GLOBAL ECONOMIC CONSEQUENCES ARISING FROM THE IMPACTS OF PHYSICAL CLIMATE RISKS ON AGRICULTURE AND ENERGY

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ABSTRACT

Climate change continues to be an existential threat to humanity. With intrinsic linkages to the natural environment, food and energy supply chains are two fundamental channels via which climate risks could spill over to the economy. This paper explores the global economic consequences arising from the implications of physical climate risks on the agriculture and energy sectors. We first construct a range of chronic and extreme climate risk indicators. We incorporate the climate risk indicators alongside the historical data on global agriculture and energy production in machine learning algorithms to estimate the historical implications of climate risks on agriculture and energy production. We project the implications of climate risks on agriculture and energy production under three Shared Socioeconomic Pathways (SSPs). The implications on other sectors are derived using the reliance of those sectors on agriculture and energy. The derived implications are introduced as a series of economic shocks to the global general equilibrium model: G-Cubed.

We evaluate the G-Cubed simulation results for Real GDP, consumption, investment, exports, imports, and trade balance and emphasize four main findings with implications for policymaking in climate change. Firstly, we illustrate the importance of incorporating a wide range of both chronic and extreme climate indicators when estimating the historical implications of physical climate risks on agriculture and energy production. Secondly, we illustrate the potential for double dividends from transitioning to sustainable livestock production and renewable energy sources. Thirdly, we demonstrate how the magnitude of climate risks could be magnified within a globally interconnected economy depending on the responses of economic agents and the structural characteristics of the economies. Fourthly, we highlight the importance of considering a wide array of studies focusing on different climate scenarios, employing different methodologies, and producing different estimates to account for the enormous uncertainty involved in analyzing climate change impacts.

Keywords: Climate Change, Extreme Events, Physical Climate Risks, Macroeconomics, CGE, DSGE, G-Cubed, Machine Learning

JEL Codes: C51, C53, C54, C55, C68, F41, Q51, Q54

1.0 INTRODUCTION

Until the latter half of the 20th century, climate change remained a theoretical or scientific phenomenon. In 1896, Svante Arrhenius, in his seminal work, illustrated the role of CO_2 in long-term variations in climate for the first time. However, climate change did not enter the global policy arena until 1972 when the first international environmental summit was held in Stockholm and the United Nations Environment Program (UNEP) was established. The first international climate conference in 1979 in Geneva, the Toronto Conference on the Changing Climate in 1988, and the establishment of the Intergovernmental Panel on Climate Change (IPCC) in the same year were significant milestones that led to the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 with a global membership of 197 countries. Since then, the IPCC has published five assessment reports and is on its way to completing the sixth assessment report. Meanwhile, the parties, or the member countries, have continued to meet annually at Conferences of Parties (COPs). The adoption of the Kyoto Protocol in 1997 and The Paris Agreement in 2015 are landmarks in global commitment toward mitigating climate change. COP 26, the most recent conference, which was held in Glasgow, finalized the Paris Rulebook which focuses on the delivery of the Paris Agreement. It includes several important agreements covering emission reporting, timeframes for emission reduction targets, and mechanisms and standards for global carbon markets among others. COP 27 to be held in Egypt in November 2022 marks the 30th anniversary of establishing UNFCCC and is expected to focus more on implementing the Paris Agreement (Harvey 2022; Carver 2022; Hirst 2020).

Despite global efforts since the 1970s, climate change remains an existential threat to humanity. The role of emission and accumulation of greenhouse gasses in the atmosphere in explaining the earth's climate and the human contribution to accelerating climate change and global warming since industrialization is now understood with much scientific rigor (Hertzberg & Schreuder 2016). Yet, after a mild slowdown owing to the COVID-19 pandemic in 2020, global emissions have rebounded to their historical highest in 2021. The earth is already 1.1 ^{0}C warmer compared to the 1800s, and 2011-2020 was the warmest decade on record. The climate change mitigation commitments set out at COP 26 are still considered to exceed the 1.5 ^{0}C target for global warming by the end of the century, which is a scientifically critical threshold to prevent catastrophic outcomes and natural tipping points. The increasing frequency, intensity, and duration of adverse consequences of climate change ranging from melting polar ice, sea-level rise, heat and cold waves, intense droughts and floods, water scarcity, severe wildfires, and more frequent and stronger storms are early signs of the unimaginable outcomes to expect (United Nations 2022; International Energy Agency 2022). Accordingly, the World Economic Forum (WEF) recognizes the climate crisis as the most significant long-term threat to humanity. Failing to act on climate and extreme weather pose the worst short-term threats (UNFCCC 2022; WEF 2022). The changes in the natural environment disrupt lives and livelihoods and spill over to the economies.

Implications on food and energy security are two major channels of these spillovers with their intrinsic linkages to the natural environment as primary economic sectors.

Climate change in fact has a two-way relationship with food and energy production[1]. On one hand, the current global energy (non-renewable) and agriculture production practices are the two highest emitters of greenhouse gases and thus the leading contributors to anthropogenic climate change. In addition to emissions produced by energy consumption mainly by households, industries, and transportation sectors, energy production (which includes electricity and heat generation, and refining of fossil fuels) directly produces emissions from exploration, processing, production, transmission, and storage of fossil fuels (European Environment Agency 2008). Land use changes from deforestation for cultivation, burning of residues, and fuel consumption for farming practices are the major sources of CO_2 emissions. Enteric fermentation, the addition of fertilizers to soils, and manure management are the major sources of non-CO_2 emissions in agriculture (Food and Agriculture Organization (FAO) 2018).

On the other hand, the energy and agriculture sectors are affected by climate change. In 2020, the production of 87 percent of global electricity directly depended on water. Accordingly, thermal power generation (using fossil fuels, nuclear sources, and biomass) and hydroelectricity generation are particularly affected by the worsening water stress under climate change and increasing temperature reducing the turbine efficiencies in the plants. Furthermore, climate change threatens the energy production, transmission, and distribution infrastructure. Nuclear power plants which are often located closer to the coast are also affected by rising sea levels (World Meteorological Organization (WMO) 2022)[2].

Livestock is one of the agriculture subsectors that is expected to suffer the most from climate change. The impacts on livestock include changes in, the production and quality of feed crops and forage, water availability, animal growth, exposure to diseases, reproduction, and milk production (Rojas-Downing et al. 2017). Crops, however, could experience a mix of both positive and negative effects depending on the crop types and geographical locations. For example, while the growing seasons could become longer with the increased CO_2 concentration, the increased incidence of attacks from pests, droughts, and floods are adverse for crops[3]. The forestry sector could experience reduced productivity amidst the loss of trees from droughts, temperature stress, and landslides, increased wind and storm damage, increased saltwater intrusion and inundation from floods, increased frequency of forest fires, and

[1] See Liu (2016) for a detailed discussion on the interlinkages of climate change with the water-energy-food nexus.

[2] See Yalew et al. (2020) for a detailed review of the implications of climate change on energy systems. They evaluate implications on demand for energy services in general and supply-side effects on renewable energy resources and thermal power generation.

[3] National Geographic (2022) provides a clear illustration of both the positive and negative implications of climate change on crops across different parts of the world.

increased incidence of pest and disease outbreaks. The fishery and aquaculture sector will be affected by the changes in physical (such as surface temperature and waves and ocean circulation), and chemical (salinity, oxygen concentration, and acidification) in the aquatic environment. These changes could promote migration and inhibit the biological processes of aquatic species (FAO 2015).

By 2050, the global population is expected to exceed 9.7 billion, the demand for food is expected to increase by 70 percent (van Dijk et al. 2021), and the global energy demand is expected to grow by 47 percent (EIA 2019). Meeting the food and energy demands of the growing population will thus require enhancing the resilience of the global food and energy supply chains in addition to expanding them. The disruptions to the global energy and food supply chains created by the Russian invasion of Ukraine and their spillovers to the global economy are a stark reminder of the centrality of food and energy security to the global economies[4]. Therefore, increasing the resilience of the global food and energy supply chains to climate change is vital for climate change adaptation. Given the implications of current agriculture and energy practices on climate change, mitigating climate change, by adopting sustainable crop and livestock management patterns, reducing emissions from non-renewable energy sources, and transitioning to low-carbon energy sources will also be vital to reducing the vulnerability of the food and energy supply chains to climate change.

This paper explores the global economic consequences arising from the impacts of physical climate risks on agriculture and energy. Specifically, we focus on crops and livestock from agriculture, energy production from non-renewable resources, and electricity generation from renewable resources[5]. Firstly, the paper develops a range of chronic and extreme climate risk indicators and explores their historical variation. It then explores the historical variation of global agriculture and energy production. The paper uses machine learning algorithms, to estimate the historical implications of climate risks on agriculture and energy production. The empirical estimates are discussed with reference to the existing knowledge on the pathways via which climate change affects agriculture and energy production.

Secondly, the paper projects the implications of climate risks on agriculture and energy production under three Shared Socioeconomic Pathways (SSPs). The implications on other sectors are derived using the reliance of those sectors on agriculture and energy. The derived implications are introduced as a series of economic shocks to the global general equilibrium model: G-Cubed. The simulation results

[4] See Benton et al. (2022) for a review of the implications of the Russian invasion of Ukraine on food and energy security. IMF (2022a and 2022b) analyse the implications of the Russian invasion of Ukraine on the global economy.

[5] Energy production from non-renewable resources includes both primary and secondary forms of energy production. Primary forms refer to the unaltered original form of a resource (such as crude oil or natural gas) and secondary forms refer to converted forms of primary energy (such as electricity or heat). Renewable resources are mostly used after conversion to a secondary form, and data is widely available only for the use of renewable in the form of electricity.

for Real GDP, consumption, investment, exports, imports, and trade balance are then discussed. The implications on Real GDP are also discussed within the context of existing studies.

The rest of the paper is organized as follows. Section 2 sets the context for this paper. It provides an overview of the various climate risks and climate scenarios currently used, the existing methodologies for assessing the economic consequences of chronic and extreme physical climate risks, and the current estimates of the economic consequences of the physical climate risks. Section 3 discusses the empirical estimation of the sensitivity of agriculture and energy production to changes in chronic and extreme risks using machine learning algorithms. It also constructs several indicators of chronic and extreme climate risks and analyses the historical behavior of those indicators. Section 4 extends those climate indicators for SSPs and derives the implications for the agriculture and energy sectors. It also discusses in depth the behavior of the projected climate indicators and the changes in agriculture and energy production in various parts of the world. Section 5 models the economic consequences of the projected implications of climate risks on agriculture and energy within the G-Cubed model and discusses the results. It also illustrates how the economic consequences vary across different parts of the world. Section 6 summarizes the paper and concludes by highlighting the policy implications of the paper.

2.0 ECONOMIC CONSEQUENCES OF CLIMATE CHANGE

2.1 Overview

Section 2 places the current paper within the existing literature on the economic consequences of climate change. Section 2.2 provides an overview of both physical and transition climate risks and Section 2.3 discusses the scenarios designed to evaluate those risks. Even though this paper does not focus on transition risks, they are discussed alongside physical risks for the completeness of the discussion. Section 2.4 reviews the existing methodologies for assessing the economic consequences of physical climate risks with particular emphasis on Integrated Assessment Models (IAMs) and general equilibrium models. Section 2.5 discusses the existing estimates of the economic consequences of physical climate risks from IAMs and general equilibrium models. Section 2.6 summarizes and concludes Section 2.

2.2 Climate Risks

Overview

The Intergovernmental Panel on Climate Change (IPCC) (2020) defines climate risks as the potential for adverse consequences for human or ecological systems, given the diversity of values and objectives associated with those systems, emanating from climate change and/or human responses to climate change. Within the economics and finance literature, climate risks are broadly identified in two broad categories: physical and transition risks, which are indicative of the two sources of risks outlined in the IPCC definition above.

Physical Risks

The physical risks refer to the adverse consequences of changes in the acute short-term events or chronic long-term changes in the weather and climate. An alternative classification of the physical risks considers the adverse consequences of chronic long-term gradual changes in the weather and climate in one category as chronic risks, and short- (acute) and long-term (chronic) extreme events in another category as extreme risks. The chronic risks include adverse consequences from long-term gradual changes in climate variables, such as temperature, precipitation, and humidity. The adverse consequences include changes in sea level and resulting changes in the availability of land for economic activities, changes in water levels, changes in heat-stress affecting plants (e.g., changes in crop yields), animals (e.g., changes in biological processes and migration), and human beings (e.g., changes in productivity), changes in disease incidence, and biodiversity losses. The extreme risks include adverse consequences from both short- and long-lived extreme events. Short-lived extreme events occur due to changes in weather and climate. Floods, heat and cold waves, storms, and wildfires are some examples of short-lived extreme events. Long-lived extreme events primarily occur due to changes in climate. Droughts and seasonal extreme precipitation are some examples of long-lived extreme events.

Transition Risks

The transition risks refer to the adverse consequences of human responses to climate change, particularly when transitioning to a low-carbon economy. The sources of transition risks could be changes in international or national policies, legislation, norms, market preferences, and technologies. The adverse consequences arising from those sources of transition risks could include stranded assets, loss of markets, lower returns from investments, additional litigation liabilities and penalties, loss of reputation, lack of liquidity, and ultimately insolvency and bankruptcy. Another key source of transition risks lies in the deployment of negative emission technologies, such as carbon capture and storage (CCS). While the large-scale development and deployment of CCS are supportive of limiting global warming, CCS also poses risks of toxicological effects (e.g., human health effects and water contamination from CO_2 leakages), environmental effects (e.g., detrimental effects on plants), implications on seismic activity due to higher induced pressure, and climate effects from CO_2 leakages (de Figueiredo et al. 2007).

2.3 Climate Scenarios

Global Warming Scenarios

Since 1990, IPCC has been developing alternative scenarios of climate risks for climate modelers. The main objective of the exercise is to provide a range of alternative futures representing different carbon emission pathways and associated climate risks within the twenty-first century built on different assumptions of socioeconomic and technological growth. Another objective of the exercise is to harmonize the modeling outputs from impact models so that the outputs could be better compared.

After publishing the first set of scenarios, called SA90, in 1990, for the First Assessment Report, IPCC published a second set of scenarios, called IS92 in 1992. The Third and Fourth Assessment Reports by the IPCC were based on an improved set of scenarios published through its Special Report on Emission Scenarios in 2000 which were called SRESs. In 2007, for the Fifth Assessment Report (AR5), IPCC further developed the scenarios to produce the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011). There were four main RCPs namely RCP 2.6, 4.5, 6.0, and 8.5, and the pathways represent different radiative forcing levels (in W/m^2) achieved by the end of the twenty-first century from greenhouse gas concentration in the atmosphere compared to the pre-industrial levels. Although there are socioeconomic narratives underlying the emission outcomes described in the RCPs, RCPs primarily focused on the climate risks of the alternative emission pathways. Table 1 summarizes the RCPs and the temperature outcomes by the end of the century under the RCPs[6].

Extending the RCPs, the IPCC 6th Assessment Report (AR6) uses the Shared Socioeconomic Pathways (SSPs). SSPs provide particular attention to how socio-economic factors might change over the twenty-first century, including population, economic growth, education, urbanization, and technological development. SSPs also indicate future energy use and greenhouse gas emissions within IAMs. SSPs indicate how different greenhouse gas concentration pathways defined by RCPs could be derived under the socio-economic narratives defined by the SSPs in the absence of climate policy. Therefore, SSPs are complementary to RCPs (Riahi et al. 2017). There were five main SSPs and since AR5, three RCPs have been added: RCP 1.9, 3.4, and 7.0. Table 2 summarizes the SSPs[7] and the temperature outcomes by the end of the century under the SSPs. Different from RCPs, SSPs enable researchers and policymakers to examine economic consequences arising from structural changes (particularly in the energy, transportation, and land-use sectors) for the same emission outcome and design efficient and effective mitigation policies.

Transition Scenarios

The emphasis on transition risks is not explicit in either the RCPs or SSPs. With the considerable increase in interest from central banks and financial markets, the Network for Greening the Financial System (NGFS), which is a collection of central banks and regulators from many countries, has organized climate scenarios with emphasis on both the physical and transition risks. Physical risks tend to be inversely related to transition risks. Depending on the ambition of climate policy, the NGFS divides scenarios into three broad groups: (1) Orderly scenarios: Climate policies are introduced early and become gradually more stringent, with both physical and transition risks relatively subdued; (2) Disorderly scenarios: Policies are delayed or divergent across countries and sectors, resulting in higher transition risk; (3) Hothouse world scenarios: Global efforts are insufficient to halt significant global warming, resulting in severe physical risk including irreversible impacts. When evaluating NGFS climate scenarios, the IAMs use SSP2 as the baseline[8]. Table 3 summarizes the NGFS scenarios and the temperature outcomes by the end of the century under the scenarios[9].

[6] See Annexure 1 for more details about the RCPs.

[7] See Annexure 2 for more details about SSPs.

[8] See NGFS (2022a) for an evaluation of three NGFS climate scenarios in a hybrid DSGE-CGE model: G-Cubed and a comparison of its results and methodologies against those of IAMs.

[9] See Annexure 3 for more details about NGFS scenarios.

Table 1: Temperature Outcomes under RCPs

RCP	Description	Estimated Global Warming		
		2046-2065 (^{0}C)	2081-2100 (^{0}C)	2081-2100 (Range in ^{0}C)
RCP 2.6	The peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline.	0.24	0.40	0.26 – 0.55
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100.	0.26	0.47	0.32 – 0.63
RCP 6.0	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100.	0.25	0.48	0.33 – 0.63
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	0.30	0.63	0.45 – 0.82

Source: van Vuuren et al. (2011).

Table 2: Temperature Outcomes under SSPs

SSP	Description	Estimated Global Warming		
		2041-2060 (^{0}C)	2081-2100 (^{0}C)	2081-2100 (Range in ^{0}C)
SSP1-1.9	Very low GHG emissions: CO_2 emissions reduced to net zero around 2050	1.6	1.4	1.0 – 1.8
SSP1-2.6	Low GHG emissions: CO_2 emissions reduced to net zero around 2075	1.7	1.8	1.3 – 2.4
SSP2-4.5	Intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0	2.7	2.1 – 3.5
SSP3-7.0	High GHG emissions: CO_2 emissions double by 2100	2.1	3.6	2.8 – 4.6
SSP5-8.5	Very high GHG emissions: CO_2 emissions triple by 2075	2.4	4.4	3.3 – 5.7

Source: Riahi et al. (2017).

Table 3: NGFS Scenarios

Scenario	Description	Estimated Global Warming by 2100 (^{0}C)
Net Zero 2050	Net CO_2 emissions reach zero around 2050, giving at least a 50% chance of limiting global warming to below 1.5 °C by the end of the century, with no or low overshoot (< 0.1 °C) of 1.5 °C in earlier years.	1.5
Below 2 °C	Below 2 °C gradually increases the stringency of climate policies, giving a 67 % chance of limiting global warming to below 2 °C.	2.0
Divergent Net Zero	Emissions are in line with a climate goal giving at least a 50 % chance of limiting global warming to below 1.5 °C by the end of the century, with no or low overshoot (< 0.1 °C) of 1.5 °C in earlier years.	1.5
Delayed Transition	Emissions exceed the carbon budget temporarily and decline more rapidly than in Well-below 2 °C after 2030 to ensure a 67% chance of limiting global warming to below 2 °C. This leads to both higher transition and physical risks than the Net Zero 2050 and Below 2 °C scenarios.	2.0
Nationally Determined Contributions	Emissions decline but lead to 2.6 °C of warming associated with moderate to severe physical risks. Transition risks are relatively low.	2.6
Current Policies	Emissions grow until 2080 leading to about 3 °C of warming and severe physical risks.	3.0

Source: NGFS (2022b).

2.4 Existing Methodologies for Assessing Economic Consequences of Physical Risks of Climate Change

Overview of Existing Methodologies

Assessing the economic consequences of climate change requires a transdisciplinary approach where the physical mechanisms of natural systems (atmosphere, biosphere, cryosphere, and hydrosphere) must be integrated with the mechanisms of socioeconomic systems. The representation of the ways that the natural and socioeconomic systems interact is also the key source of distinction for the current methodologies to assess the economic consequences of climate change.

Ciarli and Savona (2019) illustrate five types of models used to assess economy-wide climate damages: (1) Integrated Assessment Models (IAMs), (2) General Equilibrium Models (both Computable General Equilibrium (CGE) models and Dynamic Stochastic General Equilibrium (DSGE) models), (3) Structural Change Models (SCMs), (4) Ecological Macroeconomic Models (EMKs), and (5) Evolutionary Agent-based Models (EABMs). IAMs also include small-scale impact models which focus on assessing the implications of climate change on specific environmental bodies, such as biomes (e.g., forests), freshwater ecosystems, and marine ecosystems, as well as economic sectors, such as agriculture, energy, and households (health). Additionally, economists also have used econometric approaches to estimate the economic consequences of climate change. These span from cross-sectional and panel regressions (e.g., Kalkuhl and Wenz 2020; Kahn et al. 2019) to Structural Vector Auto-Regressive (SVAR) models (e.g., Gallic and Vermandel 2020).

Out of the above approaches for estimating the economic consequences of climate risks, IAMs and general equilibrium models have been the most popular. The two sub-sections below provide an overview of how IAMs and general equilibrium models assess physical risks of climate change, i.e., chronic and extreme risks of climate change following the definitions in Section 2.2.

Integrated Assessment Models (IAMs)

IAMs illustrate the interactions between the natural and socioeconomic systems within a single model. They often have separate climate and economic modules which are integrated with or without feedback. IAMs could follow either a vertical or horizontal approach to integrating natural systems with socioeconomic systems (Parson & Fisher-Vanden 1997).

Vertical integration links the causes and consequences of climate change via a causal chain. Within the causal chain, emissions and their sources, atmospheric and biogeochemical processes of climate change, and physical, ecological, and socioeconomic impacts resulting from climate change are sequentially arranged, while allowing for policy responses to adapt or mitigate at the different links. Accordingly, vertical integration, which is widely used in evaluating the economic consequences of climate change, starts with assumptions about demographic change, economic growth, technological change, and any existing climate policies. The atmospheric accumulation of the emissions from such assumptions is modeled, and the radiation and global climate are then derived. Then the regional climate and weather are modeled to observe the impacts of climate change on biological ecosystems. The economic impacts are derived from the climate impacts on biological ecosystems. Deviating from the simple causal chain, contemporary models also enable complex linkages across natural systems, socioeconomic systems, and policy responses.

Horizontal integration aims to expand the different vertical integration links horizontally to include additional sources, processes, or impacts. Accordingly, horizontal integration has often been used to evaluate climate change along with other environmental concerns, such as ozone depletion, acidification, and air pollution.

The economic modules of the earliest IAMs were neoclassical growth models with an aggregate production sector (Stern 2007). Therefore, those IAMs mostly fed temperature outcomes under alternative scenarios to the economic module via damage functions to obtain economic outcomes, primarily GDP losses. However, more recent IAMs (such as DART (Deke et al. 2001) and GTEM (Pant 2002)) allow for assessing the changes in sectoral outcomes along with aggregate economic outcomes. Depending on the model focus, IAMs often have detailed energy, transportation, and land-use sectors. Therefore, IAMs could either be solved to obtain the emission trajectories of a given set of socioeconomic, technological, and climate policy assumptions or to illustrate the structural and policy changes necessary to achieve the desired emission outcome. The economic implications of different scenarios, defined in terms of their socioeconomic and policy assumptions, are then compared against a model baseline. IAMs have also been developed to incorporate both chronic and extreme risks of climate change and illustrate their impacts on different sectors, or the macroeconomy. The chronic risks covered in IAMs include global mean temperature change and sea-level rise, and extreme risks include extreme temperature, precipitation, and heat and cold waves.

Goodess et al. (2003) identify three classes of IAMs: cost-benefit analysis models, biophysical models, and policy guidance models. The cost-benefit analysis models focus on assessing the costs and benefits of climate change against the cost of adaptation and mitigation policies. The Dynamic Integrated Model of the Climate and the Economy (DICE) by William Nordhaus is a popular example of a cost-benefit analysis model. Other popular examples include the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model and the Policy Analysis of the Greenhouse Effect (PAGE) model. The cost-benefit analysis models tend to follow the vertical integration approach with the simple causal chain and are widely used to optimize policies. Biophysical impact models emphasize climate change impacts on ecosystems and illustrate feedback across systems within the vertical integration approach. However, due to the absence of explicit focus on policies, the economic modules of biophysical impact models are less developed. Therefore, they are better suited for policy evaluation rather than optimization. Policy guidance IAMs combine the policy optimization and evaluation approaches within tolerable windows defined by the policymakers.

General Equilibrium Models

General Equilibrium models are richer in detail about the economic interactions among the economic agents—households, firms, the government, central banks, and the external sector (via trade and investments)—and often disaggregate economies into multiple sectors. However, they are less detailed about climate and energy systems and do not usually directly incorporate biophysical damages. Deriving the economic impacts of climate change using general equilibrium models, which do not explicitly define the interactions between natural and socioeconomic systems, requires the formulation of economic shocks that translate exogenous climate impacts on natural systems to impacts on economic variables.

All general equilibrium models, irrespective of their complexity and details, constitute a production function illustrating the aggregate supply side of the economy. Hence, it is often the starting point to think about climate impact transmission channels to the economy. Batten (2018) conceptualizes both the chronic and extreme climate impacts on various forms of capital within the production function (such as natural capital, physical capital (infrastructure), human capital, and social and organizational capital) and productivity (efficiency, technology, and learning) to be the main transmission channels in a real economy. The policy responses to adaptation and mitigation could also be featured as shocks to the above forms of capital and other economic policy variables (e.g., tax rates) depending on the details of the economic models. Changes in private and public consumption (via changes in wealth and consumption preferences), investment (via changes in investment preferences and country/sector risk premia), and international trade (via changes in prices) are some of the variables from the demand side of the economy that could be used to introduce economic shocks due to the physical risks of climate change. The shocks could be formulated either at the aggregate or sector level, depending on the sectoral disaggregation of the models. Similar to IAMs, general equilibrium models also have a model baseline, and the implications of economic shocks from different scenarios could be evaluated against the baseline.

As physical risks of climate change are not endogenous to economic models, assessing the economic consequences of climate change under alternative scenarios within economic models requires at least two additional steps before formulating the economic shocks under those scenarios: (1) functions translating physical risks to economic shocks (which are commonly referred to as damage functions) either at the sectoral or broader aggregate macroeconomic level and (2) projections of future physical risks under alternative scenarios.

The formulation of economic shocks due to chronic physical risks is widely covered in the existing literature. Firstly, there is a vast array of literature deriving empirical damage functions for certain sectors due to chronic climate change (such as changes in agriculture[10] and manufacturing[11] productivity, changes in land availability due to sea-level rise, and changes in labor productivity[12] due

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[10] See Seo & Mendelsohn (2008) for a global study of climate impacts on agriculture productivity, Mendelsohn (2014) for a study in Asia, and Dinesh et al. (2015) for a study in Africa.

[11] See Zhang et al. (2017) for a study on the implications of climate risks on Chinese manufacturing productivity.

[12] Dasgupta et al. (2021) is a comprehensive global study illustrating the non-linear changes in labor productivity amidst global warming and Levi et al. (2018) provide a comprehensive framework for understanding climate implications on labor productivity.

to heat stress or disease incidence). Most of the studies are specific to regions if not countries depending on the availability of historical data pertaining to impacts (e.g., labor or sector productivity data). Roson and Sartori (2016) collate several damage functions due to chronic climate risks in a form appropriate to global general equilibrium models. These damage functions primarily account for: (1) the loss of land due to sea-level rise; (2) changes in agriculture productivity; (3) changes in the incidence of vector-borne diseases; and (4) changes in heat stress for agriculture, manufacturing and service sectors and its implications on labor productivity of the sectors. Roson and der Mensbrugghe (2012) in ENVISAGE CGE model, Kompas et al. (2018) using the GTAP-INT CGE model, and Fernando et al. (2021) using the G-Cubed hybrid DSGE-CGE model, apply these damage functions to estimate the chronic physical risks of climate change under RCPs.

Secondly, historical climate data are globally available which could be used to derive indicators[13] of historical chronic risks. The same indicators could be constructed under alternative climate change scenarios as projected climate variables comparable to the historical climate variables are also widely available. Accordingly, the empirical damage functions could be derived using historical data and the damages under the scenarios could be projected using the projected climate variables or indicators.

However, the formulation of economic shocks due to extreme physical risks in a comparable format to chronic physical risks is primarily constrained by the lack of historical data on extreme physical risks and the projections of extreme physical risks (comparable to historical extreme physical risks) under alternative climate change scenarios.

Accordingly, most of the studies estimating the economic consequences of climate change have overlooked extreme climate risks (Narita et al. 2009). The most significant risks have been predicted to be in agriculture thus far. However, as Handmer et al. (2012) illustrate, extreme physical risks form an essential element in assessing the economic consequences of climate change. Firstly, global economic losses from extreme physical risks have increased over time and space. Secondly, people and assets are increasingly exposed to extreme physical risks which could prolong the economic consequences over a larger period. Thirdly, there is a much wider disparity of economic consequences of extreme physical risks across developing and developed countries. Fourthly, extreme physical risks will further threaten water, food, and health security globally. Implications for global health will also lead to significant welfare and distributional implications across generations (Schmitt et al. 2016).

Therefore, incorporating extreme physical risks into economic assessments of climate change is essential. This requires alleviating the constraints to developing indicators of extreme physical risks

[13] Climate indicators are a derivation from the climate variables. For example, the change in mean temperature compared to a baseline is a climate indicator, and the climate variable used in deriving the climate indicator is the temperature.

using historical climate variables, deriving empirical damage functions for extreme physical risks, and applying the damage functions to comparable projected indicators of extreme physical risks under alternative climate change scenarios. To the best of our knowledge, Fernando et al. (2021) is the first attempt to include extreme physical risks alongside chronic physical risks to evaluate the global economic consequences of RCPs[14].

Currently, the EM-DAT database (2022) provides the most comprehensive collation of historical extreme events and their details which include the location, duration, magnitude (where applicable), lives affected, lives lost, insured losses, and total damages. However, the details reported, especially pertaining to the location, magnitude, and duration of the events, are not complete and consistent. Furthermore, the database only reports events which meet certain criteria, specific to the event category, which could lead to underreporting. Relying minimally on the database, due to the limitations regarding the quality of the data, Fernando et al. (2021) derive climate damage functions for sectoral productivity (agriculture, energy production, and electricity generation) due to extreme physical risks covering droughts, floods, heat and cold waves, storms, and wildfires. Construction of the extreme damage functions closely follows the approach Roson and Sartori (2016) have taken when deriving the chronic damage functions. Fernando et al. (2021) also derive implications of extreme physical risks on labor productivity via morbidity and mortality. They then construct indicators of extreme physical risks for the same extreme events using projected climate variables and project the economic shocks under RCPs. The shocks are then assessed within the G-Cubed model which is a hybrid DSGE-CGE model.

Fernando and Lepore (Forthcoming), to the best of our knowledge, is the first study to assess the economic consequences of climate change starting at a more granular firm level, going beyond the sector level. They construct a series of indicators of extreme climate conditions and along with chronic climate indicators, derive empirical damage functions for a global multisectoral sample of 61,949 firms. The climate indicators account for the physical climate risks both at the location of the firm and the country in which the firm is located. The extreme indicators are representative of conditions leading to heat and cold waves, droughts, and extreme precipitation events. The damage functions are derived separately for agriculture, mining, manufacturing, and services, and the changes in sectoral productivity under three SSP scenarios (SSP 1-2.6, 2-4.5, and 5-8.5) are projected. They also project changes in firm physical capital due to floods using damage estimates from Huizinga et al. (2017). They then evaluate the economic consequences of the SSPs using the G-Cubed model.

[14] Fernando et al. (2021) also evaluate economic consequences emanating from two transition risks: (1) a carbon tax as a representative climate policy instrument in transitioning to a low-carbon economy, and (2) changes in asset valuations in financial markets due to changes in country and sector risk premia due to exposure to extreme climate risks.

2.5 Current Estimates of Economic Consequences of Physical Climate Risks

Overview

There is an extensive body of literature assessing the economic consequences of chronic climate risks using either IAMs or general equilibrium models. However, the existing studies on the economic consequences of extreme climate risks using either IAMs or general equilibrium models are limited. The studies evaluating the economic consequences of extreme risks also tend to be mostly regional if not national. The subsections to follow first discuss the current estimates of chronic climate risks from IAMs and general equilibrium models, before discussing some of the regional/national studies evaluating extreme climate risks.

Estimates of Chronic Physical Risks from Integrated Assessment Models (IAMs)

The earlier estimates of the global economic impacts of climate risks are mostly relatively smaller in IAMs. Tol (2012) reviews thirteen studies and summarizes the global economic losses under warming ranging from 1 to 3 ^{0}C. The annual changes in GDP in those studies vary from 0.1 to -4.8 percent. Weitzman (2012) attributes the lower economic losses to the conventional quadratic damage functions used in IAMs and thin-tailed temperature distributions. Stern (2016) illustrates that the underestimation of economic losses in IAMs could also be due to the limited spatial coverage of the IAMs, where impacts are averaged across countries and regions, and the relative lack of forward-looking behavior in IAMs.

There are also different damage estimates from comparable models for the same temperature outcomes. Diaz and Moore (2017) review the DICE, FUND, and PAGE IAMs from the cost-benefit analysis classification and illustrate that the GDP losses at 2 and 4 ^{0}C are vastly different due to the changes in damage functions and key characteristics, especially regarding sector details, in those IAMs. Batten (2018) demonstrates the subjectivity involved in the choice of parameters and functional forms for damage functions. As Ackerman and Stanton (2012) illustrate, the damage function estimates have not been consistent with observations partly due to the absence of any economic (or other) theory or empirical foundation underlying the damage functions. They highlight the importance of updating and calibrating damage functions constantly. Both the oversimplification of climate and economic models or the compromise of mostly economic details at the expense of extensive climate modules have the effect of masking the dynamic approaches via which climate change could affect economic growth and welfare.

Estimates of Chronic Physical Risks from General Equilibrium Models

Most of the existing studies, applying general equilibrium models to assess the economic consequences of chronic physical risks, use the CGE model available from the Global Trade Analysis Project (GTAP) or a variant of it.

Applying a recursive version of the GTAP model (GTAP-E), Bosello et al. (2006) estimate that most regions worldwide would experience labor productivity gains amidst the lack of vector-borne diseases due to higher temperatures. They observe that the decrease in mortality and morbidity associated with cold stress-related diseases dominates the increase in mortality and morbidity from heat stress-related diseases. However, energy-exporting countries and Africa experience lower labor productivity due to higher incidences of respiratory and gastrointestinal diseases in the energy-exporting countries and higher incidences of malaria in Africa. The changes in labor productivity results in positive GDP changes ranging from 0.04 to 0.08 percent for countries with productivity gains and negative GDP changes of -0.07 percent and -0.1 percent for energy-exporting countries and Africa, respectively, by 2050. Within the same model, Bosello et al. (2007) evaluate the global and national economic consequences of sea-level rise with two options for adaptation: coasts are unprotected from land loss, and coastal areas are fully protected. They show significant differences in both national and global welfare effects between the two options and argue that the optimal adaptation lies between the two extremes.

Eboli et al. (2010) apply another dynamic variant of the GTAP model (ICES) to analyze the effects of temperature change on global economic growth and wealth distribution. They find considerable macroeconomic effects, along with significant distributional effects at the regional and sectoral levels. Roson and der Mensbrugghe (2012) estimate the economic effects of climate change in the ENVISAGE model via a range of impact transmission channels: sea level increases, agricultural productivity, water availability, human health, tourism, and energy demand. They illustrate that climate impacts are highly varied across regions and impact channels. The most severe effect is from labor productivity changes at the global level, which accounts for 84 percent of the worldwide damage in 2050 (-1.8 percent of global GDP). The most seriously impacted region is the Middle East and North Africa (MENA), followed by East Asia. MENA suffers more from direct labor productivity losses while East Asia suffers more from sea-level rise. They do not however observe significant impacts on agriculture by 2050.

Kompas et al. (2018) use another variant of the GTAP model: GTAP-INT to assess the economic consequences of climate change under various temperature increases for 140 countries until 2100. They apply the chronic physical climate damage functions developed by Roson and Sartori (2016) for changes in agricultural productivity, changes in land availability due to sea-level rise, and changes in labor productivity due to heat stress and disease incidence. They illustrate that the effects on individual countries could be enormous across various warming scenarios and averaging across countries into regions could severely mask the heterogeneity across the countries. The impacts on GDP in Sub-Saharan Africa, India, and Southeast Asia are around 10 percent by the end of this century, while most European countries slightly gain by the mid-century and slightly suffer by the end of this century with less than 0.5 percent in GDP losses.

Estimates of Extreme Climate Risks

Narita et al. (2009, 2010) evaluate the global economic impact of increased incidence of tropical cyclones and extratropical storms respectively due to climate change in the FUND model. They illustrate that even though the global economic costs of the storms could be relatively lower (~ 0.01 percent of global GDP by 2100), the costs could increase up to 38 percent compared to the baseline. Hsiang et al. (2017) focus on the storms in the United States and demonstrate for every 1 cm increase in mean sea level the damages from storms could amount to 0.0014 percent of GDP.

Combined Estimates of Chronic and Extreme Physical Risks from General Equilibrium Models

Jorgenson et al. (2004) examine the implications of chronic and extreme physical risks in the United States. They use the IGEM model to project the macroeconomic consequences for the United States arising from climate change impacts on agriculture, livestock, fisheries, and forestry, energy services related to heating and cooling, commercial water supply, and protection of property and assets. They also consider the economic costs associated with the increased storms and floods as well as changes in labor supply and consumer demand due to climate-induced mortality and morbidity. They consider six scenarios where three levels of climate change (low, central, and high) are combined with two sets of market outcomes (optimistic and pessimistic) and observe that the GDP losses vary from -3 to 1 percent by 2100 across scenarios, where the economy partly benefits from climate change from the decline in commodity prices due to higher temperatures and increased precipitation in optimistic scenarios. Accordingly, the effects on agriculture dominate the other market impacts. They also observe that the changes in human mortality and morbidity are small yet essential determinants of the consequences of climate change.

Fernando et al. (2021) evaluate the economic consequences of both chronic and extreme physical risks under RCPs using the hybrid DSGE-CGE model: G-Cubed. They observe that the global economic consequences increase across RCPs. However, the temporal distribution of the effects for a given country could change across scenarios. The average GDP losses under RCP 2.6 could vary from -0.48 to -3.78 percent while under RCP 4.5 the range increases to -0.49 to – 4.96 percent. Under RCP 6.0 the lower bound of the losses increases to -0.43 percent even though the upper bound further decreases to -6.73 percent. Under RCP 8.5, the lower bound increases to -0.31 percent and the upper bound substantially decreases to -12.6 percent. They also present implications of climate risks on a wide array of economic sectors. Under RCP 2.6 and 4.5 the agriculture output could reduce by 3.5 to 9 percent compared to the baseline. Manufacturing, which is the second-most affected sector could experience losses between 1.5 to 5.5 percent compared to the baseline. The mining and energy sectors could contract between 1 to 4 percent under the same scenarios while the service sector is the least affected and experiences losses between 1 to 3.5 percent.

2.6 Summary

Section 2 provides an overview of climate risks, climate scenarios, methodologies for assessing climate risks, and the current estimates of the economic consequences of climate change. Even though this paper only focuses on physical climate risks, for the sake of completion, Sections 2.2 and 2.3 discuss transition risks and scenarios alongside physical risks and scenarios. Section 2.4 reviews the existing methodologies for assessing the economic consequences of physical climate risks with a focus on IAMs and general equilibrium models. Section 2.5 discusses the estimates of economic consequences of physical climate risks from IAMs and general equilibrium models.

Section 2 illustrates the key differences between the IAMs and general equilibrium models: the two most widely tools to assess the economic consequences of physical climate risks. The strengths and limitations of each approach illustrate the complementarity of the approaches rather than the substitutability of one with another. The range of estimates obtained from various modeling exercises also illustrates the uncertainty involved in assessing the economic consequences of climate change. Most importantly, Section 2 emphasizes the importance of continuous improvements to modeling strategies to produce finer estimates of climate change to assist policymakers.

Section 3 extends the previous work the author has contributed to, i.e., Fernando et al. (2021) and Fernando & Lepore (Forthcoming), assessing the economic consequences of physical climate risks, in two main ways. Firstly, it incorporates additional indicators of chronic and extreme climate conditions into the analyses. Secondly, it incorporates machine learning algorithms to derive climate damage functions for agriculture, energy production, and electricity generation. These improvements are incorporated into modeling the economic consequences of physical climate risks in the G-Cubed model, as discussed in Section 4. Section 5 discusses the results from the simulations which account for three SSPs.

3.0 IMPACTS OF PHYSICAL CLIMATE RISKS ON AGRICULTURE AND ENERGY

3.1 Overview

Section 3 derives empirical estimates for the implications of physical climate risks on agriculture, energy production, and electricity generation[15]. Section 3.2 introduces the climate data used in the paper and the chronic and extreme climate risk indicators constructed for the empirical estimations. It also discusses the historical variation of the climate indicators. Section 3.3 introduces the data on agriculture, energy production, and electricity generation used in the empirical estimations, and discusses their historical production patterns. The empirical estimation strategy is introduced in Section 3.4. It also discusses the empirical estimates of the implications of chronic and extreme physical risks on agriculture, energy production, and electricity generation, and the directionality of the estimates within the context of existing literature. Section 3.5 summarizes and concludes Section 3.

3.2 Chronic & Extreme Climate Risk Indicators

Climate Data

When constructing the chronic and extreme climate risk indicators, we use the historical and projected data on six climate variables: Mean Temperature, Maximum Temperature, Minimum Temperature, Precipitation, Relative Humidity, and Wind Speed.

We obtain the historical gridded monthly data on the first four variables from the Climate Research Unit of the University of East Anglia (2022) for the period from 1961 to 2020[16] at 0.5^0 x 0.5^0 resolution. The historical gridded daily data on the remaining variables (i.e., Relative Humidity and Wind Speed) for the same period (1961 – 2020) are obtained from the Geophysical Fluid Dynamics Library Earth System Model as reported by the Intersectoral Impact Model Intercomparison Project (ISIMIP) (2022).

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[15] The definition of energy as work or heat encompasses electricity, an energy carrier. The explicit distinction between energy production and electricity generation is mainly driven by the primary use of renewable energy sources, which are considered in this paper, for electricity generation. Considering electricity generation as a subset of energy production does not affect the analyses of the paper.

[16] The Climate Research Unit of the University of East Anglia provides the historical gridded data from 1901 to 2020 for Cloud cover, Diurnal Temperature Range, Frost Day Frequency, Mean Temperature, Maximum Temperature, Minimum Temperature, Potential Evapotranspiration, Precipitation, Vapor Pressure, and Wet Day Frequency.

We then aggregate the gridded data for 256 countries[17] recognized in the Database of Global Administrative Areas (GADM) (2022) and obtain the climate variables at monthly and annual frequencies.

Chronic and Extreme Climate Indicators

When constructing the climate indicators, we use the period from 1961 to 1990 as the climatological baseline following the guidelines of the World Meteorological Organization (WMO) (2017). Table 4 summarizes the climate indicators constructed and used in this paper. When constructing the indicators of short-term extreme temperature conditions, we follow the approaches outlined in Lai and Dzombak (2019), and for long-term precipitation-related extreme conditions, we use the Standard Precipitation Index (SPI) suggested by McKee et al. (1993). Following the insights in the literature[18] using indicators of extreme conditions, our indicators are relatable to heat and cold waves, droughts, extreme precipitation events, and storms[19]. Annexure 5 presents the average behavior of the historical and projected climate indicators for the 15 United Nations geographical regions from 1991 to 2020.

The Behavior of Historical Chronic Climate Indicators

As observed in Annexure 5, the mean temperature has continuously increased across all the regions with Eastern and Southern Europe already reaching temperature increases above 2 ^{0}C compared to the 1961-1990 baseline. In contrast to temperature, precipitation patterns are vastly different across the regions, and they demonstrate a much stronger cyclical variation. Western Asia notably experienced a reduction in precipitation until early 2012 and has been recovering since then. Latin America, in contrast, experienced an increase in precipitation towards the mid-2000s and has seen a reduction in precipitation since then. Relative humidity also demonstrates a higher cyclicality compared to the temperature which is not although as strong as precipitation. While some regions experience a reduction in relative humidity compared to the baseline, many regions are either indifferent or are experiencing increases compared to the early-1990s.

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[17] See Annexure 4 for the list of the 256 countries and their mapping to 15 geographical regions recognized by the United Nations, 141 GTAP regions, and 10 regions in the G-Cubed model.

[18] Ruso et al (2014) use short-term indicators of extreme conditions to project heat and cold waves. A few recent studies using SPI to predict droughts and/or extreme precipitation events include Ekwezuo et al. (2020) for West Africa, Ali et al. (2020) for Pakistan, Bhunia et al. (2020) for India, Golian et al. (2015) for Iran, Wang and Cao (2011) for China, and Manasta et al. (2010) for Zimbabwe.

[19] The indicators of extreme conditions should not however be interpreted as indicators of extreme events as the occurrence of extreme events would depend on a complex set of other factors including local weather conditions and land-use management practices, which we do not account for when constructing the indicators of extreme conditions.

