# How vulnerable is Europe to severe climate-related natural disasters abroad?

# A dynamic CGE analysis of the international financial and economic impacts of a large hurricane in the southern USA.

(revised version)

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ABSTRACT

*The European economy and financial markets are closely connected to the US economy and financial markets through trade and investment flows. Severe natural disasters in the US may not only have economic and financial impacts in the US but also have spill-over effects on Europe, especially under the increasing climate risks. This paper contributes to the thin literature that focuses on the international financial and economic impacts of natural disasters. We adopt a recently introduced climate storyline approach, which is an event-based approach aiming at building "physically self-consistent unfolding of past events, or of plausible future events or pathways", to estimate the financial and economic impacts of natural disasters. Specifically, we first estimate the economic damages of downward counterfactuals of three hurricanes (Harvey, Irma and Maria) that struck the southern US in 2017. Downward counterfactuals are plausible alternative realizations of historic events that would have been much more impactful than the actual event. We estimate that total damage due to the three hurricanes could have been half a trillion USD in the worst case scenario. We then use a dynamic global equilibrium model to assess how financial and economic impacts on the European Union unfold over time. The results show small but material effects on the European economy, with marked differences between economic sectors. On the production side, petro-chemicals increase their production by around 0.1%. in the short term. The activity of the construction sector in the EU falls by up to 0.6% in the short term, as do domestic investments. This has a small but negative impact on economic activity in the European Union. We show how these effects are related to the initial physical damages as well as to the economic responses that are likely to follow after the disaster.*

JEL classification: C68; E17; F11; F21; Q54

## 1. INTRODUCTION

Despite recent setbacks, the global economy has become highly interconnected in the past few decades through trade and investment flows, particularly between the United States and the European Union. The high economic interconnectedness implies that economic shocks in one country or region may not only have direct and indirect impacts within the country or region but also generate spillover effects on international economies and markets (e.g., Bekiros, 2014; Kim et al., 2015; Bhattarai et al., 2020), particularly for shocks in the United States (Ehrmann et al., 2005; Cambridge Centre for Risk Studies, 2018).

Natural catastrophes are negative economic shocks causing large direct economic losses and indirect economic impacts (e.g., Cavallo et al., 2013; Cavallo & Noy, 2011; Klomp & Valckx, 2014; Lazzaroni and van Bergeijk, 2014; Botzen et al., 2019). Examples of the effects on the real economy include loss of Gross Domestic Product (GDP) due to loss of property and life, inflation in the prices of certain goods due to excess demand, and a deteriorating trade balance that could potentially lead to exchange rate fluctuations. Financial effects include the devaluation of various classes of investment assets, changes in interest rates, changes in currency exchange rates and sovereign credit ratings, and bond yields (Zhou et al., 2022; Cambridge Centre for Risk Studies, 2018).

Climate change will increase the frequency and severity of weather- and climate-related natural disasters (IPCC, 2012). Hence, the economic and financial impacts, as well as international spillover effects (if any) of these natural hazards are likely to be much larger due to the increasing climate change risk. The evidence for the long-term economic impacts of natural disasters is mixed (e.g., Cavallo et al., 2013; Cavallo & Noy, 2011; Klomp & Valckx, 2014; Lazzaroni and van Bergeijk, 2014) while the evidence for the international spillover effects from natural disasters is limited.

Studying international spillover effects is typically achieved by means of econometric analysis, multiregional Computable General Equilibrium (CGE) models or multiregional Input Output models. However, to the best of our knowledge, most studies using multi-regional models to assess financial spillover effects are largely limited to analysis at national level. Faturay et al. (2020) for example study spillover effects in Taiwan, Huang et al. (2021) study financial spillover effects in China, while Sieg et al. (2019) study these effects within Germany. An exception is Arto et al. (2015) who assessed the impact of the 2011 Japanese earthquake and tsunami by means of a multi-regional input output model. They found spillover effects on several sectors of other countries (including the financial and insurance sector).

This paper aims to fill the literature gap of international spillover effects by studying the financial and economic impacts of severe natural disasters not only at the local or national levels but also at the international level. Specifically, we assess the financial and economic impacts on the United States from plausible downward counterfactuals of three hurricanes that hit the Southern United States in 2017, as well as their spillover effects on the EU economy and financial markets, using the event-based storyline approach (Shepherd, 2019; Sillmann et al., 2021). The storyline approach is particularly suitable for studying the most catastrophic impacts for which probabilities are hard to quantify (Zscheischler et al., 2018). The downward counterfactuals estimated would have caused aggregate physical damage of about USD 548 billion. We use the recently developed GDyn-FS model (Gretton

2022) to project the potential impacts of the downward counterfactuals of hurricanes over a time horizon of 86 years: 2014-2100.

For this assessment we make use of the insights from the literature on the financial and economic impacts of disasters (e.g., Cambridge Centre for Risk studies, 2018; Zhou et al., 2022; Lazzaroni and Van Bergeijk, 2014, Hallegatte, 2013). We develop a storyline *of a cascade of events* on financial and economic markets that could be triggered by a major hurricane in the USA and quantify its financial and economic impacts with the help of a macroeconomic model.

