultural productivity declines over time - rather, at each point in time from 2010 onwards, productivity is lower than in the baseline scenario, but continues to rise over time due to the presence of labor-augmenting technical progress.

Scenario S2 considers potential impacts of sea-level rise (SLR) on the growth prospects for the Egyptian economy. As the coastal zone of the Nile delta coast hosts a number of highly populated including Alexandria, Port Said, Rosetta, and Damietta, which are import centers of economic activity (Agrawala et al, 2004), global impact studies identify Egypt as one of the most vulnerable countries to SLR (Dasgupta et al, 2009, 2011, Met Office, 2011). Based on DIVA model simulations, Hinkel et al (2012) estimate annual SLR damage costs for Egypt in the absence of protective adaptation investments on the order of 0.06% of GDP in 2100 for a +64cm SLR scenario, and on the order of 0.18% of GDP for a +126cm SLR scenario. In contrast, Dagupta et al (2009) estimate a considerably higher SLR loss of 6.4% GDP for Egypt under a +100cm SLR scenario. We simulate disruptions to economic activity due to SLR in the absence of coastal protection investments as anticipated adverse shocks to TFP across all sectors that rise linearly in strength from 0 before 2015 to -2 percent of baseline productivity in 2100.

Scenario S3 simulates the impact of an anticipated increase in the frequency of extreme coastal storm surges on top of the impacts due to mean sea level rise, as contemplated by Dasgupta et al (2011) and envisaged in EEAA (2010a). A further motivation for this scenario is provided by Hanson et al (2011) who identify Alexandria - which generates a significant fraction of Egypt's GDP -, as one of the 20 port cities globally with the highest levels of exposure to extreme storm surges. This speculative scenario serves to illustrate the model responses to anticipated temporary shocks. The scenario assumes that extreme storm surges that destroy productive capital in all sectors occur every ten years from 2030 onwards through to 2100. The shocks are implemented through temporary one-off increases in the rate of capital depreciation by one percentage-point.

Scenario S4 considers impacts of thermal stresses on labor productivity in a changing climate. This potential impact channel is generally neglected in economic climate change impact assessments. Hsiang (2010) provides a strong argument in favor of the inclusion this channel and points to evidence from meta-studies that suggest that beyond a temperature threshold of 27^o C labor productivity drops by around 2 percent per 1^{o}C increase in temperature. A recent econometric study by Zivin and Neidell (2010) for the USA suggests impacts of high temperatures on effective labor supply beyond a 27^o C threshold of a similar magnitude. Given daytime temperatures in Egypt beyond this threshold for around 6 months per year and GCM temperature projections for the country on the order of 3 to 3.5°C compared to a 1960-90 baseline (Met Office, 2011), this scenario assumes a gradual linear drop in labor productivity relative to the baseline growth path from 2010 towards -1.3 percent in 2050 and to - 3 percent in 2100.

Scenario S5 simulates the joint impact of the climate shocks considered in isolation in S1 to S4. Adaptation scenarios and their underlying assumptions are described in section 5.

4. Climate change impact simulations

In the counterfactual no-climate-change baseline scenario, the economy grows steadily at the long-run equilibrium growth rate of 3.22 percent. This entails that aggregate income and real income double by 2030 relative to initial levels and are 3.8 times their initial levels by 2050. Per-capita income doubles by 2035 and is 2.9 times its 2007 level by 2050. These figures need to be kept in mind to maintain a proper perspective on the climate change impact results presented below.

Scenario S1 considers adverse climate impacts on agricultural productivity that gradually increase in strength over time from 2010 onwards. The time path of these future productivity shocks, as described in the previous section, is disclosed at the start of the simulation horizon, and agents in the present perfect foresight setting revise their intertemporal consumption and investment plans in response to the bad news. The first column of Table 1 reports the resulting percentage deviations from the baseline growth path for macroeconomic aggregates in 2030 and 2050.[2] The anticipated future productivity shocks lower the present value of expected GDP and require a corresponding reduction in the present value of domestic absorption – that is the sum of domestic consumption and investment expenditure – to obey the intertemporal external balance constraint. As households have a preference for a