Table 4: Chronic and Extreme Climate Indicators

	Indicator	Description	Unit
Chronic Climate Indicators			
1	Mean Temperature	Change in the mean annual temperature compared to the mean annual temperature within the baseline period of 1961 – 1990.	^{0}C
2	Precipitation	Percentage change in annual total precipitation compared to the mean annual total precipitation within the baseline period of 1961 – 1990.	%
3	Relative Humidity	Change in the mean annual relative humidity compared to the mean annual relative humidity within the baseline period of 1961 – 1990.	%
Extreme Climate Indicators			
4	MaxTemp90P	In a given year, the average percentage change of the monthly maximum temperature from the 90th percentile of the 1961 – 1990 monthly maximum temperature distribution.	%
5	MaxTemp10P	In a given year, the average percentage change of the monthly maximum temperature from the 10th percentile of the 1961 – 1990 monthly maximum temperature distribution.	%
6	MinTemp90P	In a given year, the average percentage change of the monthly minimum temperature from the 90th percentile of the 1961 – 1990 monthly minimum temperature distribution.	%
7	MinTemp10P	In a given year, the average percentage change of the monthly minimum temperature from the 10th percentile of the 1961 – 1990 monthly minimum temperature distribution.	%
8	SPIDry	In a given year, the average percentage deviation of the SPI index from -2 (SPI Index < -2 indicates Extreme Dry conditions).	%
9	SPIWet	In a given year, the average percentage deviation of the SPI index from 2 (SPI Index > 2 indicates Extreme Wet conditions).	%
10	Extreme Wind Speeds	In a given year, the average percentage change of the monthly maximum wind speed from the 90th percentile of the 1961 – 1990 monthly maximum wind speed distribution.	%

Source: Constructed by the Author.

The Behavior of Historical Extreme Climate Indicators

As observed in Annexure 5, the deviation of the maximum temperature from the 90th percentile of the baseline distribution (which is representative of warm days) has increased across all the regions between 1991 and 2000, notably in North America. Eastern and Western Europe are also on a notably increasing path. The deviation of the minimum temperature from the 90th percentile of the baseline distribution (which is representative of warm nights) is similar. Central Asia, and Eastern, Northern, and Western Europe demonstrate significant increases compared to the other regions.

The deviation of the maximum temperature from the 10th percentile of the baseline distribution (which is representative of cold days) has not changed much for most of the regions. Eastern Europe observed a cyclical reduction towards the early 2000s and then an increase since then, while Southern Europe has experienced an opposite cycle with the deviations reducing since the mid-2000s. North America too demonstrated a similar pattern to Eastern Europe even though the deviations have remained positive compared to Eastern Europe where the deviations remained within the negative range. The deviation of the minimum temperature from the 10th percentile of the baseline distribution (which is representative of cold nights) has remained fairly constant for almost all the regions. However, Southern Europe has observed a notable decline since the early 1990s.

Historical extreme wet and dry conditions demonstrate cyclical patterns similar to precipitation. However, the lengths of the cycles and the timing of the different phases of the cycle are different. The extremely dry and wet conditions have continued to increase for Southern Africa, North America, Oceania (ANZ), and Western Europe, notably. Extreme wind speeds have remained higher than the bassline and have been volatile for most of the regions. Southeast Asia and Northern Africa have notably experienced higher windspeeds throughout the period from 1991 to 2020.

3.3 Agriculture, Energy Production, and Electricity Generation Data

Data on Agriculture

Food and Agriculture Organization (FAO 2022) presents the annual data on agriculture production in 300 sectors for 224 countries. The 300 sectors are broadly categorized as Crops, Processed Crops, Live Animals, Primary Livestock, and Processed Livestock. Table 5 summarizes the distribution of the 300 FAO sectors across the five FAO groups.

We map the 300 FAO sectors to 13 primary agriculture sectors and seven manufacturing sectors in the GTAP 10 database (2022) following the Central Product Classification (CPC Version 2.1) and International Standard Industrial Classification (ISIC Revision 4). Annexure 6 presents the detailed mapping of the FAO sectors to GTAP sectors and Table 6 summarizes the distribution of the FAO sectors across the 20 GTAP sectors. We also map the 224 FAO countries to 141 GTAP regions, 15 United Nations geographical regions, and 10 G-Cubed regions using the International Organization for Standardization (ISO) classification of countries as presented in Annexure 7.

For crops and primary livestock, we compute the annual growth in Total Factor Productivity (TFP) as the data on inputs is available. However, for the other three FAO groups, the data on inputs is not available. Therefore, we compute the annual growth in production for those three groups. Annexure 8 summarizes the growth in the annual agriculture production/productivity patterns from 1991 to 2020 across the United Nations geographical regions.

Table 5: Distribution of FAO Sectors across FAO Groups

	FAO Group	Number of FAO Sectors
1	Crops	173
2	Processed Crops	23
3	Live Animals	20
4	Primary Livestock	53
5	Processed Livestock	31

Source: FAO (2022).

Table 6: Distribution of FAO Sectors across GTAP Sectors

GTAP Sector Code	Description	Number of FAO Sectors	Corresponding FAO Group
1	Paddy Rice	2	Crops
2	Wheat	1	Crops
3	Cereal Grains (nec)	14	Crops
4	Vegetables, Fruits, and Nuts	98	Crops
5	Oil Seeds	23	Crops
6	Sugar Cane & Beet	4	Crops
7	Plant-based Fibres	11	Crops
8	Crops (nec)	19	Crops
9	Bovine Cattle, Sheep, Goats, and Horses	11	Live Animals
10	Animal Products (nec)	25	Live Animals
11	Raw Milk	5	Primary Livestock
12	Wool and Silk-worm Cocoons	2	Primary Livestock
13	Forestry	1	Crops
19	Bovine Meat Products	18	Processed Livestock
20	Meat Products (nec)	12	Processed Livestock
21	Vegetables Oils and Fats	17	Processed Crops
22	Dairy Products	30	Processed Livestock
24	Processed Sugar	2	Processed Crops
26	Beverages and Tobacco Products	2	Processed Crops
27	Textiles	3	Processed Crops

Source: FAO (2022) and GTAP (2022). nec: Not classified elsewhere.

Historical Agriculture Production Patterns

As observed in Annexure 8, historical annual growth in the TFP of crops has remained fairly constant across many regions. However, some regions illustrate strong cyclical patterns. For example, Central Asia increased its TFP in crops until the early 2000s before experiencing a decline and a plateauing since then. Latin America experiences a similar cycle since the mid-200s, which Eastern Europe tends to follow. Southern Africa and Southern and Northern Europe have managed to increase productivity since the mid-2010s. Annual growth in the production of processed crops has diminished starting from the early 2010s. Southern Africa and Central Asia follow the same trend despite experiencing some peaks in the mid-2000s and the mid-2010s respectively.

Annual growth in the production of live animals has remained constant with some reduction starting from the early-2010s. The annual growth in TFP of primary livestock decreased from the early-1990s until the end of the decade and then plateaued until the early-2010s. It has experienced a reduction since then, despite Western Asia and Latin America demonstrating some signs of increase. The annual growth in the production of processed livestock has been decreasing since the early 2010s across all the regions alike, after remaining fairly constant since the early-1990s for most of the regions.

Data on Energy Production and Electricity Generation

Statistical Review of World Energy hosted by British Petroleum Company PLC (BP 2022) is a widely used source for global energy production and electricity generation. We obtain the annual data for energy production using coal, oil, gas, and electricity generation from nuclear, hydro, solar, wind, and other (which include biomass, tidal, and geothermal energy) sources. Table 7 summarizes the sectors and the number of countries for which the data is available. Annexure 9 maps the BP countries to the GTAP, G-Cubed, and the United Nations geographical regions. Annexure 10 summarizes the growth in annual energy production and electricity generation patterns from 1991 to 2020 across the United Nations geographical regions.

Table 7: Country Coverage for Energy Production and Electricity Generation Data

	Sector	Number of Countries Covered
1	Coal Production	34
2	Oil Production	48
3	Gas Production	49
4	Electricity Generation: Nuclear	79
5	Electricity Generation: Hydro	79
6	Electricity Generation: Solar	79
7	Electricity Generation: Wind	79
8	Electricity Generation: Other	79

Source: BP (2022).

Historical Energy Production Patterns

As observed in Annexure 10 the annual growth in coal production has overall declined since the 1990s. The decline is notable in Southeast Asia and Northern Europe. The change in annual growth of oil production is much more cyclical compared to coal production even though some regions have experienced declines. Oceania (ANZ), Sothern, and Northern Europe are however increasing their growth in oil production. The annual growth in gas production is less cyclical than oil production and similar to coal production, is on a declining trend for almost all the regions.

Electricity generation from nuclear has remained constant throughout most of the regions. Growth in the production of hydroelectricity however decreased until the early-2000s and is recovering for most of the regions. The generation of solar electricity has been volatile with different regions starting to use solar resources at different points in time. Some of the regions illustrate increasing uptake while some regions appear to be in a downward trend. Electricity generation from wind resources has steadily declined for some of the regions that have been early adopters, such as Northern and Western Europe and South and East Asia. Electricity generation from other sources has remained fairly constant across most of the regions a few regions experiencing cyclical changes in the generation.

3.4 Empirical Estimation of Impacts of Physical Risks on Agriculture and Energy

Empirical Estimation Strategy

Linear regression and its variants are widely used in estimating the empirical relationships between variables. Linear regression, in general, attempts to find the magnitudes of the coefficients that minimize the residual error between the actual observations and their predicted counterparts. The general representation of a linear regression model is presented in Equation 1 and the objective function is presented in Equation 2.

Equation 1: General Form of a Linear Regression Model

$$Y_i = \beta_0 + \sum_{j=1}^{n} \beta_j X_{ij} + \varepsilon$$

Equation 2: Objective Function of a Linear Regression Problem

$$\mathrm{argmin}\left(\sum_{i=1}^{N} (Y_i - \widehat{Y}_i)^2 = \sum_{i=1}^{N}\left[Y_i - \beta_0 - \sum_{j=1}^{n} \beta_j X_{ij}\right]^2\right)$$

However, when using linear regression models for predictions, two major problems could occur, namely overfitting and underfitting. Overfitting happens when the regression model performs well on the training data but poorly on the testing data. Underfitting happens when the regression model does not perform well on either data. Regularization is aimed at preventing overfitting in regression models without changing the number of features or predictor variables. Two widely used regularization algorithms are called LASSO (Least Absolute Shrinkage and Selection Operator) and Ridge. The objective functions of LASSO and Ridge are presented in Equations 3 and 4.

Equation 3: Objective Function of a LASSO Regression Problem

$$\text{argmin}\left(\sum_{i=1}^{N}\left[Y_i - \beta_0 - \sum_{j=1}^{n}\beta_j X_{ij}\right]^2 + \alpha\sum_{j=1}^{n}|\beta_j|\right)$$

Equation 4: Objective Function of a Ridge Regression Problem

$$\text{argmin}\left(\sum_{i=1}^{N}\left[Y_i - \beta_0 - \sum_{j=1}^{n}\beta_j X_{ij}\right]^2 + \alpha\sum_{j=1}^{n}{\beta_j}^2\right)$$

As illustrated in Equations 3 and 4, both LASSO and Ridge regressions start with the conventional objective function of linear regression and impose a non-negative penalty on the coefficients of the predictors. The penalty prevents the coefficients from being too large when optimizing the conventional objective function. The penalty in LASSO regression works with the linear summation of coefficients and thus could shrink some coefficients up to zero. However, Ridge regression works with the squared summation of the coefficients and thus does not necessarily reduce coefficients to zero. This characteristic qualifies LASSO to be used as a feature selection algorithm when there is a large group of predictors out of which the optimum set of predictors has to be identified.

The two algorithms also behave differently when there are correlated predictors. While LASSO would shrink some of the coefficients of correlated variables to zero, Ridge regression would treat all the correlated variables the same. Given these differences across LASSO and Ridge, a generalized form of regularized regression combining both approaches could also be used. Equation 5 presents the objective function of the generalized form[20].

Equation 5: Objective Function of a General Regularized Regression Problem

$$\text{argmin}\left(\sum_{i=1}^{N}\left[Y_i - \beta_0 - \sum_{j=1}^{n}\beta_j X_{ij}\right]^2 + \alpha\sum_{j=1}^{n}\left((1-\theta)\,{\beta_j}^2 + \theta\,|\beta_j|\right)\right)$$

In this paper, using the data on agriculture, energy production, and electricity generation, we calculate the growth in production or productivity (for crops and primary livestock) for the five FAO agriculture groups and the eight BP energy/electricity sectors for each country for which the data is available. Our objective then is to understand how the chronic and extreme climate indicators introduced in Section 3.2 have historically affected the agriculture and energy/electricity production in those countries. We then encounter two challenges.

[20] See Hastie et al. (2017) for a detailed discussion on linear, LASSO, and Ridge regression models.

Firstly, some of the chronic and extreme climate indicators are linked to the same distributions although their methods of construction are independent[21]. Secondly, we have a considerably higher number of climate indicators as predictors (especially compared to existing studies which have mostly used temperature and (rarely) precipitation). Accordingly, both accounting for collinearity and reducing the features to understand the most vital predictors are central to our estimations. Therefore, we estimate the regression model illustrated in Equation 6, which is similar to a panel regression, in the generalized form of the regularized regression (Elastic Net: General). The generalized form of the regularized regression combines the strengths of LASSO and Ridge regression models, indicating the optimum fit for the data.

Equation 6: Estimated Model Form for a Given Sector in Country *i* and Year *j*

$$Growth\ in\ Production\ (or\ Productivity)_{i,j} = \beta_0 + \sum_{k=1}^{n} \beta_k * Climate\ Indicator_{k,i,j} + \gamma_i + \delta_j + \varepsilon_{i,j}$$

Annexures 11 and 12 present a summary of the empirical estimates for the agriculture and energy sectors respectively. The summaries also include a linear regression model (which is comparable to a linear panel regression), LASSO, and Ridge regression models. Tables 8 and 9 summarize the estimates from the Elastic Net: General model for the agriculture and energy sectors, respectively[22].

Impact of Physical Risks on Agriculture

The agriculture sector mainly comprises crops, livestock, fishery, and forestry. As outlined in Hulme (1996), climate risks could affect crops at least in three main ways: (1) changes in the soil moisture content due to evaporation, crop respiration rate, and the length and timing of the growing seasons due to variations in temperature and precipitation affecting the crop growth; (2) changes in the water-use efficiency and photosynthesis due to variations in carbon dioxide concentration, and (3) changes in quality of water and soil, shifts in weed growth and vulnerability to diseases due to extreme events such as droughts and floods.

The livestock and fishery could also be vulnerable to diseases as climate variability and extreme temperatures affect the physiology, behavior and movements, growth and development, and fertility of animals, birds, and fish. Even though higher carbon dioxide concentrations could increase the quantity

[21] For example, while a chronic indicator could measure the deviation in mean temperature in a given year from baseline, an extreme indicator could measure the average deviations of the monthly maximum temperature from a percentile of the distribution. Accordingly, both indicators could be related to the same distribution, but the method of construction enables identifying mean vs extreme values.

[22] The objective of the empirical estimates in this paper is not to comprehensively explain the productivity or production patterns of the agriculture and energy/electricity sector, but to obtain the implications of physical climate risks on those sectors. Therefore, the omitted variables that could contribute to explaining productivity/production patterns could affect the estimates only to the extent they are correlated with the climate indicators. As climate risks are largely exogenous, we assume that the current estimates are not significantly affected by the omitted variables.

of feed available for livestock, the quality of the feed could deteriorate affecting the productivity of the livestock sector. In fishery, the lifecycle of aquatic species and their migration patterns are also affected by the changes in climate, thus, affecting the productivity of the sector. In the forestry sector, changes in climate could alter the growth cycle of trees and change their resilience to diseases, even though increased carbon dioxide concentration could promote the growth of trees (US Climate Change Science Program 2008a; Rojas-Downing et al. 2017).

The existing studies use both empirical estimations and impact models to evaluate the impacts of climate risks on agriculture. Most of the studies have focused on developing countries, given their strong reliance on agriculture. Using a Ricardian model of the agriculture sector, Mendelsohn (2014) estimates 13.3 and 28.1 percent reductions in annual revenue from Asian agriculture under 1.5 ^{0}C and 3 ^{0}C warming scenarios respectively. In Africa, Dinesh et al. (2015) estimate that the productivity in the livestock sector could shrink by almost 50 percent in most of the regions and the productivity of maize cultivation could shrink up to 25 percent under the RCP 8.5 scenario by 2050. Seo and Mendelsohn (2008) estimate that the agriculture sector could lose 14, 20, and 53 percent of its revenue under a severe climate scenario by 2020, 2060, and 2100 respectively. The developed countries could also experience substantial impacts on agriculture due to climate change. Sheng and Xu (2019) evaluate the impact of the Millennium drought on the Australian agriculture sector and measures an 18 percent reduction in TFP from 2002 to 2010. In Europe, climate change is expected to mainly affect agriculture via droughts, heatwaves, pest diseases, weeds, and soil erosion (Olsen et al. 2011).

In this paper, as illustrated in Table 8, we observe that crops and live animals are responsive to the whole range of climate indicators while other agriculture sectors are responsive to fewer. Within the period of three decades covered in this paper, the increase in mean temperature from the baseline tends to increase the productivity of crops almost by one percent potentially due to an increase in the efficiencies of photosynthesis, transpiration, and respiration. However, extreme temperature conditions tend to adversely affect crops, with extremely warm temperatures reducing crop productivity by almost five percent.

Precipitation has a similar impact to temperature on crops. Even though the chronic change in precipitation is favorable to crop productivity with higher water availability, both extremely wet and dry conditions could be disruptive to crops. An increase in relative humidity, potentially leading to inconvenience for growers and increased existence of pests, and extreme wind speeds, potentially due to unfavorable mechanical implications on crops (such as uprooting, shedding, and injuries) reduce crop productivity[23].

[23] See TNAU Agritech Portal (2022) for a further description of implications of climate variables on crops.

Crop production, which uses crops as inputs and involves manufacturing, however, only gets affected by a limited number of climate indicators. Precipitation tends to increase the production of crops, potentially via the favorable implications on crops. However, extreme temperatures and relative humidity decrease production, potentially both via the implications on crops and discomfort for workers.

Similar to crops, live animals get affected by the whole range of climate indicators, even though livestock gets affected only by a few indicators. In general, both chronic and extreme temperatures adversely affect animals, potentially via the adverse implications of temperature on their biological processes, discussed earlier in this section. Precipitation and extreme wet conditions could incentivize the production of live animals, due to favorable conditions for water and food sources, and habitats. Relative humidity however reduces live animal production due to implications on the transpiration of animals.

Livestock production has similar impacts to live animals for most of the variables with the impacts being higher for chronic temperature. Different to live animals, which benefit from extreme cold conditions, livestock production suffers, potentially due to the implications of cold weather on manufacturing processes. Extreme wind speeds also affect livestock production adversely even though are somewhat favorable for live animals. Processed livestock, different to live animals and livestock production, only gets affected by a few extreme climate indicators. Extreme temperature deviations from the 90th percentile of the baseline maximum temperature distribution tend to adversely affect livestock processing, potentially due to implications on the manufacturing equipment and workers.

Impact of Physical Risks on Energy

Existing studies explicitly exploring the implications of climate risks on the energy sector are limited. The exposure of the energy sector to climate risks could however be somewhat understood from the studies exploring the climate impact pathways for the mining sectors, which also are limited in number though more comprehensive. As non-renewable energy sectors are heavily reliant on mining, the energy sectors could be expected to experience similar production challenges to mining from climate risks. Thus, we summarize some of the relevant insights from the studies exploring the exposure of the mining sector to climate risks below.

In the mining sector, both chronic and extreme climate risks could disrupt and primarily increase the cost of exploration, extraction, production, transportation, and decommission, even though there could also arise newer opportunities for exploration and access to natural resources which were previously inaccessible[24]. Rising water scarcity is the main driver of increasing costs in the mining sector (Pearce

[24] See Odell et al (2018) for country-level evidence on the impacts of climate risks on the mining sector.

et al. 2011). Rising temperatures could further deteriorate the environmentally challenging conditions in mining regions and operational sites, reducing the labor efficiency in the mining sector (Sun et al. 2020).

In addition to experiencing climate risks similar to the mining sector, the productivity of generation, transmission, and distribution of energy and electricity will deteriorate with the demand for more inputs to produce the same output. The requirement for more cooling water in thermal power plants, disruptions to hydroelectric power plants due to changes in water availability, and more frequent maintenance of transmission and distribution lines due to disruptions from extreme climate risks are exemplary of the impacts of climate risks on the energy sector (US Climate Change Science Program 2008b).

In this paper, as illustrated in Table 9, we observe that most of the non-renewable energy sectors are rarely affected by extreme physical risks. They are however affected by chronic physical risks, particularly temperature. Production of fossil fuels is adversely affected by the rising temperature potentially due to implications on already challenging conditions in operational sites, particularly for the labor, and scarcity of water. Higher precipitation tends to adversely affect coal and gas production, which could be attributable to disruptions to mining operations, and implications on humidity particularly for natural gas production via deterioration of the quality of natural gas. Coal production is also vulnerable to rises in relative humidity potentially due to unfavorable conditions for labor.

Changes in extreme temperature conditions minimally affect fossil fuel production, with warm days affecting gas production and cold nights affecting coal production. Cold nights have a negative effect on oil production and cold days have the exact positive effect. Extreme dry conditions tend to favor coal production and slightly negatively affect gas production. Nuclear generation is only affected by extremely low temperatures potentially due to disruptions to equipment due to implications of temperature on the oil used in machinery freezing and their viscosity changing[25].

Electricity generation from renewable resources also illustrates a mix of effects characteristic to their nature. Hydroelectricity generation gets adversely affected by increases in temperature and extreme temperatures even more potentially due to higher evaporation losses in hydropower plants. Higher precipitation however is quite favorable to hydropower generation due to the positive implications on the hydrological cycle.

Electricity generation from solar resources increases with temperature and reduces with precipitation, potentially as clouds reduce solar irradiation exposure. Wind generation is incentivized with higher temperatures potentially due to better circulation of air particles from temperature-induced excitement

[25] See Hylko (2014) for a discussion of implications of cold weather on nuclear reactors.

even though extremely high temperatures could reduce the efficiency of wind turbines due to reduced air density[26]. Relative humidity reduces the density of air and leads to lower power generation from wind turbines[27]. Electricity generation from other sources, which mainly include biomass, tends to get negatively affected by rising temperatures and higher relative humidity due to higher concentrations of water vapor reducing the efficiency of biomass incineration.

3.5 Summary

Section 3 discusses the empirical estimation of the impact of physical climate risks on agriculture and energy. Section 3.2 presents the climate data, the construction of climate indicators, and an overview of their historical behavior. Section 3.3 discusses the data on agriculture, energy production, and electricity generation and their historical trends. Section 3.4 incorporates the data on agriculture and energy production and indicators of chronic and extreme physical climate risks to derive empirical estimates of the implications of physical climate risks on agriculture and energy production. It then discusses the estimates within the existing understanding of climate implications on agriculture and energy production.

Extending the approaches in Fernando et al. (2021) and Fernando & Lepore (Forthcoming), Section 3 estimates the implications of a wider range of climate risks on agriculture and energy production. It emphasizes the importance of considering a wide range of physical risks moving beyond the frequent practice in the existing literature to incorporate only temperature and/or precipitation. Using also the methodological innovation of regularized regressions, Section 3 accounts for potential collinearity among the climate risk indicator group and extracts the most important insights to understand how physical climate risks affect agriculture and energy production.

Section 4 uses the estimates derived in Section 3 to project the implications of chronic and extreme climate physical risks under three SSPs on agriculture and energy production. It then derives the shocks to other sectors (mainly manufacturing and services) and models the global economic consequences of the three SSPs within the hybrid DSGE-CGE model: G-Cubed. Section 5 discusses the simulation results.

[26] See Aeolos Wind Energy (Ltd.) (2022) for a discussion on factors affecting wind turbines.

[27] See Danook et al. (2019) for a detailed discussion on the impact of humidity on wind turbines.

Table 8: Global Sensitivity of Agriculture to Physical Climate Risks during the Period from 1991 to 2020

Sector	Mean Temperature	Precipitation	Relative Humidity	MaxTemp90P	MinTemp 90P	MaxTemp10P	MinTemp 10P	SPI Wet	SPI Dry	Extreme Wind Speeds
Crops	0.98	0.75	-0.02	-5.30	-0.04	0.17	-0.25	-0.31	-0.34	-0.09
Processed Crops	0.00	0.25	-0.36	-1.99	0.00	0.00	0.00	0.00	0.00	0.00
Live Animals	-0.04	0.06	-0.22	-2.30	0.94	-0.07	-0.05	0.06	0.32	0.09
Primary Livestock	-0.09	0.00	-0.03	-1.77	-0.04	0.00	0.00	0.05	0.00	-0.14
Processed Livestock	0.00	0.00	0.00	-4.56	0.00	0.00	0.00	-0.13	0.25	0.00

Source: Empirical Estimates from Elastic Net: General Model.

Table 9: Global Sensitivity of Energy Production and Electricity Generation to Physical Climate Risks from 1991 to 2020

Sector	Mean Temperature	Precipitation	Relative Humidity	MaxTemp 90P	MinTemp 90P	MaxTemp 10P	MinTemp 10P	SPI Wet	SPI Dry	Extreme Wind Speeds
Coal Production	-0.31	-0.25	-0.57	0.00	0.00	0.00	-0.47	0.00	0.26	0.00
Oil Production	-0.04	0.00	0.00	0.00	-0.14	0.14	0.00	0.00	0.00	0.00
Gas Production	-0.07	-1.14	0.00	-1.12	0.00	0.28	0.00	0.00	-0.06	0.00
Nuclear Generation	0.00	0.00	0.00	0.00	-1.32	0.00	0.00	0.00	0.00	0.00
Hydro Generation	-0.18	8.23	0.00	-1.94	0.00	0.00	0.00	0.00	0.00	0.22
Solar Generation	0.97	-1.17	0.00	0.00	-0.01	0.00	0.23	0.00	0.00	0.00
Wind Generation	0.94	0.00	-1.12	0.00	-0.92	0.81	0.00	0.00	-0.24	0.00
Other Generation	-0.04	0.00	-0.16	0.00	0.00	0.00	0.34	0.00	0.00	0.00

Source: Empirical Estimates from Elastic Net: General Model.

4.0 MODELLING ECONOMIC CONSEQUENCES OF THE IMPACTS OF PHYSICAL CLIMATE RISKS ON AGRICULTURE AND ENERGY

4.1 Overview

Section 4 details the approach to modeling the economic consequences of the impacts of physical climate risks on the agriculture and energy sectors. Section 4.2 provides an overview of the G-Cubed model used for the modeling. Section 4.3 outlines the model baseline and the climate scenarios evaluated in the simulations. Section 4.4 presents an overview of the behavior of climate indicators, explained in Section 3.2, under the climate scenarios. Section 4.5 derives the economic implications on agriculture and energy using the projected climate variables and the empirical estimates derived in Section 3.4. Section 4.5 also explains how the economic shocks to sectors other than agriculture and energy are derived. Section 4.6 summarizes and concludes Section 4.

4.2 G-Cubed Model

The G-Cubed model is a multi-country, multi-sector, intertemporal general equilibrium model developed by McKibbin and Wilcoxen (2013; 1999). The model is designed to bridge the gaps between econometric general equilibrium modeling, international trade theory, and modern macroeconomics. In the version of the model (version GGG20J_v164) used in this paper, there are ten regions and twenty sectors. The model regions are summarized in Table 10. Annexure 4 maps the 256 GADM countries to 141 GTAP countries and the 10 G-Cubed regions. The model sectors are presented in Table 11. The first twelve sectors are aggregated from the 65 sectors in the GTAP 10 database as indicated in Annexure 13. The electricity sector is then disaggregated into the electricity delivery sector (Sector 1 in Table 11) and eight electricity generation sectors (Sectors 13-20 in Table 11). Annexure 14 schematically presents the production structure of the G-Cubed model version used in this paper.

One of the key features of the G-Cubed lies in its consistent accounting for stocks and flows of physical and financial assets. For example, budget deficits accumulate into government debt, and current account deficits accumulate into foreign debt. The model imposes an intertemporal budget constraint on all households, firms, governments, and countries, which enables achieving a long-run stock equilibrium through the adjustment of asset prices, such as the interest rate for government fiscal positions or real exchange rates for the balance of payments. However, adjusting to each economy's long-run equilibrium can be slow, occurring over much of a century.

Secondly, the agents in G-Cubed must use money issued by central banks for all transactions. Thus, central banks in the model set short-term nominal interest rates to target macroeconomic outcomes (such as inflation, unemployment, exchange rates, etc.) based on Henderson-McKibbin-Taylor monetary rules (Henderson & McKibbin 1993; Taylor 1993). These rules approximate actual monetary regimes in each country or region in the model. These monetary rules tie down the long-run inflation rates in each country and allow short-term policy adjustments to smooth fluctuations in the real economy.

Thirdly, nominal wages are sticky and adjust over time based on country-specific labor contracting assumptions. Firms hire labor in each sector up to the point that labor's marginal product equals the real wage defined in terms of the output price level in each sector. Any excess labor enters the unemployed pool of workers. Unemployment or the presence of excess demand for labor causes the nominal wage to adjust to clear the labor market in the long run. In the short run, unemployment can arise due to structural supply shocks or aggregate demand changes in the economy.

Fourthly, rigidities prevent the economy from moving quickly from one equilibrium to another. The sources of rigidities include the stickiness of nominal wages, lack of complete foresight in the formation of expectations, cost of adjustment in investment by firms with physical capital being sector-specific in the short run, and monetary and fiscal authorities following particular monetary and fiscal rules. Consequently, the short-term adjustment to economic shocks can be very different from the long-run equilibrium outcomes.

The model also incorporates heterogeneous households and firms. Firms are modeled separately within each sector. There are two types of consumers and firms in each sector and country. The first group has forward-looking expectations, while the second group follows more straightforward rules of thumb, which are optimal in the long run but not necessarily in the short run.

The fiscal rule in the model varies across model versions. The version of the model used in this paper assumes that governments levy lump-sum taxes on households to ensure fiscal sustainability. In the long run, the changes in interest servicing costs from any changes in revenue or expenditure exogenously imposed are offset through a lump sum tax on households. Thus, the government debt level can permanently change in the long run with the change in debt to GDP ratio being equal to the long-run fiscal deficit ratio to the economy's long-run real growth rate.

Table 10: Regions in the G-Cubed Model

Region Code	Region Description
AUS	Australia
CHI	China
EUW	Europe
IND	India
JPN	Japan
OPC	Oil-exporting Developing Countries
OEC	Rest of the OECD
ROW	Rest of the World
RUS	Russian Federation
USA	United States

Source: G-Cubed Model (Version GGG20J_v164).

Table 11: Sectors in the G-Cubed Model

Number	Sector Name	Notes
1	Electricity delivery	Energy Sectors excluding Electricity Generation
2	Gas extraction and utilities	
3	Petroleum refining	
4	Coal mining	
5	Crude oil extraction	
6	Construction	Goods and Services
7	Other mining	
8	Agriculture and forestry	
9	Durable goods	
10	Non-durable goods	
11	Transportation	
12	Services	
13	Coal generation	Electricity Generation Sectors
14	Natural gas generation	
15	Petroleum generation	
16	Nuclear generation	
17	Wind generation	
18	Solar generation	
19	Hydroelectric generation	
20	Other generation	

Source: G-Cubed Model (Version GGG20J_v164).

4.3 Baseline & Climate Scenarios

Baseline

The G-Cubed baseline from 2019 to 2100 is constructed without any additional climate policies other than those already in place by 2018. The key inputs into the baseline are the initial dynamics from 2018 to 2019 and subsequent projections from 2019 onwards for sectoral productivity growth rates by sector and country. Sectoral productivity growth is driven by labor force growth and labor productivity growth.

The working-age population projections from the United Nations Population Prospects (2019) are used to estimate the economy-wide labor force growth rates. A catch-up model is constructed to generate the labor productivity growth rates (labor-augmenting technological progress). The sectoral productivity projections follow the Barro approach, estimating the average catch-up rate of an individual country to the worldwide productivity frontier at an annual two percent. The Groningen Growth and Development database (2022) is used to assess the initial productivity level of each sector in the model and then take the initial productivity ratio to the equivalent sector (the frontier) in the United States. Given this initial gap, the Barro catch-up model generates long-term projections of the productivity growth rate of each sector within each country. Given that some regions are likely to catch up more quickly to the frontier due to economic reforms or more slowly to the frontier due to institutional rigidities, the catch-up rate is varied over time. The calibration of the catch-up rate attempts to replicate the recent growth experiences of each country/region in the model.

Climate Scenarios

Shared Socioeconomic Pathways (SSPs)[28] are the latest set of scenarios used by the IPCC for assessing the implications of climate change and recommending policy measures for climate change mitigation and adaptation. This paper assesses the economic consequences of physical climate impacts on agriculture and energy sectors under three of the five SSPs discussed in Section 2.3, i.e., SSP 1-2.6, SSP 2-4.5, and SSP 5-8.5.

It is worth noting that these scenarios (particularly SSP 5-8.5) are used to obtain a range of estimates about the economic consequences of physical climate risks. We do not attribute any likelihood to any of the scenarios and do not assume any scenario to be "business as usual". Hausfather and Peters (2020) provide a detailed discussion on how best to interpret representative concentration pathways in line with the most recent developments. We follow the literature to interpret RCP 8.5 (which is linked to SSP 5-8.5) only as an upper bound of the estimates.

[28] Section 2.3 introduces the SSPs. Table 2 and Annexure 2 present more details about them.

4.4 Behavior of Climate Variables

Overview

Given the global economy projection in the G-Cubed baseline, economic shocks, representative of the SSPs, are necessary to model the economic consequences of the climate scenarios. We use projected climate variables along with the empirical estimates derived in Section 3.4 to formulate the economic shocks. We obtain the projected climate variables from the daily data gridded at 0.5^0 x 0.5^0 resolution from 2021 to 2100 for all the climate variables introduced in Section 3.2: Mean Temperature, Maximum Temperature, Minimum Temperature, Precipitation, Relative Humidity, and Wind Speed from ISIMIP (2022). We then derive the chronic and extreme physical climate indicators introduced in Table 4 of Section 3.2. Annexure 15 summarizes the chronic climate indicators under SSPs. Annexures 16 and 17 summarize the extreme temperature-related climate risk indicators, and extreme precipitation and windspeed-related climate indicators under SSPs respectively. Section 4.4 discusses the behavior of the climate indicators under SSPs, and Section 4.5 derives the economic shocks on sectoral productivity based on the behavior of the climate indicators.

The Behavior of Chronic Climate Indicators under SSPs

As observed in Annexure 15, under SSP 1-2.6 mean temperature increases across the period for almost all the regions reaching 1 to 2 ^{0}C above the baseline temperature. Northern, Eastern, and Western Europe experience higher temperatures at the beginning of the period and then, after a cyclical fluctuation, the temperatures converge to about 1.5 ^{0}C above the baseline temperature. Under SSP 2-4.5 the temperatures illustrate a more gradual increase across all the regions until the end of the century where Oceania (ANZ) experiences the minimum increase of about 1 ^{0}C and Central Asia and Eastern Europe experience the highest increase which is above 3 ^{0}C. Under SSP 5-8.5 the temperatures continue to increase following the same pattern but ending up with a range of 2 – 6 ^{0}C higher than the baseline period.

Precipitation demonstrates a much more cyclical behavior, compared to temperature, under SSP 1-2.6. While a few regions (such as Central Asia, Oceania (ANZ), Northern Africa, and Latin America) experience increases in precipitation, the regions experience declines in precipitation compared to the baseline. The range of precipitation further widens under SSP 2-4.5 with more regions experiencing declines in precipitation. The pattern continues under SSP 5-8.5 with a reduction in increases compared to the baseline and a notable decrease in cyclical volatility across most of the regions.

Changes in relative humidity indicate the trade-offs between changes in temperature and precipitation under a given scenario. Under SSP 1-2.6, its behavior is more similar to that of precipitation. Some regions experience increases in humidity while most of the regions experience decreases in humidity, indicating more dry conditions. The pattern remains largely the same across the other two scenarios.

The Behavior of Temperature-related Extreme Climate Risk Indicators under SSPs

The deviation of the maximum temperature from the 90^{th} percentile represents on average in a given year how the monthly maximum temperature deviates from the 90^{th} percentile of the baseline distribution (1961-1990) which implies warmer conditions during the day-time. As observed in Annexure 16, under SSP 1-2.6 all the regions experience an increase in the maximum temperature with Southeast Asia and Southern, Eastern, and Western Europe experiencing the largest increase approximately around 0.2 percent. The differences remain almost constant for most of the regions throughout the century. However, under SSP 2-4.5, all regions experience increasing temperatures with the upper bound increasing to about 0.4 percent. Southeast Asia experiences the highest increase. The pattern remains the same under SSP 5-8.5 and the upper bound reaches almost 1 percent, with Southeast Asia experiencing the highest deviation and Oceania (ANZ) experiencing the lowest deviation.

The deviation of the minimum temperature from the 90^{th} percentile represents on average in a given year how the monthly minimum temperature deviates from the 90^{th} percentile of the baseline distribution (1961-1990) which implies warmer conditions during the night-time. As observed in Annexure 16, under SSP 1-2.6, most of the regions experience an increase within 0.1 to 0.2 percent, even though Latin America and Oceania (ANZ) experience increases above 0.5 percent. The increases remain fairly constant across the century. Under SSP 2-4.5, all the regions experience upward trends with the upper bound exceeding 0.7 percent by the end of the century. Under SSP 5-8.5, the deviations exceed 1 percent from the baseline by the end of the century.

The deviation of the maximum temperature from the 10^{th} percentile represents on average in a given year how the monthly maximum temperature deviates from the 10^{th} percentile of the baseline distribution (1961-1990) which implies colder conditions during the day-time. As observed in Annexure 16, under SSP 1-2.6, most of the regions experience very minimal deviations, even though Oceania (ANZ) experience deviations close to negative 0.3 percent across the century. Under SSP 2-4.5 most of the regions remain indifferent while regions that had somewhat higher negative deviations start converging to zero, which only becomes faster under SSP 5-8.5, without any additional noticeable differences to SSP 2-4.5.

The deviation of the minimum temperature from the 10^{th} percentile represents on average in a given year how the monthly minimum temperature deviates from the 10^{th} percentile of the baseline distribution (1961-1990) which implies colder conditions during the night-time. As observed in Annexure 16, under SSP 1-2.6, most of the regions experience very minimal changes. The minimal changes become closer to zero with the increase in warming as observed in SSP 2-4.5. The deviations converge to zero in a more pronouncing manner under SSP 5-8.5.

The Behavior of Precipitation and Windspeed-related Extreme Climate Risk Indicators under SSPs

The extreme wet and dry conditions measure the variation of a given month's SPI index from -2 or +2 respectively following the definition of the SPI Index. The annual variation is constructed by averaging the monthly variations for a given year.

As observed in Annexure 17, under SSP 1-2.6, while some of the regions experience almost constant changes in extremely wet conditions, some regions experience some fluctuations. The variation in Northern Africa is notable where the extremely wet conditions increase towards the mid-century and reduce towards the end of the century. In contrast, Oceania (ANZ) and Latin America experience a gradual reduction towards the mid-century and an increase towards the end-century. The strength of the extremely wet conditions increases with SSP 2-4.5 where most of the regions demonstrate similar patterns at a higher range. Notably, Oceania (ANZ) continues to experience an increasing strength in extremely wet conditions towards the end of the century compared to the reduction in SSP 1-2.6. The upper bound of the strength continues to increase under SSP 5-8.5 with similar patterns of variation to SSP 2-4.5.

In contrast to extremely wet conditions, the variations in extremely dry conditions are more volatile for most regions. Under SSP 1-2.6, South Asia experiences the highest deviation in extremely dry conditions which remain almost constant throughout the century. North America and Oceania (ANZ) experience the least deviations. Under SSP 2-4.5, the strength of the extremely dry conditions increases with particularly regions experiencing higher strength experiencing more volatility. Under SSP 5-8.5, the upper bound of the extremely dry conditions continues to increase. Notably, Southern Europe experiences higher strength in extremely dry conditions compared to SSP 2-4.5 reaching a two percent deviation on average from the extremely dry conditions.

The extreme wind speeds indicate how a given month's maximum wind speed deviates from the 90^{th} percentile of the underlying distribution of the wind speeds in the baseline period (1961-1990). The annual variation is the simple arithmetic average of the monthly deviations. The deviations of the extreme wind speeds compared to the baseline is much less volatile compared to extremely dry or wet conditions. Under SSP 1-2.6, most of the regions remain below a two percent deviation from the baseline wind speeds. Eastern Europe and Southeast Asia experience notably higher wind speeds. The patterns of variation across the century remain similar to SSP 1-2.6 under SSP 2-4.5 However, Southeast Asia continues to experience higher deviations within 11 to 12 percent from the baseline towards the end of the century. There is also a notable shift in the wind speeds Eastern Europe experiences. Under SSP 5-8.5, many other regions experience higher wind speeds compared to the other two scenarios.

4.5 Formulation of Economic Shocks

Overview

Section 4.5 illustrates the implications of physical climate risks on agriculture, energy production, and electricity generation under three climate scenarios: SSP 1-2.6, 2-4.5, and 5-8.5. The implications have been derived from the empirical estimates obtained in Section 3.5 and the climate risk indicators discussed in Section 4.4.

When discussing climate physical risks, aggregating the countries by United Nations geographical regions is more meaningful, as the climate conditions are more comparable across geographical regions. However, as presented in Section 4.2, the regions of the G-Cubed model version used for this paper are different from the United Nations regions. The choice of the regions in the G-Cubed model version has been primarily determined by the importance of countries and regions in climate negotiations, and the overall number of countries/regions is constrained by the computational demands and the data requirements for model calibration. Therefore, when discussing shocks in the subsequent sections and results in Section 5, they will be discussed for the 10 G-Cubed regions. The shocks to agriculture and energy sectors have been estimated separately for countries and have been aggregated across the G-Cubed regions using the 2019 GDP[29] of the countries as weights.

Shocks on Agriculture: Crops

Annexure 18 presents the variation of production of crops across the G-Cubed regions under SSPs. TFP of crops in most of the G-Cubed regions would get adversely affected by climate risks under SSP 1-2.6. The effects on the Australian crops are notably higher where TFP growth could reach as low as almost -15 percent. However, Russia and the Rest of the OECD countries experience positive growth effects in TFP across the century. Under SSP 2-4.5 and 5-8.5, the lower bound of the effects reduces and more regions start experiencing positive growth effects towards the end of the century. Russia and the Rest of the OECD countries continue to experience positive effects while most of the countries continue to experience negative growth.

The growth in the production of processed crops is very similar to the changes in the TFP of crops. Production of processed crops in most of the regions is adversely affected by increasing climate risks. Russia and the Rest of the OECD countries experience positive growth effects throughout the century across the scenarios.

[29] The data on Purchasing Power Parity adjusted GDP for 2019 in constant 2017 USD was obtained from the World Development Indicators (2022) database.

Shocks on Agriculture: Livestock

Annexure 19 presents the variation of production in the livestock sector across the G-Cubed regions under SSPs. Growth in live animals is adversely affected by climate risks in almost all regions, although the United States and the Rest of the OECD countries experience some positive growth under SSP 1-2.6. Under SSP 2-4.5 Russia also starts experiencing positive growth effects different from SSP 1-2.6. Under SSP 5-8.5, most of the regions remain adversely affected by climate risks, while India demonstrates some recovery towards the end of the century.

Growth in the TFP of Primary Livestock is adversely affected by climate risks in all regions across all scenarios. The effects remain fairly constant under SSP 1-2.6 and take a downward trend under SSP 2-4.5. The downward trend increases under SSP 5-8.5 with the growth effects reaching between one to two percent by the end of the century. Growth in the production of processed livestock under climate risks is similar to yet stronger than those of TFP of primary livestock with the negative effects reaching two to four percent towards the end of the century.

Shocks on Energy Production from Non-renewable Resources

Annexure 20 presents the variation of energy production from non-renewable resources across the G-Cubed regions under SSPs. Climate indicators tend to be favorable for coal production in the early 2020s, even though they gradually become adverse reducing the production towards the end of the century. Climate indicators tend to favor coal production in Australia even though Russia is experiencing declines throughout the century. All the regions, including Australia, experience declines in coal production, compared to SSP 1-2.6, as the climate conditions continue to worsen across the climate scenarios. The reductions are more pronounced, higher, and more uniform across all the regions under SSP 5-8.5.

The effects of climate risks on gas production are much similar to those of coal production with the positive effects being higher and the negative effects being stronger. Russia and the Rest of the OECD countries (which mainly comprises Canada and New Zealand) experience the worst effects throughout the scenarios.

Unlike coal and gas production, oil and nuclear production are negatively affected by climate indicators, and the effects are apparent throughout all the scenarios, with the effects increasing with the increase in warming. India and Russia experience the lowest and the highest negative effects on oil production respectively. Electricity generation from nuclear energy in the Oil Producing Countries and the Rest of the World would be the most vulnerable to climate change if they were to generate energy from nuclear power.

Shocks on Electricity Generation from Renewable Resources

Annexure 21 presents the variation of electricity generation from renewable resources across the G-Cubed regions under SSPs. Hydroelectricity generation is vulnerable to climate change in most of the G-Cubed regions, while the United States and Japan could recover towards the mid-century. Hydroelectricity in Europe, the Rest of the OECD countries, and Russia could thrive under SSP 1-2.6. The variation of the effects remains similar to SSP 1-2.6 in SSP 2-4.5, and both the positive and negative effects become more pronounced. Different from SSP 1-2.6 and 2-4.5, under SSP 5-8.5, the Indian hydroelectricity sector recovers towards the end of the century.

Changing climate conditions become more favorable to electricity generation from solar, and accordingly, most of the regions could experience positive growth effects in the sector. Australia, the hydroelectricity sector of which suffered under SSP 1-2.6, could thrive in solar electricity generation. China, India, Oil producing developing countries, and the Rest of the World would experience the highest growth in solar electricity production. However, solar electricity generation in Europe, the Rest of the OECD countries, and Russia would suffer under SSP 1-2.6. Under SSP 2-4.5 and 5-8.5, both the positive and negative effects would increase. However, under SSP 5-8.5, towards the end of the century, extreme warming could become detrimental to solar electricity generation in most regions.

Different from hydro and solar resources, electricity generation from wind resources would be positively affected in almost all the regions where Australia could experience the largest gains compared to others. The gains would further increase for all the regions across both SSP 2-4.5 and SSP 5-8.5 with some convergence across regions towards SSP 5-8.5. Different from the sources of electricity generation discussed above, electricity generation from other sources remains constant throughout the climate scenarios. Notably, Australia has the highest potential for generating electricity from other sources.