## 2. DATA AND METHODS

We adopt a storyline approach to assess the economic and financial impacts of hurricanes. Below we explain the storyline approach and how we use the CLIMADA model to compute the downward counterfactuals of the three hurricanes. We then use the GDyn-FS model to project the impacts of the counterfactual on the US and European economies.

### *2.1. The Storyline Approach*

Recent literature challenged the conventional approach in generating regional climate information to be used for decision support (Hazeleger et al. 2015). Such approaches are considered "top-down" approaches that downscale results from global climate model simulations and are considered inadequate in dealing with uncertainties in regional climate predictions (Shepherd, 2019). As an alternative, Shepherd et al. (2018) introduced the climate storyline approach, where a storyline is defined as "a physically self-consistent unfolding of past events, or of plausible future events or pathways". Rather than downscaling outputs from global climate models, climate storylines aim at describing and understanding (series of) individual regional climate events by focusing on what plausible climate factors may bring the system under study into severe stress. Thus, the climate storyline approach is well-suited to study compound climate risk, such as risk rising from a sequence of weather events affecting the same area (Zscheischler et al., 2020; 2018).

Ciullo et al. (2021) proposed to build a climate storyline approach as a combination of downward counterfactual events. Downward counterfactuals are plausible alternative realizations of historic events that would have been much more impactful than the actual event. Many disasters that took societies by surprise could have been anticipated if one had looked at such downward counterfactuals. (Woo (2019) and Woo et al. (2017)). In the case of extreme weather events, a way of looking at the past while ensuring reasonable plausibility is using past forecast data. Each alternative forecast is a valid and physically plausible realization of the event under consideration and the fact that the event manifested in a given way is often due to pure chance.

### *2.2. The CLIMADA Model*

To estimate direct economic damages from tropical cyclones we use the open- source and -access CLIMADA impact model (Aznar-Siguan and Bresch (2019)). As with most natural catastrophe models, CLIMADA assesses damages from natural hazards as a combination of hazard e.g., a tropical cyclone's wind field, exposure, i.e., the people and goods subject to such hazard, and vulnerability, i.e., the degree at which a given exposed object is harmed by the hazard.

For the analysis carried out in the present paper, the hazard is given by a tropical cyclone's wind field, which is modelled in CLIMADA via a parametric wind model following Holland (2008). The model requires track-related information such as time, location, radius of maximum winds, and central pressure and it then computes the gridded 1-minute sustained winds as the sum of a circular wind field and the translational wind speed due to the tropical cyclone movement. More details can be found in Geiger, Frieler and Bresch (2018). Hazard track data about cyclones Harvey, Irma and Maria are retrieved from the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (Knapp et al., 2010), whereas downward counterfactual tracks data are obtained from the THORPEX Interactive Grand Global Ensemble (TIGGE) program, which contains tropical cyclones' forecast data from several international meteorological agencies (Swinbank et al., 2016; Park et al., 2008).

Exposure for the United States is built following the LitPop approach introduced by (Eberenz et al., 2020b), where disaggregated asset values are estimated by combining nightlight intensity and population data. Finally, vulnerability is modelled via a function relating wind field intensity to share of exposure damage. We use the regionally-calibrated vulnerability functions for tropical cyclones generated by Eberenz et al. (2020a).

### *2.3. The GDyn-FS model*

CGE (and Input Output models) are among the most important assessment models to evaluate the economic loss of disasters. The GDyn-FS model is a multi-sector, multi-region recursive dynamic computable general equilibrium (CGE) of the world economy. It is based on the standard GDyn model (Ianchovichina and McDougall 2012), but includes a number of innovations in model stability, saving behavior and international capital mobility (Gretton 2022). The model represents the economies of individual regions that are connected through bilateral trade and capital-finance flows. Each individual region includes a number of industries that operate with constant-returns-to-scale technologies. In perfectly competitive markets, producers try to maximize profits. Capital and labor are imperfectly mobile between industries. Households in each region earn income from labor services, ownership of capital, land, and natural resources. Households also receive the revenues of factor services and product taxes. The households maximize utility by purchasing private and public consumption, and savings. With the savings, investments are financed both at home and abroad through 'foreign' investments. The demand for investments is driven by expectations of future profits. One of the innovations of the GDyn-FS model is that it firmly bases international capital-finance mobility on optimizing behavior of households and firms in their choices of domestic versus foreign supply and demand of investments, respectively (Gretton 2022).

Although DGyn-FS (as GDyn) is in essence a model that describes and simulates the 'real' economy, it includes a simple representation of financial markets. The markets trade only one composite financial asset in local and foreign firms – that is traded internationally. The model can therefore, to some extent, project the impacts of a hurricane in the US on the portfolios of European foreign investors.