[2] While the model is technically solved at annual resolution for 110 time steps up to the year 2117 and is assumed to evolve along the new steady-state growth path beyond that point ad infinitum, the presentation of result focuses on the period up to 2050.

smooth consumption expenditure growth path over time[3], nominal consumption drops by 0.14 percent immediately after the announcement of the shocks, but then continues to grow smoothly at the unchanged steady-state growth rate z from this lower level. However, since the price index of consumption P rises over time as a result of increases in the supply prices for domestic agricultural goods (Table 1), aggregate real consumption levels – and hence intratemporal utility – drop significantly relative to the baseline with the passage as the adverse climate change impacts on agricultural yields become more severe over the decades. By 2050, aggregate real consumption is 3.6 percent below its baseline equilibrium level for the same year.

Associated with these macroeconomic adjustments to the yield shocks is an increase in the country's net foreign asset position over time. As domestic absorption drops immediately while the negative income impacts materialize later, the current account balance rises initially and the external debt level grows at a lower rate than along the baseline steady-state growth path. As a result debt service payments in subsequent periods are lower than in the baseline, thus allowing to maintain a smooth consumption expenditure growth path as the climate change impact become more pronounced. Essentially the same intertemporal macro adjustment patterns emerge for scenarios S2 to S5.

Table 1: Climate Change Impacts on Macro Aggregates

(Percentage deviations from baseline growth path)

	S1	S2	S3	S4	S5
Real Consumption$_0$	-0.09	-0.05	-0.07	-0.06	-0.20
Real Consumption$_{2030}$	-0.63	-0.22	-0.42	-0.12	-1.17
Real Consumption$_{2050}$	-1.33	-0.66	-1.21	-0.23	-2.95
Real Investment$_0$	-0.28	-0.12	-0.17	-0.02	-0.47
Real Investment$_{2030}$	-2.49	-2.48	-2.79	-0.47	-5.55
Real Investment$_{2050}$	-5.02	-5.61	-6.78	-1.00	-11.96
Nominal Consumption	-0.14	-0.08	-0.11	-0.06	-0.3
Consumer Price Index$_{2050}$	1.21	0.59	1.12	0.16	2.53
Real Capital Stock$_{2050}$	-3.32	-3.54	-6.44	-0.65	-9.93
Welfare U_0 (ρ=0.16)	-0.04	-0.01	-0.02	-0.01	-0.07
Welfare U_0 (ρ=0.05)	-0.12	-0.06	-0.09	-0.02	-0.24
Real GDP$_{2050}$	-3.86	-3.40	-5.46	-0.82	-9.84

S1: Agricultural yield impacts. S2: SLR impacts. S3: SLR impacts as in S2 plus decadal coastal storm surge damages. S4: Thermal stress impacts on labor productivity S5: Joint S1 and S3 and S5 impacts.

[3] Recall that since $r = \rho+g+\rho g$, condition (4) entails smooth consumption expenditure growth at the rate g+n+gn.

Looking at the sectoral results for Egyptian agriculture under scenario S1, net imports of agricultural commodities rise strongly under this scenario, with real AGR imports in 2050 rising by 11 percent above base line level and Egypt's real AGR exports dropping 48 percent below baseline level towards the middle of the century. Agricultural output in 2050 is 9.5 percent below base (but still more than three times as large as in the initial 2007 equilibrium). Interestingly, the 2050 agricultural capital stock is slightly larger than in the baseline (Table 2) despite a significant drop in Egypt's agricultural output (Table 3), as the producer price increase for domestic AGR output is sufficiently strong to make additional net investment in the sector profitable.[4]

Table 2: Impacts on Sectoral Capital Stocks 2050

(Percentage deviations from baseline growth path)

	S1	**S2**	**S3**	**S4**	**S5**
AGR	0.24	-2.17	-4.10	-0.51	-4.11
IND	-3.88	-4.87	-8.69	-0.97	-12.94
OIL	-6.01	-3.41	-6.19	-0.58	-11.73
CON	-6.60	-6.50	-0.58	-0.53	-16.10
SER	-3.25	-3.04	-11.73	-0.39	-8.43

S1: Agricultural yield impacts. S2: SLR impacts. S3: SLR impacts as in S2 plus decadal coastal storm surge damages. S4: Thermal stress impacts on labor productivity. S5: Joint S1 and S3 and S5 impacts AGR: Agriculture, IND: Industry; OIL: Oil; CON: Construction; SER: Other Services.