Shocks on Other Sectors

Annexures 22 and 23 present the reliance of other G-Cubed sectors on agriculture and energy respectively following the Input-Output tables from the GTAP 10 database (GTAP 2022). The shocks on the other economic sectors are derived based on the reliance of those sectors on agriculture and energy sectors. According to Annexure 22, the transport and mining sectors rely the most on the energy sector across all regions. Manufacturing relies next on energy. As illustrated in Annexure 23, the non-durable manufacturing sector relies most on the agriculture sector across all regions. Construction relies the second most on agriculture for its inputs from the forestry sector.

4.6 Summary

Section 4 summarizes the approach to modeling the economic consequences of the impacts of physical climate risks on the agriculture and energy sectors. Section 4.2 provides an overview of the G-Cubed model used for the modeling and Section 4.3 introduces the G-Cubed baseline and the climate scenarios assessed in this paper. Section 4.4 provides an overview of the behavior of the climate indicators across the climate scenarios. Section 4.5 derives the economic shocks on agriculture, energy production, and electricity generation, and outlines the approach for deriving the economic shocks on the remaining G-Cubed sectors.

Section 4 illustrates how agriculture and energy sectors in different G-Cubed regions could get affected under different climate scenarios. The shocks could be interpreted in two different ways. Firstly, as the SSP scenarios have inherent assumptions about the structural characteristics of the economies (e.g., the sectoral composition of the economies), the shocks could be interpreted as deviations from the underlying production patterns of those sectors due to the feedback effects of climate outcomes of the SSPs. However, as discussed in Section 2.4, there could be many variants to the sectoral composition of the economies producing the same emission outcome.

The second interpretation is however independent of the assumption of the underlying structural characteristics of the economy. There, the shocks could be interpreted as the impacts on the sectors arising from temperature outcomes produced by an emission path equivalent to that of a given climate scenario. As the G-Cubed is a general equilibrium model, it does not have a climate module, and it follows the second interpretation when introducing the shocks.

One highlight from Section 4.5 is that the non-renewable energy sectors, which are also contributing to emissions and thereby to global warming, could also get adversely affected due to the feedback effects of global warming. This observation applies to the coal and gas production in most of the leading producers, including Russia. Oil production is adversely affected across all regions including Australia. Accordingly, continuing warming would further compromise global energy security and the transition to renewables would yield a double dividend: restoring global energy security as well as mitigating further worsening of the global climate.

Another similar highlight from Section 4.5 is that the livestock sector will also be significantly affected by continued global warming. As the demand for livestock is expected to double by 2050 (Garnett 2009), climate change poses an imminent threat to global food security. At the same time, similar to non-renewable energy sectors, livestock influences climate change via emissions from land use changes, feed and animal production, manure processing, and transportation. Therefore, improving livestock production efficiency and substitution where possible will deliver a double dividend similar to the substitution of non-renewables with renewables.

Section 5 discusses the results obtained using the estimates discussed in Section 4. Section 5 illustrates how the gross domestic product is affected across the G-Cubed regions, and also other economic variables such as consumption, investment, exports, imports, and trade balance.

5.0 ECONOMIC CONSEQUENCES OF THE IMPACTS OF PHYSICAL CLIMATE RISKS ON AGRICULTURE AND ENERGY

5.1 Overview

Section 5 discusses the global economic consequences arising from the impacts of physical climate risks on the agriculture and energy sectors. While the G-Cubed model produces results for a wide range of both real and nominal economic variables and sector results for several variables, Section 5 focuses on a few selected real macroeconomic variables which include Real GDP, consumption and investment, and exports, imports, and trade balance. Annexure 24 summarizes the behavior of the above macroeconomic variables across the three climate scenarios.

The effects observed across the economic variables are primarily driven by the supply-side effects arising from the implications of the physical climate risks on the productivity of agriculture, energy sectors, and other sectors depending on their reliance on agriculture and energy. These ultimate effects are also affected by the reactions of economic agents, particularly forward-looking households and firms, and monetary and fiscal authorities which all follow the respective rules discussed in Section 4.2. There are also general equilibrium effects, particularly from the price effects (where countries dominant in certain sectors could influence the global prices and subsequent changes in terms of trade and consumption patterns across the world), with changes in production patterns across the sectors in the world.

Accordingly, given the sophistication of the G-Cubed and close reflection of the realistic responses of the world to global economic shocks, the ultimate effects observed could be very different from what could be linearly predicted from the economic shocks.

5.2 Real GDP

As observed in Annexure 24, China, India, and the Rest of the World suffers throughout the century under SSP 1-2.6 with a reduction in Real GDP up to 2.5 percent from the baseline, which does not have any additional climate shocks other than those observed up to 2018. The Rest of the OECD countries experience almost a 2.5 percent deviation from the baseline towards the mid-century which is reduced towards the end of the century. Notably, Russia experiences large declines from the baseline, which could exceed five percent from the baseline. The effects on Russia illustrate how adverse consequences of climate impacts could be magnified by the existing structural characteristics of the country/region built-in to the model via its calibration using the historical economic data from the respective country/region.

The patterns observed under SSP 1-2.6 continue across SSP 2-4.5 and 5-8.5. However, the gains experienced by some of the countries reduce with the increase in global warming. The adverse consequences also increase particularly for those vulnerable both due to the economic shocks and structural characteristics, as illustrated by the case of Russia, where the declines in Real GDP could reach 20 percent by the end of the century under SSP 5-8.5.

Table 12 summarizes estimates of climate change scenarios from some of the existing studies, discussed in Section 2.5, which also includes a previous study the author contributed to (Fernando et al. 2021), and compares this paper to the existing studies. As observed, Kahn et al. (2019) assessing both chronic risks and some extreme risks illustrate that the GDP losses per capita could vary between 0.58 to 9.96 percent across RCPs by the end of the century. Kompass et al. (2018) expect the annual global losses to be between $US 5.55 and 23.15 trillion under three warming scenarios. Roson and van der Mensbrugghe (2010) illustrate that the average percentage in GDP could vary between 3.5 to -12 percent under an extreme warming scenario. Fernando et al. (2021), which evaluates the global economic consequences of both chronic and extreme physical risks of RCPs, illustrate global annual losses to be between $US 4 and 15 trillion[30].

According to Table 12, the estimates of the global economic losses in terms of Real GDP in this paper are lower than some of the existing studies. The main reason for the lower losses is the sole focus on the global economic consequences of climate implications on the productivity of the agriculture and energy sectors. In comparison to Fernando et al. (2021), this paper does not include climate shocks emanating from the loss of land due to sea-level rise, and the implications on labor productivity due to changes in heat stress and disease incidence. The approach to estimating the shocks also is different, as discussed in Section 2.5. Different from other general equilibrium studies, Roson and van der Mensbrugghe (2010) and Kompass et al. (2018), this paper includes the climate implications on energy production and uses estimates derived from a combined framework which incorporates both chronic and extreme climate risks and accounts for their potential multicollinearities.

The studies compared in Table 12 also have important differences from each other. The methodologies they have followed, the scenarios they have focused on, and the characteristics of the scenarios, are some sources of differences. Therefore, a comprehensive comparison across the studies is not possible. As Fernando et al. (2022) argue, following an illustration of the methodological difference between IAMs and general equilibrium models and their estimates of different climate scenarios, in NGFS (2022a), these methodological and philosophical differences of a wide range of different studies and the estimates they produce are precisely what is necessary for policymaking under the enormous sources of uncertainty climate change involves. The diversity across the studies in fact enriches the discussion of the economic consequences of climate change by bringing in different insights.

[30] Fernando et al. (2021) also evaluate two sources of transition risks, in addition to physical risks. The estimates compared and presented in this paper only relate to the physical risks.

5.3 Changes in Consumption and Investment

As observed in Annexure 24, the patterns of changes in consumption closely follow the changes in Real GDP, indicating the income effects on consumption. However, the changes, both positive and negative, especially in the early periods are stronger than those of Real GDP. This observation is mainly due to the behavior of the forward-looking agents, which comprise 30 percent of the agents. They observe the future trends in physical risks and smoothen their consumption patterns across the century. Consequently, they consume less than the income effects demand, in the early periods, the deviations of which could be stronger than those of Real GDP, and then experience consumption reductions less than those of Real GDP. Despite the smoothing, the consumption patterns remain closer to Real GDP with the rule-of-thumb agents leading the overall consumption in the economy.

Changes in investment are influenced similarly to consumption by the behavior of the heterogeneous agents. However, the changes in investment could be much larger than consumption and Real GDP. Particularly, the reductions in investment in G-Cubed could be larger from similar CGE/DSGE models and especially IAMs. This is mainly due to the explicit distinction of capital as physical and financial capital. In response to an economic shock or a series of economic shocks expected in the future for a given sector, the financial markets in G-Cubed could respond swiftly. As a result, the financial capital in the given sector could immediately get relocated to markets with sectors experiencing lower risks. Furthermore, the physical adjustment costs involved in readjusting investment discourage investors from reinvesting in the sectors and countries more vulnerable to physical climate risks. The stranded assets or the idling stock of capital without productive use in a given sector, as a result of the vulnerability of the sector to climate risks, also have feedback effects on the Real GDP[31]. The readjustment of investments is also affected by the structural features of the economies, for example, capital controls. Countries/regions with capital controls therefore could experience much larger reductions in investments when investors respond to physical climate risks.

As a result of the combinations of the economic shocks, characteristics of the agents, and structural features of the economies, Russia experiences a decline in investment exceeding 10 percent in the early 2020s, whereas the investment in the Rest of the OECD countries increases beyond 10 percent at the same time. China also experiences reductions in investment which is almost twice the reductions in Real GDP in the early 2020s. Most of the regions manage to return closer to the baseline over the century, despite the Rest of the World experiencing a permanent decline from the baseline. Under SSP 2-4.5, the adjustment patterns remain similar to SSP 1-2.6, with larger effects. However, different from SSP 1-2.6, Russia experiences permanent reductions with a negative trend from the baseline. SSP 5-8.5

[31] See NGFS (2022a) for a discussion of the implications of investment adjustment costs on determining the carbon prices as an instrument to incentivize transitions to low-carbon economies in G-Cubed vs IAMs.

is similar to SSP 2-4.5 with Russia experiencing almost a 40 percent reduction in investment from the baseline.

5.4 Changes in Exports and Imports

The changes in exports and imports could be affected not only by the implications of the climate risks on the productivity of the economic sectors. They could also be affected by the income and price effects via feedback. The cumulative effect of the exports and imports would reflect the changes in Trade Balance.

As observed in Annexure 24, under SSP 1-2.6, overall exports decline notably in Russia and most of the regions. With most countries/regions experiencing adverse consequences in the non-renewables, the Oil producing countries manage to increase their exports, whose exports are dominated by fossil fuels. The Rest of the OECD countries, which are relatively less affected by climate risks, experience positive effects in their exports. SSP 2-4.5 is much similar to SSP 1-2.6 with an increase in both positive and negative effects. However, different from SSP 1-2.6, under SSP 2-4.5, Russia continues to experience reductions in exports compared to the baseline, and, under SSP 1-2.6, Russia returns to the baseline towards the end of the century. SSP 5-8.5 reflects similar patterns to the previous two scenarios. Notably, while exports from Russia reduce, the Oil producing countries manage to increase their exports and potentially their export share in the global market.

Changes in imports are a particular reflection of the changes in consumption patterns due to both income and price effects. Different from previous macroeconomic variables, China experiences the strongest reduction in imports under SSP 1-2.6. However, as China returns to the baseline towards the mid-century, reflecting a consumption smoothing by Chinese consumers, Russia continues to experience a reduction in consumption throughout the century. Due to the positive income effects experienced in the Rest of the OECD countries, their imports are permanently higher. Most of the other countries, despite fluctuations in the early periods, return almost to the baseline towards the end of the century. Under SSP 2-4.5 and 5-8.5, adjustment patterns of imports are similar to SSP 1-2.6 with increases in both positive and negative effects. Different from SSP 1-2.6 and 5-8.5, under SSP 2-2.45, Japan, the United States, and Europe experience stronger consumption adjustments.

The trade balance reflects the net changes in exports and imports. Accordingly, while Russia experiences a trade deficit resulting from a larger reduction in exports compared to imports, the Rest of the OECD countries experience a trade deficit mainly due to the increase in imports under SSP 1-2.6. While Russia continues to experience a persistent deficit until the early 2090s, the Rest of the OECD countries manage to experience a surplus by the early 2030s. Notably, China experiences a trade surplus in the early 2020s, with its reduction in imports and increase in exports. The dynamic adjustment remains similar throughout SSP 2-4.5 and 5-8.5 for most of the regions with larger magnitudes. Russia experiences permanent divergence from the baseline in the last two scenarios different from SSP 1-2.6. The Oil producing countries experience a more volatile adjustment in SSP 2-4.5 compared to the other two scenarios.

5.5 Summary

Section 5 discusses the results from simulating the economic shocks discussed in Section 4 in the G-Cubed model for several macroeconomic variables: Real GDP, Consumption, Investment, Exports, Imports, and Trade Balance. In Section 5.2, in addition to discussing the results from the current paper, a comparison of results with the existing studies is also presented. Section 5.3 illustrates the changes in Consumption and Investment with particular references to the general equilibrium effects, structural characteristics of the countries/regions, and behavioral rules of economic agents in the G-Cubed model, in addition to the economic shocks. Section 5.4 discusses the changes in exports, imports, and trade balance as a result.

Section 5 illustrates several important policy implications. In a general equilibrium setting, the implications of economic shocks could get magnified. Thus, the economic shocks are not adequate to project the economic consequences and the economic consequences will not be linear and explicit. The rules of behavior of the economic agents and the structural characteristics of a given country are important qualifiers of economic shocks. Embedding the actual behavior of the countries/regions in the model via calibrations is crucial to portraying the realistic effects of climate change.

Still, the applications of models following different methodologies and different scenarios to assess the global economic consequences of climate risks are central to policymaking under enormous sources of uncertainty. All models are at most reflections of a part of the climate puzzle. Alternative philosophies and methodologies are essential to progress the knowledge about the economic consequences of climate risks.

Section 6 summarizes the paper and its policy implications. It also provides some directions future studies could explore to move the frontier of research into the global economic consequences of climate risks.

Table 12: Summary of Current Estimates of the Global Economic Consequences of Physical Climate Risks

Study	Risks	Scenario	Focus	Horizon	Unit	Estimates
Fernando (2022)	Chronic and extreme risks	SSP 1-2.6	World	2100	$US Trillion in GDP per annum	-0.78
		SSP 2-4.5				-1.19
		SSP 5-8.5				-1.54
Fernando et al. (2021)	Chronic and extreme risks	RCP 2.6	World	2100	$US Trillion in GDP per annum	-3.82
		RCP 4.5				-6.91
		RCP 6.0				-7.85
		RCP 8.5				-13.83
Kahn et al. (2019)	Chronic and (some) extreme risks	RCP 2.6	World	2100	% Loss in GDP per capita	0.58% to 1.57%
		RCP 8.5	World	2100	% Loss in GDP per capita	4.44% to 9.96%
Kompas et al. (2018)	Chronic risks	2 ^{0}C	World	2020 - 2100	$US Trillion in GDP per annum	-5.55
		3 ^{0}C				-9.59
		4 ^{0}C				-23.15
Roson & van der Mensbrugghe (2010)	Chronic risks	5.2 ^{0}C	World	2100	Average % Change in GDP	+3.5% to -12%
Hsiang et al. (2017)	Extreme risks	2 ^{0}C	USA	2080 - 2099	% Loss in GDP per annum	0.5%
		4 ^{0}C				2.0%
Narita et al. (2010)	Storms		World	2100	% Loss in GDP	0.006%

Source: Constructed by the Author.

6.0 CONCLUSION & POLICY IMPLICATIONS

Climate change is an existential threat to humanity. With their intrinsic linkages to the natural environment, agriculture and energy sectors are fundamental channels via which the impacts of climate risks spill over to the economy. This paper evaluates the global economic consequences arising from the impacts of climate physical risks on agriculture and energy production. The paper first introduces the climate risks and climate scenarios widely used in policymaking regarding climate change and reviews the existing methodologies for assessing the global economic consequences of climate change and their estimates. Secondly, the paper evaluates the sensitivity of historical agriculture and energy production patterns to climate risks. Agriculture includes both the crops and livestock sectors, while energy includes both non-renewable energy sectors and electricity generation from renewables. For this exercise, ten climate indicators representative of chronic and extreme physical climate risks are constructed, which are then used in machine learning algorithms to estimate the historical implications of climate risks on agriculture and energy production. The empirical estimates are used to project the changes in agriculture and energy production under three Shared Socioeconomic Pathways (SSPs). Following a detailed discussion on the variation of climate effects across 15 United Nations geographical regions and the potential global effects of climate risks on agriculture and energy production, the shocks are used to simulate the global economic model: G-Cubed. The results from G-Cubed simulations for Real GDP, consumption, investment, exports, imports, and trade balance for different parts of the world are discussed with reference to the existing studies.

This paper makes four main contributions to the ongoing policy discussion on the economic consequences of climate change. Firstly, it illustrates the importance of incorporating a wide range of both chronic and extreme climate indicators when estimating the historical implications of physical climate risks on agriculture and energy production. As illustrated in Section 3.4, considering only chronic risks would overlook the important implications extreme physical risks have on agriculture and energy production. We also emphasize that such estimations should be conducted using methodologies that could handle a large group of potentially correlated variables and produce estimates robust to multicollinearity and the number of variables. We illustrate how machine learning algorithms could be useful in those exercises overcoming the limitations in conventional estimations.

Secondly, by analyzing the behavior of agriculture and energy production under climate scenarios, this paper illustrates the potential for double dividends from climate mitigation. Non-renewables and livestock sectors are major contributors to greenhouse gas emissions. Those sectors are also going to experience significant adverse implications from climate risks as feedback effects from the emissions they generate. The vulnerability of those sectors to climate risks will also threaten global food and energy security. Thus, the transition to low-carbon economies with higher use of renewables, and improved efficiency and substitution in the livestock sector, could reduce emissions and the global vulnerability to climate risks, and enhance the resilience of global food and energy supply chains.

Thirdly, this paper illustrates how the magnitude of climate risks could be magnified within a globally interconnected economy depending on the responses of economic agents. Using a global general equilibrium model, G-Cubed, Section 5 discusses the changes in an array of economic variables, moving beyond Real GDP, which is the popular focus in the existing studies, under alternative climate scenarios. There, through changes in consumption and investment, we demonstrate how the characteristics of the agents, such as the forward-looking behavior, could deviate the economic effects from what could be linearly predicted from economic the same series of economic shocks. Through changes in investments, we also illustrate the importance of distinguishing physical capital from financial capital and the implications of investment adjustment costs when assessing climate risks. The insights we obtain from the simulations reemphasize the insights from Sections 2.4 and 2.5 where general equilibrium models are compared to IAMs.

Fourthly, this paper illustrates the importance of a wide array of studies focusing on different climate scenarios, employing different methodologies, and producing different estimates to enrich the climate policy discourse. As illustrated in Sections 2.4, 2.5, and 5.2, assessing the economic consequences of climate change involves an enormous degree of uncertainty. The global understanding of the complex system dynamics of climate change is not adequate to recognize a single framework to be superior to other frameworks when assessing the economic consequences of climate change. Accordingly, consensus across estimates from various frameworks is not necessary. A variety of philosophical viewpoints on how climate change would affect socioeconomic systems and a variety of estimates should precisely be the input to policymaking on climate change[32].

This paper is an extension of two previous studies the author has contributed to: Fernando et al. (2021) and Fernando & Lepore (Forthcoming). The most important extensions from those studies include the incorporation of machine learning and the use of consistent estimates of chronic and extreme physical risk indicators to analyze both the historical and projected climate risks. Further extensions to this paper to evaluate the global economic consequences of SSPs (moving beyond the agriculture and energy sectors) could derive and incorporate implications of both chronic and extreme climate risks on land, labor, and capital[33]. An alternative to assessing the spillover effects on manufacturing and service

[32] Fernando et al. (2022) is a useful supplementary reference to further explore this argument.

[33] Incorporation of implications on land and labor productivity could follow the approach in Fernando et al. (2021), and the incorporation of physical and financial capital could follow the approaches in Fernando & Lepore (Forthcoming) and Fernando et al. (2021) respectively.

sectors would be to directly assess the implications of climate risks on the productivity of those sectors as illustrated in Fernando & Lepore (Forthcoming).

A general question concerning studies incorporating historical estimates to project implications under future scenarios is to what extent the historical patterns reflect the future. Especially, in climate change-related studies, extensive focus on historical estimates could cloud the implications of both natural and socioeconomic tipping points. Nevertheless, we illustrate that the projections based on historical estimates are a useful starting point and sensitivity analyses could be used to account for both the uncertainty surrounding the studies (e.g., in model calibration, empirical estimations, construction of climate indicators) and socioeconomic tipping points. Machine learning, as illustrated in this paper, is another useful computational advancement that could be harnessed in economic analyses of climate change particularly to overcome the challenges pertaining to big data handling and large-scale (both temporal and spatial) analyses.

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ANNEXURE 1: RCPs

Scenario	Description
RCP 2.6	A peak radiative forcing of ~3 W/m^2 (~490 ppm CO2 eq) is achieved before 2100 and then declines. (The selected pathway decreases to 2.6 W/m^2 by 2100.)
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO2 eq) at stabilization after 2100.
RCP 6.0	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO2 eq) at stabilization after 2100.
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO2 eq) by 2100.

Source: van Vuuren et al (2011). Approximate radiative forcing levels were defined as ±5% of the stated level in W/m^2 relative to pre-industrial levels. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents.

ANNEXURE 2: SSPs

SSP	Narrative
SSP1	**Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)** The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves; educational and health investments accelerate the demographic transition and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	**Middle of the Road (Medium challenges to mitigation and adaptation)** The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements, and overall, the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	**Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)** A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	**Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)** Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor-intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high-income areas.
SSP5	**Fossil-fuelled Development – Taking the Highway** **(High challenges to mitigation, low challenges to adaptation)** This world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy-intensive lifestyles around the world. All these factors lead to the rapid growth of the global economy, while the global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Source: Riahi et al (2017).

ANNEXURE 3: NGFS Scenarios

Scenario	Policy Ambition (^0C)	Policy Reaction	Technology Change	CO2 Removal	Regional Policy Variation
Net Zero 2050	1.4	Immediate & Smooth	Fast	Medium to High Use	Medium
Below 2 ^0C	1.6	Immediate & Smooth	Moderate	Medium to High Use	Low
Divergent Net Zero	1.4	Immediate but Divergent	Fast	Low to Medium Use	Medium
Delayed Transition	1.6	Delayed	Slow/Fast	Low to Medium	High
Nationally Determined Contributions (NDCs)	2.6	NDCs	Slow	Low to Medium	Medium
Current Policies	3	Nothing additional to current policies	Slow	Low	Low

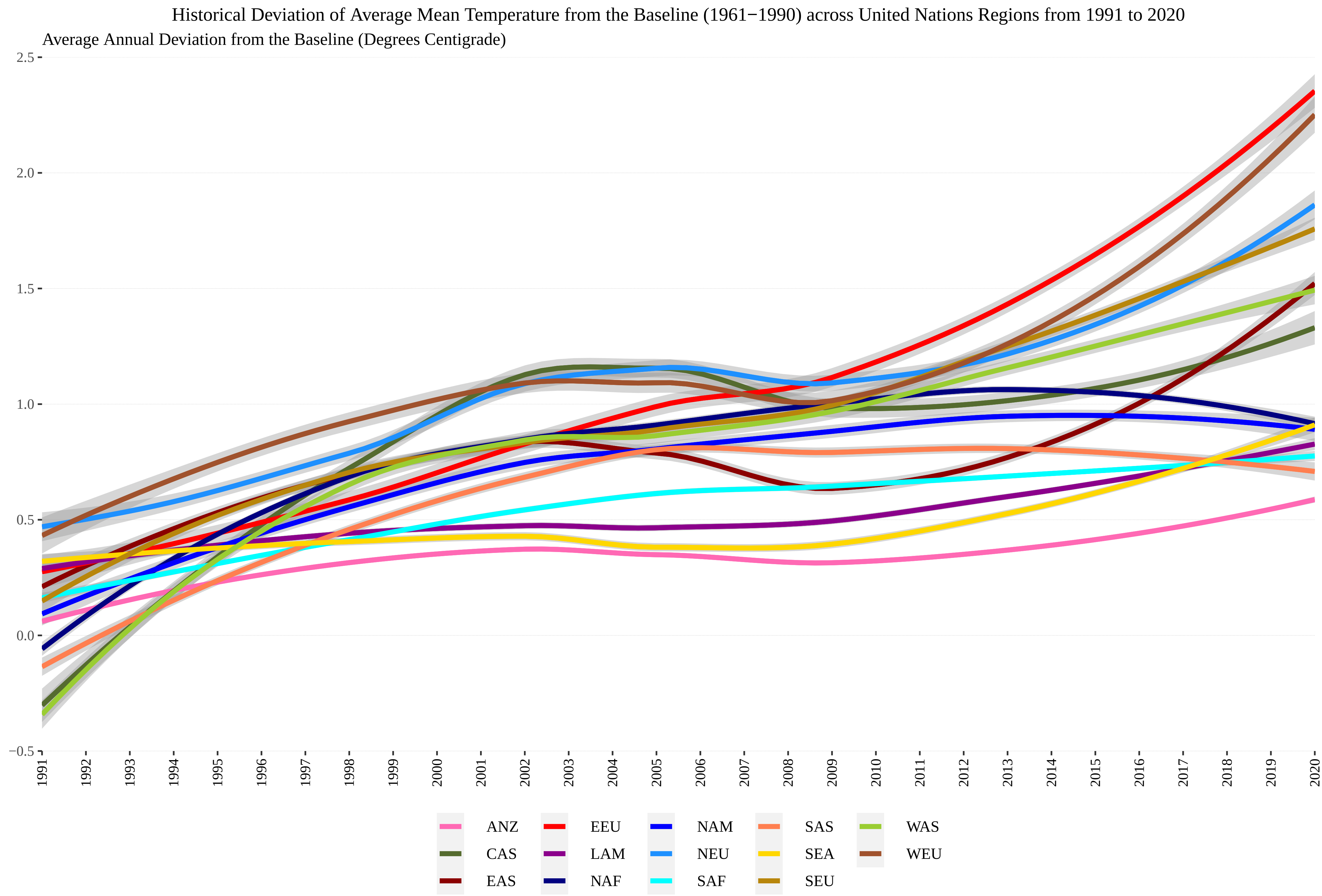
Source: NGFS (2022b).

ANNEXURE 4: CONCORDANCE BETWEEN COUNTRIES FROM DIFFERENT CLASSIFICATIONS

	GADM	GTAP	UN	G-Cubed		GADM	GTAP	UN	G-Cubed
1	ABW	XCB	LAM	ROW	62	DMA	XCB	LAM	ROW
2	AFG	XSA	SAS	ROW	63	DNK	DNK	NEU	EUW
3	AGO	XAC	SAF	OPC	64	DOM	DOM	LAM	ROW
4	AIA	XCB	LAM	ROW	65	DZA	XNF	NAF	OPC
5	ALA	FIN	NEU	EUW	66	ECU	ECU	LAM	OPC
6	ALB	ALB	SEU	ROW	67	EGY	EGY	NAF	ROW
7	AND	XER	SEU	ROW	68	ERI	XEC	SAF	ROW
8	ARE	ARE	WAS	OPC	69	ESH	XNF	NAF	OPC
9	ARG	ARG	LAM	ROW	70	ESP	ESP	SEU	EUW
10	ARM	ARM	WAS	ROW	71	EST	EST	NEU	EUW
11	ASM	XOC	ANZ	ROW	72	ETH	ETH	SAF	ROW
12	ATA	XTW	ANT	ROW	73	FIN	FIN	NEU	EUW
13	ATF	XTW	SAF	ROW	74	FJI	XOC	ANZ	ROW
14	ATG	XCB	LAM	ROW	75	FLK	XSM	LAM	ROW
15	AUS	AUS	ANZ	AUS	76	FRA	FRA	WEU	EUW
16	AUT	AUT	WEU	EUW	77	FRO	XER	NEU	ROW
17	AZE	AZE	WAS	ROW	78	FSM	XOC	ANZ	ROW
18	BDI	XEC	SAF	ROW	79	GAB	XCF	SAF	ROW
19	BEL	BEL	WEU	EUW	80	GBR	GBR	NEU	EUW
20	BEN	BEN	SAF	ROW	81	GEO	GEO	WAS	ROW
21	BES	XCB	LAM	ROW	82	GGY	XER	NEU	ROW
22	BFA	BFA	SAF	ROW	83	GHA	GHA	SAF	ROW
23	BGD	BGD	SAS	ROW	84	GIB	XER	SEU	ROW
24	BGR	BGR	EEU	EUW	85	GIN	GIN	SAF	ROW
25	BHR	BHR	WAS	OPC	86	GLP	FRA	LAM	EUW
26	BHS	XCB	LAM	ROW	87	GMB	XWF	SAF	ROW
27	BIH	XER	SEU	ROW	88	GNB	XWF	SAF	ROW
28	BLM	XCB	LAM	ROW	89	GNQ	XCF	SAF	ROW
29	BLR	BLR	EEU	ROW	90	GRC	GRC	SEU	EUW
30	BLZ	XCA	LAM	ROW	91	GRD	XCB	LAM	ROW
31	BMU	XNA	NAM	ROW	92	GRL	XNA	NAM	ROW
32	BOL	BOL	LAM	ROW	93	GTM	GTM	LAM	ROW
33	BRA	BRA	LAM	ROW	94	GUF	XSM	LAM	ROW
34	BRB	XCB	LAM	ROW	95	GUM	XOC	ANZ	ROW
35	BRN	BRN	SEA	ROW	96	GUY	XSM	LAM	ROW
36	BTN	XSA	SAS	ROW	97	HKG	HKG	EAS	ROW
37	BVT	XTW	LAM	ROW	98	HMD	AUS	ANZ	AUS
38	BWA	BWA	SAF	ROW	99	HND	HND	LAM	ROW
39	CAF	XCF	SAF	ROW	100	HRV	HRV	SEU	EUW
40	CAN	CAN	NAM	OEC	101	HTI	XCB	LAM	ROW
41	CCK	AUS	ANZ	AUS	102	HUN	HUN	EEU	EUW
42	CHE	CHE	WEU	EUW	103	IDN	INO	SEA	NA
43	CHL	CHL	LAM	ROW	104	IMN	XER	NEU	ROW
44	CHN	CHI	EAS	NA	105	IND	IND	SAS	IND
45	CIV	CIV	SAF	ROW	106	IOT	XTW	SAF	ROW
46	CMR	CMR	SAF	ROW	107	IRL	IRL	NEU	EUW
47	COD	XAC	SAF	OPC	108	IRN	IRN	SAS	OPC
48	COG	XCF	SAF	ROW	109	IRQ	XWS	WAS	OPC
49	COK	XOC	ANZ	ROW	110	ISL	XEF	NEU	OEC
50	COL	COL	LAM	ROW	111	ISR	ISR	WAS	OPC
51	COM	XEC	SAF	ROW	112	ITA	ITA	SEU	EUW
52	CPV	XWF	SAF	ROW	113	JAM	JAM	LAM	ROW
53	CRI	CRI	LAM	ROW	114	JEY	XER	NEU	ROW
54	CUB	XCB	LAM	ROW	115	JOR	JOR	WAS	OPC
55	CUW	XCB	LAM	ROW	116	JPN	JPN	EAS	JPN
56	CXR	AUS	ANZ	AUS	117	KAZ	KAZ	CAS	ROW
57	CYM	XCB	LAM	ROW	118	KEN	KEN	SAF	ROW
58	CYP	CYP	WAS	EUW	119	KGZ	KGZ	CAS	ROW
59	CZE	CZE	EEU	EUW	120	KHM	KHM	SEA	ROW
60	DEU	DEU	WEU	EUW	121	KIR	XOC	ANZ	ROW
61	DJI	XEC	SAF	ROW	122	KNA	XCB	LAM	ROW

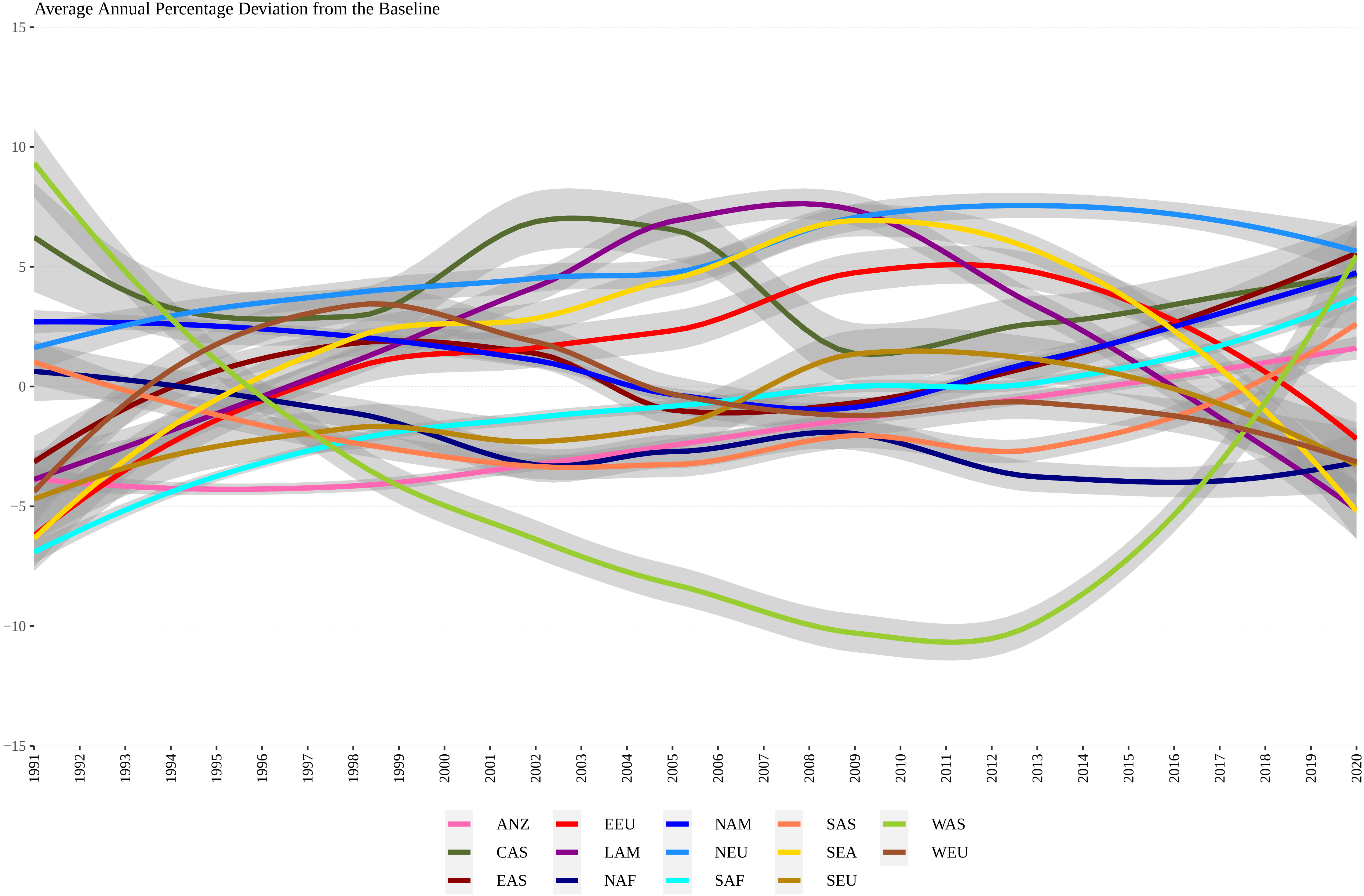
	GADM	GTAP	UN	G-Cubed		GADM	GTAP	UN	G-Cubed
123	KOR	KOR	EAS	ROW	190	RUS	RUS	EEU	RUS
124	KWT	KWT	WAS	OPC	191	RWA	RWA	SAF	ROW
125	LAO	LAO	SEA	ROW	192	SAU	SAU	WAS	OPC
126	LBN	XWS	WAS	OPC	193	SDN	XEC	NAF	ROW
127	LBR	XWF	SAF	ROW	194	SEN	SEN	SAF	ROW
128	LBY	XNF	NAF	OPC	195	SGP	SGP	SEA	ROW
129	LCA	XCB	LAM	ROW	196	SGS	XSM	LAM	ROW
130	LIE	XEF	WEU	OEC	197	SHN	XWF	SAF	ROW
131	LKA	LKA	SAS	ROW	198	SJM	NOR	NEU	EUW
132	LSO	XSC	SAF	ROW	199	SLB	XOC	ANZ	ROW
133	LTU	LTU	NEU	EUW	200	SLE	XWF	SAF	ROW
134	LUX	LUX	WEU	EUW	201	SLV	SLV	LAM	EUW
135	LVA	LVA	NEU	EUW	202	SMR	XER	SEU	ROW
136	MAC	XEA	EAS	ROW	203	SOM	XEC	SAF	ROW
137	MAF	XCB	LAM	ROW	204	SPM	XNA	NAM	ROW
138	MAR	MAR	NAF	ROW	205	SRB	XER	SEU	ROW
139	MCO	XER	WEU	ROW	206	SSD	NA	SAF	NA
140	MDA	XEE	EEU	ROW	207	STP	XCF	SAF	ROW
141	MDG	MDG	SAF	ROW	208	SUR	XSM	LAM	ROW
142	MDV	XSA	SAS	ROW	209	SVK	SVK	EEU	EUW
143	MEX	MEX	LAM	ROW	210	SVN	SVN	SEU	EUW
144	MHL	XOC	ANZ	ROW	211	SWE	SWE	NEU	EUW
145	MKD	XER	SEU	ROW	212	SWZ	XSC	SAF	ROW
146	MLI	XWF	SAF	ROW	213	SXM	XCB	LAM	ROW
147	MLT	MLT	SEU	EUW	214	SYC	XEC	SAF	ROW
148	MMR	XSE	SEA	ROW	215	SYR	XWS	WAS	OPC
149	MNE	XER	SEU	ROW	216	TCA	XCB	LAM	ROW
150	MNG	MNG	EAS	ROW	217	TCD	XCF	SAF	ROW
151	MNP	XOC	ANZ	ROW	218	TGO	TGO	SAF	ROW
152	MOZ	MOZ	SAF	ROW	219	THA	THA	SEA	ROW
153	MRT	XWF	SAF	ROW	220	TJK	TJK	CAS	ROW
154	MSR	XCB	LAM	ROW	221	TKL	XOC	ANZ	ROW
155	MTQ	FRA	LAM	EUW	222	TKM	XSU	CAS	ROW
156	MUS	MUS	SAF	ROW	223	TLS	XSE	SEA	ROW
157	MWI	MWI	SAF	ROW	224	TON	XOC	ANZ	ROW
158	MYS	MYS	SEA	ROW	225	TTO	TTO	LAM	ROW
159	MYT	XEC	SAF	ROW	226	TUN	TUN	NAF	ROW
160	NAM	NAM	SAF	ROW	227	TUR	TUR	WAS	ROW
161	NCL	XOC	ANZ	ROW	228	TUV	XOC	ANZ	ROW
162	NER	XWF	SAF	ROW	229	TWN	TWN	EAS	ROW
163	NFK	AUS	ANZ	AUS	230	TZA	TZA	SAF	ROW
164	NGA	NGA	SAF	OPC	231	UGA	UGA	SAF	ROW
165	NIC	NIC	LAM	ROW	232	UKR	UKR	EEU	ROW
166	NIU	XOC	ANZ	ROW	233	UMI	XOC	ANZ	ROW
167	NLD	NLD	WEU	EUW	234	URY	URY	LAM	ROW
168	NOR	NOR	NEU	EUW	235	USA	USA	NAM	USA
169	NPL	NPL	SAS	ROW	236	UZB	XSU	CAS	ROW
170	NRU	XOC	ANZ	ROW	237	VAT	XER	SEU	ROW
171	NZL	NZL	ANZ	OEC	238	VCT	XCB	LAM	ROW
172	OMN	OMN	WAS	OPC	239	VEN	VEN	LAM	OPC
173	PAK	PAK	SAS	ROW	240	VGB	XCB	LAM	ROW
174	PAN	PAN	LAM	ROW	241	VIR	XCB	LAM	ROW
175	PCN	XOC	ANZ	ROW	242	VNM	VNM	SEA	ROW
176	PER	PER	LAM	ROW	243	VUT	XOC	ANZ	ROW
177	PHL	PHL	SEA	ROW	244	WLF	XOC	ANZ	ROW
178	PLW	XOC	ANZ	ROW	245	WSM	XOC	ANZ	ROW
179	PNG	XOC	ANZ	ROW	246	XAD	NA	NA	NA
180	POL	POL	EEU	EUW	247	XCA	NA	NA	NA
181	PRI	PRI	LAM	ROW	248	XCL	NA	NA	NA
182	PRK	XEA	EAS	ROW	249	XKO	NA	NA	NA
183	PRT	PRT	SEU	EUW	250	XNC	NA	NA	NA
184	PRY	PRY	LAM	ROW	251	XPI	NA	NA	NA
185	PSE	XWS	WAS	OPC	252	XSP	NA	NA	NA
186	PYF	XOC	ANZ	ROW	253	YEM	XWS	WAS	OPC
187	QAT	QAT	WAS	OPC	254	ZAF	ZAF	SAF	ROW
188	REU	FRA	SAF	EUW	255	ZMB	ZMB	SAF	ROW
189	ROU	ROU	EEU	EUW	256	ZWE	ZWE	SAF	ROW

ANNEXURE 5: BEHAVIOR OF THE HISTORICAL CLIMATE INDICATORS

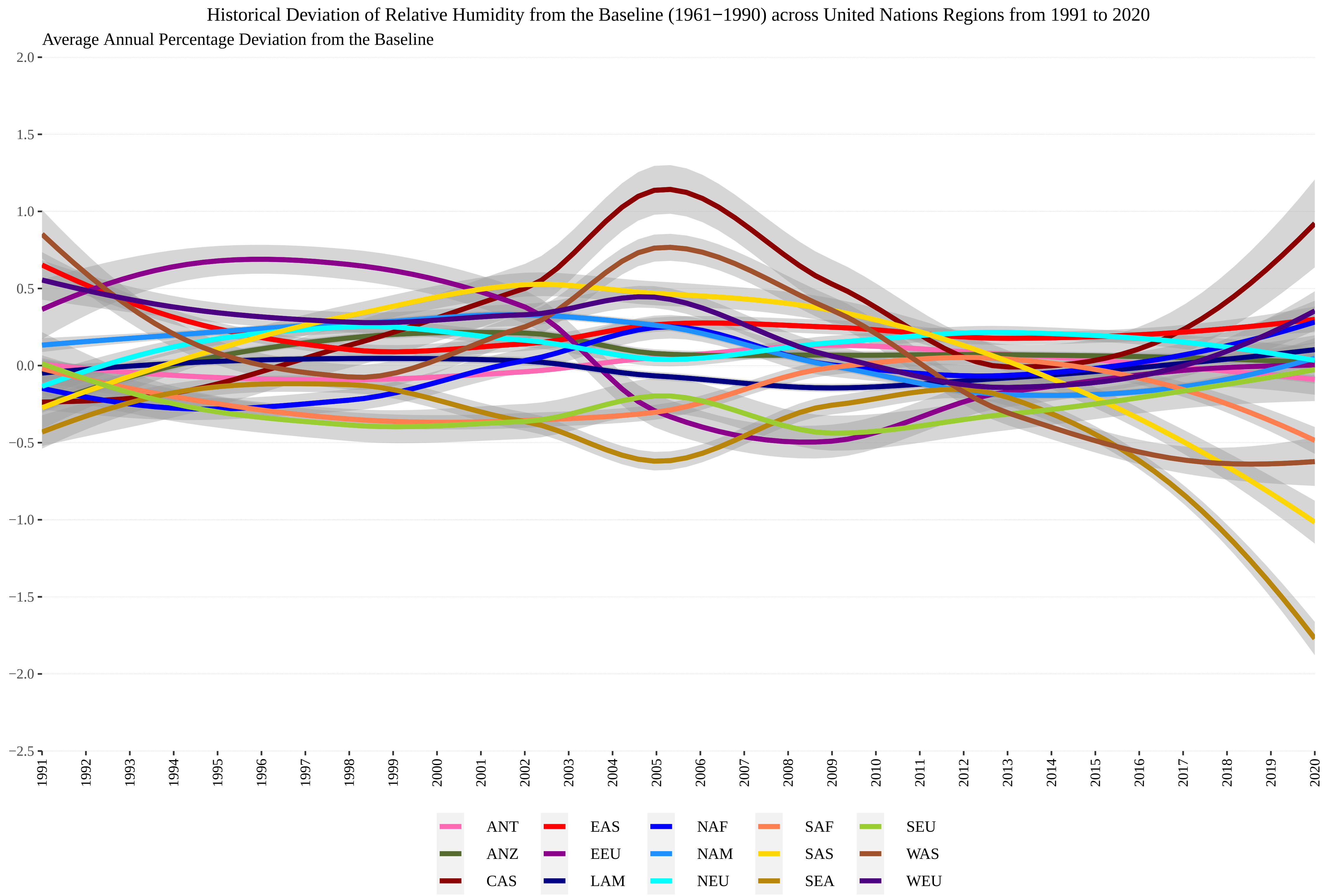


Source: Constructed by the Author using Data from CRU (2022).