#### *2.3.1.Data and Parameters*

The base data of the model represents the global economy in 2014, divided into six countries and regions (EU28, USA, China, Japan, Australia and Rest of the World), six economic sectors (Agriculture, Minerals and mining, Petro-chemicals, Other manufactures, Construction, and Services), and five factors of production (Land, Skilled Labor, Unskilled Labor, Capital and Natural Resources). Projections of population, skilled and unskilled labor and economic activity (GDP) per country and region up to the year 2100 are derived from CEPII's SSP2 scenario.[1]

We made some changes to the standard parameters of GDyn-FS. The speed of investment after an unexpected capital loss has been loosely calibrated for the USA on the speed of recovery of Hurricane Katrina as described in Hallegatte (2013). We provide details in the sensitivity analysis using this parameter set and the original in Section 4 below. Additionally, we allow for some flexibility in the substitution between value added and intermediate goods in production (elasticity value of 1.2 for each industry), and a less-than-perfect substitution of capital and skilled labor in the domestic markets. The elasticity values of 10 and 20, respectively, allow for some sluggishness in the short term and for gradual mobility of these production factors over time (Gretton 2022).

### *2.3.2.Simulation scenario*

The simulation scenario focuses on the economic and financial impacts on the EU of a very large natural disaster in the US. While the impacts of natural disasters on the domestic economy have received attention in the professional and academic literature, international spillover effects have received less attention. The scenario is modelled as a sudden, unanticipated loss of capital in the USA and an associated loss in labor productivity (modelled as an exogenous decrease in labor supply) such that US GDP falls in proportion to Hallegatte's (2013) estimate of GDP loss of hurricane Katrina in 2005. In the following year, labor productivity recovers to it baseline level. The recovery of the capital stock is endogenous in the model and is caused by the increase in expected rate of return on capital on a lower capital base, after the hurricane-induced loss of capital and temporary decline in labor services.

Table 1: Scenario shocks that represent the initial economic impacts of the hurricanes.

| Variable | Description | Shock value |
|---|---|---|
| sqk("USA") | Arbitrary region-specific shock to capital stock | -0.81 |
| qfactsup("UnSkLab", "USA") | Supply of unskilled labor in the US | -0.42 |
| qfactsup("SkLab", "USA") | Supply of skilled labor in the US | -0.42 |

Source: Assumptions of the authors.

## 3. RESULTS

When the counterfactual hurricanes strike in the southwest USA in 2017, they cause widespread destruction. Many capital goods such as buildings, machinery, equipment, and tools are destroyed. The CLIMADA model estimates the total damage at USD 548 billion. With labor services assumed to decline by less than capital expected (and actual) returns on the national capital stock rise. Attracted by the expectation of high returns, recovery investments start soon, and the destroyed and damaged capital goods are swiftly replaced and repaired over the next few years. Figure 1 shows the percentage

[1] The SSP2 scenario from CEPII's EconMap 2.4 (Fouré, 2016). To obtain the scenario information for the current application, the scenario information on GDP, skilled and unskilled labor, and population of the 147 CEPII countries and regions is mapped to the 137 GTAP countries and regions by our own R-script (available upon request), and then the 137 GTAP countries and regions are aggregated to the countries and regions used in our simulation by the GEMPACK program Aggproj.tab (Chappuis and Walmsley, 2011).

deviations of the US capital stock and investments relative to baseline capital stocks and investments up to the year 2100. The baseline evolution of capital stocks and investments is taken from the SSP2 socio-economic scenario. In the year of the hurricanes the capital stock falls by 0.6% relative to the baseline stock. Recovery investments start immediately. For the recovery of the destroyed capital goods, additional capital goods (machines, equipment, and tools, such as cranes and trucks) are needed, so that the total capital stock after the recovery is *larger* than in the baseline. The maximum capital stock is reached in 2027, after which additional capital goods are slowly depreciated and discarded or scrapped. The capital stock returns to baseline levels by around the middle of the century (Figure 1). The *speed of recovery* is a sensitive issue and is discussed in the sensitivity analysis in Section 4 of this paper.