Scenarios S2 and S3 consider SLR impacts on economic activity without and with additional real capital losses due to extreme storm surges. The significant adverse impacts on aggregate real investment and the aggregate capital stock well before the middle of the century displayed in Table 2 may look surprising at first sight, given that the bulk of the adverse physical SLR impacts are assumed to materialize only in the second half of the century. However, it is precisely the anticipation of these future impacts beyond 2050 that reduce the expected returns to domestic durable capital and thus discourage domestic investment in favor of the alternative to invest in foreign assets at the given world market interest rate or to reduce the foreign debt. From an economy-wide perspective, the aggregate domestic capital stock must drop relative to

[4] Here and in the following, nominal prices are expressed relative to the import price index, i.e. the numeraire of the model is the associated basket of import goods.

the baseline growth path until the expected value of the marginal product of capital has risen sufficiently to restore asset equilibrium. This anticipation effect is completely absent in standard recursive-dynamic general equilibrium impact assessment models, and the present illustrative simulations indicate that its impact on economic growth can be quite significant.

Scenario S4 considers direct thermal stress impacts on labor productivity. As noted earlier, this potential impact channel on economic performance has been commonly neglected in previous economic climate change assessment studies. The simulation results in Table 1 suggest a noticeable impact on aggregate economic outcomes. Under the stated assumptions, real GDP in 2050 is projected to be 0.82 percent lower than in the baseline and the aggregate capital stock drops by 0.65 percent below base, which due to the impact of lower labor productivity on the expected returns to domestic investment.

Table 3: Impacts on Sectoral Output 2050

(Percentage deviations from baseline growth path)

	S1	S2	S3	S4	S5
AGR	-9.51	-2.57	-4.23	-0.59	-13.62
IND	-5.16	-3.29	-5.34	-0.78	-10.68
OIL	-3.71	-5.49	-9.17	-1.02	-13.29
CON	-4.56	-5.38	-6.38	-1.01	-11.15
SER	-1.57	-2.85	-4.76	-0.87	-7.01

S1: Agricultural yield impacts. S2: SLR impacts. S3: SLR impacts as in S2 plus decadal coastal storm surge damages. S4: Thermal stress impacts on labor productivity. S5: Joint S1 and S3 and S5 impacts
AGR: Agriculture, IND: Industry; OIL: Oil; CON: Construction; SER: Other Services.

Finally scenario S5 simulates the joint occurrence of the climate shocks considered under S1, S3 and S4. Under this comprehensive impact scenario, real GDP in 2050 is projected to be 7.3 percent below the 2050 baseline level, the aggregate capital stock drops by 12 percent and aggregate consumption drops by nearly 3 percent below baseline in the absence of adaptation investments. Such investments are briefly explored in the following section.

Despite these pronounced effects, the intertemporal welfare effects as measured by the intertemporal utility function (1) appear to very modest. This is not surprising, given that the simulated adverse effects are expected to evolve gradually over the decades and given that the fairly high time preference rate used in the model gives a very low weight to consumption streams in a distant future (e.g. the weight attached to aggregate real consumption in 2050 is 0.0017). If the same dynamic consumption stream for S5 is evaluated with a lower time preference rate of $\rho = 0.05$, as is typically employed in applied social cost-benefit analysis, the welfare loss rises by an order of magnitude (Table 1), but still remains well below one percent.[5]

5. Stylized climate change adaptation scenarios

This section considers a range of adaptation investment options that aim to address the climate change impacts analysed in section IV. EEAA (2010b) identifies a set of priority actions for the agricultural sector including investments to improve surface irrigation system efficiency and support for changes in crop and livestock management practices. The study provides cost estimates for these measures over the period 2010 to 2035, amounting to USD 3 billion, the bulk of which (USD 2.1 billion) represents irrigation improvement measures. A casual glance at the relation of this cumulated undiscounted cost figures to the cumulated economic losses under scenario 1 suggests that this adaptation option is potentially promising from a cost-benefit perspective.