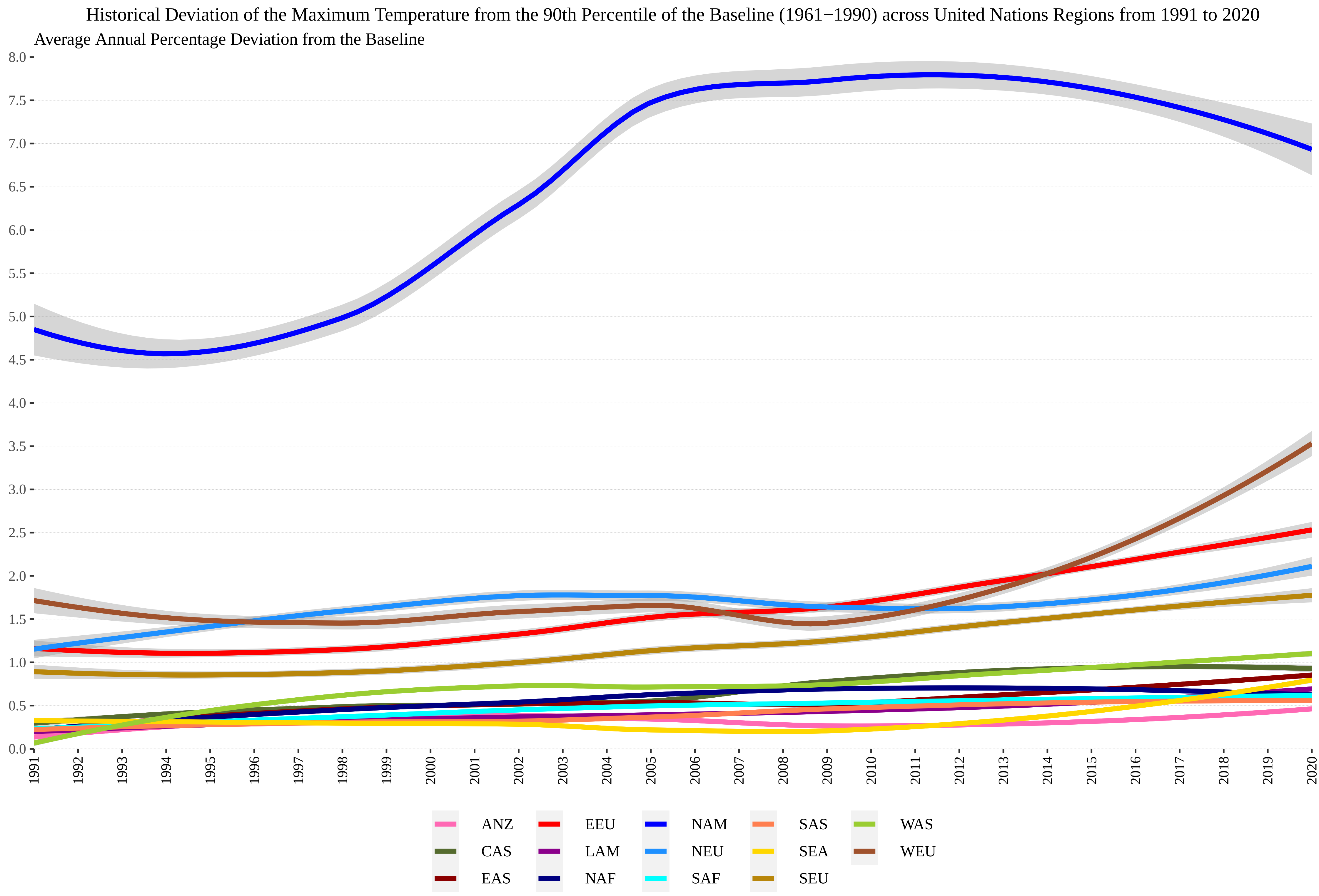
Historical Deviation of Average Precipitation from the Baseline (1961−1990) across United Nations Regions from 1991 to 2020



Source: Constructed by the Author using Data from CRU (2022).

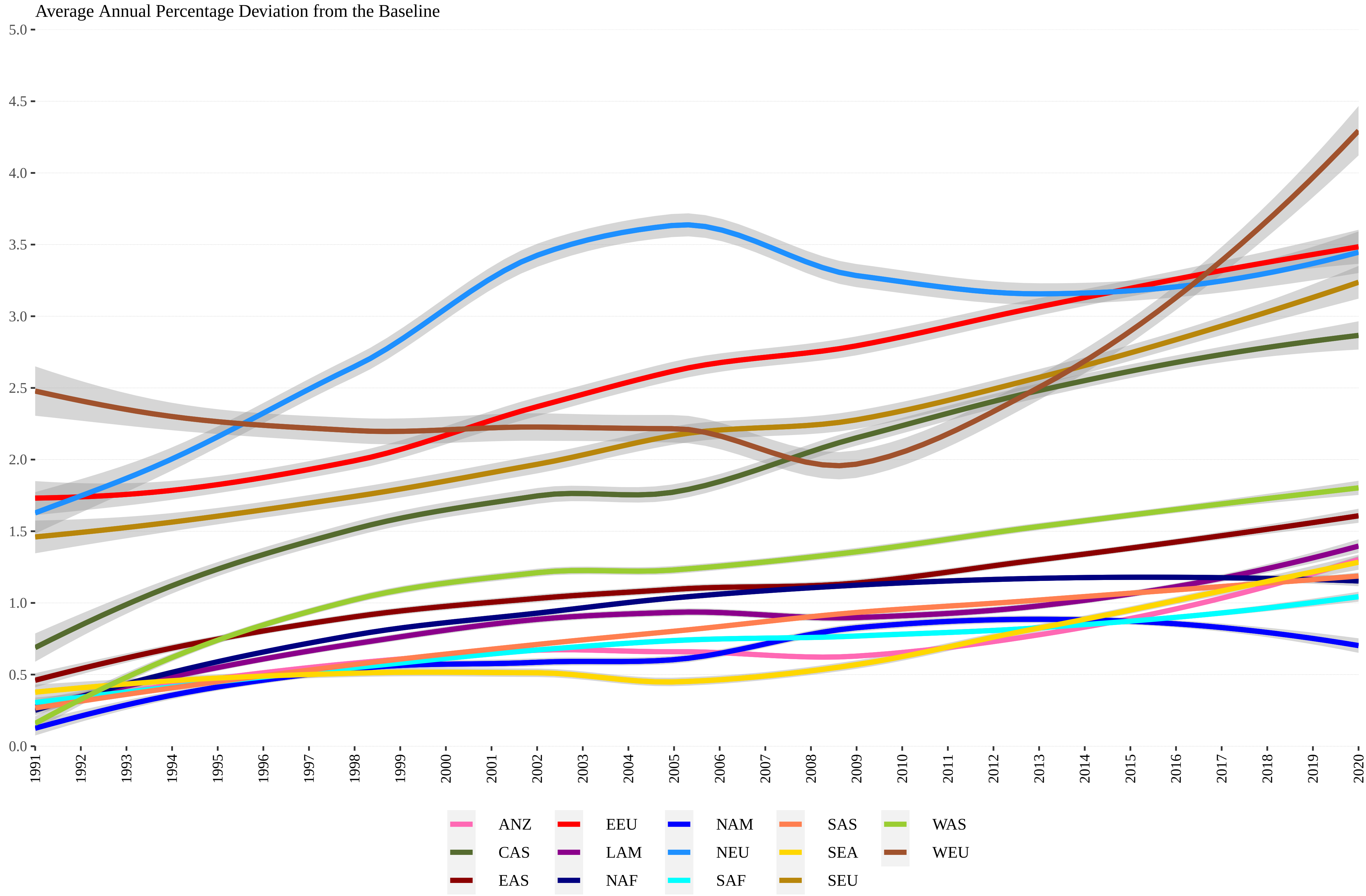


Source: Constructed by the Author using Data from CRU (2022).

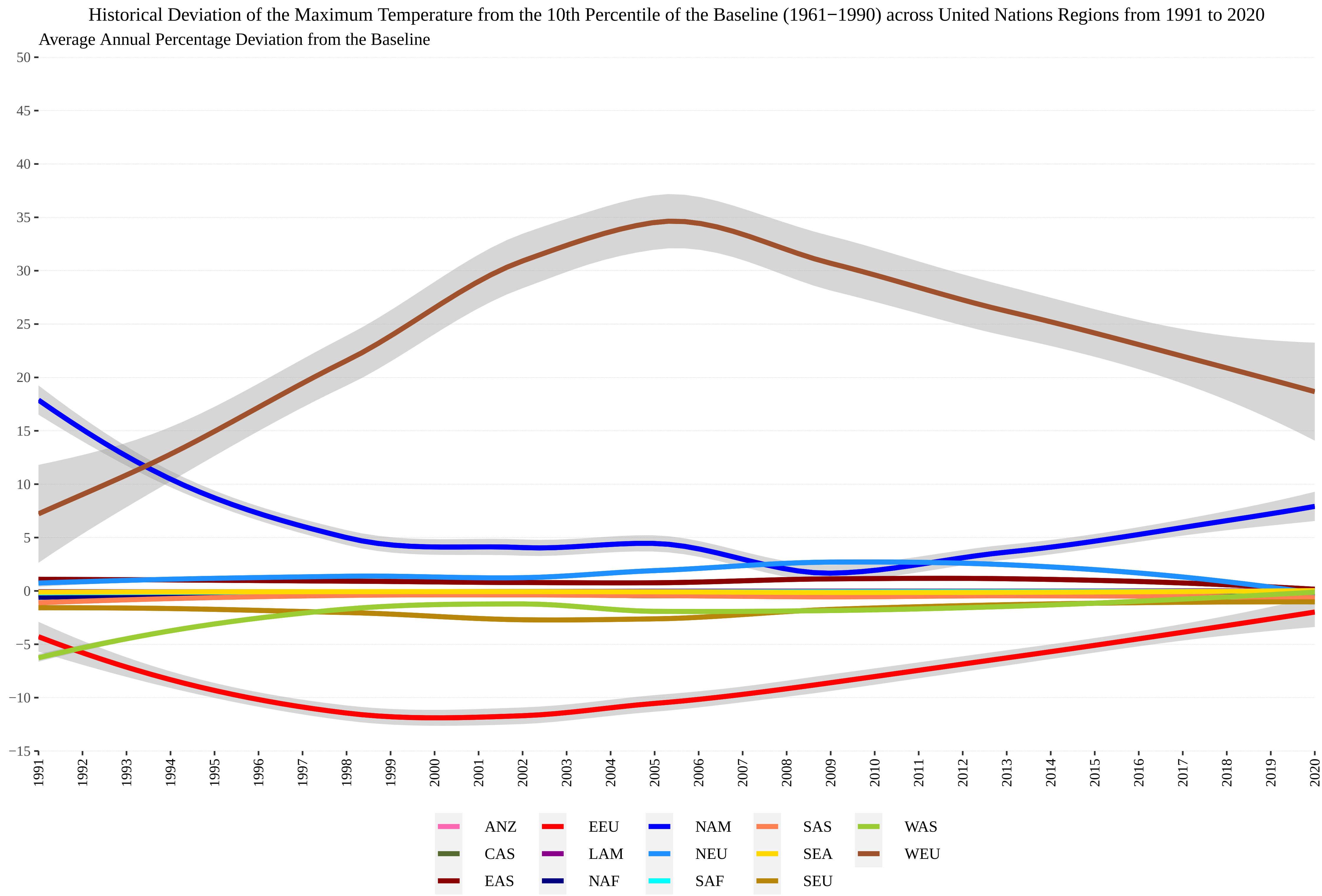


Source: Constructed by the Author using Data from CRU (2022).

Historical Deviation of the Minimum Temperature from the 90th Percentile of the Baseline (1961−1990) across United Nations Regions from 1991 to 2020

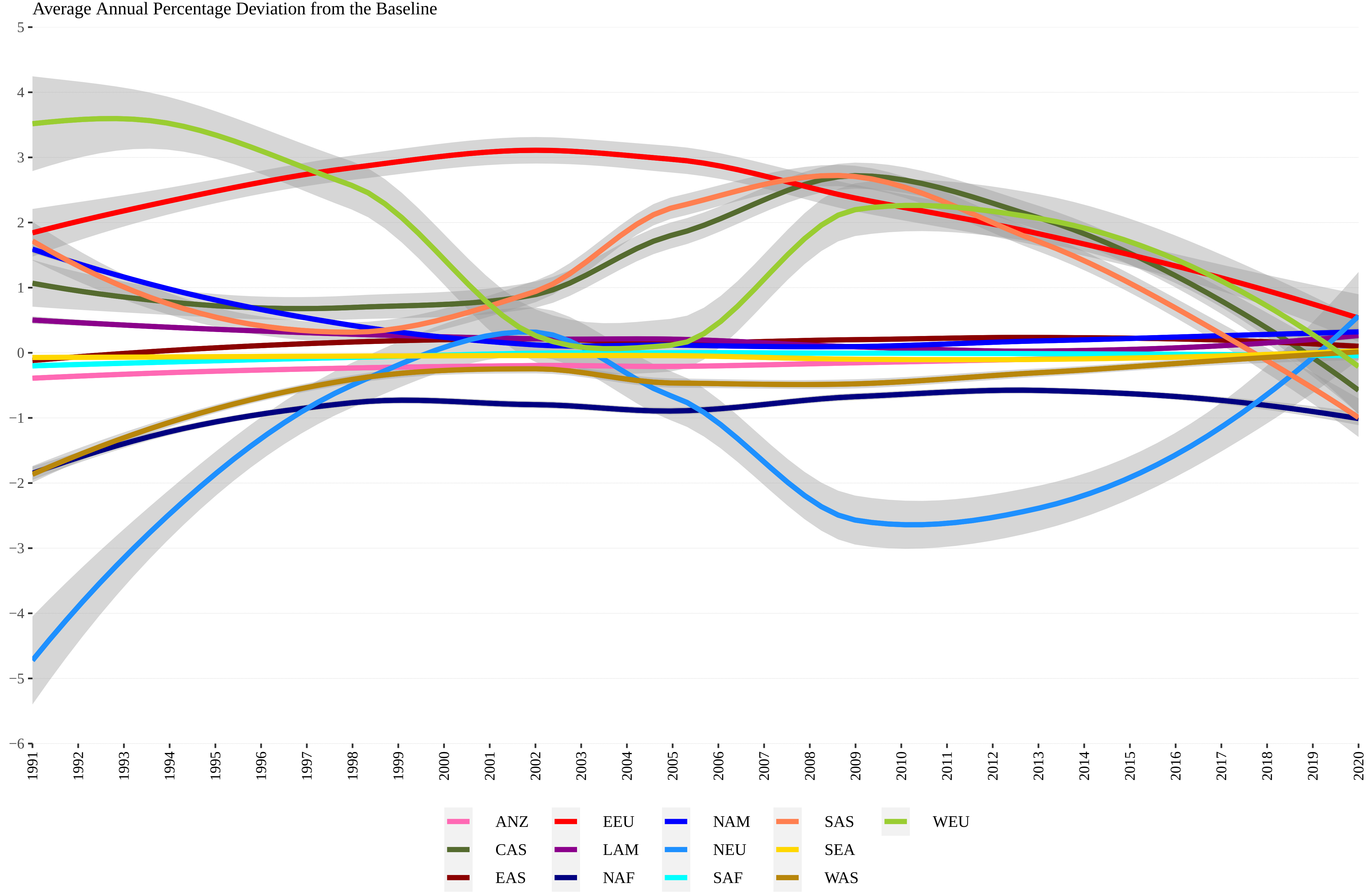


Source: Constructed by the Author using Data from CRU (2022).

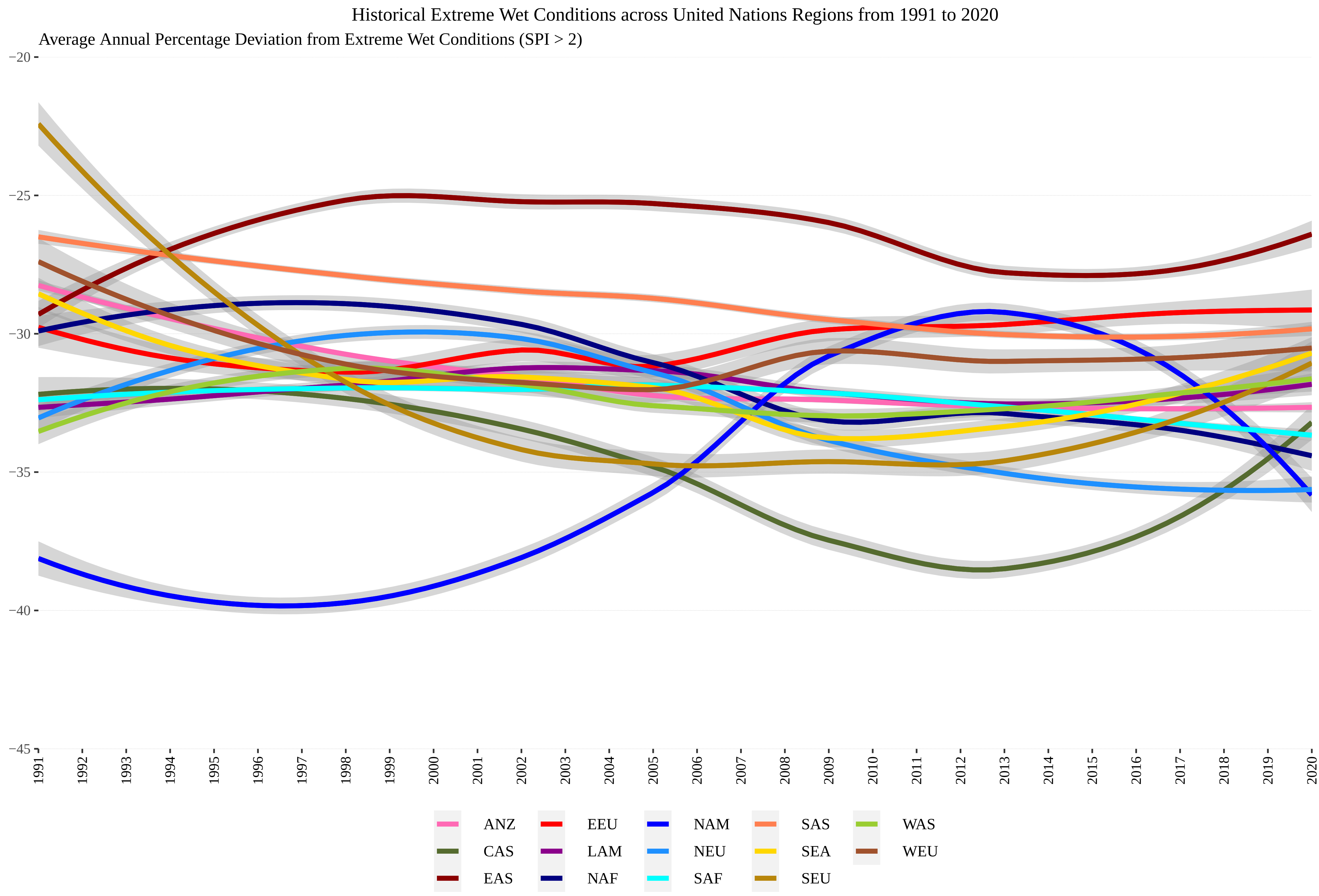


Source: Constructed by the Author using Data from CRU (2022).

Historical Deviation of the Minimum Temperature from the 10th Percentile of the Baseline (1961−1990) across United Nations Regions from 1991 to 2020

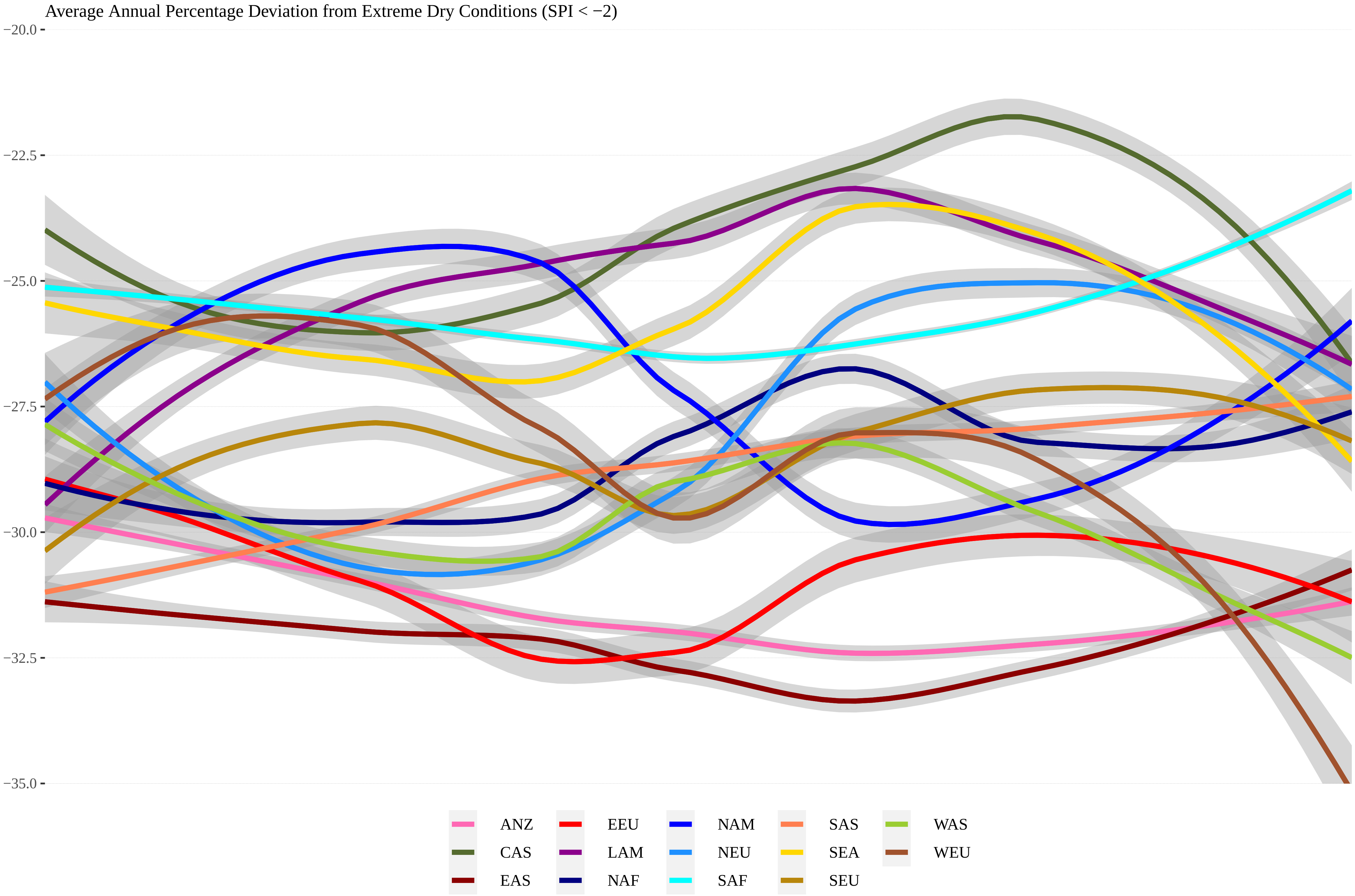


Source: Constructed by the Author using Data from CRU (2022).



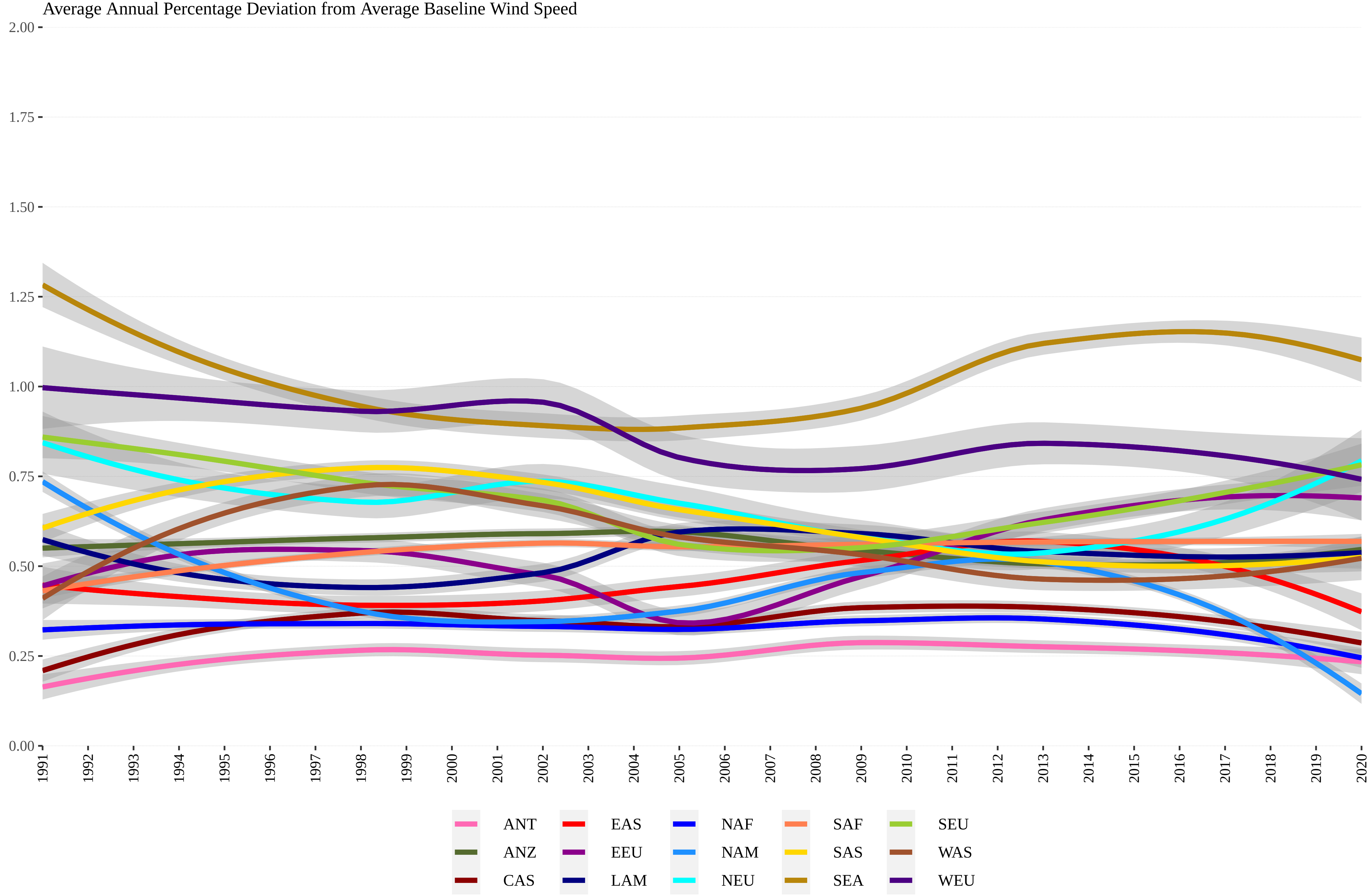
Source: Constructed by the Author using Data from CRU (2022).

Historical Extreme Dry Conditions across United Nations Regions from 1991 to 2020



Source: Constructed by the Author using Data from CRU (2022).

Historical Extreme Wind Speeds compared to Baseline (1961−1990) across United Nations Regions from 1991 to 2020



Source: Constructed by the Author using Data from ISIMIP (2022).

ANNEXURE 6: CONCORDANCE BETWEEN FAO AND GTAP SECTORS

	FAO	GTAP		FAO	GTAP
FAO Group: Crops					
1	Agave fibres nes	7	61	Fruit, stone nes	4
2	Almonds, with shell	4	62	Fruit, tropical fresh nes	4
3	Anise, badian, fennel, coriander	8	63	Garlic	4
4	Apples	4	64	Ginger	8
5	Apricots	4	65	Gooseberries	4
6	Areca nuts	4	66	Grain, mixed	3
7	Artichokes	4	67	Grapefruit (inc. pomelos)	4
8	Asparagus	4	68	Grapes	4
9	Avocados	4	69	Groundnuts, with shell	5
10	Bambara beans	4	70	Gums, natural	13
11	Bananas	4	71	Hazelnuts, with shell	4
12	Barley	3	72	Hemp tow waste	7
13	Bastfibres, other	7	73	Hempseed	5
14	Beans, dry	4	74	Hops	8
15	Beans, green	4	75	Jojoba seed	5
16	Berries nes	4	76	Jute	7
17	Blueberries	4	77	Kapok fruit	5
18	Brazil nuts, with shell	4	78	Karite nuts (sheanuts)	5
19	Broad beans, horse beans, dry	4	79	Kiwi fruit	4
20	Buckwheat	3	80	Kola nuts	4
21	Cabbages and other brassicas	4	81	Leeks, other alliaceous vegetables	4
22	Canary seed	3	82	Lemons and limes	4
23	Carobs	4	83	Lentils	4
24	Carrots and turnips	4	84	Lettuce and chicory	4
25	Cashew nuts, with shell	4	85	Linseed	5
26	Cashew apple	4	86	Lupins	4
27	Cassava	4	87	Maize	3
28	Cassava leaves	4	88	Maize, green	4
29	Castor oil seed	5	89	Mangoes, mangosteens, guavas	4
30	Cauliflowers and broccoli	4	90	Manila fibre (abaca)	7
31	Cereals nes	3	91	Maté	8
32	Cereals, Total	3	92	Melons, other (Inc. Cantaloupes)	4
33	Cherries	4	93	Melonseed	5
34	Cherries, sour	4	94	Millet	3
35	Chestnut	4	95	Mushrooms and truffles	4
36	Chickpeas	4	96	Mustard seed	5
37	Chicory roots	8	97	Nutmeg, mace and cardamoms	8
38	Chillies and peppers, dry	8	98	Nuts nes	4
39	Chillies and peppers, green	4	99	Oats	3
40	Cinnamon (cannella)	8	100	Oil palm fruit	5
41	Citrus Fruit, Total	4	101	Oilcrops, Cake Equivalent	5
42	Cloves	8	102	Oilcrops, Oil Equivalent	5
43	Cocoa, beans	8	103	Oilseeds nes	5
44	Coconuts	5	104	Okra	4
45	Coffee, green	8	105	Olives	5
46	Coir	7	106	Onions, dry	4
47	Cow peas, dry	4	107	Onions, shallots, green	4
48	Cranberries	4	108	Oranges	4
49	Cucumbers and gherkins	4	109	Papayas	4
50	Currants	4	110	Peaches and nectarines	4
51	Dates	4	111	Pears	4
52	Eggplants (aubergines)	4	112	Peas, dry	4
53	Fibre crops nes	7	113	Peas, green	4
54	Figs	4	114	Pepper (piper spp.)	8
55	Flax fibre and tow	7	115	Peppermint	8
56	Fonio	3	116	Persimmons	4
57	Fruit Primary	4	117	Pigeon peas	4
58	Fruit, citrus nes	4	118	Pineapples	4
59	Fruit, fresh nes	4	119	Pistachios	4
60	Fruit, pome nes	4	120	Plantains and others	4

	FAO	GTAP		FAO	GTAP
FAO Group: Crops					
121	Plums and sloes	4	148	String beans	4
122	Poppy seed	5	149	Sugar beet	6
123	Potatoes	4	150	Sugar cane	6
124	Pulses nes	4	151	Sugar crops nes	6
125	Pulses, Total	4	152	Sugar Crops Primary	6
126	Pumpkins, squash and gourds	4	153	Sunflower seed	5
127	Pyrethrum, dried	8	154	Sweet potatoes	4
128	Quinces	4	155	Tallowtree seed	5
129	Quinoa	3	156	Tangerines, mandarins, clementines, satsumas	4
130	Ramie	7	157	Taro (cocoyam)	4
131	Rapeseed	5	158	Tea	8
132	Raspberries	4	159	Tobacco, unmanufactured	8
133	Rice, paddy	1	160	Tomatoes	4
134	Rice, paddy (rice milled equivalent)	1	161	Treenuts, Total	4
135	Roots and tubers nes	4	162	Triticale	3
136	Roots and Tubers, Total	4	163	Tung nuts	5
137	Rubber, natural	8	164	Vanilla	8
138	Rye	3	165	Vegetables Primary	4
139	Safflower seed	5	166	Vegetables, fresh nes	4
140	Seed cotton	7	167	Vegetables, leguminous nes	4
141	Sesame seed	5	168	Vetches	4
142	Sisal	7	169	Walnuts, with shell	4
143	Sorghum	3	170	Watermelons	4
144	Soybeans	5	171	Wheat	2
145	Spices nes	8	172	Yams	4
146	Spinach	4	173	Yautia (cocoyam)	4
147	Strawberries	4			

	FAO	GTAP		FAO	GTAP
FAO Group: Processed Crops					
174	Beer of barley	26	186	Oil, olive, virgin	21
175	Cotton lint	21	187	Oil, palm	21
176	Cottonseed	21	188	Oil, palm kernel	21
177	Kapok fibre	27	189	Oil, rapeseed	21
178	Kapokseed in shell	27	190	Oil, safflower	21
179	Margarine, short	21	191	Oil, sesame	21
180	Molasses	24	192	Oil, soybean	21
181	Oil, coconut (copra)	21	193	Oil, sunflower	21
182	Oil, cottonseed	21	194	Palm kernels	21
183	Oil, groundnut	21	195	Sugar Raw Centrifugal	24
184	Oil, linseed	21	196	Wine	26
185	Oil, maize	21			

	FAO	GTAP		FAO	GTAP
FAO Group: Live Animals					
197	Asses	9	207	Goats	9
198	Beehives	10	208	Horses	9
199	Buffaloes	9	209	Mules	9
200	Camelids, other	9	210	Pigs	10
201	Camels	9	211	Poultry Birds	10
202	Cattle	9	212	Rabbits and hares	10
203	Cattle and Buffaloes	9	213	Rodents, other	10
204	Chickens	10	214	Sheep	9
205	Ducks	10	215	Sheep and Goats	9
206	Geese and guinea fowls	10	216	Turkeys	10

	FAO	GTAP		FAO	GTAP
FAO Group: Primary Livestock					
217	Beef and Buffalo Meat	19	244	Meat, other camelids	19
218	Beeswax	10	245	Meat, other rodents	20
219	Eggs Primary	10	246	Meat, pig	20
220	Eggs, hen, in shell	10	247	Meat, Poultry	20
221	Eggs, other bird, in shell	10	248	Meat, rabbit	20
222	Fat, buffaloes	10	249	Meat, sheep	19
223	Fat, camels	10	250	Meat, Total	20
224	Fat, cattle	10	251	Meat, turkey	20
225	Fat, goats	10	252	Milk, whole fresh buffalo	11
226	Fat, pigs	10	253	Milk, whole fresh camel	11
227	Fat, sheep	10	254	Milk, whole fresh cow	11
228	Hides, buffalo, fresh	10	255	Milk, whole fresh goat	11
229	Hides, cattle, fresh	10	256	Milk, whole fresh sheep	11
230	Honey, natural	10	257	Offals, edible, buffaloes	19
231	Meat nes	20	258	Offals, edible, camels	19
232	Meat, ass	19	259	Offals, edible, cattle	19
233	Meat, bird nes	20	260	Offals, edible, goats	19
234	Meat, buffalo	19	261	Offals, horses	19
235	Meat, camel	19	262	Offals, pigs, edible	19
236	Meat, cattle	19	263	Offals, sheep, edible	19
237	Meat, chicken	20	264	Sheep and Goat Meat	19
238	Meat, duck	20	265	Silk-worm cocoons, reelable	12
239	Meat, game	20	266	Skins, goat, fresh	10
240	Meat, goat	19	267	Skins, sheep, fresh	10
241	Meat, goose and guinea fowl	20	268	Snails, not sea	10
242	Meat, horse	19	269	Wool, greasy	12
243	Meat, mule	19			

	FAO	GTAP		FAO	GTAP
FAO Group: Processed Livestock					
270	Butter and Ghee	22	286	Milk, dry buttermilk	22
271	Butter and ghee, sheep milk	22	287	Milk, skimmed condensed	22
272	Butter, buffalo milk	22	288	Milk, skimmed cow	22
273	Butter, cow milk	22	289	Milk, skimmed dried	22
274	Butter, goat milk	22	290	Milk, skimmed evaporated	22
275	Cheese (All Kinds)	22	291	Milk, Total	22
276	Cheese, buffalo milk	22	292	Milk, whole condensed	22
277	Cheese, goat milk	22	293	Milk, whole dried	22
278	Cheese, sheep milk	22	294	Milk, whole evaporated	22
279	Cheese, skimmed cow milk	22	295	Silk, raw	27
280	Cheese, whole cow milk	22	296	Skim Milk & Buttermilk, Dry	22
281	Cream fresh	22	297	Tallow	22
282	Evaporated & Condensed Milk	22	298	Whey, condensed	22
283	Ghee, buffalo milk	22	299	Whey, dry	22
284	Ghee, butteroil of cow milk	22	300	Yoghurt	22
285	Lard	22			

ANNEXURE 7: CONCORDANCE BETWEEN FAO COUNTRIES AND DIFFERENT CLASSIFICATIONS

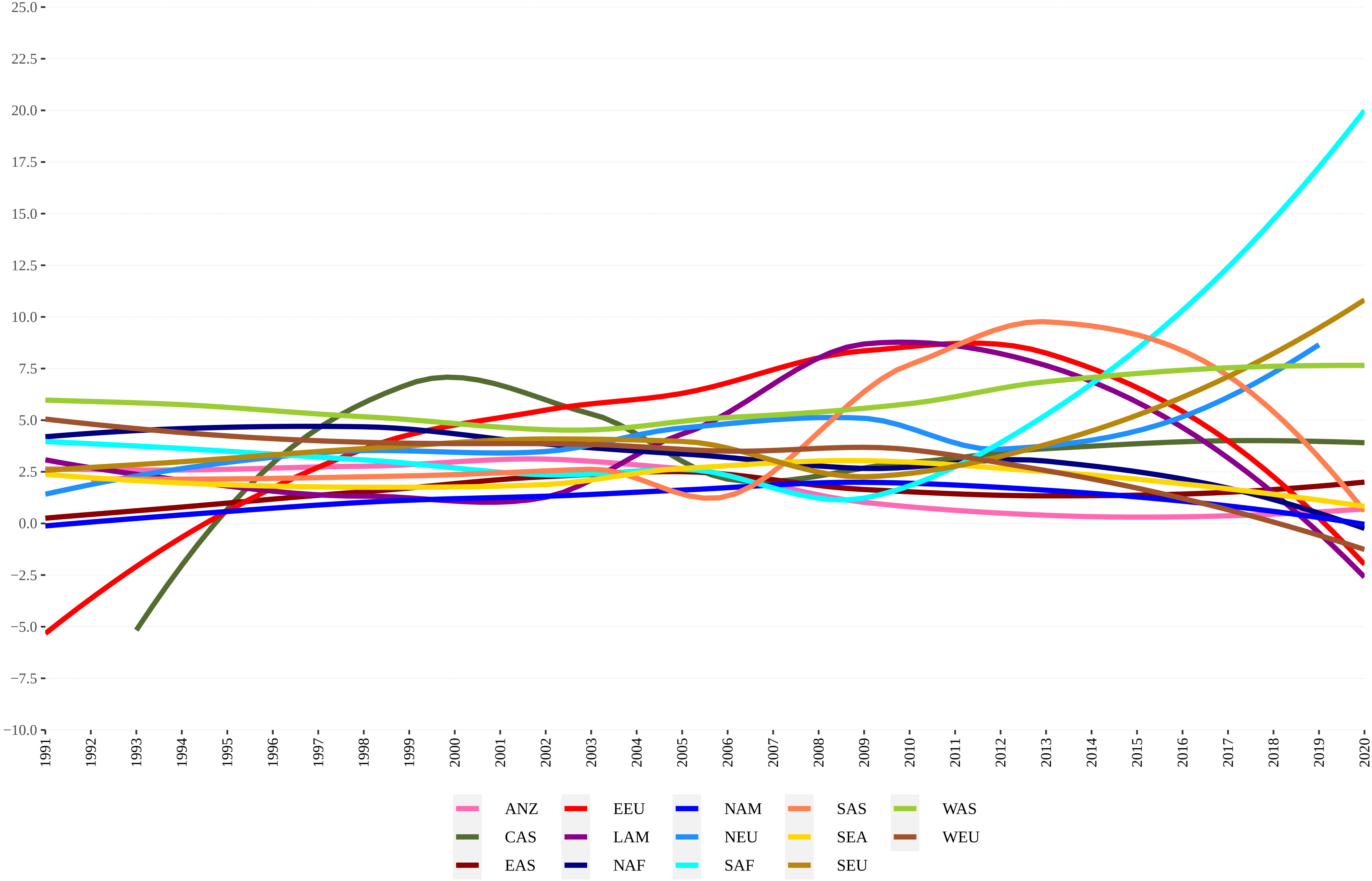
	FAO	GTAP	UN	G-Cubed		FAO	GTAP	UN	G-Cubed
1	AFG	XSA	SAS	ROW	61	ESP	ESP	SEU	EUW
2	AGO	XAC	SAF	OPC	62	EST	EST	NEU	EUW
3	ALB	ALB	SEU	ROW	63	ETH	ETH	SAF	ROW
4	ARE	ARE	WAS	OPC	64	ETH	ETH	SAF	ROW
5	ARG	ARG	LAM	ROW	65	FIN	FIN	NEU	EUW
6	ARM	ARM	WAS	ROW	66	FJI	XOC	ANZ	ROW
7	ASM	XOC	ANZ	ROW	67	FRA	FRA	WEU	EUW
8	ATG	XCB	LAM	ROW	68	FSM	XOC	ANZ	ROW
9	AUS	AUS	ANZ	AUS	69	GAB	XCF	SAF	ROW
10	AUT	AUT	WEU	EUW	70	GBR	GBR	NEU	EUW
11	AZE	AZE	WAS	ROW	71	GEO	GEO	WAS	ROW
12	BDI	XEC	SAF	ROW	72	GHA	GHA	SAF	ROW
13	BEL	BEL	WEU	EUW	73	GIN	GIN	SAF	ROW
14	BEL	BEL	WEU	EUW	74	GLP	FRA	LAM	EUW
15	BEN	BEN	SAF	ROW	75	GMB	XWF	SAF	ROW
16	BFA	BFA	SAF	ROW	76	GNB	XWF	SAF	ROW
17	BGD	BGD	SAS	ROW	77	GNQ	XCF	SAF	ROW
18	BGR	BGR	EEU	EUW	78	GRC	GRC	SEU	EUW
19	BHR	BHR	WAS	OPC	79	GRD	XCB	LAM	ROW
20	BHS	XCB	LAM	ROW	80	GTM	GTM	LAM	ROW
21	BIH	XER	SEU	ROW	81	GUF	XSM	LAM	ROW
22	BLR	BLR	EEU	ROW	82	GUM	XOC	ANZ	ROW
23	BLZ	XCA	LAM	ROW	83	GUY	XSM	LAM	ROW
24	BMU	XNA	NAM	ROW	84	HKG	HKG	EAS	ROW
25	BOL	BOL	LAM	ROW	85	HND	HND	LAM	ROW
26	BRA	BRA	LAM	ROW	86	HRV	HRV	SEU	EUW
27	BRB	XCB	LAM	ROW	87	HTI	XCB	LAM	ROW
28	BRN	BRN	SEA	ROW	88	HUN	HUN	EEU	EUW
29	BTN	XSA	SAS	ROW	89	IDN	INO	SEA	ROW
30	BWA	BWA	SAF	ROW	90	IND	IND	SAS	IND
31	CAF	XCF	SAF	ROW	91	IRL	IRL	NEU	EUW
32	CAN	CAN	NAM	OEC	92	IRN	IRN	SAS	OPC
33	CHE	CHE	WEU	EUW	93	IRQ	XWS	WAS	OPC
34	CHL	CHL	LAM	ROW	94	ISL	XEF	NEU	OEC
35	CHN	CHI	EAS	NA	95	ISR	ISR	WAS	OPC
36	CIV	CIV	SAF	ROW	96	ITA	ITA	SEU	EUW
37	CMR	CMR	SAF	ROW	97	JAM	JAM	LAM	ROW
38	COD	XAC	SAF	OPC	98	JOR	JOR	WAS	OPC
39	COG	XCF	SAF	ROW	99	JPN	JPN	EAS	JPN
40	COK	XOC	ANZ	ROW	100	KAZ	KAZ	CAS	ROW
41	COL	COL	LAM	ROW	101	KEN	KEN	SAF	ROW
42	COM	XEC	SAF	ROW	102	KGZ	KGZ	CAS	ROW
43	CPV	XWF	SAF	ROW	103	KHM	KHM	SEA	ROW
44	CRI	CRI	LAM	ROW	104	KIR	XOC	ANZ	ROW
45	CSK	NA	NA	NA	105	KNA	XCB	LAM	ROW
46	CUB	XCB	LAM	ROW	106	KOR	KOR	EAS	ROW
47	CYM	XCB	LAM	ROW	107	KWT	KWT	WAS	OPC
48	CYP	CYP	WAS	EUW	108	LAO	LAO	SEA	ROW
49	CZE	CZE	EEU	EUW	109	LBN	XWS	WAS	OPC
50	DEU	DEU	WEU	EUW	110	LBR	XWF	SAF	ROW
51	DJI	XEC	SAF	ROW	111	LBY	XNF	NAF	OPC
52	DMA	XCB	LAM	ROW	112	LCA	XCB	LAM	ROW
53	DNK	DNK	NEU	EUW	113	LIE	XEF	WEU	OEC
54	DNK	DNK	NEU	EUW	114	LKA	LKA	SAS	ROW
55	DOM	DOM	LAM	ROW	115	LSO	XSC	SAF	ROW
56	DZA	XNF	NAF	OPC	116	LTU	LTU	NEU	EUW
57	ECU	ECU	LAM	OPC	117	LUX	LUX	WEU	EUW
58	EGY	EGY	NAF	ROW	118	LVA	LVA	NEU	EUW
59	ERI	XEC	SAF	ROW	119	MAC	XEA	EAS	ROW
60	ESH	XNF	NAF	OPC	120	MAR	MAR	NAF	ROW