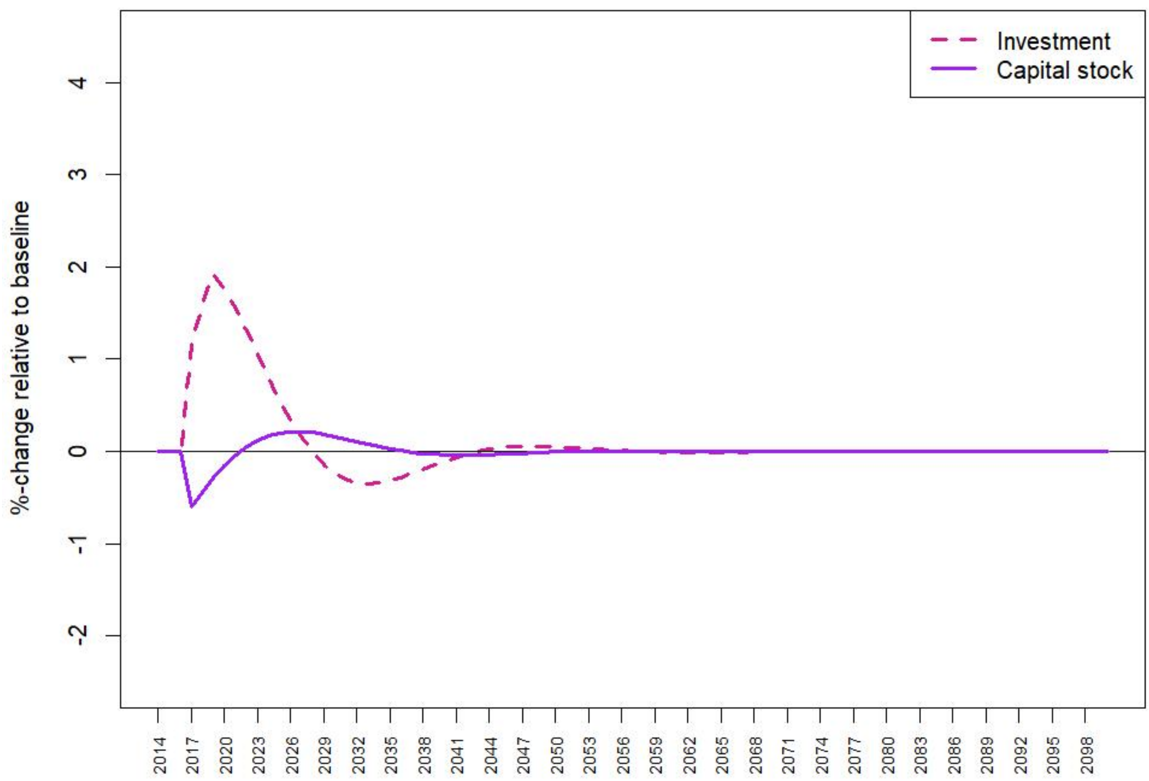


Figure 1 Cumulative rate of growth of capital stock and investment in the USA relative to baseline.

Economic activity (as measured by GDP) in the USA 2017 is negatively affected by the capital loss that is caused by the counterfactual hurricanes. National income, savings and investments are negatively affected, workers are laid-off and real wages of workers decline. In the following years, GDP increases again, powered by the investment "boom" that we saw in Figure 1. After this "boom", GDP growth returns to baseline levels (Figure 2). Due to the loss of productive capacity that is caused by the hurricanes, US exports initially decline, and after some delay, when damage to ports and basic infrastructure is repaired, converge to approximate baseline levels. US imports rise in the short run to meet consumption and investment demand with goods from abroad. This has a negative impact on the balance of trade in the immediate post-hurricane period. After a few years, when productive capacity is being rebuilt, exports pick-up and the growth of imports falls as rebuilt domestic capacity comes on line. After some oscillations after 2025, the growth of exports and imports return to their baseline levels (Figure 2).

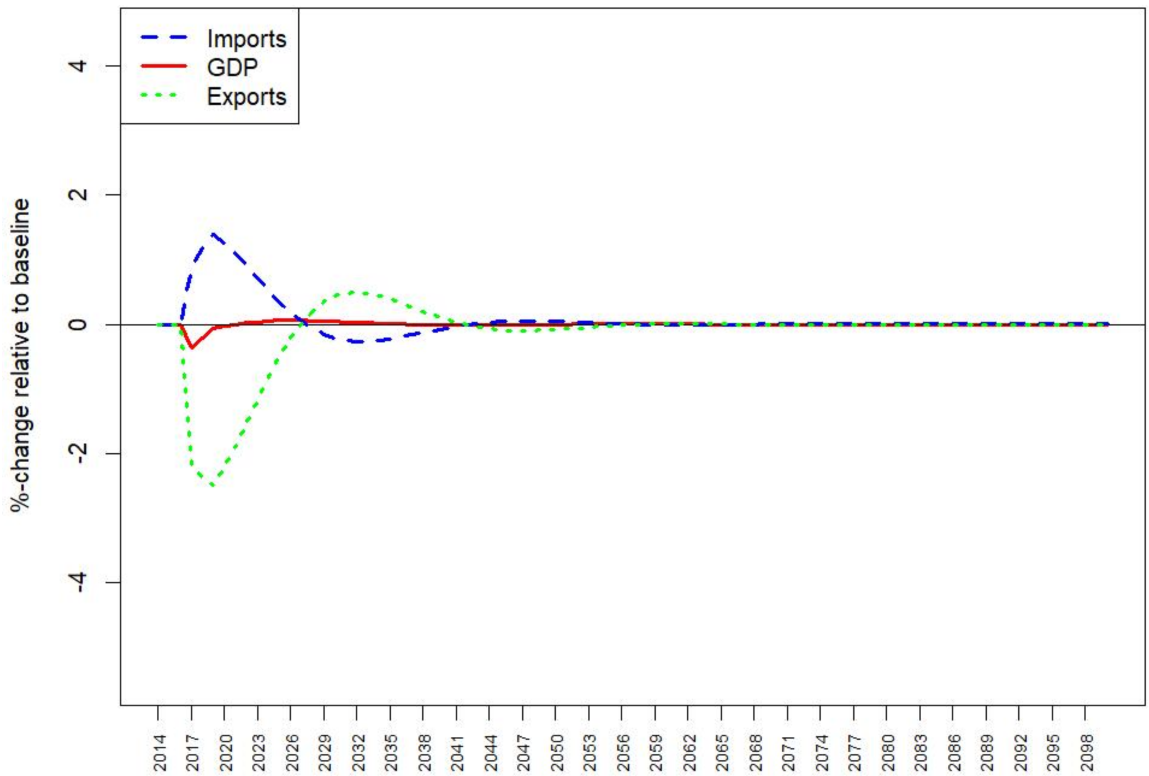


Figure 2 Cumulative rate of growth of domestic product (GDP), exports and imports in the USA relative to baseline.