In simulation scenario S1A, we assume that the irrigation investments are entirely domestically financed, while the research, extension, training and capacity building services required to induce change in farming practices are provided in kind by external experts and financed by international donors without notable additional demands on domestic real resources. Following EEAA (2010b), it is assumed that the capital investments are spread over the period 2010 to 2020, while maintenance and repair costs arise in subsequent periods. The financing of the investment reduces the investible funds available for other uses in the economy and the general equilibrium model takes consistent account of this knock-on effect for other sectors. It is assumed that the set of agricultural adaptation measures succeeds in reducing the adverse productivity shocks simulated under scenario S1 by 50 percent at each point in time from 2020 onwards, and thus this scenario allows for a considerable amount of residual damage. A comparison of the aggregate results for S1A in Table 4 with the

[5] Attaching low weights to the well-being of agents in the distant future is frequently criticized on intergenerational equity grounds, but if these agents are expected to enjoy a far higher per-capita income, this practice can likewise be justified on intergenerational equity grounds. For a detailed discussion within the context of an overlapping generations setting with finite life expectancies see Willenbockel (2008).

corresponding figures for S1 in Table 1 suggests a noticeable net beneficial impact of the agricultural adaptation measures.

For protective coastal adaptation measures EEAA (2010b:24) estimates investment costs on the order of USD 10,000 per meter of vulnerable coastline along the Nile Delta, and deems 200km of coastline in need of protection, concluding (erroneously) that "this would amount to about 2 million US$". In scenario S3A we employ the algebraically correct figure of USD 2 billion, which also appears to be more closely in line with the annualized coastal adaptation cost estimates for Egypt reported in Brown, S. et al (2010). This sizable figure amounts to circa 1.5 percent of Egypt's total GDP in 2007. Scenario S3A assumes that these investment costs are distributed over a 10-year interval from 2020 to 2030 and adds annual maintenance and replacement expenses equal to 5 percent of the initial investment expenditure subsequently. We assume in this stylized scenario that under a medium-range SLR scenario on the order of +50cm the protective measures are sufficient to avoid 80 percent of the economic losses simulated under the S3 scenario from 2030 onwards.

The comparison of results for S3A in Table 4 with results for S3 in Table 1 suggests substantial net benefits for investments in coastal protection investments. The GDP loss in 2050 is reduced by over 3.2 percentage-points in relation to the no-adaptation scenario, and the drop in 2050 real consumption is reduced from -1.21 to -0.25 percent below the baseline level.

As an adaptation measure towards labor productivity losses from heat stresses, we consider in scenario S4A the subsidised installation of additional cooling equipment in industry and the services sector as a conceivable adaptation strategy. This raises the demand for electricity and raises power prices for all sectors and households, and the model takes account of this intersectoral spillover effect. It is assumed that the annualized investment cost is on the order of 0.5 percent of the baseline investment expenditure for the two sectors and that electricity demand in industry and services rises by 2.5 percent per unit of output. We further assume that these investments reduce the labor productivity losses imposed under S4 by 80 percent in industry and by 60 percent in the service sector.

From an economy-wide perspective, the aggregate real consumption losses under S4A remain very close to the losses under S4. This indicates that the gains due to higher labor productivity associated with these adaptation measures are largely cancelled out by the additional investment costs and the spillover effects of higher energy prices.

Finally, scenario S5A simulates the joint implementation of all adaptation measures considered in this section in the presence of all climate shocks analysed in section 4.

Table 4: Climate Change Impacts on Macro Aggregates with Adaptation

(Percentage deviations from baseline growth path)

	S1A	S3A	S4A	S5A
Real Consumption$_0$	-0.09	-0.02	-0.04	-0.15
Real Consumption$_{2030}$	-0.52	-0.10	-0.12	-0.58
Real Consumption$_{2050}$	-0.69	-0.25	-0.21	-1.16
Real Investment$_0$	-0.10	-0.03	-0.01	-0.14
Real Investment$_{2030}$	-1.24	-0.58	-0.65	-2.44
Real Investment$_{2050}$	-2.49	-1.46	-1.24	-5.04
Nominal Consumption	-0.13	-0.03	-0.05	-0.21
Consumer Price Index$_{2050}$	0.57	0.27	0.20	0.97
Real Capital Stock$_{2050}$	-1.66	-1.36	-0.83	-3.76
Welfare U_0 (ρ=0.16)	-0.03	-0.01	-0.01	-0.05
Welfare U_0 (ρ=0.05)	-0.07	-0.02	-0.02	-0.11
Real GDP$_{2050}$	-1.91	-1.20	-0.89	-3.87