	FAO	GTAP	UN	G-Cubed		FAO	GTAP	UN	G-Cubed
121	MDA	XEE	EEU	ROW	181	SPM	XNA	NAM	ROW
122	MDG	MDG	SAF	ROW	182	SRB	XER	SEU	ROW
123	MDV	XSA	SAS	ROW	183	SSD	NA	SAF	NA
124	MEX	MEX	LAM	ROW	184	SSD	NA	SAF	NA
125	MHL	XOC	ANZ	ROW	185	STP	XCF	SAF	ROW
126	MKD	XER	SEU	ROW	186	SUR	XSM	LAM	ROW
127	MLI	XWF	SAF	ROW	187	SVK	SVK	EEU	EUW
128	MLT	MLT	SEU	EUW	188	SVN	SVN	SEU	EUW
129	MMR	XSE	SEA	ROW	189	SWE	SWE	NEU	EUW
130	MNE	XER	SEU	ROW	190	SWZ	XSC	SAF	ROW
131	MNG	MNG	EAS	ROW	191	SYC	XEC	SAF	ROW
132	MOZ	MOZ	SAF	ROW	192	SYR	XWS	WAS	OPC
133	MRT	XWF	SAF	ROW	193	TCD	XCF	SAF	ROW
134	MSR	XCB	LAM	ROW	194	TGO	TGO	SAF	ROW
135	MTQ	FRA	LAM	EUW	195	THA	THA	SEA	ROW
136	MUS	MUS	SAF	ROW	196	TJK	TJK	CAS	ROW
137	MWI	MWI	SAF	ROW	197	TKL	XOC	ANZ	ROW
138	MYS	MYS	SEA	ROW	198	TKM	XSU	CAS	ROW
139	NA	XTW	ANT	ROW	199	TLS	XSE	SEA	ROW
140	NAM	NAM	SAF	ROW	200	TON	XOC	ANZ	ROW
141	NCL	XOC	ANZ	ROW	201	TTO	TTO	LAM	ROW
142	NER	XWF	SAF	ROW	202	TUN	TUN	NAF	ROW
143	NGA	NGA	SAF	OPC	203	TUR	TUR	WAS	ROW
144	NIC	NIC	LAM	ROW	204	TUV	XOC	ANZ	ROW
145	NIU	XOC	ANZ	ROW	205	TWN	TWN	EAS	ROW
146	NLD	NLD	WEU	EUW	206	TZA	TZA	SAF	ROW
147	NOR	NOR	NEU	EUW	207	UGA	UGA	SAF	ROW
148	NPL	NPL	SAS	ROW	208	UKR	UKR	EEU	ROW
149	NRU	XOC	ANZ	ROW	209	URY	URY	LAM	ROW
150	NZL	NZL	ANZ	OEC	210	USA	USA	NAM	USA
151	OMN	OMN	WAS	OPC	211	UZB	XSU	CAS	ROW
152	PAK	PAK	SAS	ROW	212	VCT	XCB	LAM	ROW
153	PAN	PAN	LAM	ROW	213	VEN	VEN	LAM	OPC
154	PER	PER	LAM	ROW	214	VGB	XCB	LAM	ROW
155	PHL	PHL	SEA	ROW	215	VIR	XCB	LAM	ROW
156	PNG	XOC	ANZ	ROW	216	VNM	VNM	SEA	ROW
157	POL	POL	EEU	EUW	217	VUT	XOC	ANZ	ROW
158	PRI	PRI	LAM	ROW	218	WLF	XOC	ANZ	ROW
159	PRK	XEA	EAS	ROW	219	WSM	XOC	ANZ	ROW
160	PRT	PRT	SEU	EUW	220	YEM	XWS	WAS	OPC
161	PRY	PRY	LAM	ROW	221	ZAF	ZAF	SAF	ROW
162	PSE	XWS	WAS	OPC	222	ZMB	ZMB	SAF	ROW
163	PYF	XOC	ANZ	ROW	223	ZWE	ZWE	SAF	ROW
164	QAT	QAT	WAS	OPC					
165	REU	FRA	SAF	EUW					
166	ROU	ROU	EEU	EUW					
167	RUS	RUS	EEU	RUS					
168	RUS	RUS	EEU	RUS					
169	RWA	RWA	SAF	ROW					
170	SAU	SAU	WAS	OPC					
171	SCG	XER	SEU	ROW					
172	SCG	XER	SEU	ROW					
173	SDN	XEC	NAF	ROW					
174	SEN	SEN	SAF	ROW					
175	SGP	SGP	SEA	ROW					
176	SHN	XWF	SAF	ROW					
177	SLB	XOC	ANZ	ROW					
178	SLE	XWF	SAF	ROW					
179	SLV	SLV	LAM	EUW					
180	SOM	XEC	SAF	ROW					

ANNEXURE 8: BEHAVIOR OF THE HISTORICAL AGRICULTURAL PRODUCTION

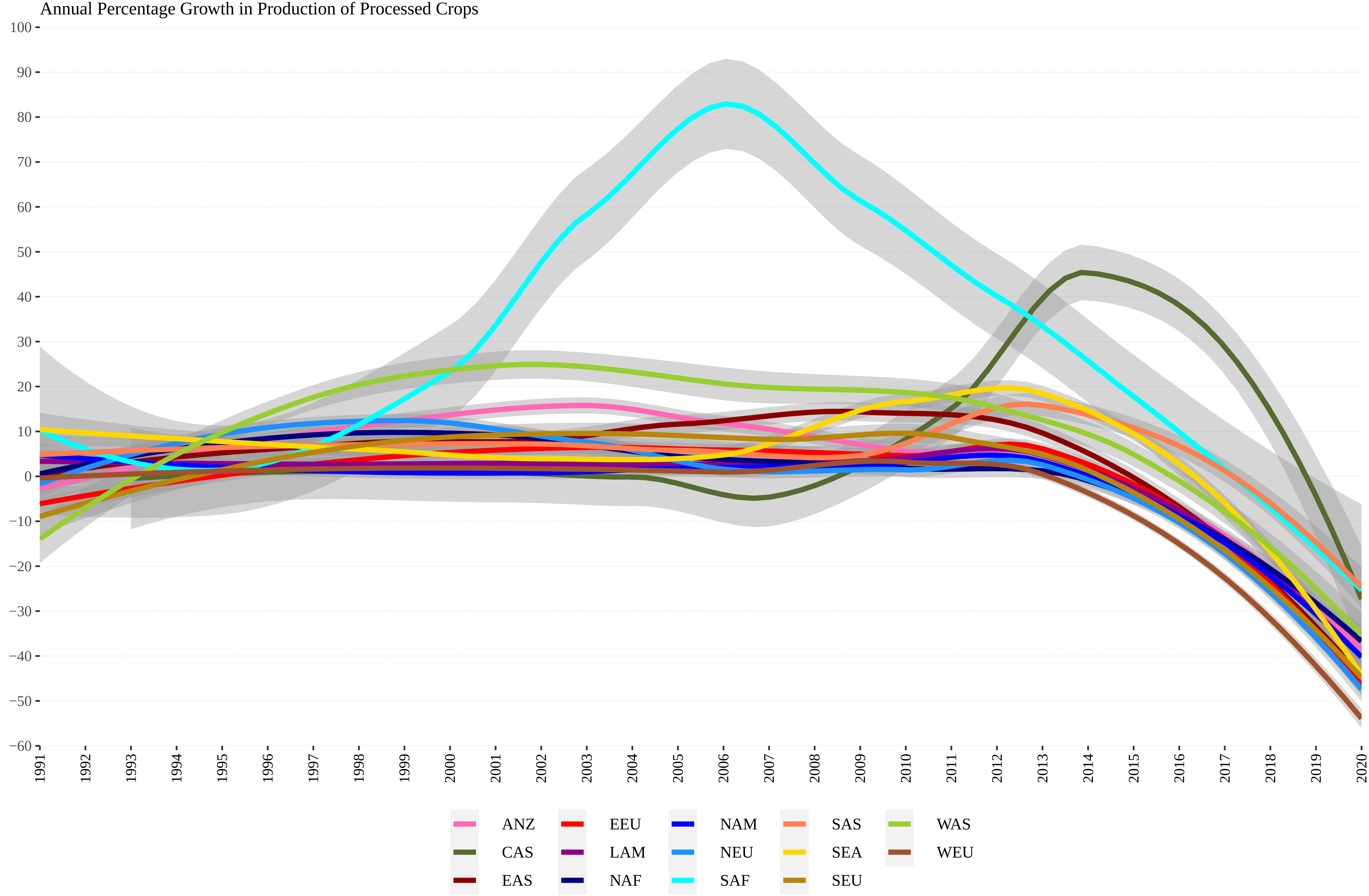
Historical Growth in Total Factor Productivity of Crops across United Nations Regions from 1991 to 2020

Annual Percentage Growth in Total Factor Productivity of Crops



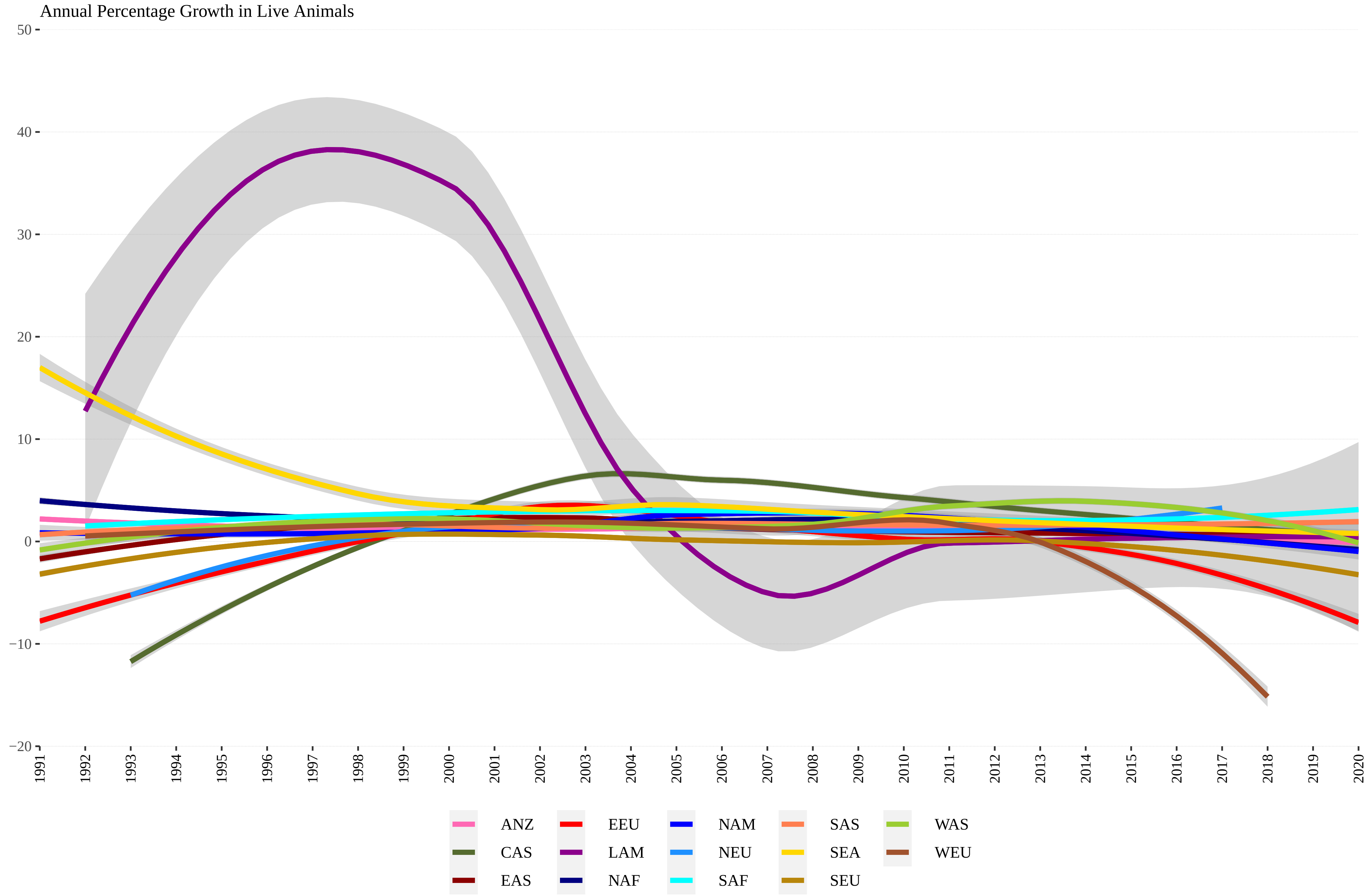
Source: FAO (2022).

Historical Growth in Production of Processed Crops across United Nations Regions from 1991 to 2020



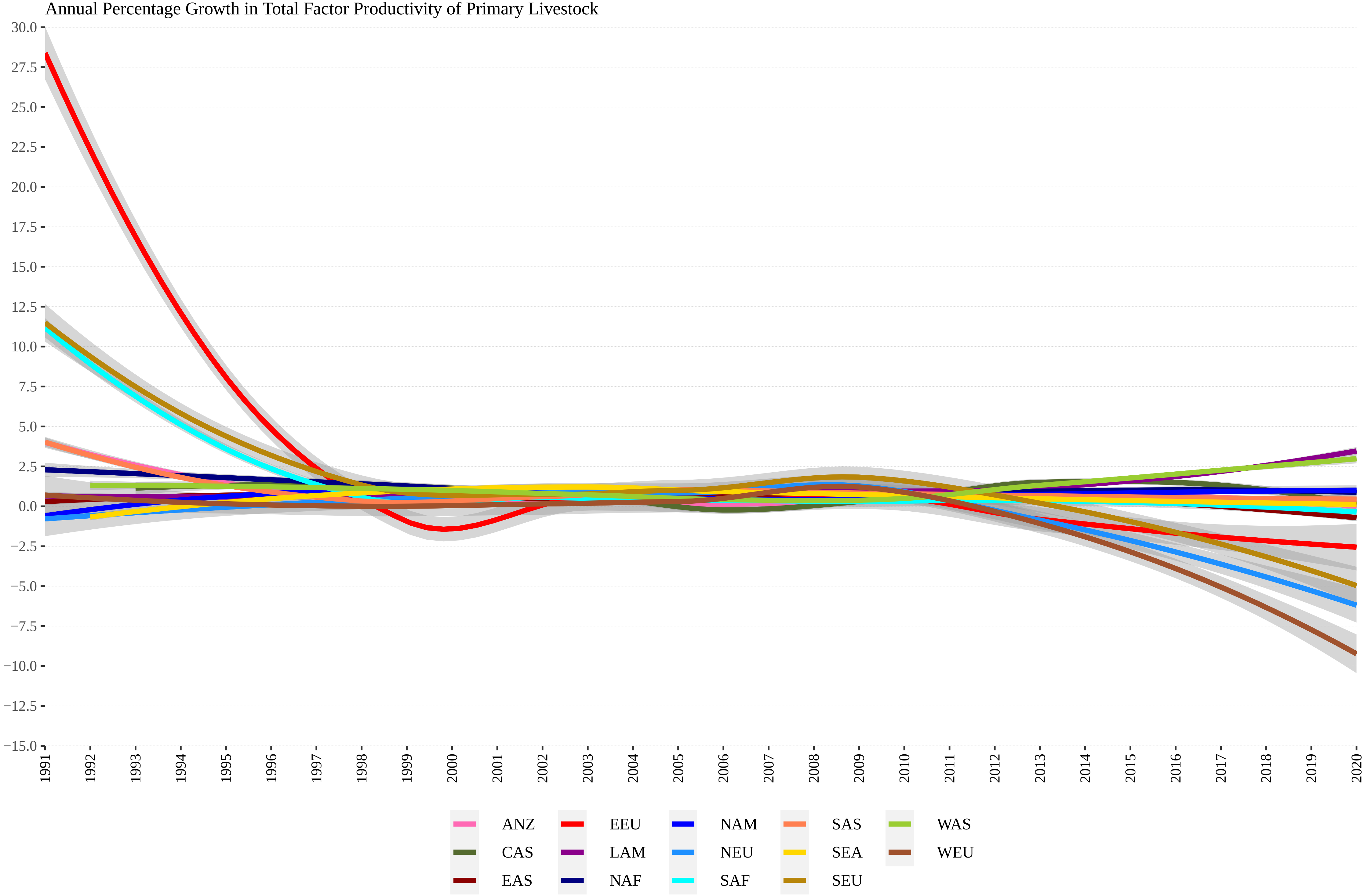
Source: FAO (2022).

Historical Growth in Live Animals across United Nations Regions from 1991 to 2020

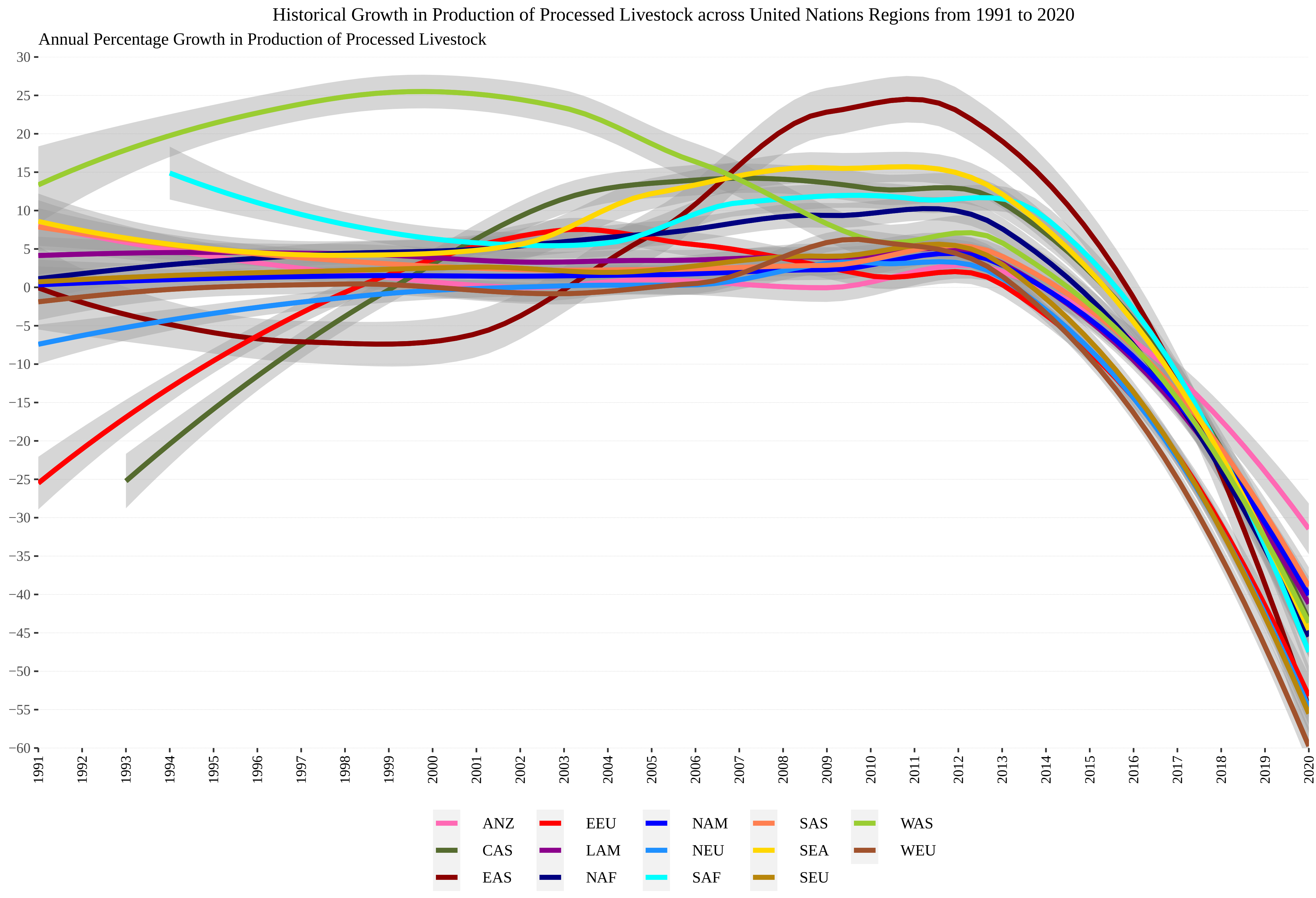


Source: FAO (2022).

Historical Growth in Total Factor Productivity of Primary Livestock across United Nations Regions from 1991 to 2020



Source: FAO (2022).

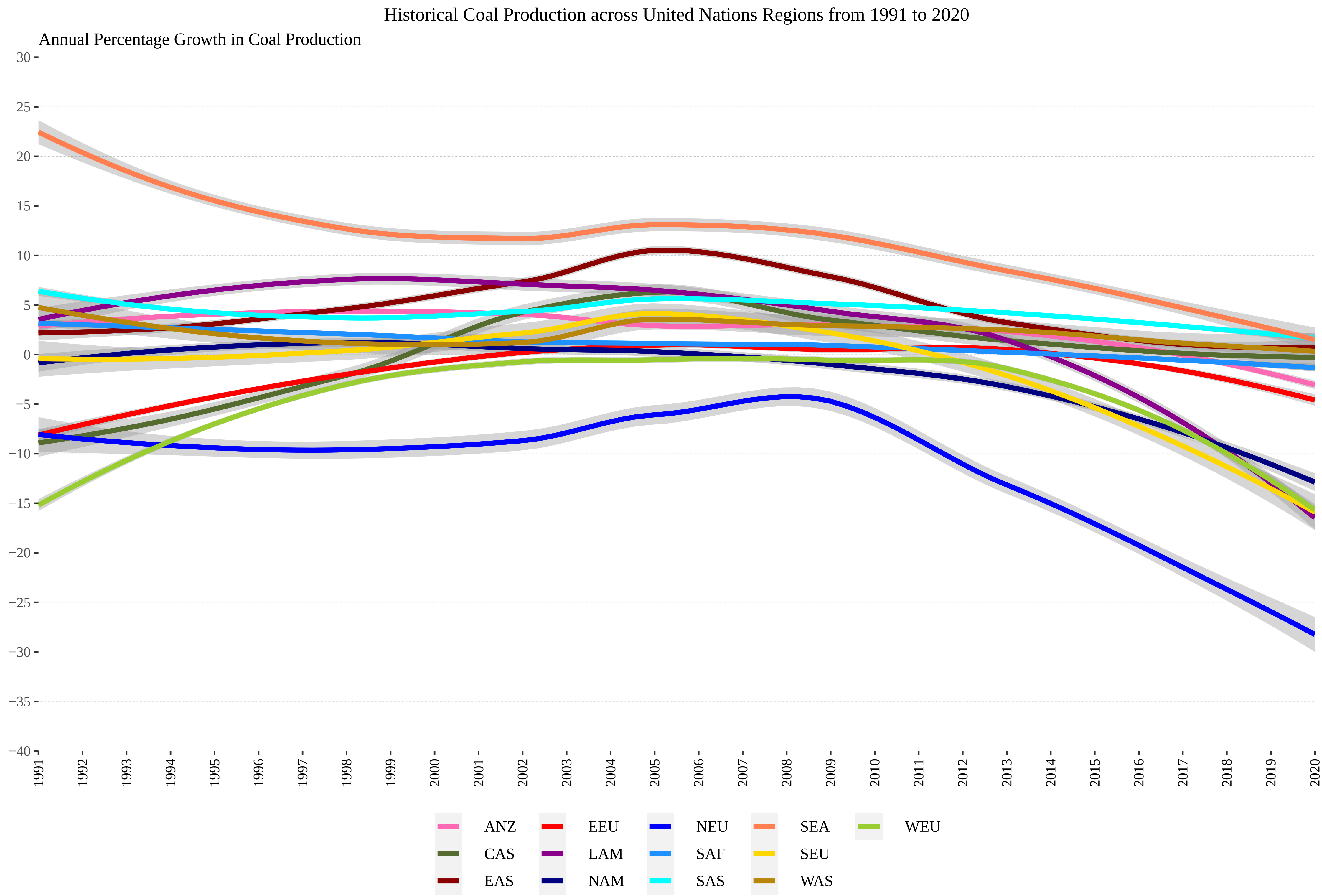


Source: FAO (2022).

ANNEXURE 9: CONCORDANCE BETWEEN BP COUNTRIES AND DIFFERENT CLASSIFICATIONS

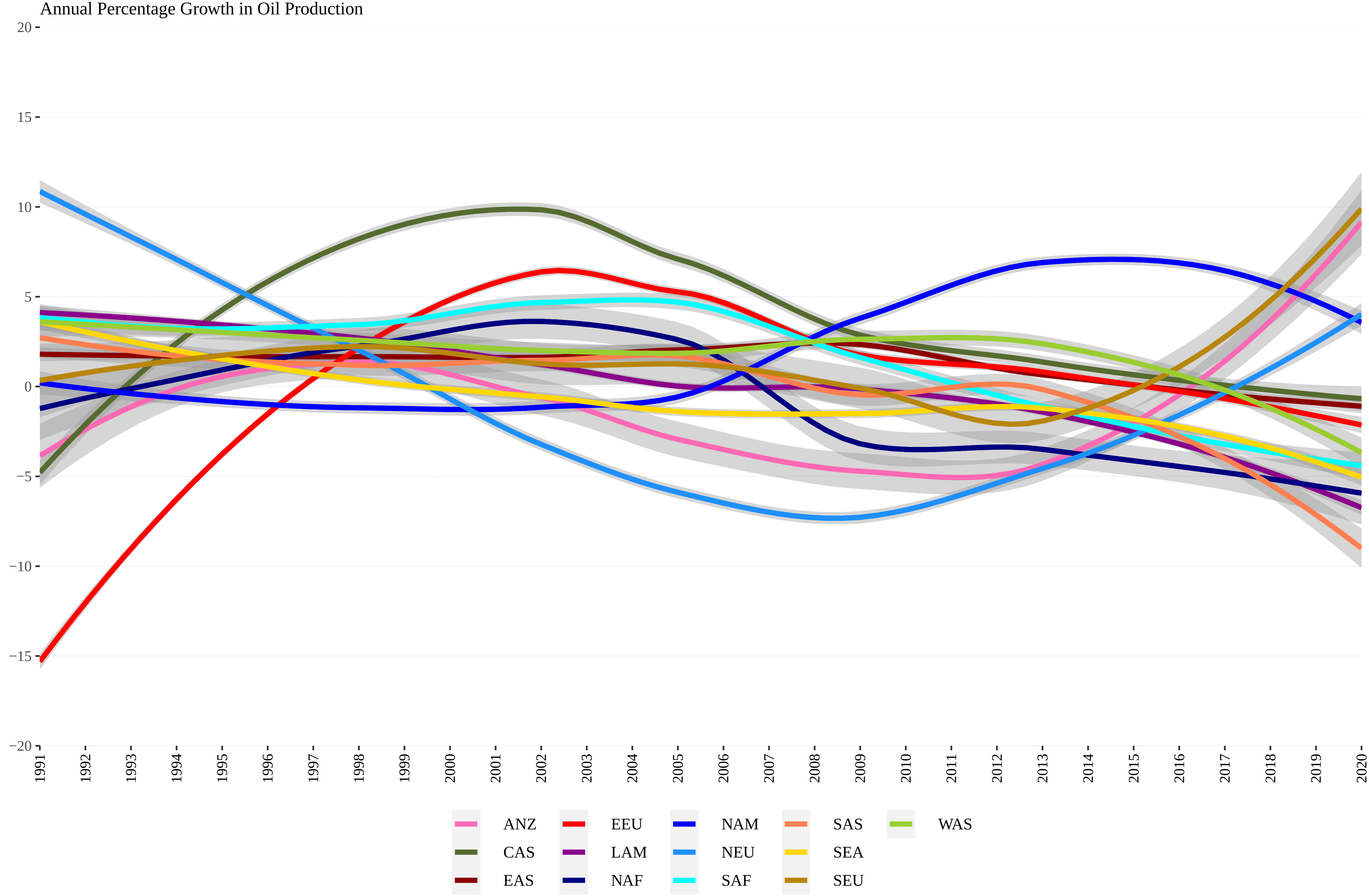
	BP	GTAP	UN	G-Cubed		BP	GTAP	UN	G-Cubed
1	AGO	XAC	SAF	OPC	61	MDG	MDG	SAF	ROW
2	ANT	XCB	LAM	ROW	62	MEX	MEX	LAM	ROW
3	ARE	ARE	WAS	OPC	63	MKD	XER	SEU	ROW
4	ARG	ARG	LAM	ROW	64	MMR	XSE	SEA	ROW
5	AUS	AUS	ANZ	AUS	65	MNG	MNG	EAS	ROW
6	AUT	AUT	WEU	EUW	66	MOZ	MOZ	SAF	ROW
7	AZE	AZE	WAS	ROW	67	MYS	MYS	SEA	ROW
8	BEL	BEL	WEU	EUW	68	NCL	XOC	ANZ	ROW
9	BGD	BGD	SAS	ROW	69	NGA	NGA	SAF	OPC
10	BGR	BGR	EEU	EUW	70	NLD	NLD	WEU	EUW
11	BHR	BHR	WAS	OPC	71	NOR	NOR	NEU	EUW
12	BLR	BLR	EEU	ROW	72	NZL	NZL	ANZ	OEC
13	BOL	BOL	LAM	ROW	73	OMN	OMN	WAS	OPC
14	BRA	BRA	LAM	ROW	74	PAK	PAK	SAS	ROW
15	BRN	BRN	SEA	ROW	75	PER	PER	LAM	ROW
16	CAN	CAN	NAM	OEC	76	PHL	PHL	SEA	ROW
17	CHE	CHE	WEU	EUW	77	PNG	XOC	ANZ	ROW
18	CHL	CHL	LAM	ROW	78	POL	POL	EEU	EUW
19	CHN	CHI	EAS	CHN	79	PRT	PRT	SEU	EUW
20	COD	XAC	SAF	OPC	80	QAT	QAT	WAS	OPC
21	COG	XCF	SAF	ROW	81	ROU	ROU	EEU	EUW
22	COL	COL	LAM	ROW	82	ROW	NA	NA	ROW
23	CUB	XCB	LAM	ROW	83	RUS	RUS	EEU	RUS
24	CUW	XCB	LAM	ROW	84	SAU	SAU	WAS	OPC
25	CYP	CYP	WAS	EUW	85	SDN	XEC	NAF	ROW
26	CZE	CZE	EEU	EUW	86	SGP	SGP	SEA	ROW
27	DEU	DEU	WEU	EUW	87	SRB	XER	SEU	ROW
28	DNK	DNK	NEU	EUW	88	SSD	NA	SAF	NA
29	DZA	XNF	NAF	OPC	89	SUN	NA	NA	NA
30	ECU	ECU	LAM	OPC	90	SVK	SVK	EEU	EUW
31	EGY	EGY	NAF	ROW	91	SVN	SVN	SEU	EUW
32	ESP	ESP	SEU	EUW	92	SWE	SWE	NEU	EUW
33	EST	EST	NEU	EUW	93	SYR	XWS	WAS	OPC
34	FIN	FIN	NEU	EUW	94	TCD	XCF	SAF	ROW
35	FRA	FRA	WEU	EUW	95	THA	THA	SEA	ROW
36	GAB	XCF	SAF	ROW	96	TKM	XSU	CAS	ROW
37	GBR	GBR	NEU	EUW	97	TTO	TTO	LAM	ROW
38	GNQ	XCF	SAF	ROW	98	TUN	TUN	NAF	ROW
39	GRC	GRC	SEU	EUW	99	TUR	TUR	WAS	ROW
40	HKG	HKG	EAS	ROW	100	TWN	TWN	EAS	ROW
41	HRV	HRV	SEU	EUW	101	UKR	UKR	EEU	ROW
42	HUN	HUN	EEU	EUW	102	USA	USA	NAM	USA
43	IDN	INO	SEA	ROW	103	UZB	XSU	CAS	ROW
44	IND	IND	SAS	IND	104	VEN	VEN	LAM	OPC
45	IRL	IRL	NEU	EUW	105	VNM	VNM	SEA	ROW
46	IRN	IRN	SAS	OPC	106	YEM	XWS	WAS	OPC
47	IRQ	XWS	WAS	OPC	107	ZAF	ZAF	SAF	ROW
48	ISL	XEF	NEU	OEC	108	ZMB	ZMB	SAF	ROW
49	ISR	ISR	WAS	OPC	109	ZWE	ZWE	SAF	ROW
50	ITA	ITA	SEU	EUW					
51	JPN	JPN	EAS	JPN					
52	KAZ	KAZ	CAS	ROW					
53	KOR	KOR	EAS	ROW					
54	KWT	KWT	WAS	OPC					
55	LBY	XNF	NAF	OPC					
56	LKA	LKA	SAS	ROW					
57	LTU	LTU	NEU	EUW					
58	LUX	LUX	WEU	EUW					
59	LVA	LVA	NEU	EUW					
60	MAR	MAR	NAF	ROW					

ANNEXURE 10: BEHAVIOR OF THE HISTORICAL ENERGY PRODUCTION

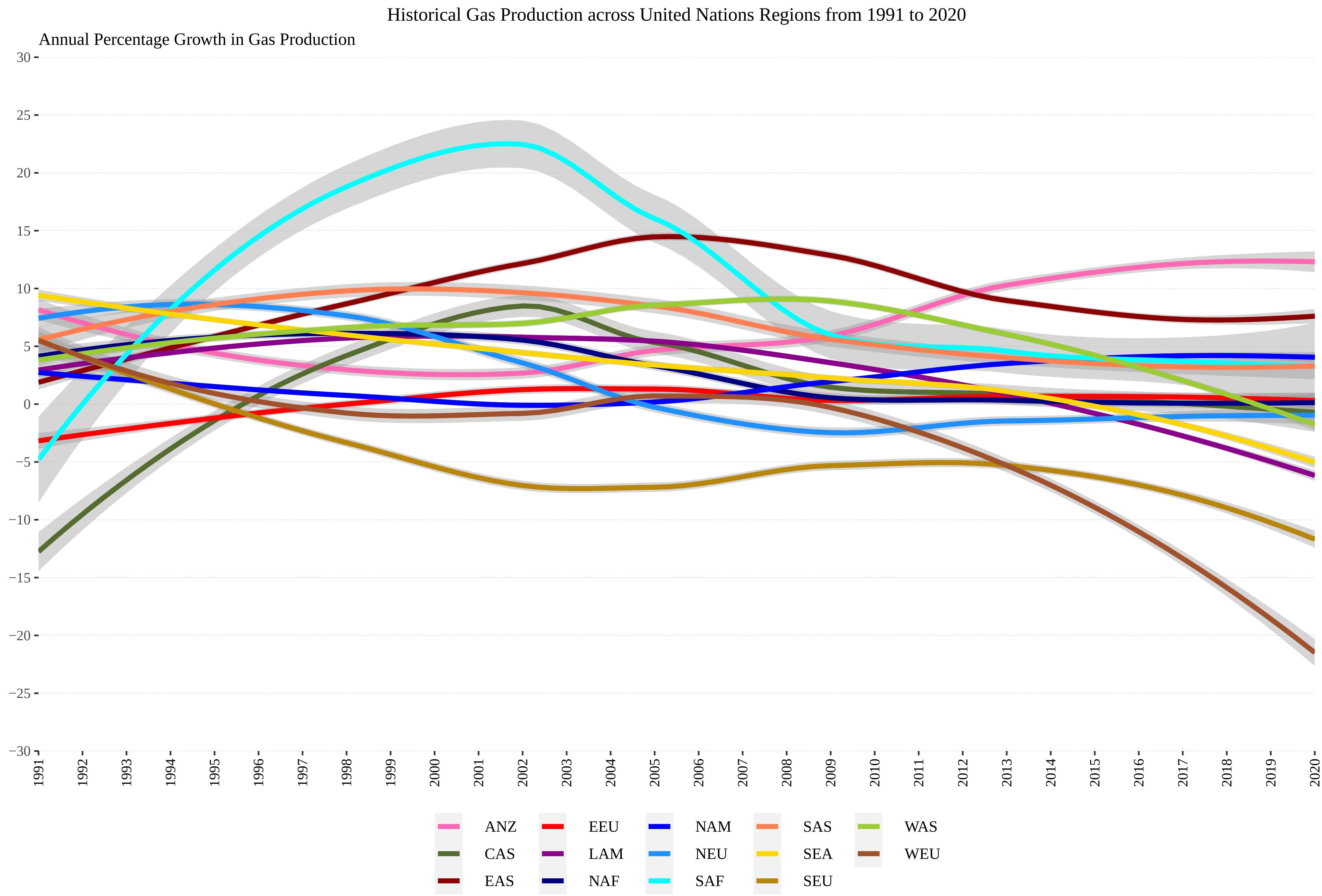


Source: BP (2022).

Historical Oil Production across United Nations Regions from 1991 to 2020



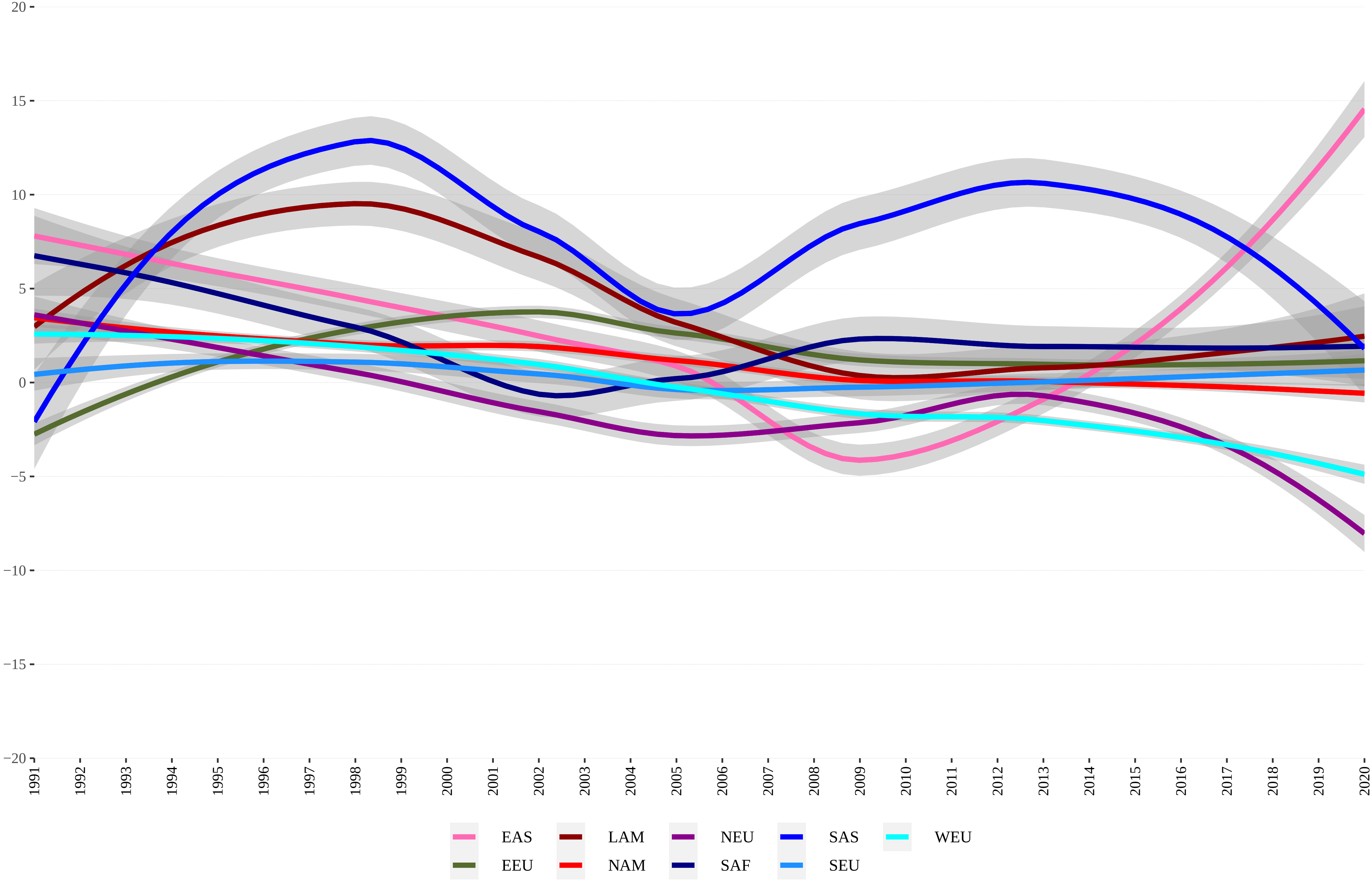
Source: BP (2022).



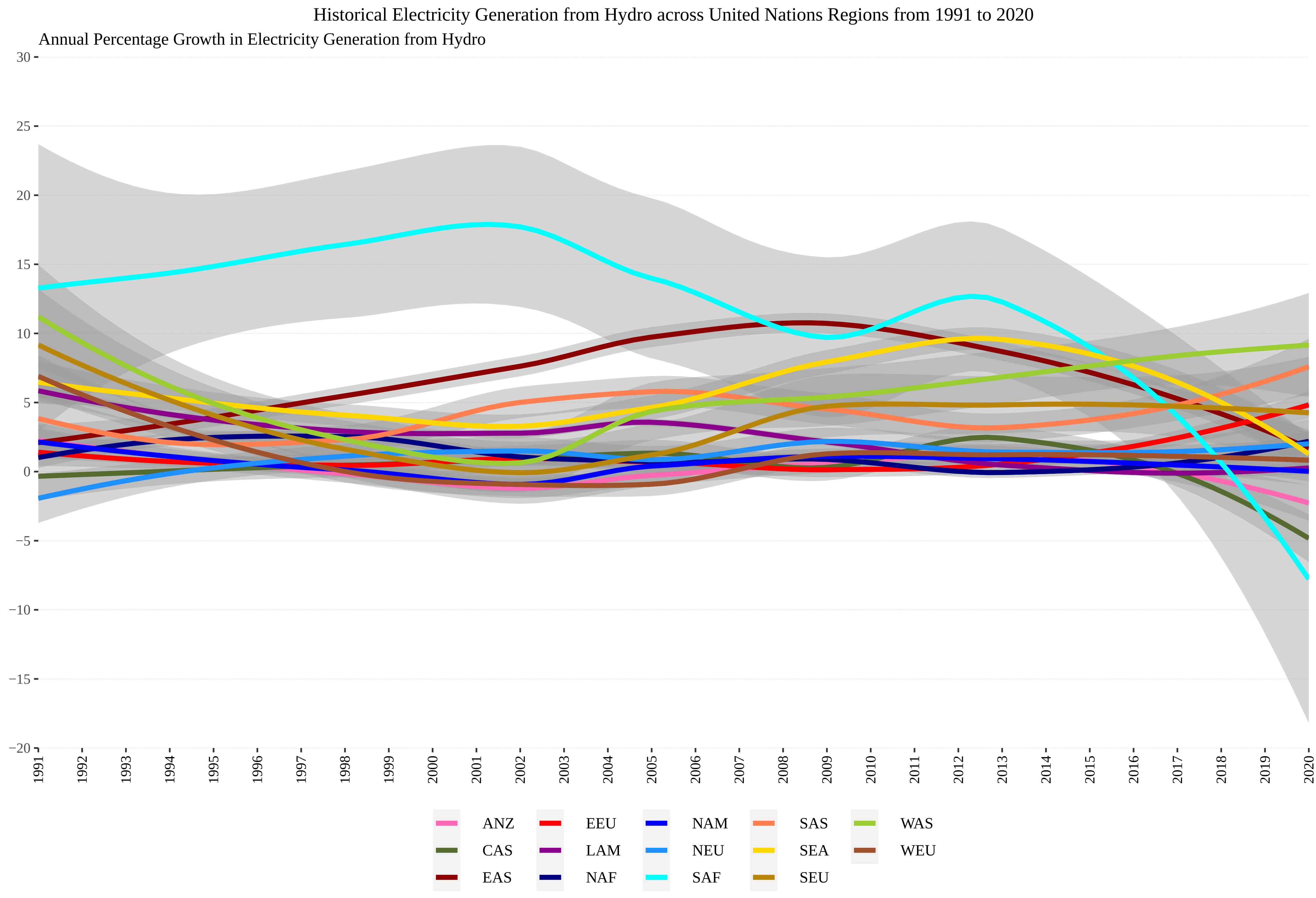
Source: BP (2022).

Historical Electricity Generation from Nuclear across United Nations Regions from 1991 to 2020

Annual Percentage Growth in Electricity Generation from Nuclear

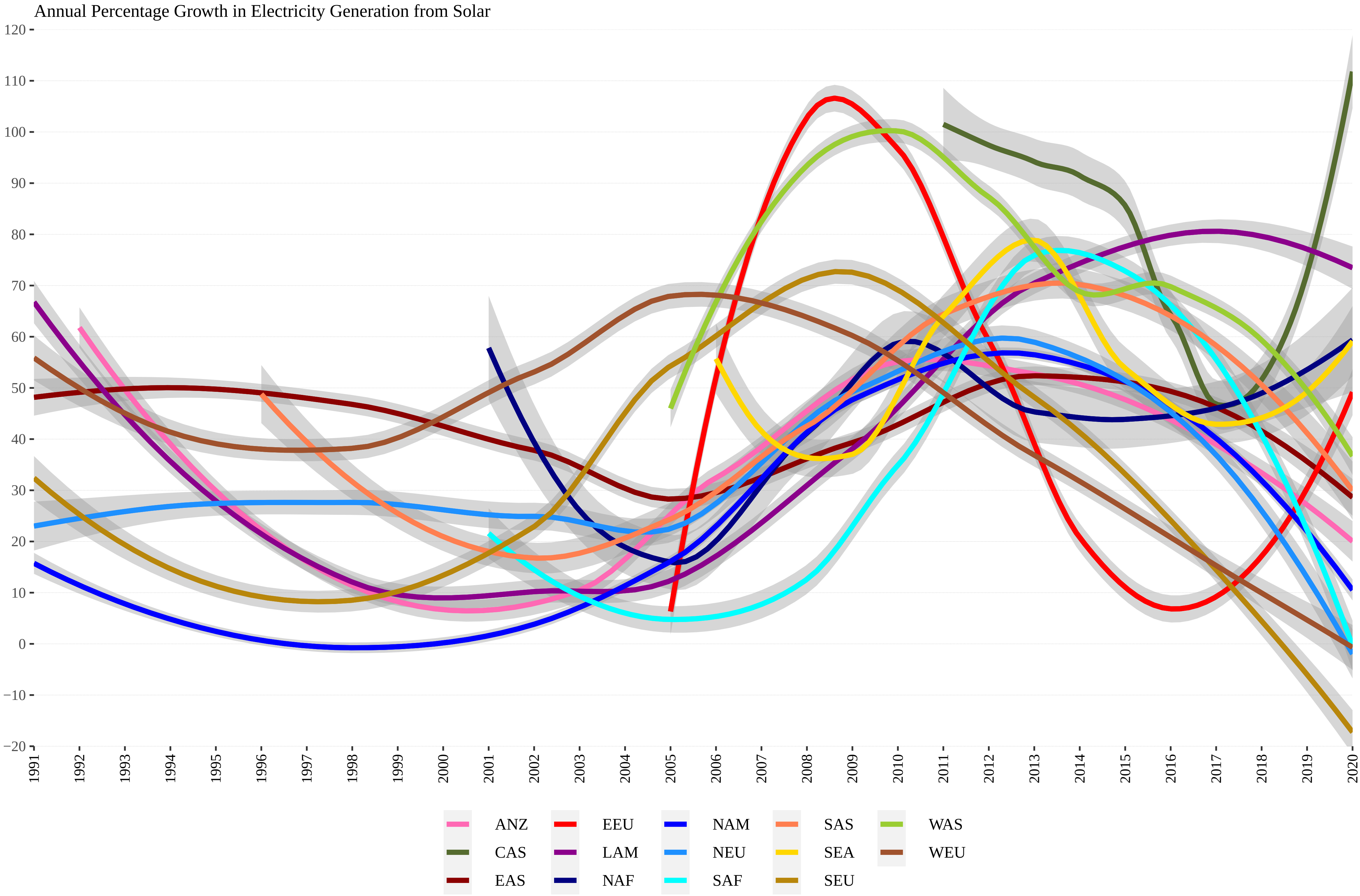


Source: BP (2022).