Not all sectors of the US economy are equally affected. As can be expected, the most capital intensive industries are most negatively affected, while the capital goods producing sector and the construction sector are positively affected. Figure 3 shows the percentage deviations of the industry output in the US relative to baseline. The most negatively affected sectors are Other manufacture and Petro-chemicals. In contrast, the output of sectors supplying goods and services for investment, particularly the construction sector and services sectors, increases rapidly. For other industries full recovery takes longer.

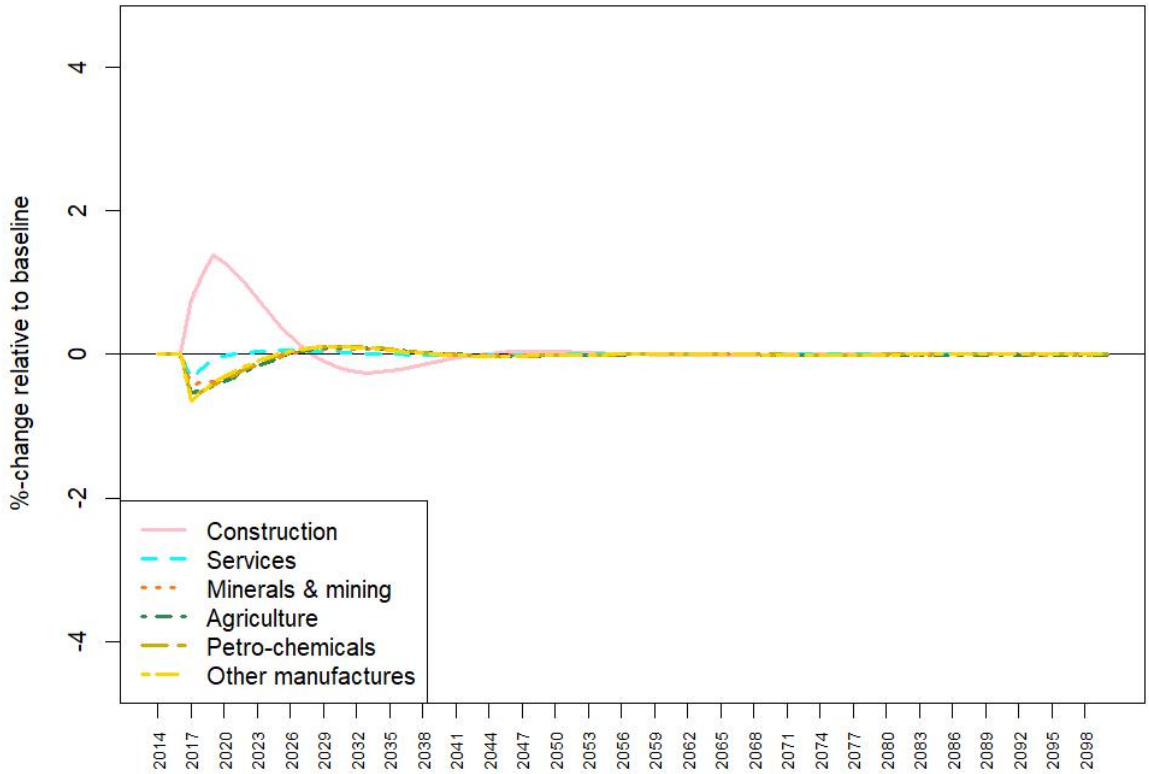


Figure 3 Cumulative rate of growth of sector output in the US relative to baseline.

After the hurricanes the trade balance of the USA deteriorates. Hence the USA must borrow from abroad to pay for its imports. The USA can do this in two ways: sell its foreign physical assets, or buy domestic physical assets from its foreign owners. In the year 2017, US investors own USD 12.8 trillion in foreign assets. Foreigners own USD 16.7 trillion of real assets in the USA in the form of equity, bond or loan instruments. Model simulations indeed show that foreign investments of US investors decline as funds are attracted home to rebuild local capital. Foreign investment in the USA is subject to two effects. First, it declines after the hurricane induced loss of US-located capital. This decline is partially offset by additional foreign funds being attracted to the US in response to higher returns relative to international investment options during the rebuilding period.

The EU's economy is affected in a number of ways. In the initial aftermath of the hurricanes, EU exports rise as a response to increased US import demand and to fill the gap on the world market that is created by the decrease in US exports (see Figure 4). The high demand for (recovery) investments in the US drives up the global price of investments, attracts capital worldwide, and decreases the demand for investments in the EU. EU exporters benefit from the US hurricanes.