S1A: Agricultural yield impacts with adaptation. S2: SLR impacts. S3A: SLR impacts with adaptation. S4: Thermal stress impacts on labor productivity. S5: Joint S1 and S3 and S5 impacts

6. Sensitivity of results and limitations of the analysis

Given the highly stylized nature of the model employed in this study, a cautious interpretation of the analysis would view the simulation results as a mere numerical illustration of the underlying theory with a particular focus on an exploration of the role of forward-looking expectations. However, as the share parameters have been calibrated to an empirical data set that reflects the observed initial structure of the Egyptian economy and the size orders for the assumed climate shocks and adaptation costs are based on country-specific expert estimates that reflect the respective current state of knowledge, it may be argued that the model is capable of generating reasonable policy-relevant indications for the general order of magnitude of the effects under investigation.

Under either interpretation of the results the question arises how sensitive the reported results are to variations in parameter assumptions. Obviously, the per-capita *levels* of the key variables are particularly sensitive to the assumed exogenous growth rate of labor-augmenting technical progress, while the key parameter determining the speed of adjustment to exogenous shocks is the capital stock adjustment cost parameter φ.

However, our prime interest is in the percentage *deviations* of variables from the baseline growth path as a result of climate shocks, and both the signs and the broad orders of magnitude of these percentage deviations are robust to variations in these parameters. The direction of the reported intertemporal consumption smoothing responses to anticipated shocks are likewise insensitive to behavioural parameter constellations, given the assumption that the Egyptian economy can respond to shocks to the returns to physical domestic capital via adjustments in the net foreign asset position at a fixed world market interest rate.

This study analyzes only a limited set of stylized adaptation options, leaving plenty of scope for more detailed future research to compare a wider set of carefully costed adaptation measures. Other potentially fruitful avenues for further research are the incorporation of uncertainty about climate shocks to relax the perfect foresight assumption, the replacement of the counterfactual assumption of exponential population growth at a constant rate by a logistic population growth specification along the lines of Guerrini (2010), and extensions of the model to include endogenous growth features.

7. Conclusions

This study develops a multisectoral intertemporal general equilibrium model with forward-looking agents, population growth and technical progress to analyse the long-run growth prospects of Egypt in a changing climate. Based on a review of existing estimates of climate change impacts on agricultural productivity, labor productivity and the potential losses due to sea-level rise for the country, the model is used to simulate the effects of climate change on aggregate consumption, investment and welfare up to 2050. Available cost estimates for adaptation investments are employed to explore adaptation strategies.

The simulation analysis suggests that in the absence of policy-led adaptation investments, real GDP towards the middle of the century will be nearly 10 percent lower than in a hypothetical baseline without climate change. A combination of adaptation measures, that include coastal protection investments for vulnerable sections along the low-lying Nile delta, support for changes in crop management practices and investments to raise irrigation efficiency, could reduce the GDP loss in 2050 to around 4 percent.

In contrast to existing recursive-dynamic computable general equilibrium models for climate change impact assessment, the analysis takes expectation effects into account, and this adds an important additional dimension to the assessment of households' and firms' autonomous adaptation to climate change. Since current consumption and investment decisions depend on expectations about the future, a dynamic climate change impact analysis up to 2050 must take account of anticipations of future climate change beyond 2050, and this is what the present study does.

In the small open-economy setting considered here, the anticipation of future adverse climate change impacts beyond 2050 reduces the expected returns to domestic durable capital and thus discourage domestic investment in favor of the alternative to invest in foreign assets at the given world market interest rate or to reduce the foreign debt. As a result, domestic capital accumulation slows down well before the severe climate change impacts envisaged for the second half of the 21st century. This anticipation effect is completely absent in standard recursive-dynamic general equilibrium impact assessment models, and the simulations presented in this study indicate that its impact on economic growth can be quite significant.

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