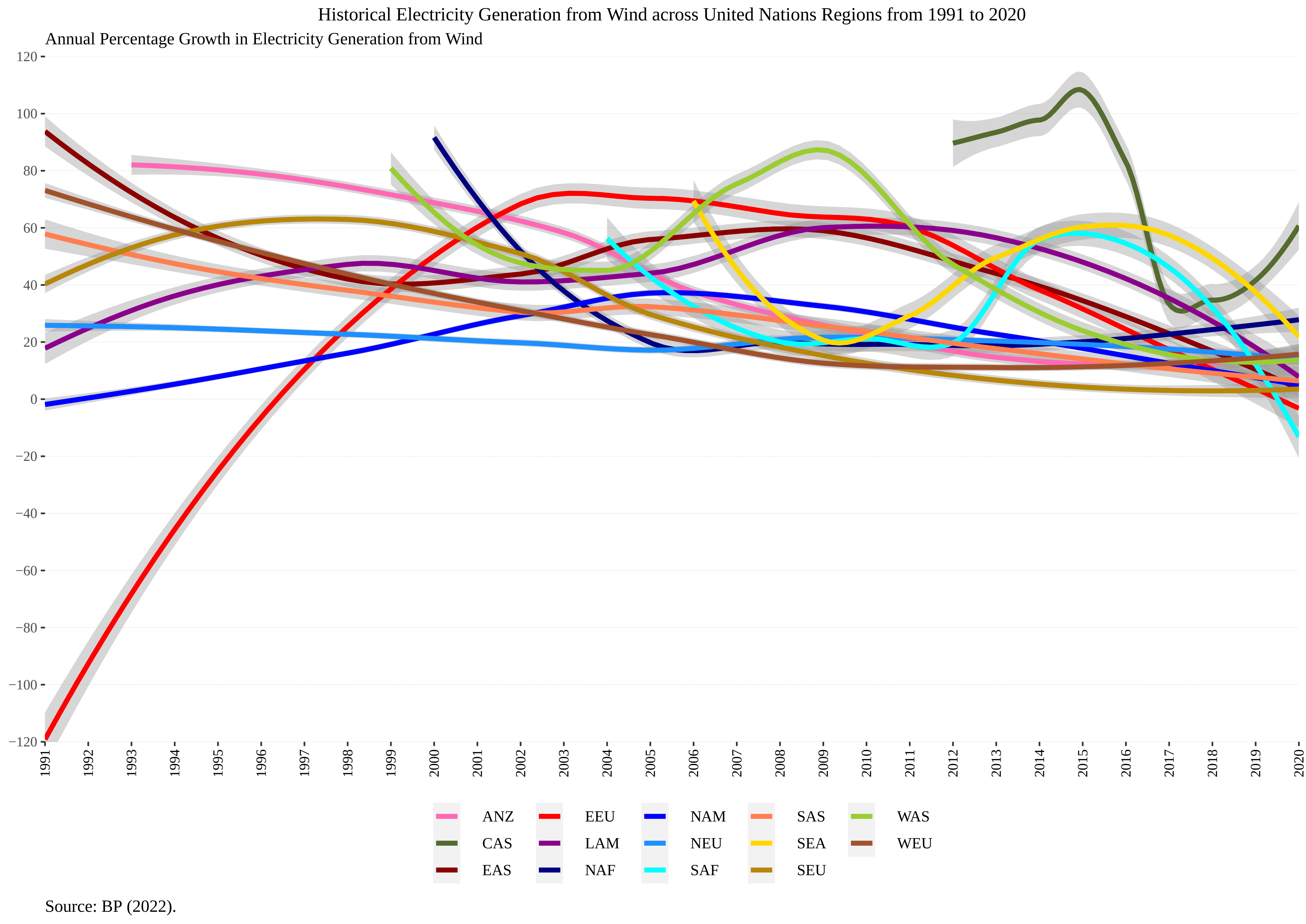


Source: BP (2022).

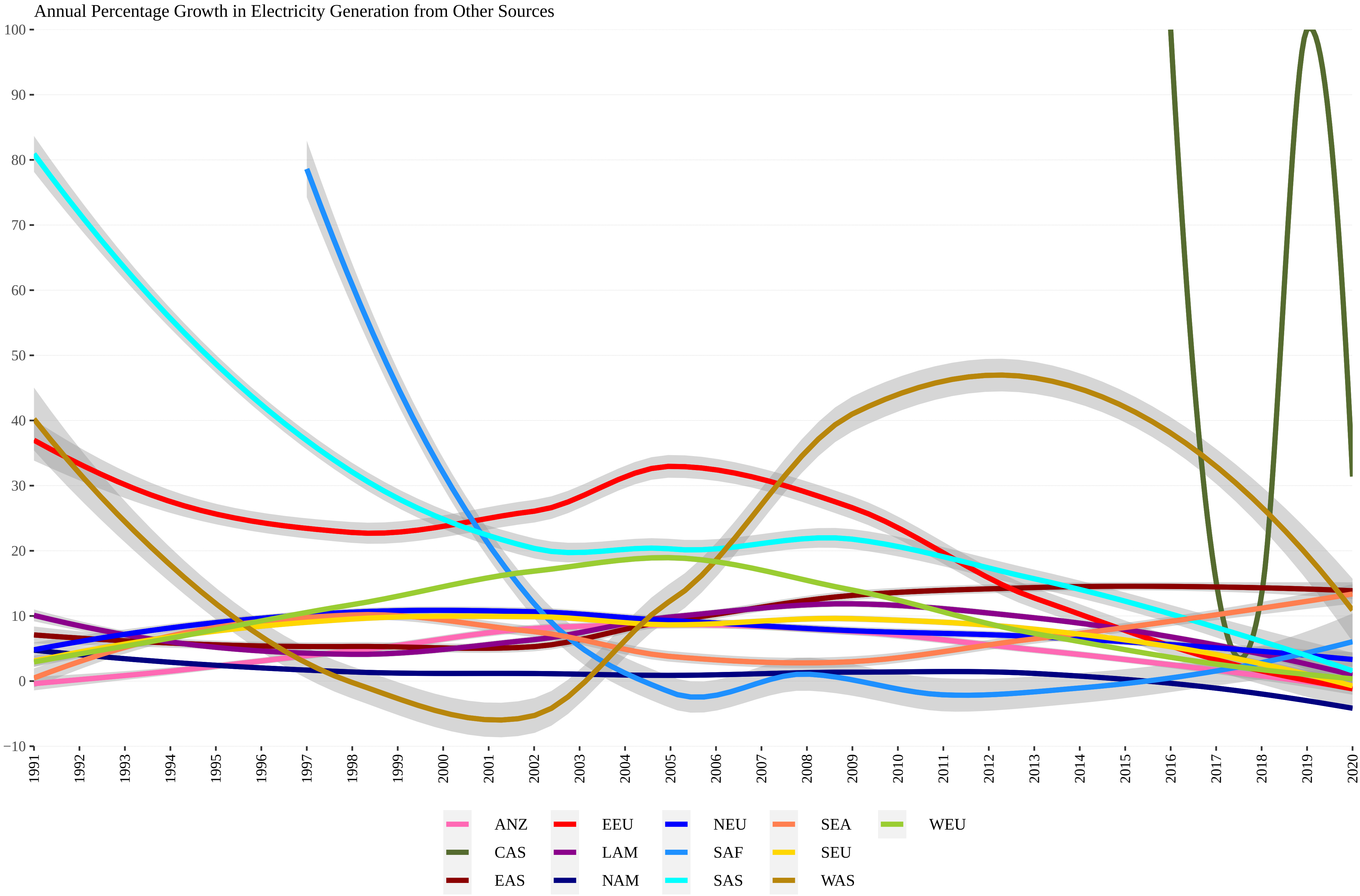
Historical Electricity Generation from Solar across United Nations Regions from 1991 to 2020



Source: BP (2022).


Historical Electricity Generation from Wind across United Nations Regions from 1991 to 2020
Annual Percentage Growth in Electricity Generation from Wind
120
100
80
60
40
20
0
−20
−40
−60
−80
−100
−120
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
ANZ
CAS
EAS
EEU
LAM
NAF
NAM
NEU
SAF
SAS
SEA
SEU
WAS
WEU
Source: BP (2022).

Historical Electricity Generation from Other Sources across United Nations Regions from 1991 to 2020



Source: BP (2022).

ANNEXURE 11: EMPIRICAL ESTIMATES FOR THE IMPACT OF PHYSICAL RISKS AGRICULTURE

Sector	Model	Mean Temperature	Precipitation	Relative Humidity	MaxTem p90P	MinTem p90P	MaxTem p10P	MinTem p10P	SPI Wet	SPI Dry	Extreme Wind Speeds
Crops		0.98	0.75	-0.02	-5.30	-0.04	0.17	-0.25	-0.31	-0.34	-0.09
Processed Crops		0.00	0.25	-0.36	-1.99	0.00	0.00	0.00	0.00	0.00	0.00
Live Animals	ENET: General	-0.04	0.06	-0.22	-2.30	0.94	-0.07	-0.05	0.06	0.32	0.09
Primary Livestock		-0.09	0.00	-0.03	-1.77	-0.04	0.00	0.00	0.05	0.00	-0.14
Processed Livestock		0.00	0.00	0.00	-4.56	0.00	0.00	0.00	-0.13	0.25	0.00
Crops		1.14	0.79	-0.06	-6.29	-0.38	0.25	-0.37	-0.49	-0.54	-0.16
Processed Crops		0.00	0.25	-0.36	-1.99	0.00	0.00	0.00	0.00	0.00	0.00
Live Animals	ENET: LASSO	-0.03	0.05	-0.23	-3.18	1.51	-0.07	-0.06	0.08	0.33	0.10
Primary Livestock		-0.13	-0.03	-0.07	-1.71	-0.39	-0.02	0.01	0.16	0.09	-0.19
Processed Livestock		0.00	0.00	0.00	-4.62	0.00	0.02	0.00	-0.17	0.28	-0.08
Crops		0.91	0.76	-0.05	-4.79	-0.58	0.21	-0.34	-0.38	-0.41	-0.13
Processed Crops		-0.11	0.64	-0.56	-2.01	0.36	-0.42	-0.27	-0.32	-0.20	-0.07
Live Animals	ENET: Ridge	-0.04	0.06	-0.22	-2.30	0.94	-0.07	-0.05	0.06	0.32	0.09
Primary Livestock		-0.17	-0.01	-0.06	-1.37	-0.32	-0.03	0.01	0.12	0.06	-0.16
Processed Livestock		-0.66	0.19	0.09	-3.92	0.25	0.16	-0.26	-0.63	0.13	-0.38
Crops		1.15	0.79	-0.06	-6.33	-0.37	0.25	-0.37	-0.49	-0.54	-0.16
Processed Crops		0.37	0.77	-0.63	-3.06	1.15	-0.53	-0.26	-0.32	-0.25	-0.16
Live Animals	ENET: Linear	-0.04	0.05	-0.23	-3.15	1.50	-0.07	-0.06	0.08	0.34	0.10
Primary Livestock		-0.12	-0.03	-0.07	-1.72	-0.39	-0.02	0.01	0.15	0.09	-0.19
Processed Livestock		-0.39	0.22	0.09	-5.43	1.18	0.16	-0.30	-0.64	0.12	-0.48

Source: Constructed by the Author (2022).

ANNEXURE 12: EMPIRICAL ESTIMATES FOR THE IMPACT OF PHYSICAL RISKS ON ENERGY PRODUCTION AND ELECTRICITY GENERATION

Sector	Model	Mean Temperature	Precipitation	Relative Humidity	MaxTemp 90P	MinTemp 90P	MaxTemp 10P	MinTemp 10P	SPI Wet	SPI Dry	Extreme Wind Speeds
Coal Production	ENET: General	-0.31	-0.25	-0.57	0.00	0.00	0.00	-0.47	0.00	0.26	0.00
Oil Production		-0.04	0.00	0.00	0.00	-0.14	0.14	0.00	0.00	0.00	0.00
Gas Production		-0.07	-1.14	0.00	-1.12	0.00	0.28	0.00	0.00	-0.06	0.00
Nuclear Generation		0.00	0.00	0.00	0.00	-1.32	0.00	0.00	0.00	0.00	0.00
Hydro Generation		-0.18	8.23	0.00	-1.94	0.00	0.00	0.00	0.00	0.00	0.22
Solar Generation		0.97	-1.17	0.00	0.00	-0.01	0.00	0.23	0.00	0.00	0.00
Wind Generation		0.94	0.00	-1.12	0.00	-0.92	0.81	0.00	0.00	-0.24	0.00
Other Generation		-0.04	0.00	-0.16	0.00	0.00	0.00	0.34	0.00	0.00	0.00
Coal Production	ENET: LASSO	-0.26	-0.21	-0.59	0.00	0.00	0.00	-0.52	0.00	0.23	0.00
Oil Production		-0.02	0.00	0.00	0.00	-0.07	0.08	0.00	0.00	0.00	0.00
Gas Production		0.00	-1.17	0.00	-1.14	0.00	0.23	0.00	0.00	-0.04	0.00
Nuclear Generation		0.00	0.00	0.00	0.00	-1.32	0.00	0.00	0.00	0.00	0.00
Hydro Generation		-0.18	8.23	0.00	-1.94	0.00	0.00	0.00	0.00	0.00	0.22
Solar Generation		1.34	-1.39	0.00	0.00	-0.49	0.00	0.33	0.00	0.00	0.00
Wind Generation		1.19	-0.05	-1.18	0.00	-1.13	0.88	0.00	0.00	-0.24	0.00
Other Generation		0.00	0.00	-0.07	0.00	0.00	0.00	0.29	0.00	0.00	0.00

Source: Constructed by the Author (2022).

ANNEXURE 12: EMPIRICAL ESTIMATES FOR THE IMPACT OF PHYSICAL RISKS ON ENERGY PRODUCTION AND ELECTRICITY GENERATION

Sector	Model	Mean Temperature	Precipitation	Relative Humidity	MaxTemp 90P	MinTemp 90P	MaxTemp 10P	MinTemp 10P	SPI Wet	SPI Dry	Extreme Wind Speeds
Coal Production	ENET: Ridge	-0.37	-0.25	-0.67	2.26	0.31	-0.29	-0.86	0.32	0.68	-0.15
Oil Production	ENET: Ridge	0.03	0.01	-0.22	1.14	-0.64	0.79	-0.10	0.01	-0.22	-0.13
Gas Production	ENET: Ridge	-0.08	-1.12	-0.12	-0.82	1.36	0.40	0.03	-0.13	-0.40	-0.03
Nuclear Generation	ENET: Ridge	0.88	-0.07	-0.31	-0.70	-3.41	0.27	-0.41	0.08	-0.49	0.12
Hydro Generation	ENET: Ridge	-0.22	9.88	0.04	-3.99	0.12	0.33	0.43	0.34	0.19	1.31
Solar Generation	ENET: Ridge	3.30	-2.68	-0.80	-1.88	-2.76	0.46	0.68	0.96	1.35	-0.63
Wind Generation	ENET: Ridge	2.18	-0.62	-1.72	3.81	-4.28	1.46	0.40	-0.70	-0.52	-0.07
Other Generation	ENET: Ridge	-0.99	0.45	-0.96	0.95	-0.10	0.07	0.61	-0.48	-0.35	-0.16
Coal Production	ENET: Linear	-0.28	-0.02	-0.67	4.32	0.23	-0.45	-1.02	0.27	0.74	-0.04
Oil Production	ENET: Linear	0.24	0.11	-0.20	2.42	-0.84	0.82	-0.09	-0.11	-0.44	-0.14
Gas Production	ENET: Linear	0.10	-1.08	-0.11	-1.83	2.84	0.33	0.04	-0.27	-0.60	-0.02
Nuclear Generation	ENET: Linear	1.09	0.10	-0.36	1.70	-5.39	0.35	-0.45	0.10	-0.45	0.14
Hydro Generation	ENET: Linear	-0.07	10.43	0.00	-4.69	0.50	0.38	0.47	0.34	0.13	1.33
Solar Generation	ENET: Linear	3.52	-2.76	-0.79	-1.22	-3.27	0.48	0.69	1.13	1.65	-0.61
Wind Generation	ENET: Linear	2.62	-0.46	-1.90	6.72	-6.24	1.55	0.50	-0.85	-0.72	-0.21
Other Generation	ENET: Linear	-1.08	0.48	-0.99	1.25	-0.09	0.09	0.61	-0.52	-0.34	-0.20

Source: Constructed by the Author (2022).

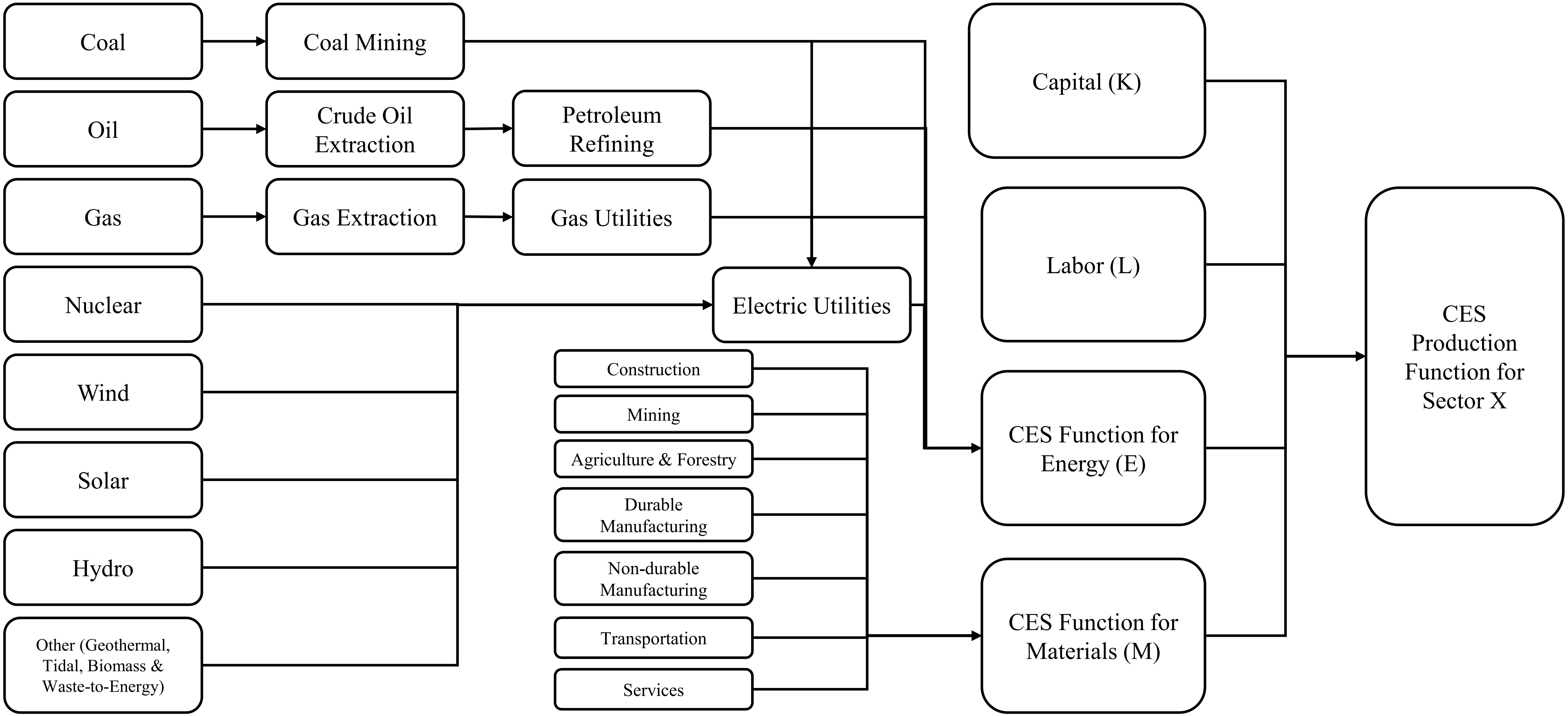
ANNEXURE 13: CONCORDANCE BETWEEN GTAP AND G-CUBED SECTORS

	BP	GTAP	UN	G-Cubed		BP	GTAP	UN	G-Cubed
1	PDR	8	AGR	PDR	34	BPH	10	NMA	34
2	WHT	8	AGR	WHT	35	RPP	10	NMA	35
3	GRO	8	AGR	GRO	36	NMM	9	DMA	36
4	V_F	8	AGR	V_F	37	I_S	9	DMA	37
5	OSD	8	AGR	OSD	38	NFM	9	DMA	38
6	C_B	8	AGR	C_B	39	FMP	9	DMA	39
7	PFB	8	AGR	PFB	40	ELE	9	DMA	40
8	OCR	8	AGR	OCR	41	EEQ	9	DMA	41
9	CTL	8	AGR	CTL	42	OME	9	DMA	42
10	OAP	8	AGR	OAP	43	MVH	9	DMA	43
11	RMK	8	AGR	RMK	44	OTN	9	DMA	44
12	WOL	8	AGR	WOL	45	OMF	9	DMA	45
13	FRS	8	AGR	FRS	46	ELY	1	ETCU	46
14	FSH	8	AGR	FSH	47	GDT	2	GASU	47
15	COA	4	COAM	COA	48	WTR	12	SVC	48
16	OIL	5	COLE	OIL	49	CNS	6	CNS	49
17	GAS	2	GASU	GAS	50	TRD	12	SVC	50
18	OXT	7	MIN	OXT	51	AFS	12	SVC	51
19	CMT	10	NMA	CMT	52	OTP	11	TRA	52
20	OMT	10	NMA	OMT	53	WTP	11	TRA	53
21	VOL	10	NMA	VOL	54	ATP	11	TRA	54
22	MIL	10	NMA	MIL	55	WHS	11	TRA	55
23	PCR	10	NMA	PCR	56	CMN	12	SVC	56
24	SGR	10	NMA	SGR	57	OFI	12	SVC	57
25	OFD	10	NMA	OFD	58	INS	12	SVC	58
26	B_T	10	NMA	B_T	59	RSA	12	SVC	59
27	TEX	10	NMA	TEX	60	OBS	12	SVC	60
28	WAP	10	NMA	WAP	61	ROS	12	SVC	61
29	LEA	10	NMA	LEA	62	OSG	12	SVC	62
30	LUM	8	AGR	LUM	63	EDU	12	SVC	63
31	PPP	10	NMA	PPP	64	HHT	12	SVC	64
32	P_C	3	PETR	P_C	65	DWE	12	SVC	65
33	CHM	10	NMA	CHM					

ETCU: Electricity Delivery; GASU: Gas Utilities; PETR – Petroleum Refining; COAM – Coal Mining; COLE – Crude Oil Extraction; CNS – Construction; MIN – Mining; AGR – Agriculture; DMA – Durable Manufacturing; NMA – Non-durable Manufacturing; TRA – Transportation; SVC – Services. Source: G-Cubed Model (Version GGG20J_v164).

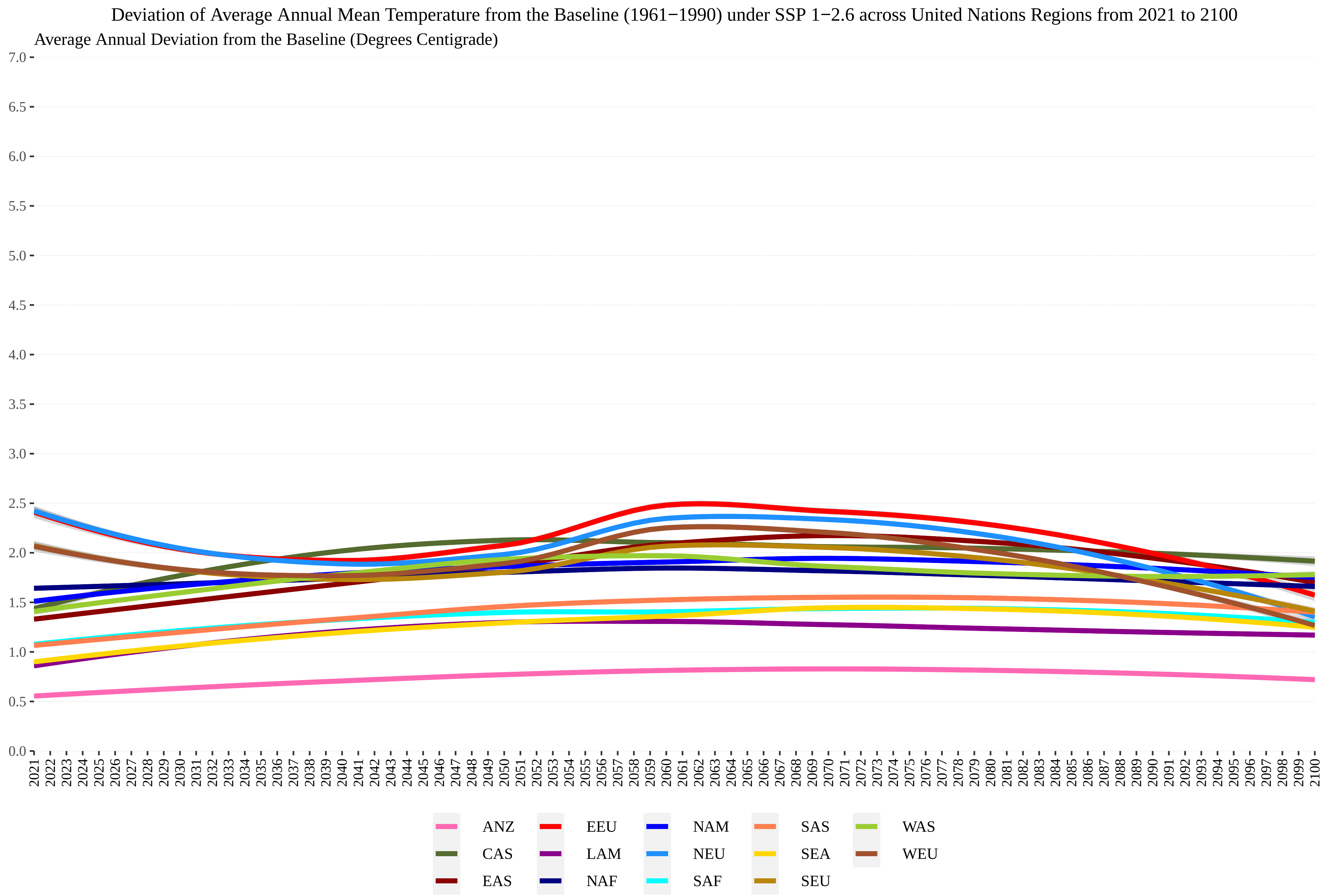
ANNEXURE 14: SCHEMATIC PRODUCTION STRUCTURE OF THE G-CUBED MODEL

Schematic Presentation of the G-Cubed Model Production Structure



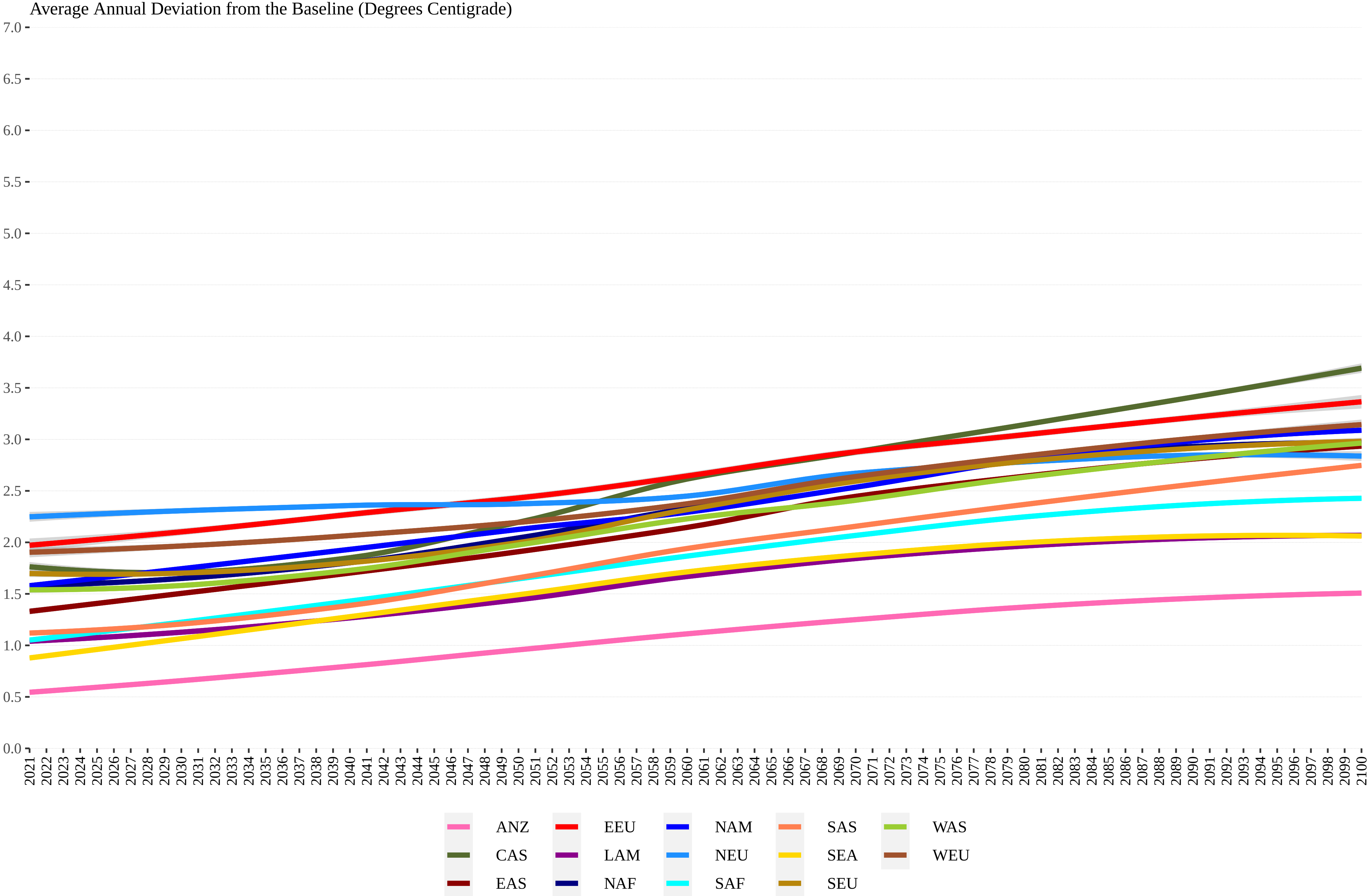
Source: G-Cubed Model (Version 20J_v164).

ANNEXURE 15: BEHAVIOR OF CHRONIC CLIMATE INDICATORS UNDER SSPS



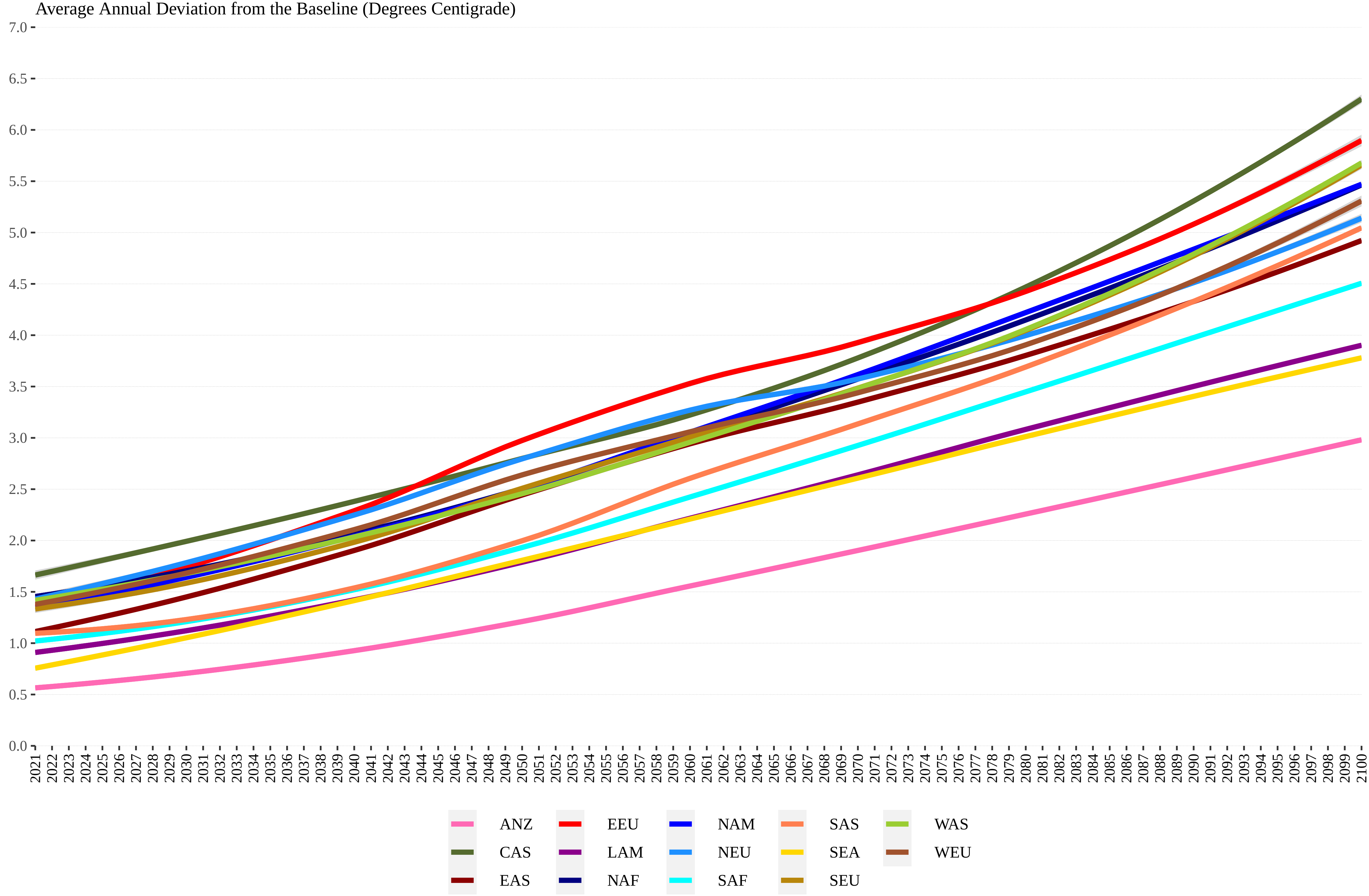
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of Average Annual Mean Temperature from the Baseline (1961−1990) under SSP 2−4.5 across United Nations Regions from 2021 to 2100



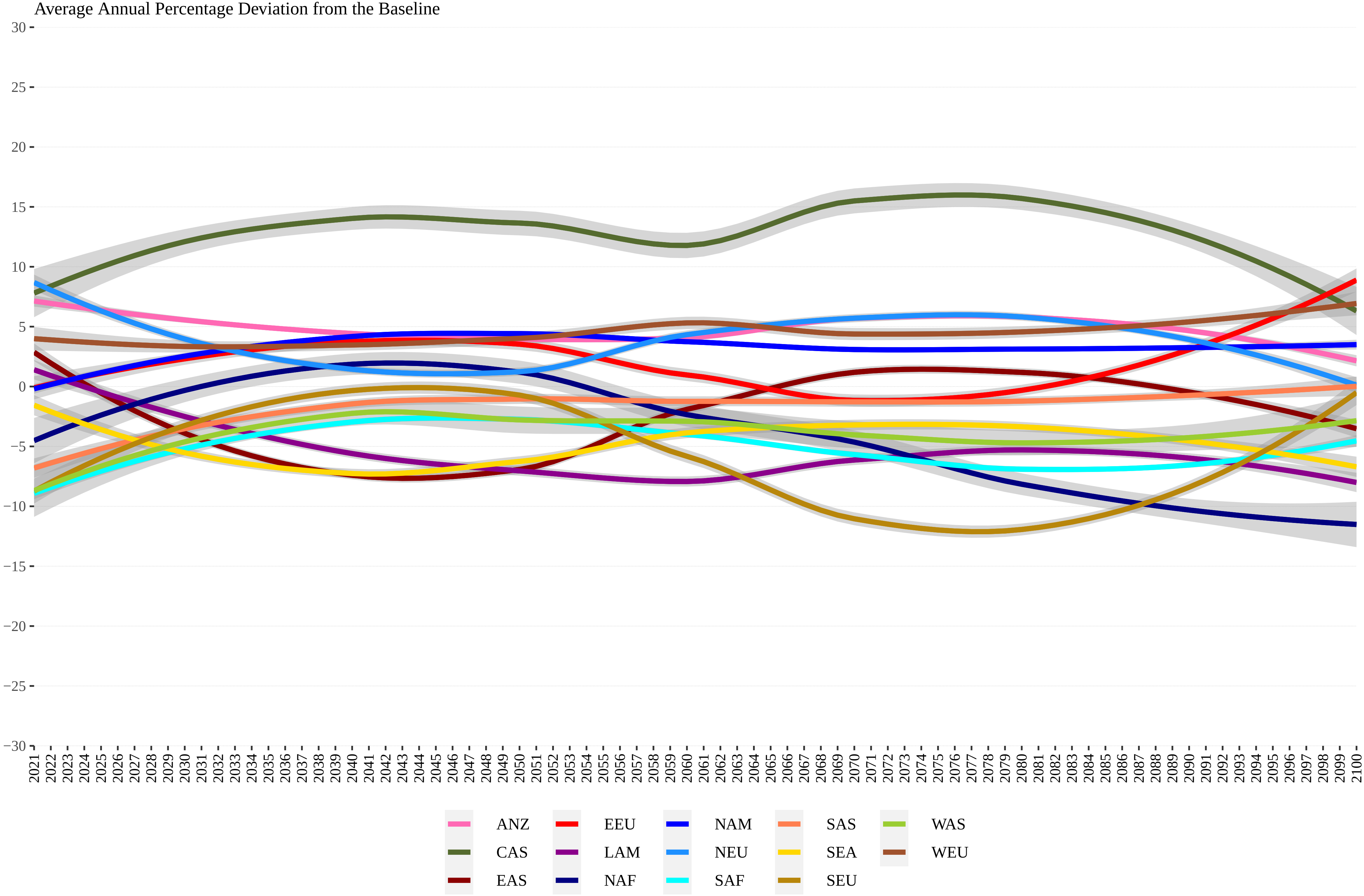
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of Average Annual Mean Temperature from the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100



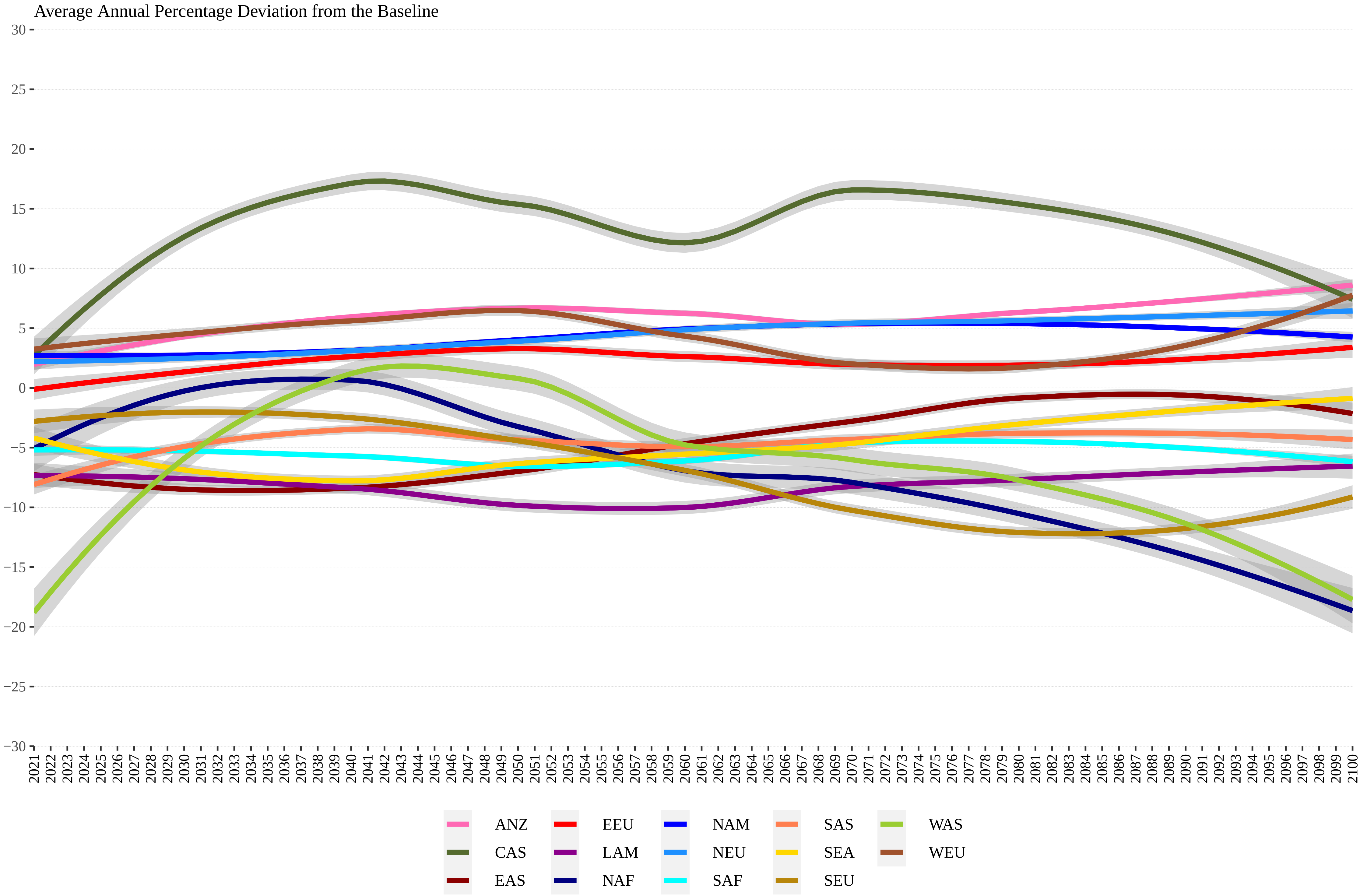
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of Average Annual Precipitation from the Baseline (1961−1990) under SSP 1−2.6 across United Nations Regions from 2021 to 2100