The effect on EU's GDP warrants some explanation. Directly after the hurricane, EU's GDP increases a little by 0.05%. Looking closely at the detailed output of the GDyn-FS model, this is due to an increase in capital services. GDyn-FS assumes non-convex adjustment costs in the capital accumulation process, meaning that there are some fixed costs to an adjustment of the capital stock. In the model, these fixed costs are represented by a slack variable (*sqkworld*). In most applications, this slack variable is positive, indicating positive adjustment costs (Gretton, 2022). In our simulation, the slack variable turns out to be *negative*. A possible interpretation *could be* that the economic turmoil in the US enhances the global utilization of capital, such that the existing global capital stock produces more capital services. After the initial increase, GDP in the EU falls below its baseline level, due to the decrease in domestic investments that is directly related to the global shift in investments to the US in response to the relatively high returns to reconstruction.

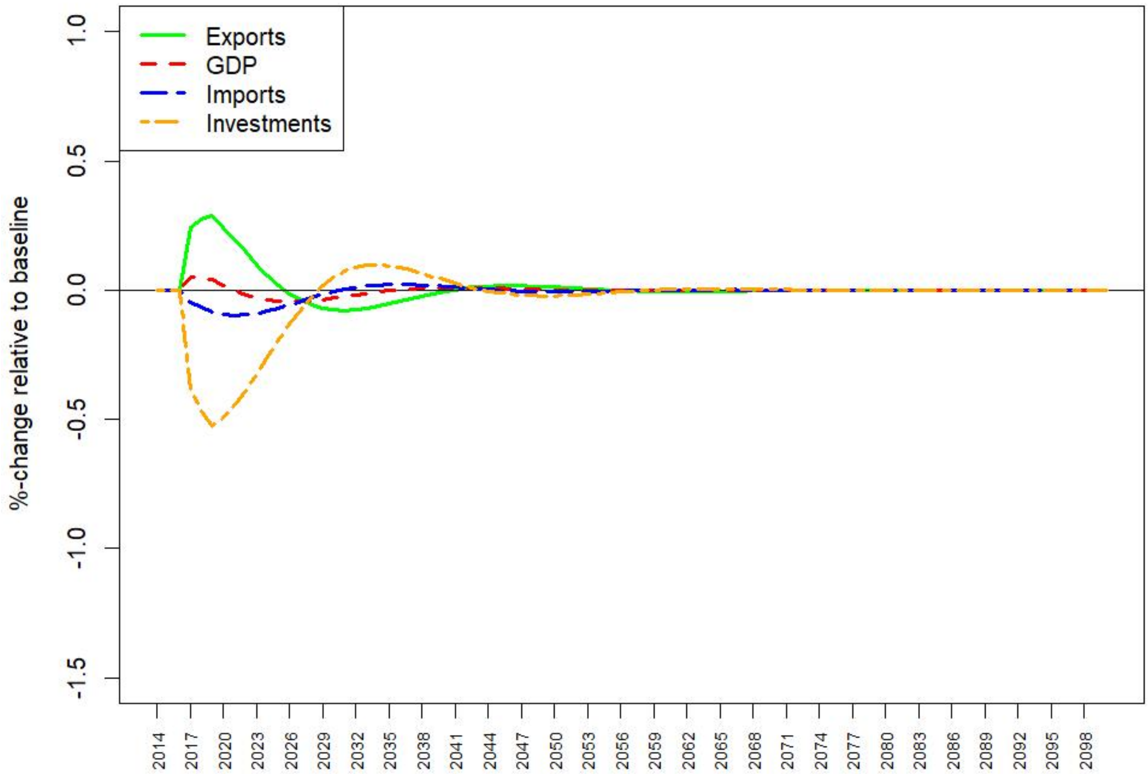


Figure 4 Cumulative rate of growth of GDP and its main components in the EU relative to baseline

Note. The figures for the EU have a different scale on the Y-axis than the figures for the USA. The effect-sizes for the EU are substantially smaller than for the USA.

As in the US, not all sectors of the EU economy are hurt or equally affected. Figure 5 shows the percentage deviations of sectoral output of industrial sectors relative to their baselines. Perhaps not entirely surprisingly, Figure 5 is almost a mirror image of the graph of the US (Figure 3) but with smaller deviations. The sectors that are most negatively hurt in the EU are the Construction sector and Services.

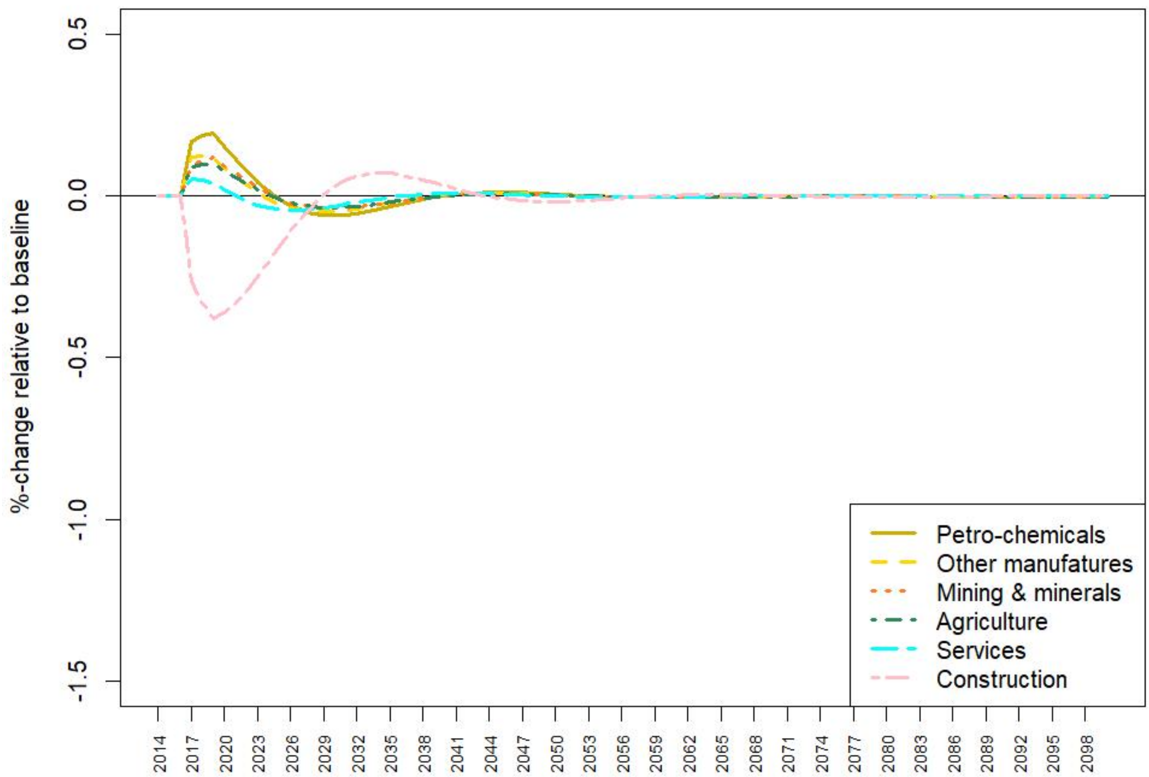


Figure 5 Cumulative rate of growth of sector output in the EU relative to baseline.

See note under figure 4.

The capital loss of nearly USD 548 billion by the hurricanes is carried by domestic and foreign investors, including investors from the EU. A share of 32% of capital in the US is owned by foreign investors. The EU is the biggest foreign investor with a share of 41% of all foreign investments (EU foreign investments total USD 21.9 trillion). Assuming a well-balanced portfolio of EU foreign investments, EU investors would lose 0.32 x 0.41 x 548 billion = 72 billion or 0.33% across its portfolio. However, due to the increase in the return on capital in the USA and the increased utilization of capital worldwide, the loss that is predicted by GDyn-FS in 2017 is only 0.03% and therefore almost negligible. This loss is also quickly recovered (we will return to this issue in the Discussion).

## 4. SENSITIVIY ANALYSIS

In the GDyn-FS model, as well as in the standard GTAP model, investors behave as if they expect that the rate-of return on capital in the future will increase (decline) with negative (positive) additions to the capital stock. Investors also behave in such a way that regional rates of return are gradually equalized across regions. The sensitivity of the expected rate-of-return to changes in capital stock is a function of the flexibility model parameter RORGFLEX. With a relatively large value of RORGFLEX, the supply of capital goods is not very sensitive to the expected rate-of-return. Equalizing changes in rates-of-return across regions can be accommodated by small changes in regional investment. In contrast, with small values of RORGFLEX the supply of capital goods is very sensitive to expected rates-of-return and the model will produce large changes in regional investment (Hertel and Tsigas, 1997).

The default value of RORGFLEX in GDyn-FS model is 1.0. That is, a 1% decrease in capital stock is expected to increase the rate of return on capital by 1%. Figure 6 below shows the speed of national recovery after the hurricane in terms of the evolution of investments and capital stock with values of RORGFLEX of 0.3, 0.5, 1.0 and 1.5, respectively.