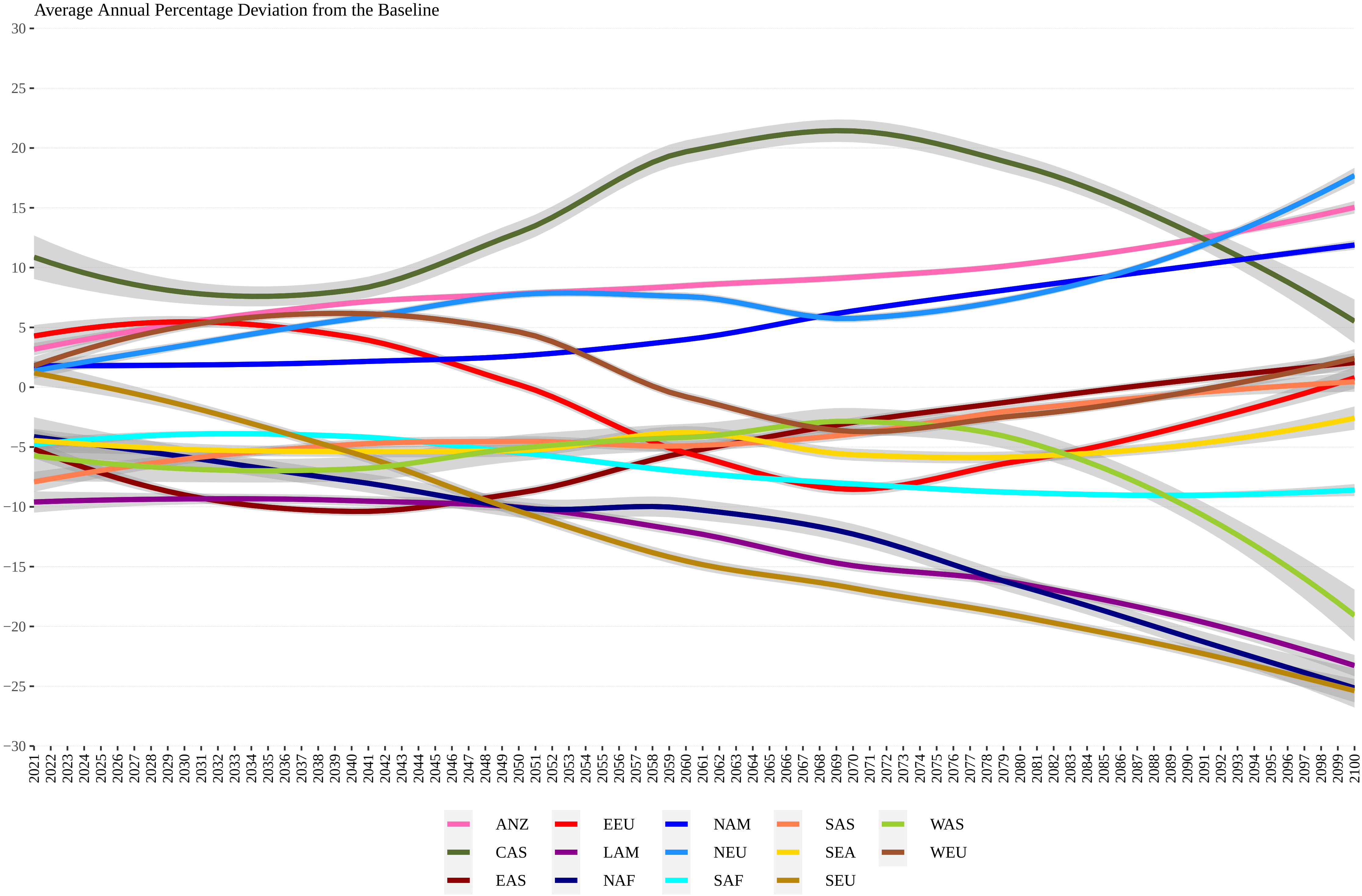
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of Average Annual Precipitation from the Baseline (1961−1990) under SSP 2−4.5 across United Nations Regions from 2021 to 2100



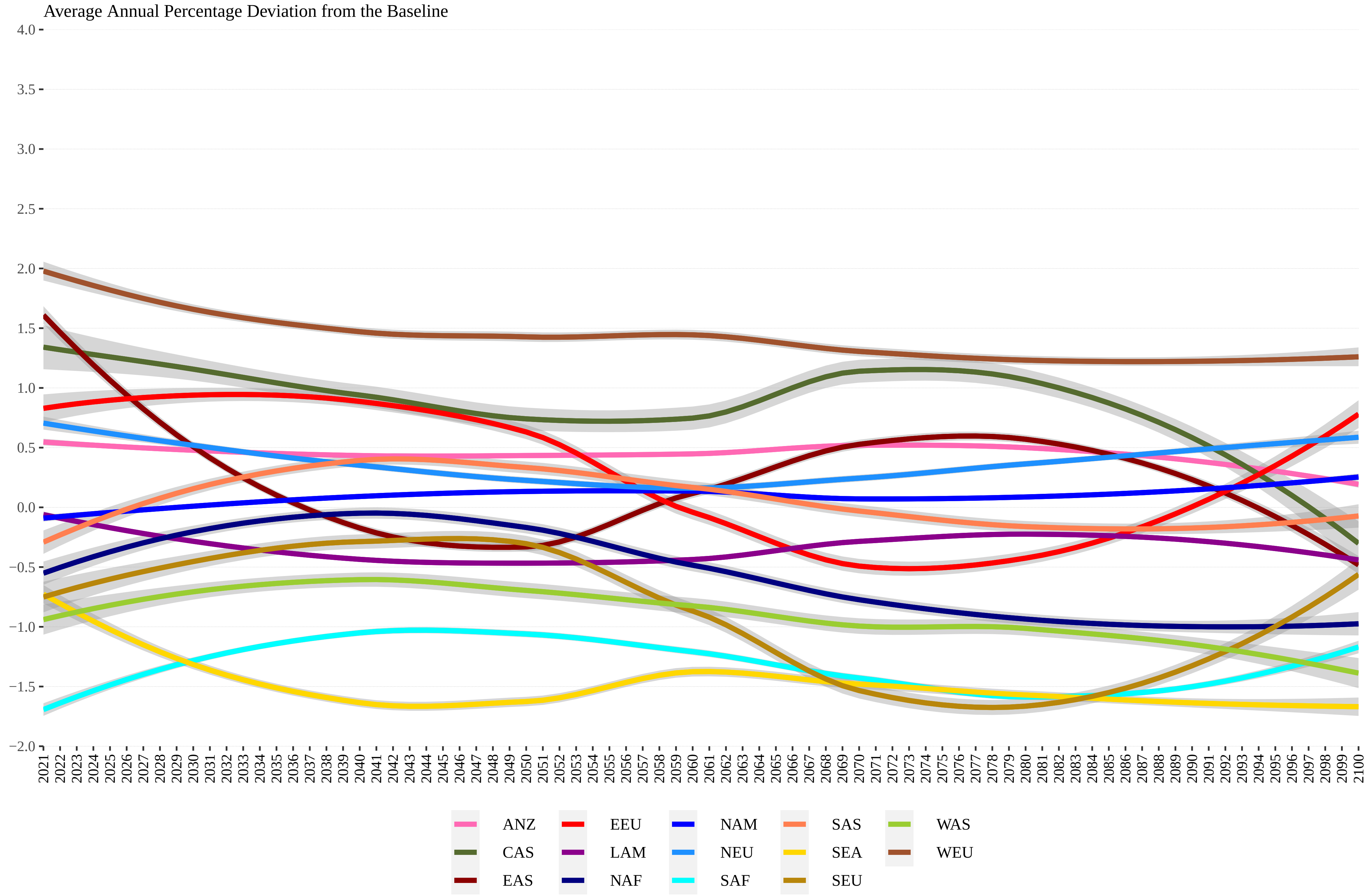
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of Average Annual Precipitation from the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100



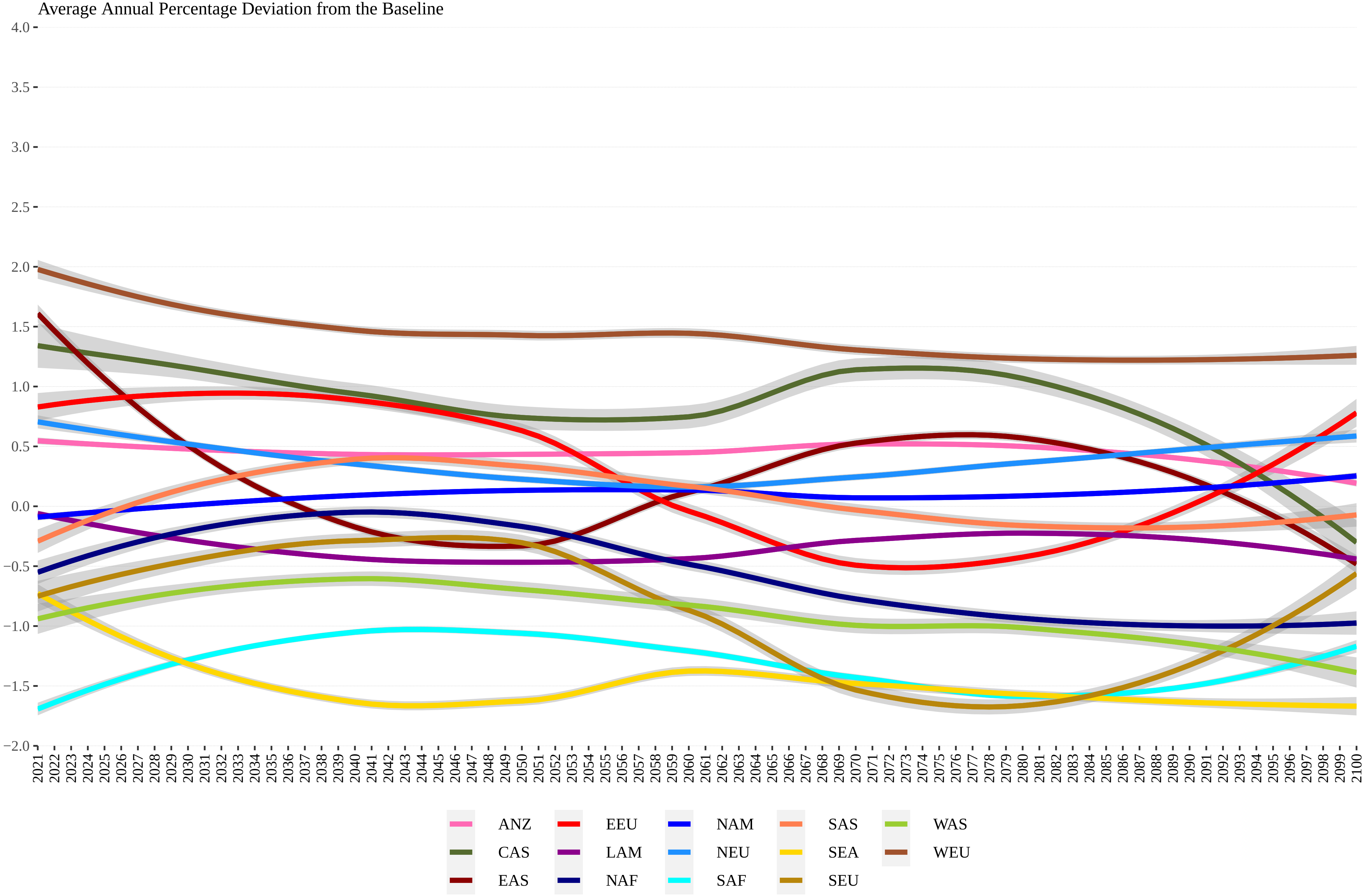
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of Average Annual Relative Humidity from the Baseline (1961−1990) under SSP 1−2.6 across United Nations Regions from 2021 to 2100



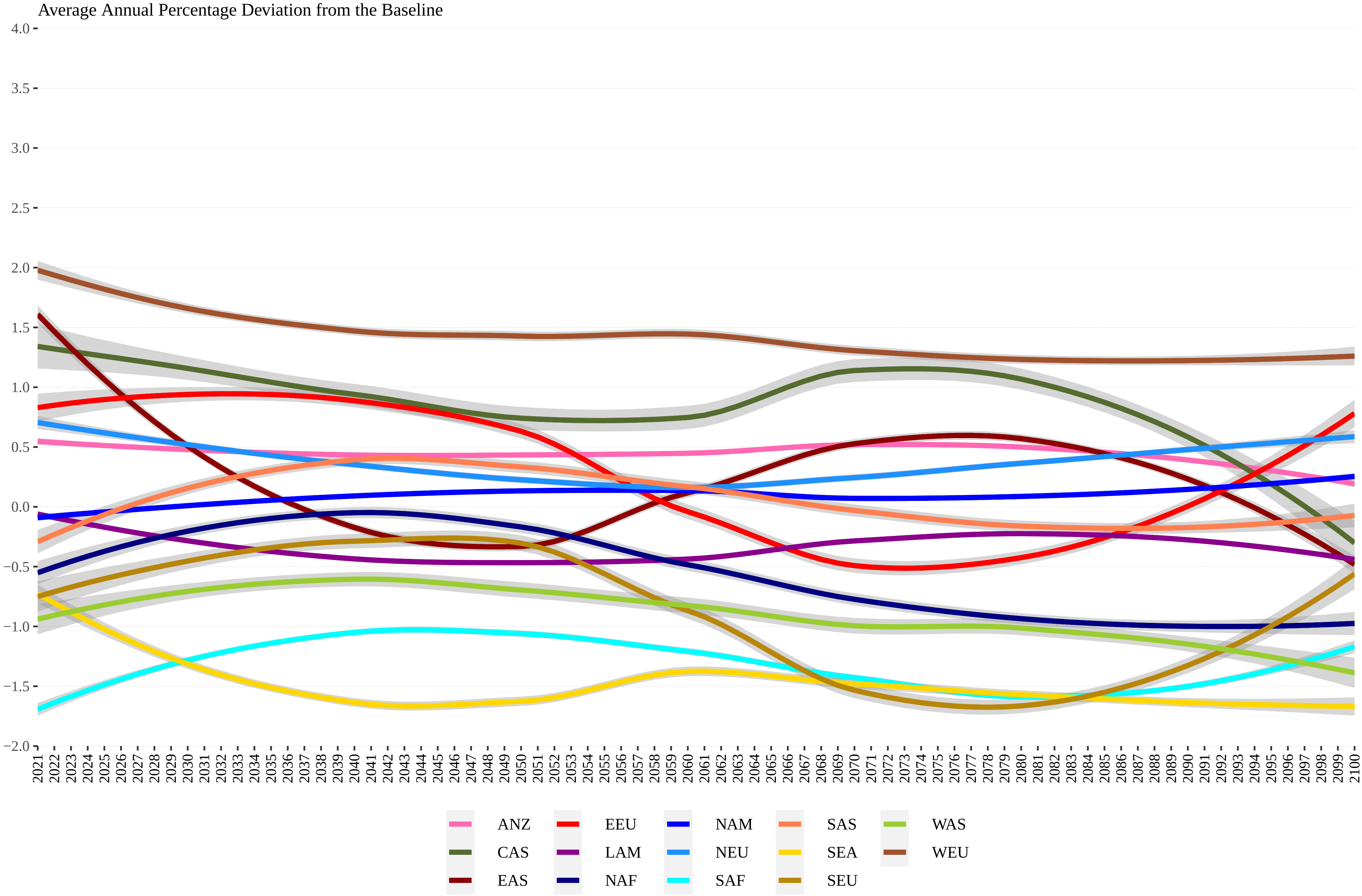
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of Average Annual Relative Humidity from the Baseline (1961−1990) under SSP 2−4.5 across United Nations Regions from 2021 to 2100



Source: Constructed by the Author using Data from ISIMIP (2022).

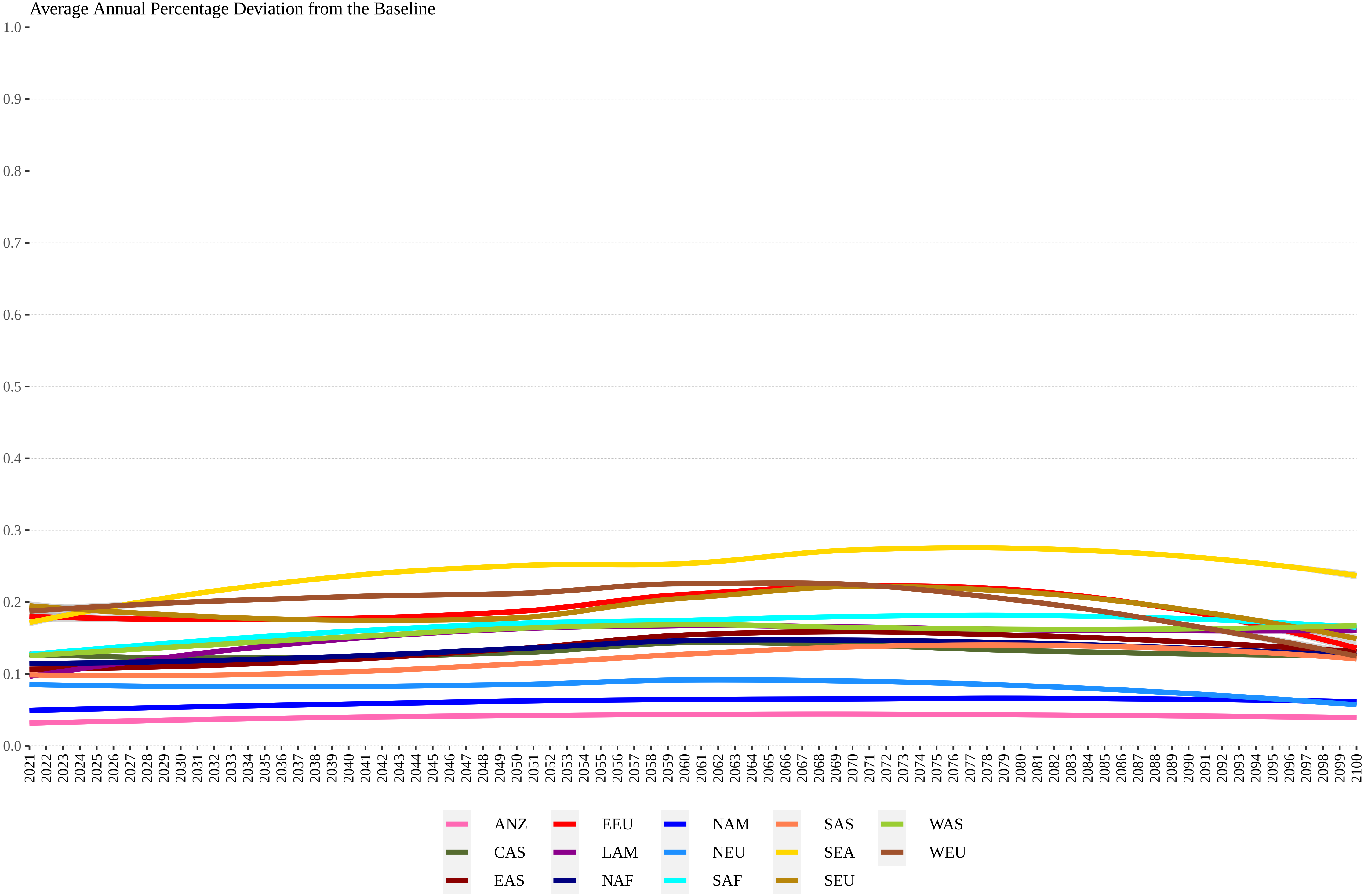
Deviation of Average Annual Relative Humidity from the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100



Source: Constructed by the Author using Data from ISIMIP (2022).

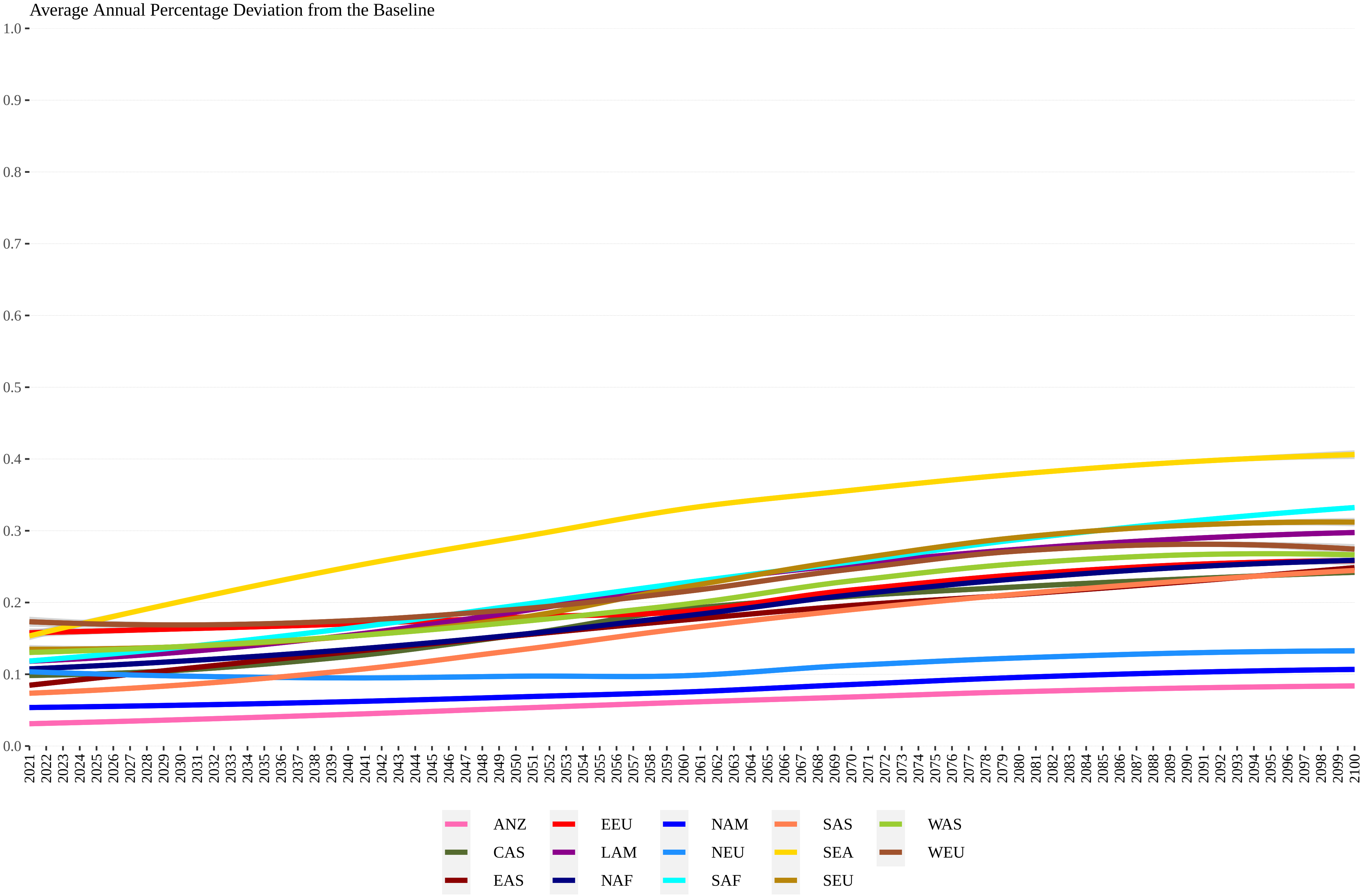
ANNEXURE 16: BEHAVIOR OF TEMPERATURE-RELATED EXTREME CLIMATE INDICATORS UNDER SSPS

Deviation of the Maximum Temperature from the 90th Percentile of the Baseline (1961−1990) under SSP 1−2.6 across United Nations Regions from 2021 to 2100



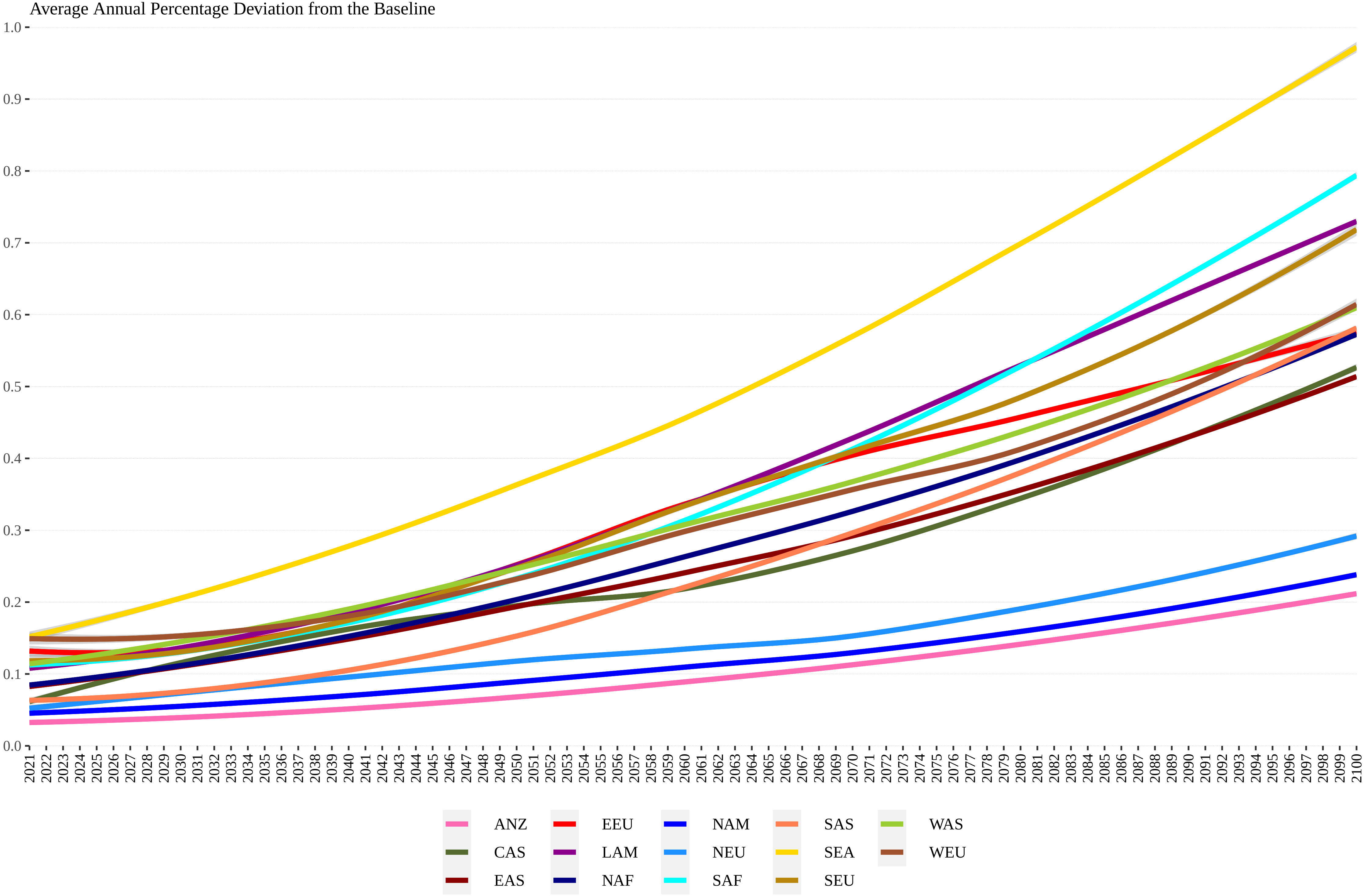
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of the Maximum Temperature from the 90th Percentile of the Baseline (1961−1990) under SSP 2−4.5 across United Nations Regions from 2021 to 2100



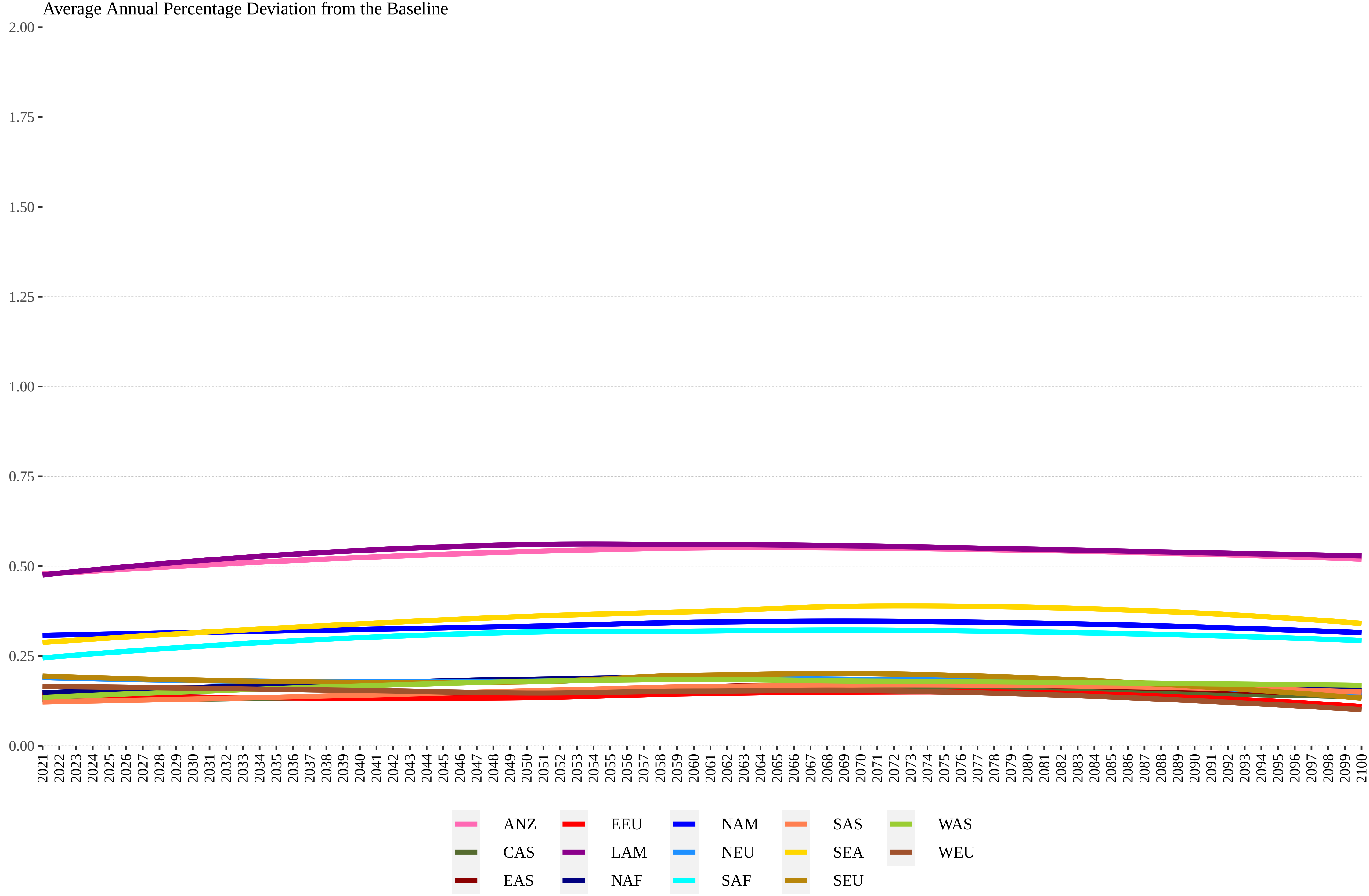
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of the Maximum Temperature from the 90th Percentile of the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100

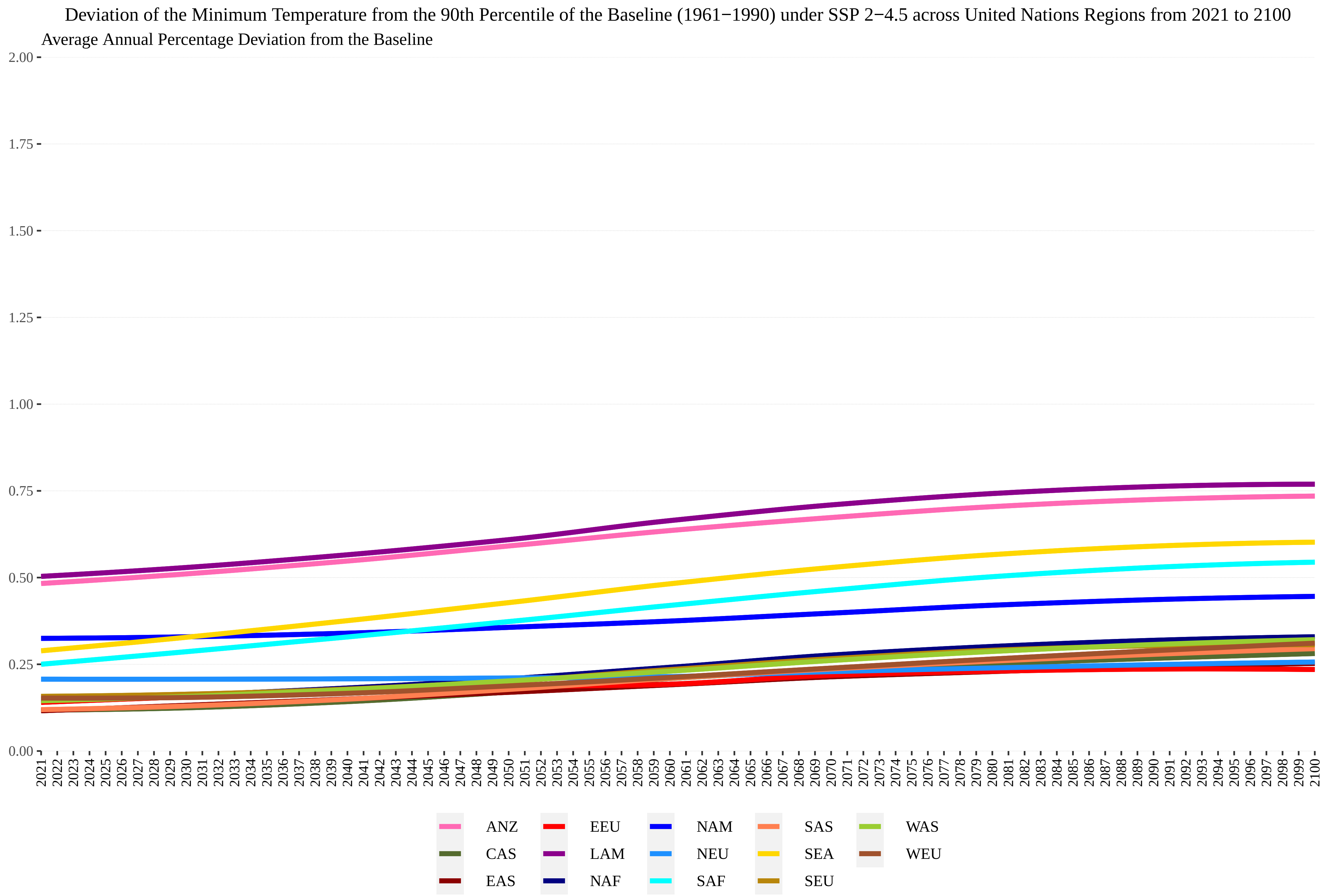


Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of the Minimum Temperature from the 90th Percentile of the Baseline (1961−1990) under SSP 1−2.6 across United Nations Regions from 2021 to 2100

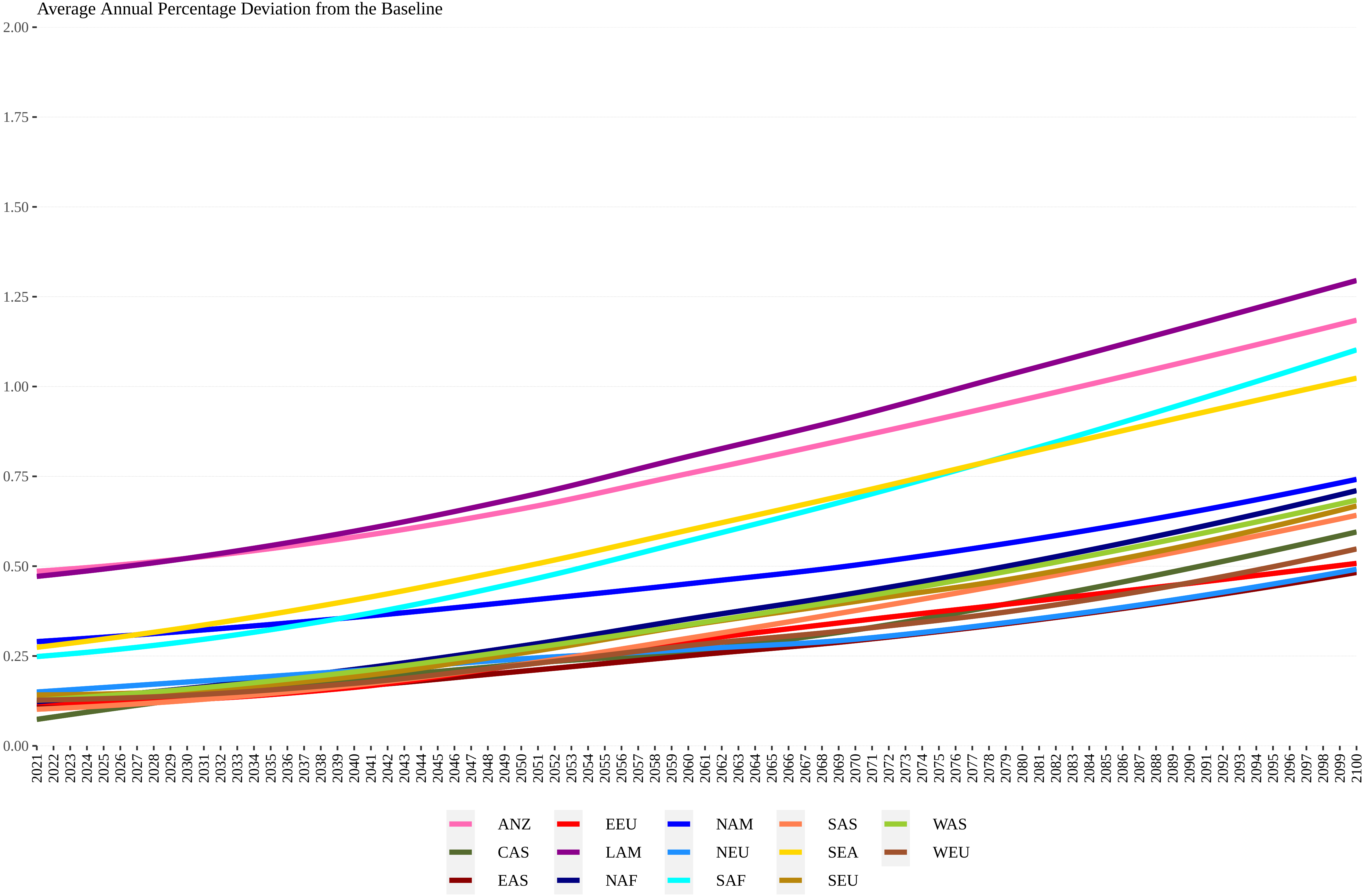


Source: Constructed by the Author using Data from ISIMIP (2022).

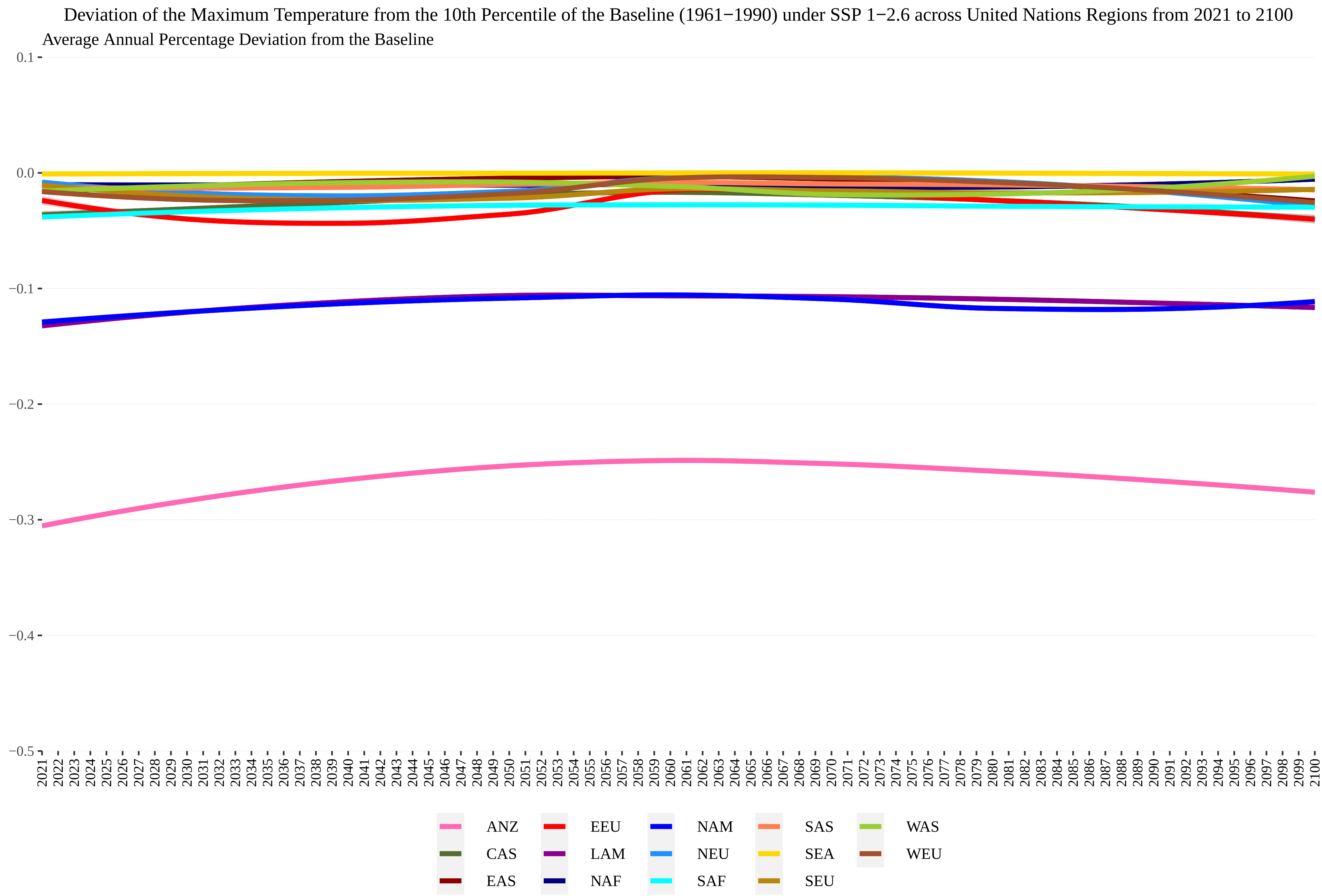


Source: Constructed by the Author using Data from ISIMIP (2022).

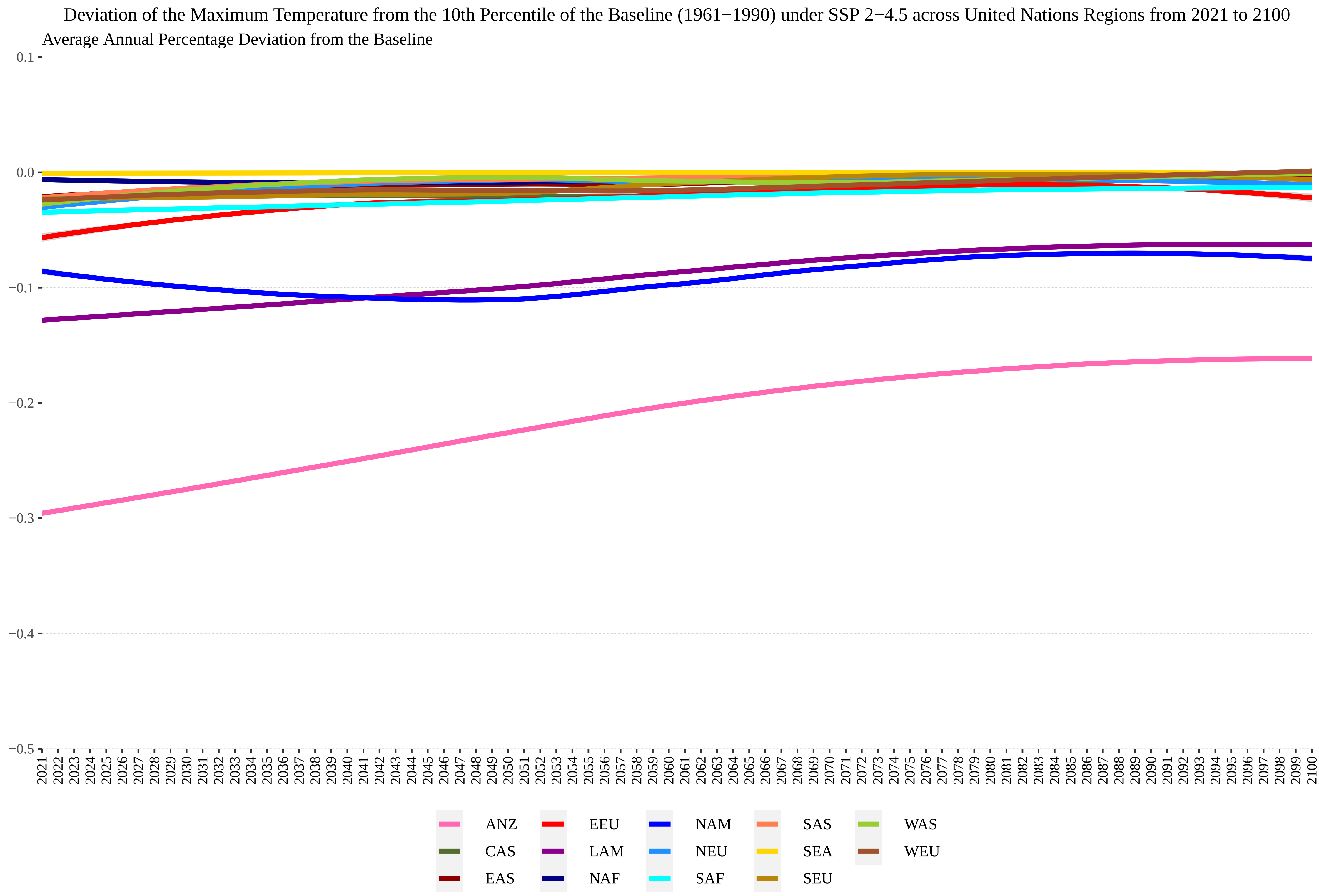
Deviation of the Minimum Temperature from the 90th Percentile of the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100



Source: Constructed by the Author using Data from ISIMIP (2022).