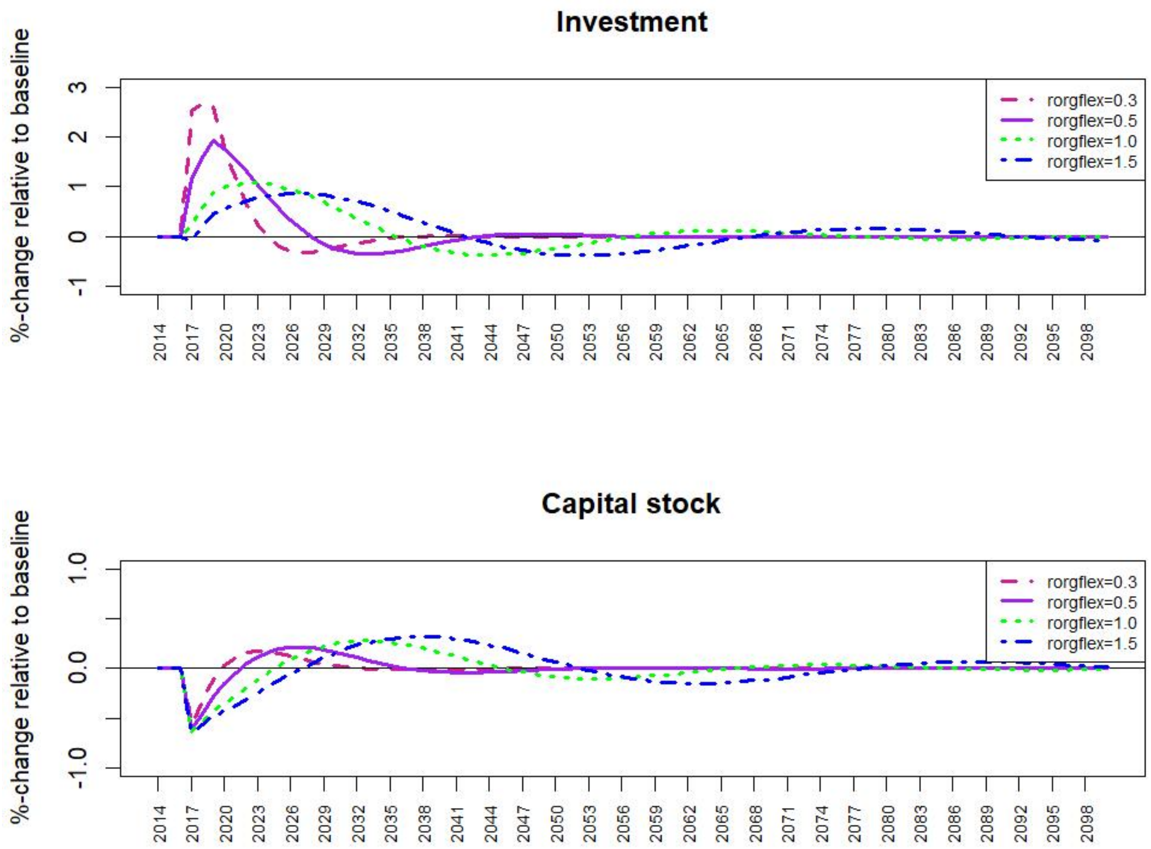


Figure 6 Speed of recovery of capital stock using alternative values of RORGFLEX.

As Figure 6 shows, recovery is fastest with a value of RORGFLEX of 0.3. In this case, investments reach a maximum of 2.6% above baseline in 2018, and the capital stock returns to baseline 2020. For values of RORGFLEX of 1.0 and higher, investments reach a maximum in 2023 (RORGFLEX = 1.0) and 2027 (RORGFLEX = 1.5) and the capital stock returns to baseline in 2025 (1.0) and 2027 (1.5). These values would be consistent with the view that recovery investment in the hurricane affected regions is partly supported by the temporary diversion of investment activity from other regions in the US. For the analysis in this paper, we took a value of RORGFLEX = 0.5, where investments peak in 2019 and the capital stock returns to baseline level in 2023. The capital stock reaches its highest level in 2027. We believe that this speed of recovery gives a reasonable match with empirical literature on natural disasters, while not forcing an extreme sensitivity to expected rates-of-return to capital. It also represents an intermediate case between the high and low elasticity scenarios.

## 5. CONCLUSIONS AND DISCUSSION

A large disaster in the USA, such as three consecutive hurricanes in one season, can have small but material effects on the EU economy. In the first place, physical assets in the USA that are owned by EU investors may be destroyed or damaged, leading to a direct loss for EU investors, although this loss is not large in relative terms. In the second place, the economic impacts in the USA may indirectly lead to economic responses in the EU (such as increasing exports) that can affect the EU economy. In our simulations with the dynamic computable general equilibrium model GDyn-FS, we find that initially exports increase above their baseline levels. Domestic Investment activity, however, decreases and that negatively affects economic activity for a number of years. There are marked differences between economic sectors.

In our research we did not specifically look at public policies. When a large natural disaster occurs abroad, EU and national authorities of EU member states obviously want to help the affected region, if only for humanitarian reasons. Nevertheless, our research suggests that it would also be wise for those authorities to keep an eye on domestic investments in the aftermath of such a foreign disaster, and stimulate those if necessary.

An interesting but somewhat surprising result of our simulations is the enhanced global utilization of capital in response to the hurricane. While this is well in line with the model's logic, we are unable to support this result with empirical evidence. If this increase in utilization rate would not be forthcoming, the impact on EU's GDP and the impact on EU investors would be more negative. In a simulation where we kept the slack variable *sqkworld* at zero, the fall in EU's GDP is immediate and the loss in wealth of EU investors in 2017 adds up to 0.17% (USD 37 billion) and is not fully recovered throughout the century.[2]

In our simulations, it is assumed that EU investors do not change their risk perceptions. But as climate-risk increases in remote areas, EU investors may update their risk perception and thus be forced to reconsider and redirect their investments. One immediate effect of this update of risk aversion is that recovery in the USA will be slower as it will be more difficult to attract foreign investments. The exact impacts of climate-related disasters on financial flows and investor perceptions will be the subject of future research.

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[2] In this alternative simulation, the variable *sqkworld* was fixed and a shift variable for the world average rate of return *srorc_r* was made endogenous.

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