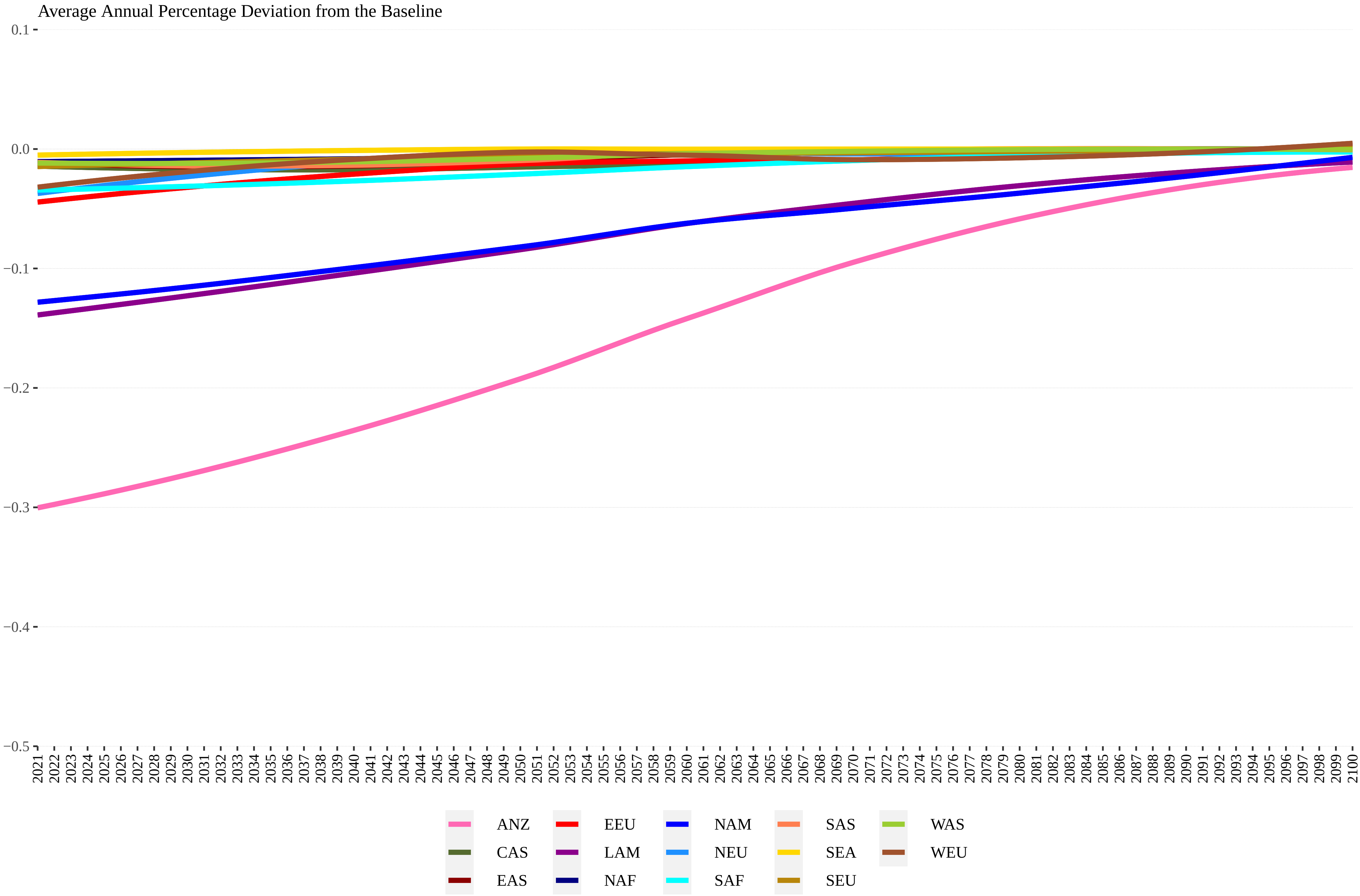


Source: Constructed by the Author using Data from ISIMIP (2022).



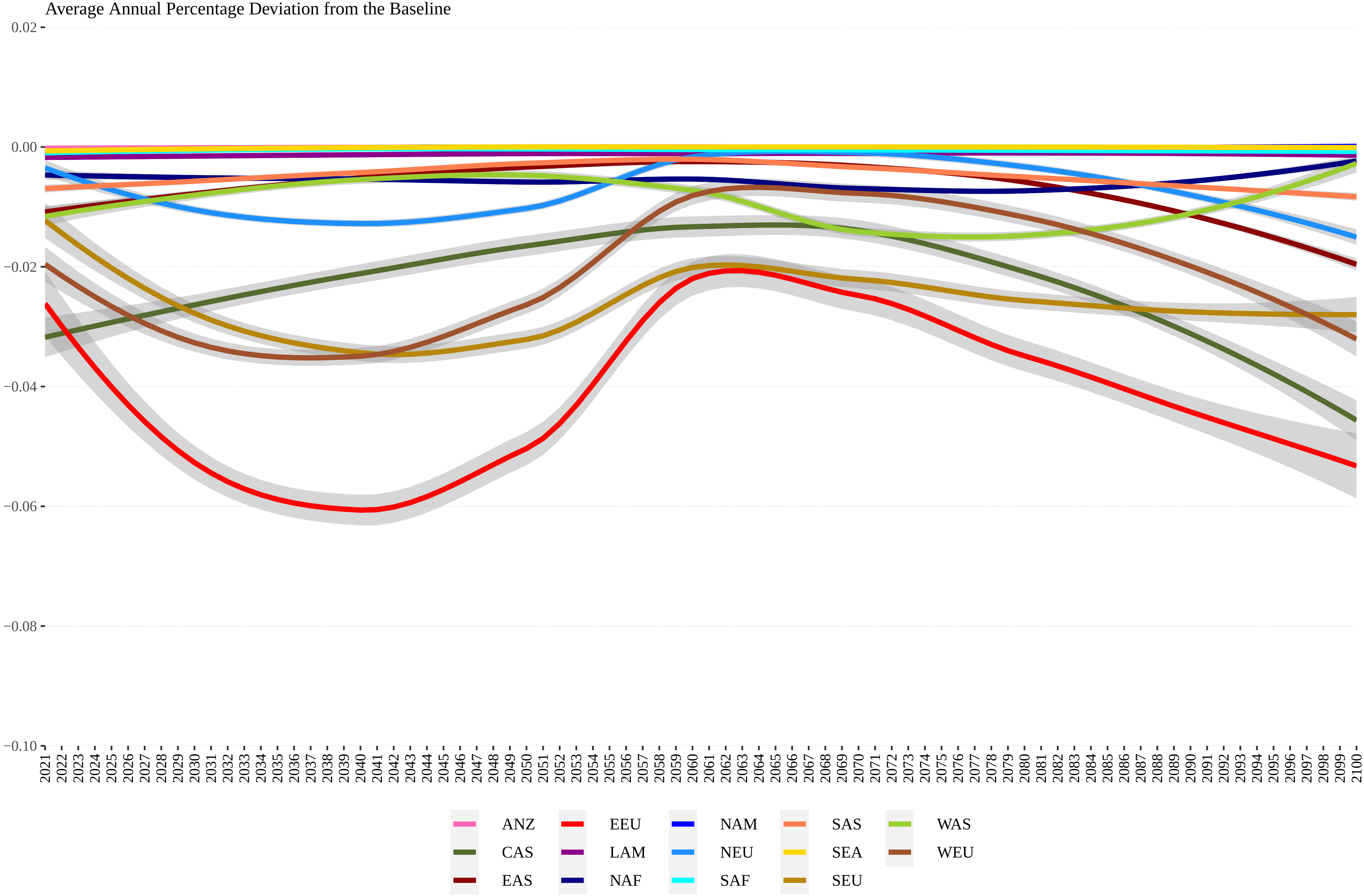
Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of the Maximum Temperature from the 10th Percentile of the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100

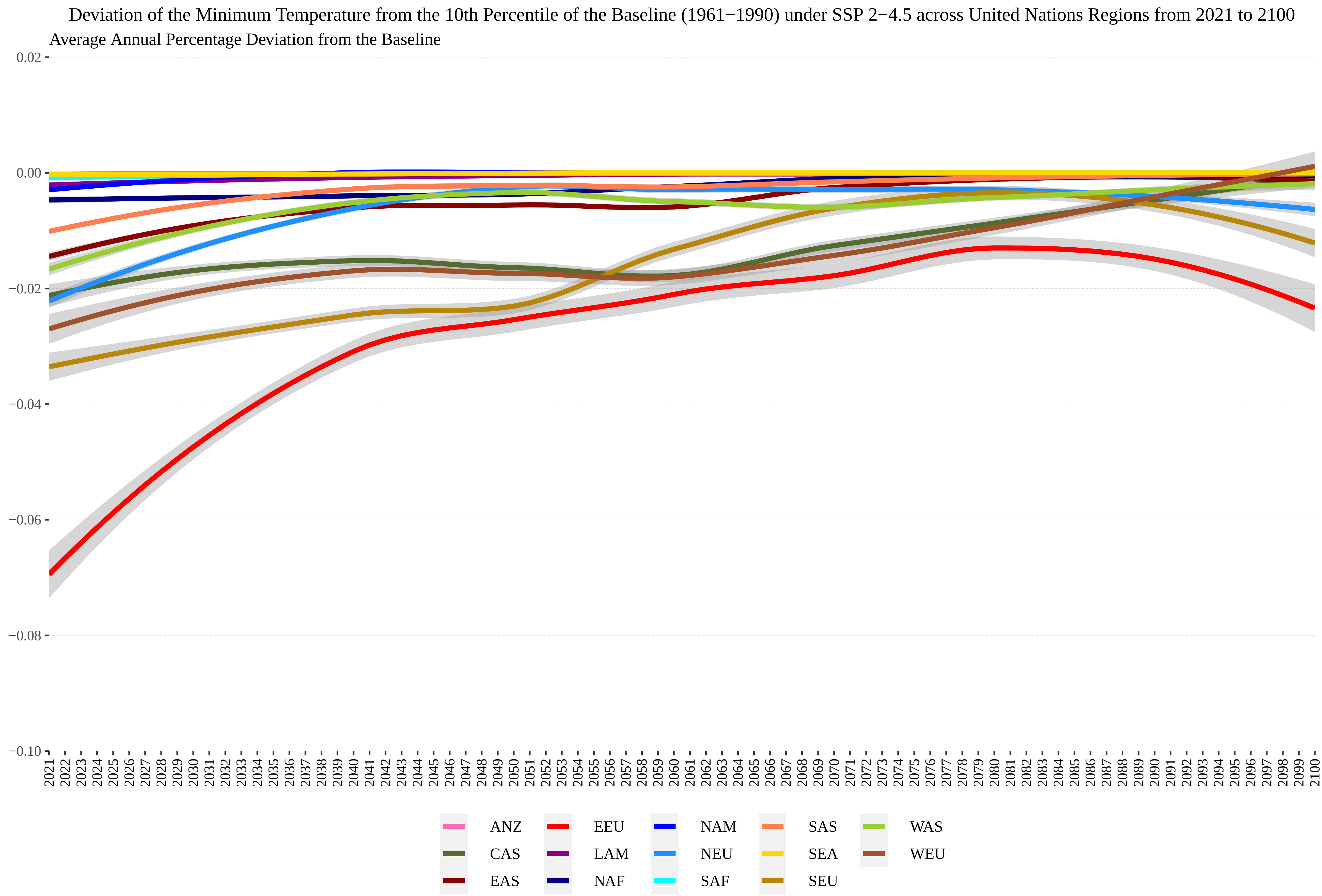


Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of the Minimum Temperature from the 10th Percentile of the Baseline (1961−1990) under SSP 1−2.6 across United Nations Regions from 2021 to 2100



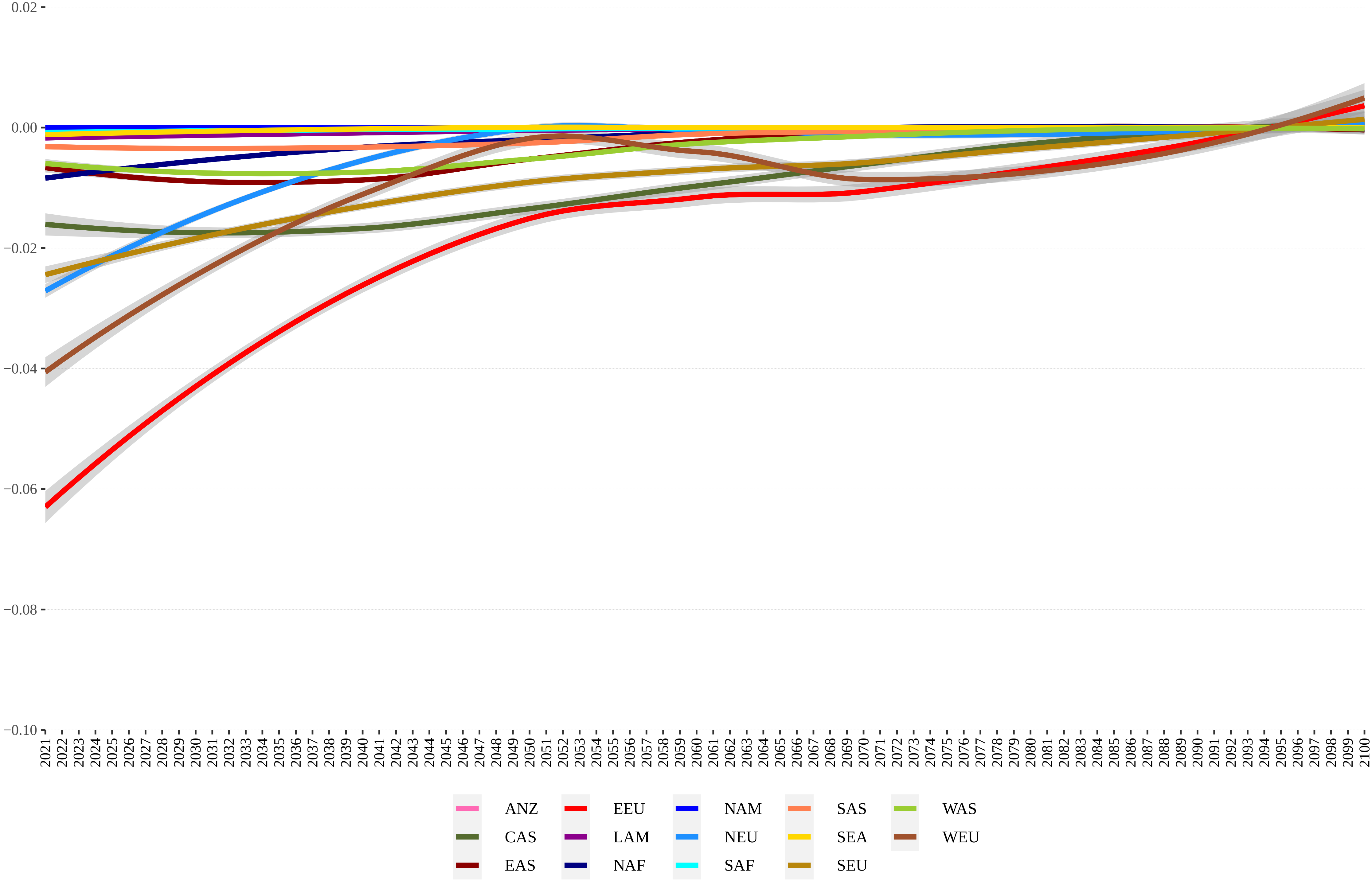
Source: Constructed by the Author using Data from ISIMIP (2022).



Source: Constructed by the Author using Data from ISIMIP (2022).

Deviation of the Minimum Temperature from the 10th Percentile of the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100

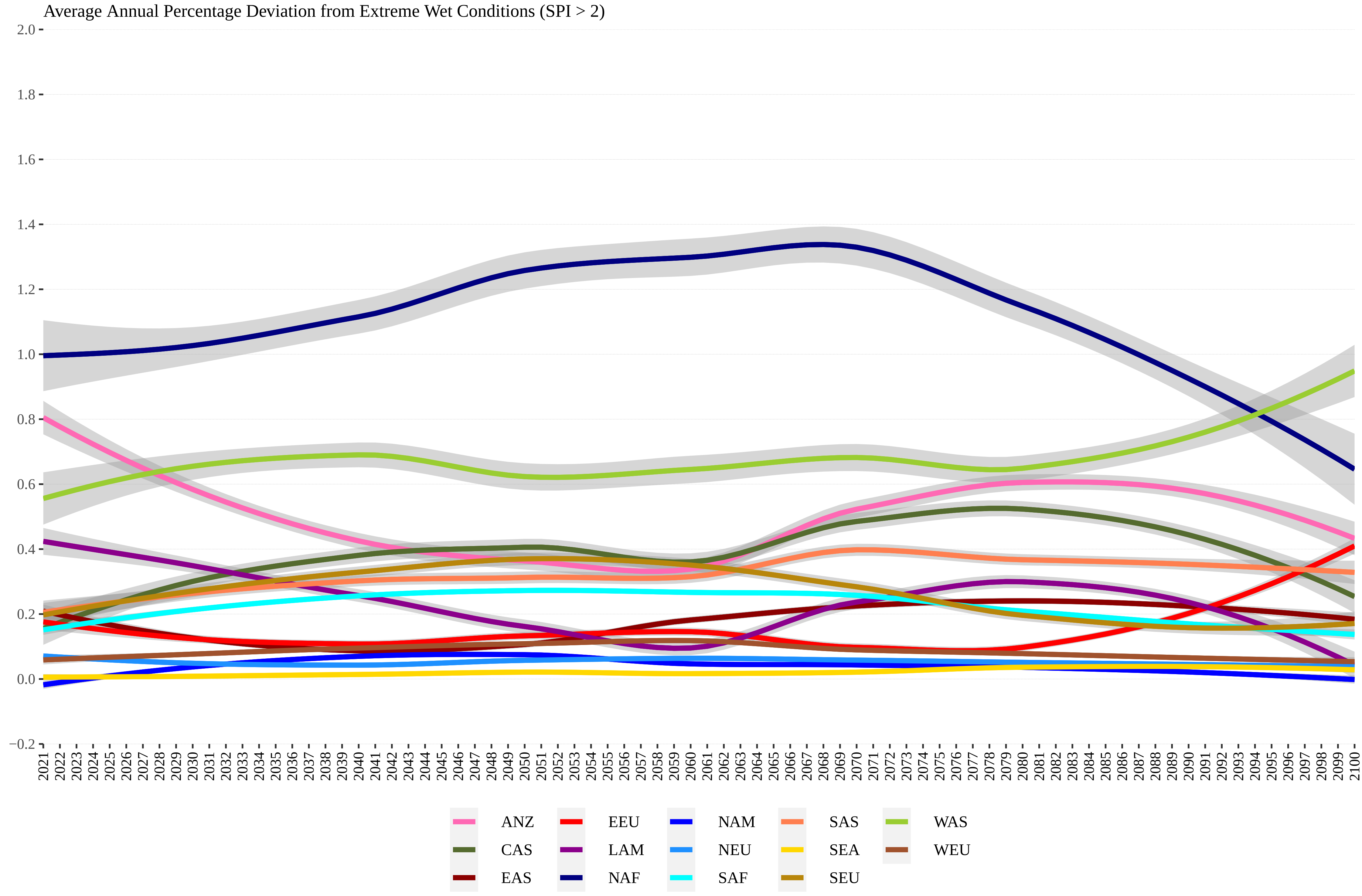
Average Annual Percentage Deviation from the Baseline



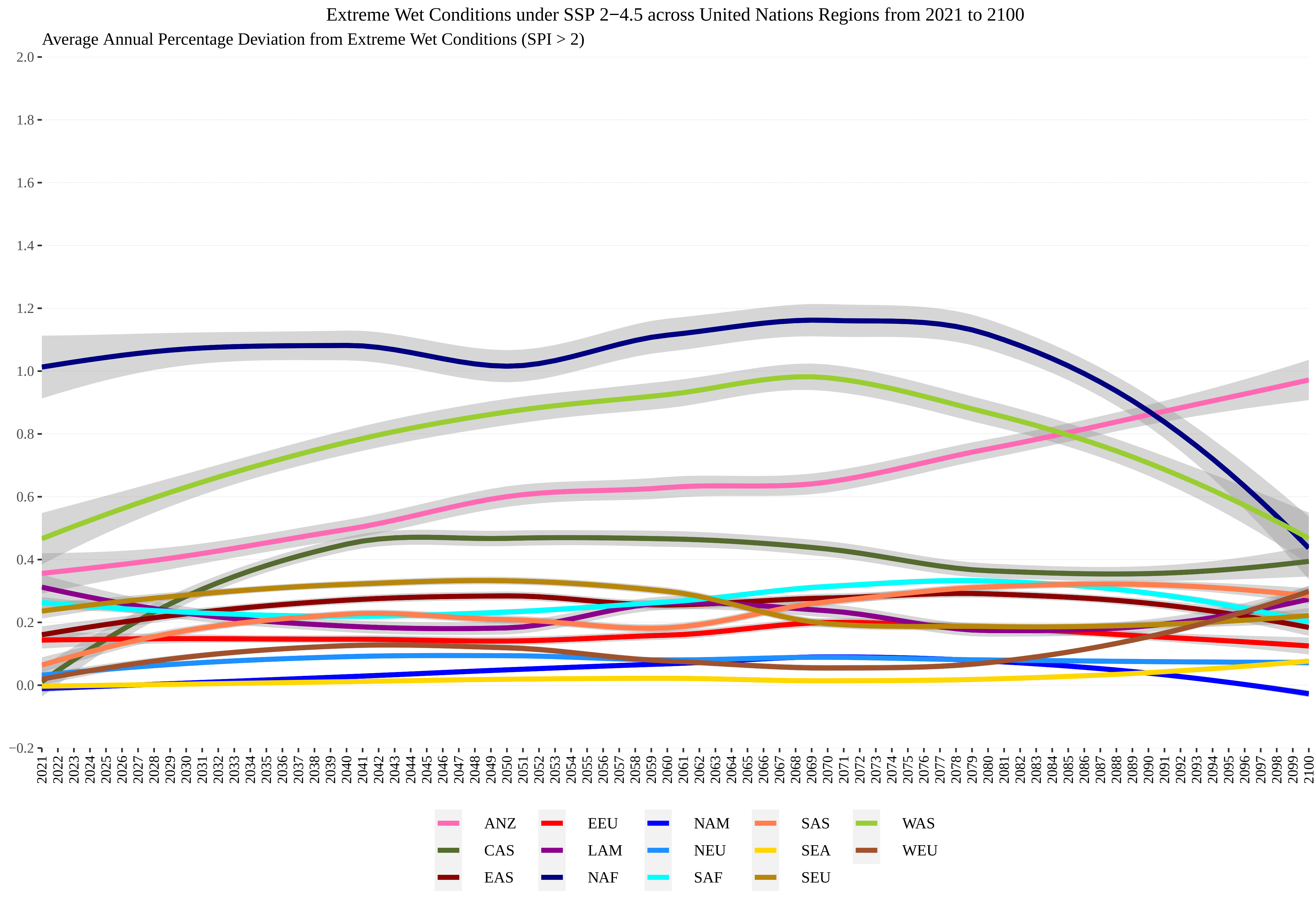
Source: Constructed by the Author using Data from ISIMIP (2022).

ANNEXURE 17: BEHAVIOR OF PRECIPITATION AND WINDSPEED-RELATED EXTREME CLIMATE INDICATORS UNDER SSPS

Extreme Wet Conditions under SSP 1−2.6 across United Nations Regions from 2021 to 2100



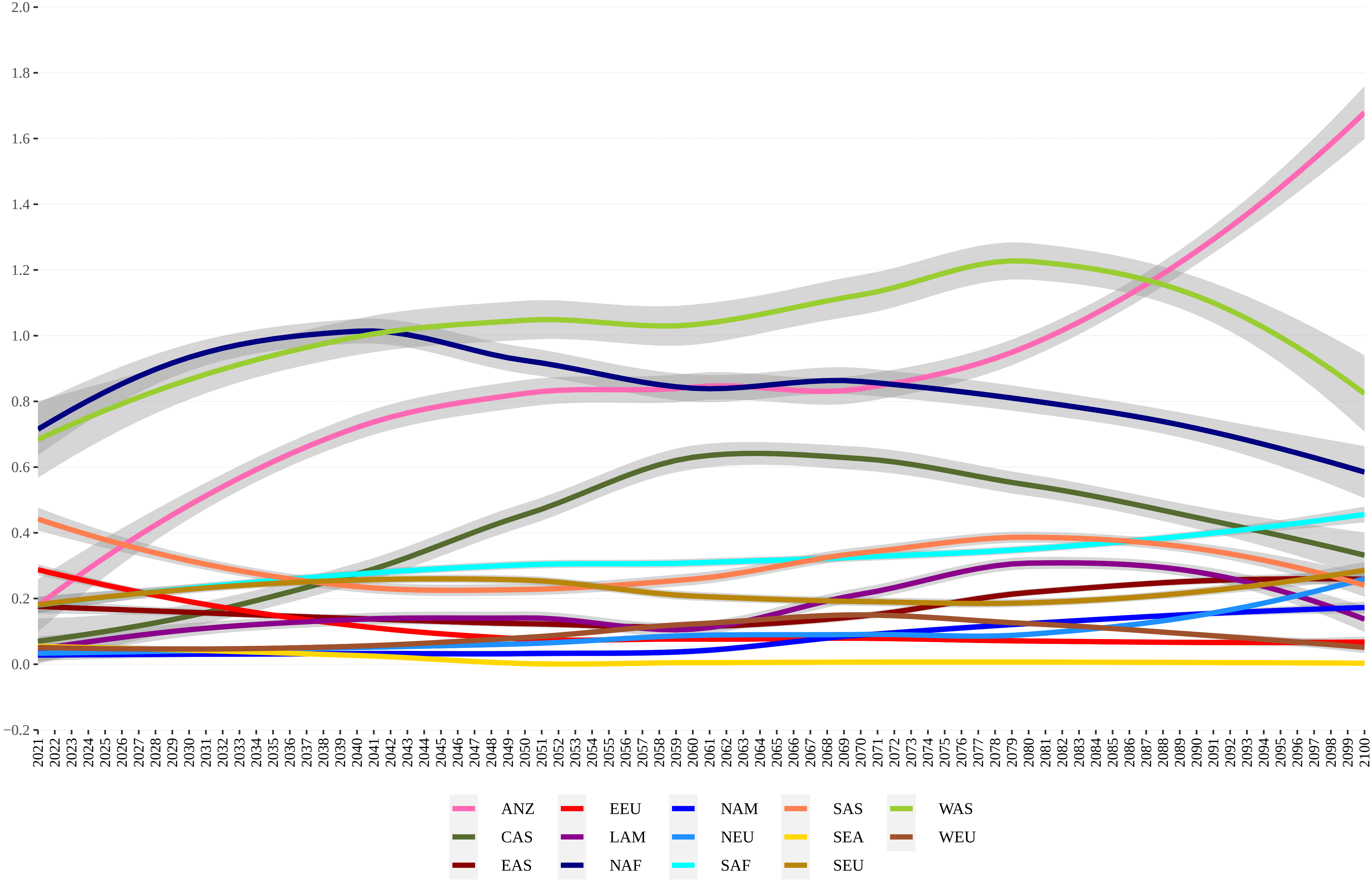
Source: Constructed by the Author using Data from ISIMIP (2022).



Source: Constructed by the Author using Data from ISIMIP (2022).

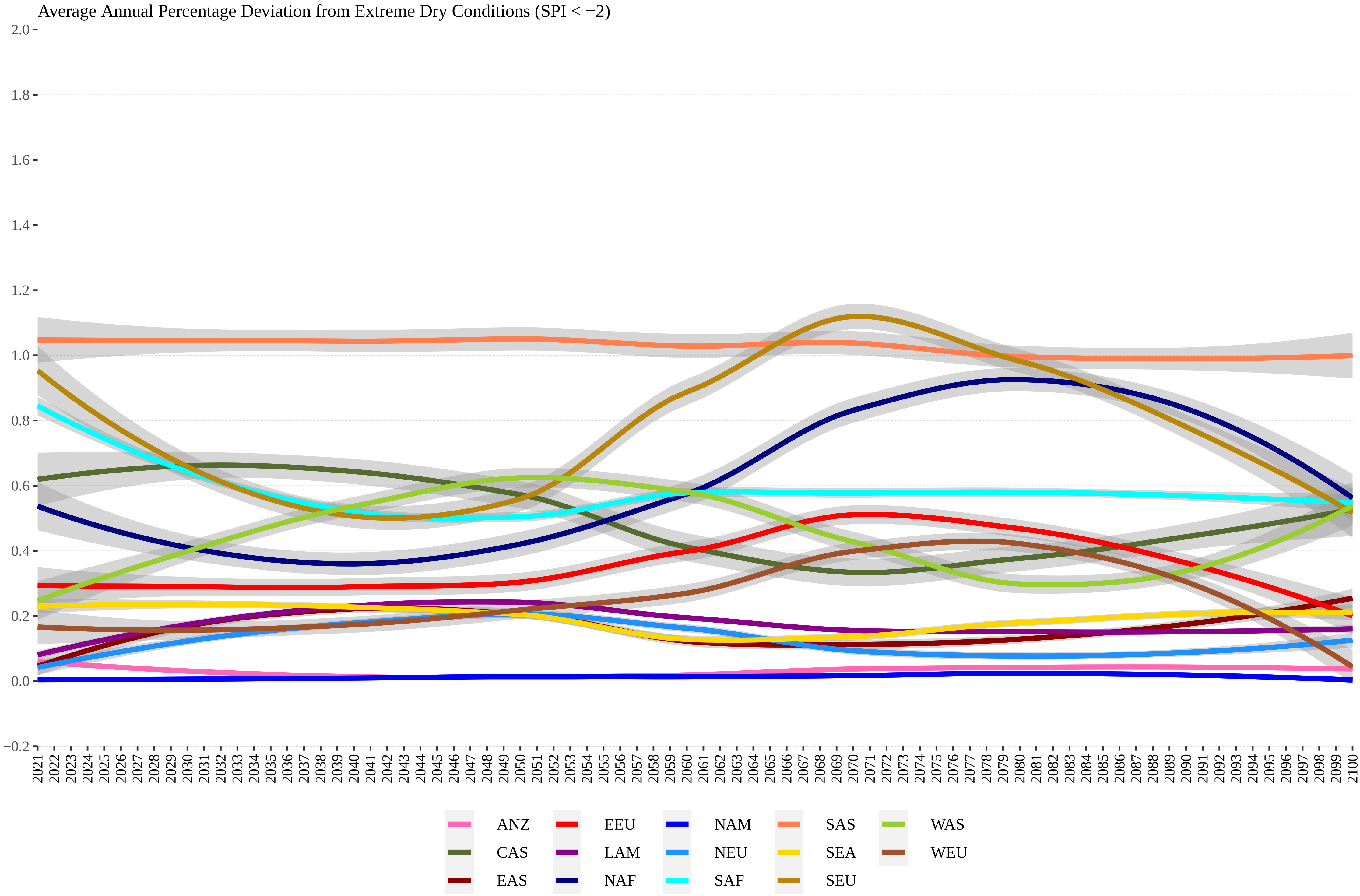
Extreme Wet Conditions under SSP 5−8.5 across United Nations Regions from 2021 to 2100

Average Annual Percentage Deviation from Extreme Wet Conditions (SPI > 2)

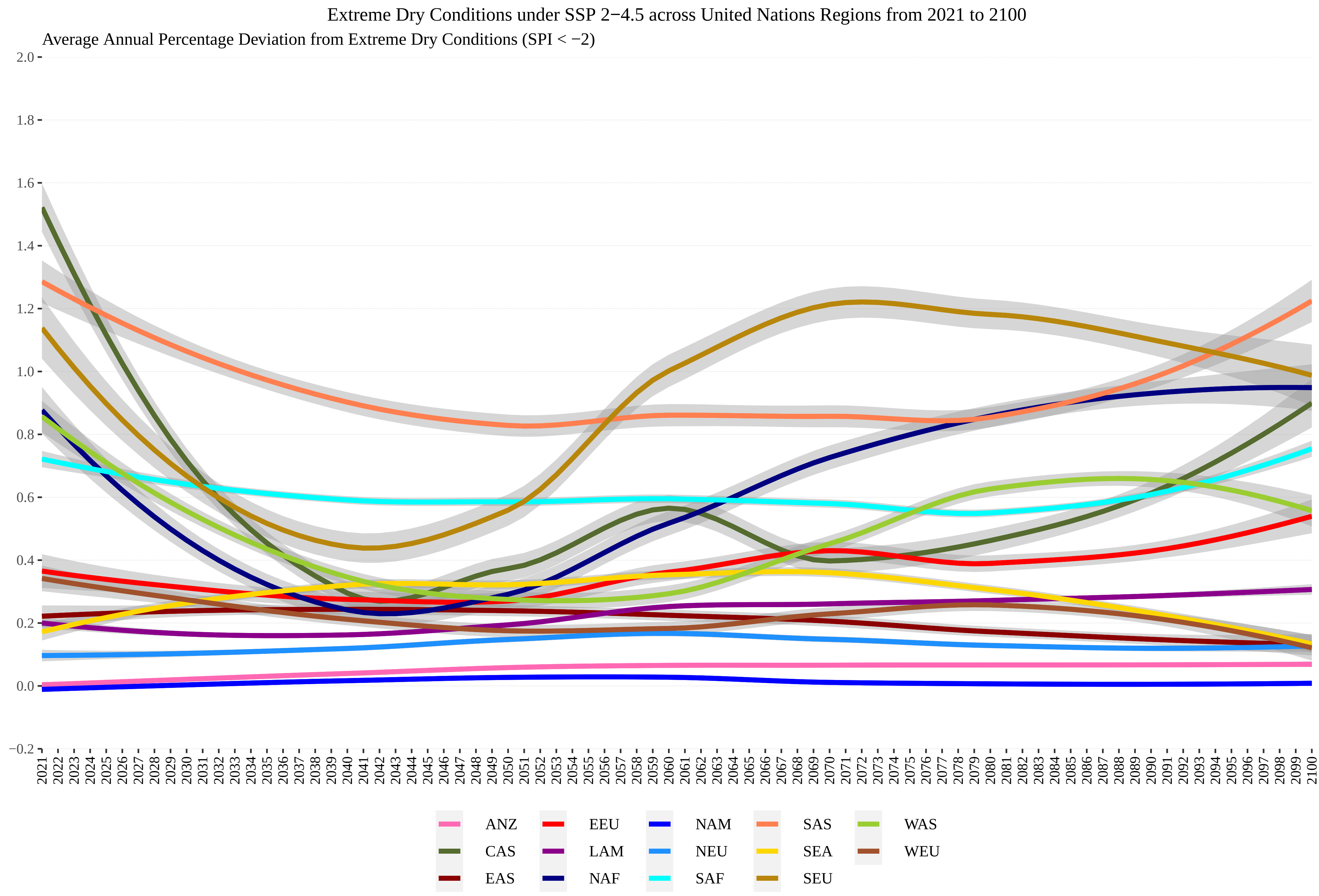


Source: Constructed by the Author using Data from ISIMIP (2022).

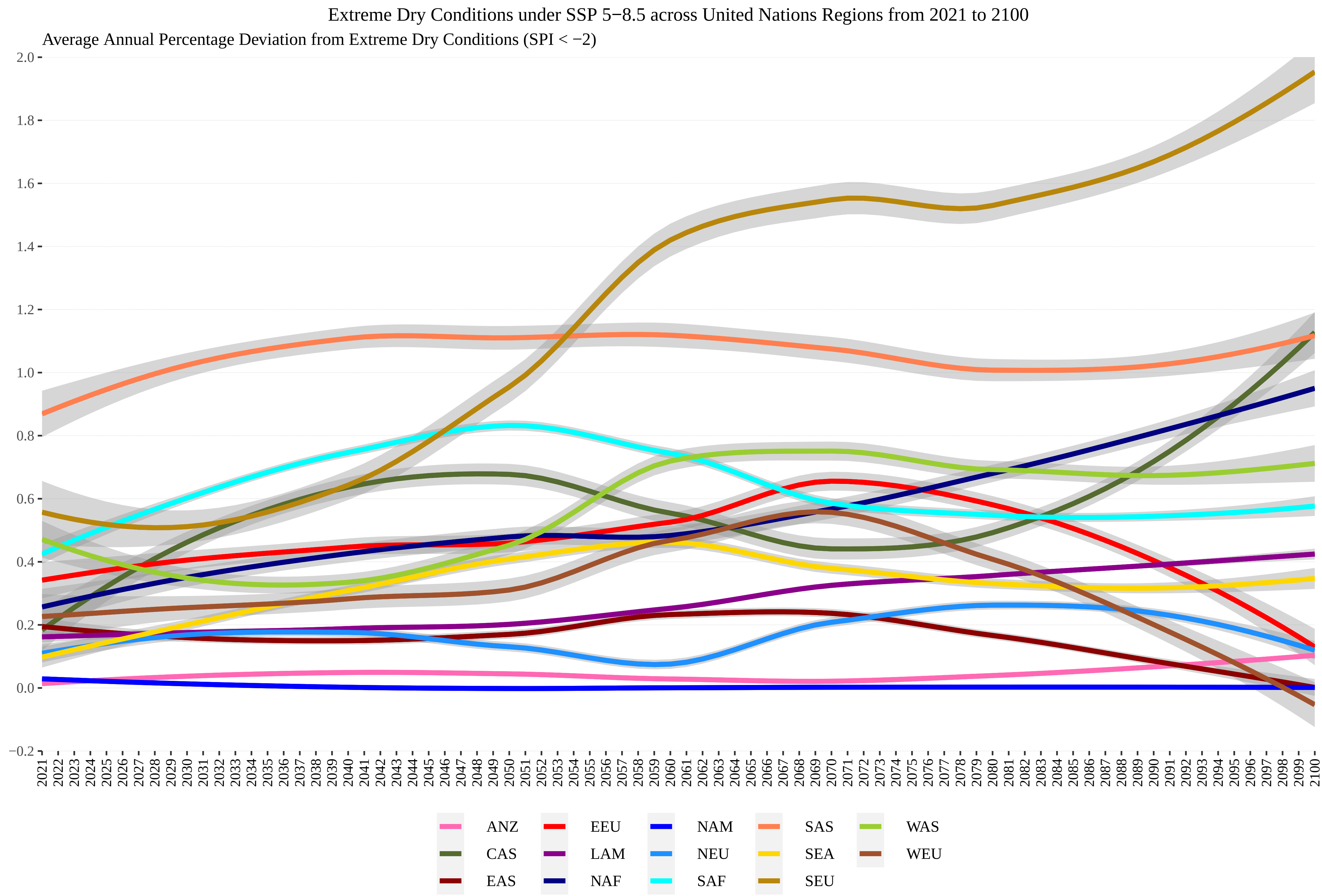
Extreme Dry Conditions under SSP 1−2.6 across United Nations Regions from 2021 to 2100



Source: Constructed by the Author using Data from ISIMIP (2022).



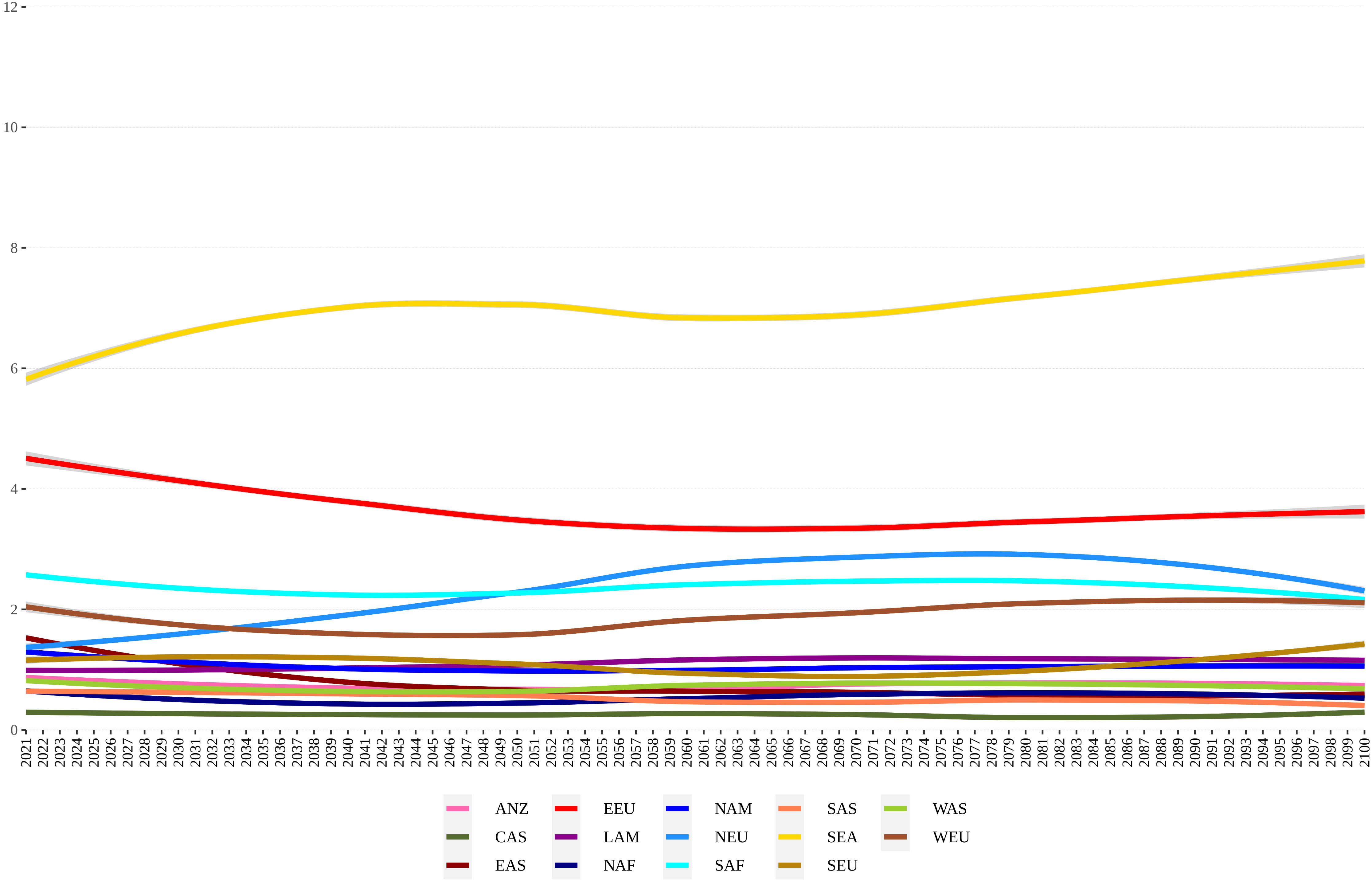
Source: Constructed by the Author using Data from ISIMIP (2022).



Source: Constructed by the Author using Data from ISIMIP (2022).

Extreme Wind Speeds compared to the Baseline (1961−1990) under SSP 1−2.6 across United Nations Regions from 2021 to 2100

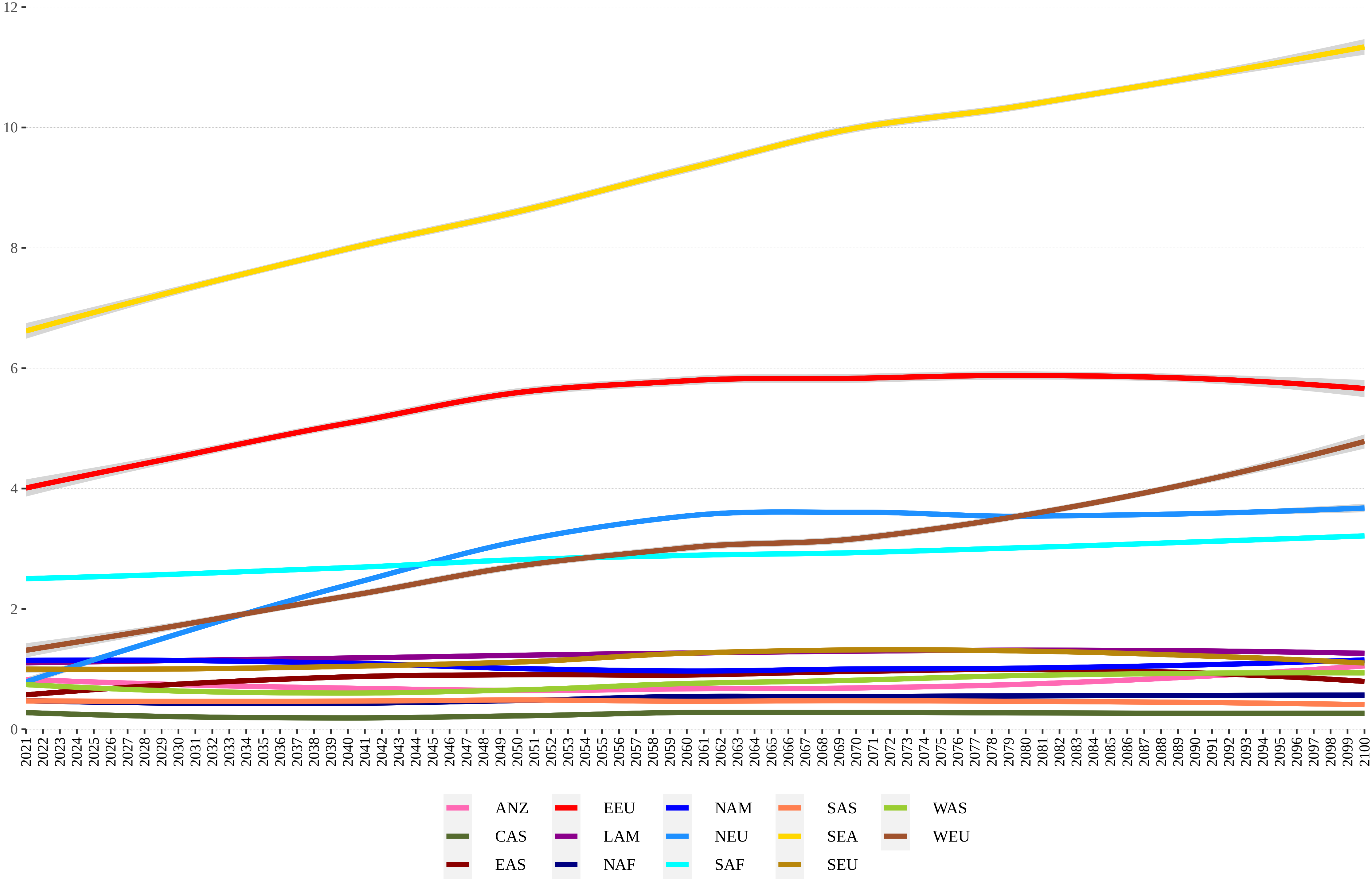
Average Annual Percentage Deviation from the Average Baseline Wind Speed



Source: Constructed by the Author using Data from ISIMIP (2022).

Extreme Wind Speeds compared to the Baseline (1961−1990) under SSP 2−4.5 across United Nations Regions from 2021 to 2100

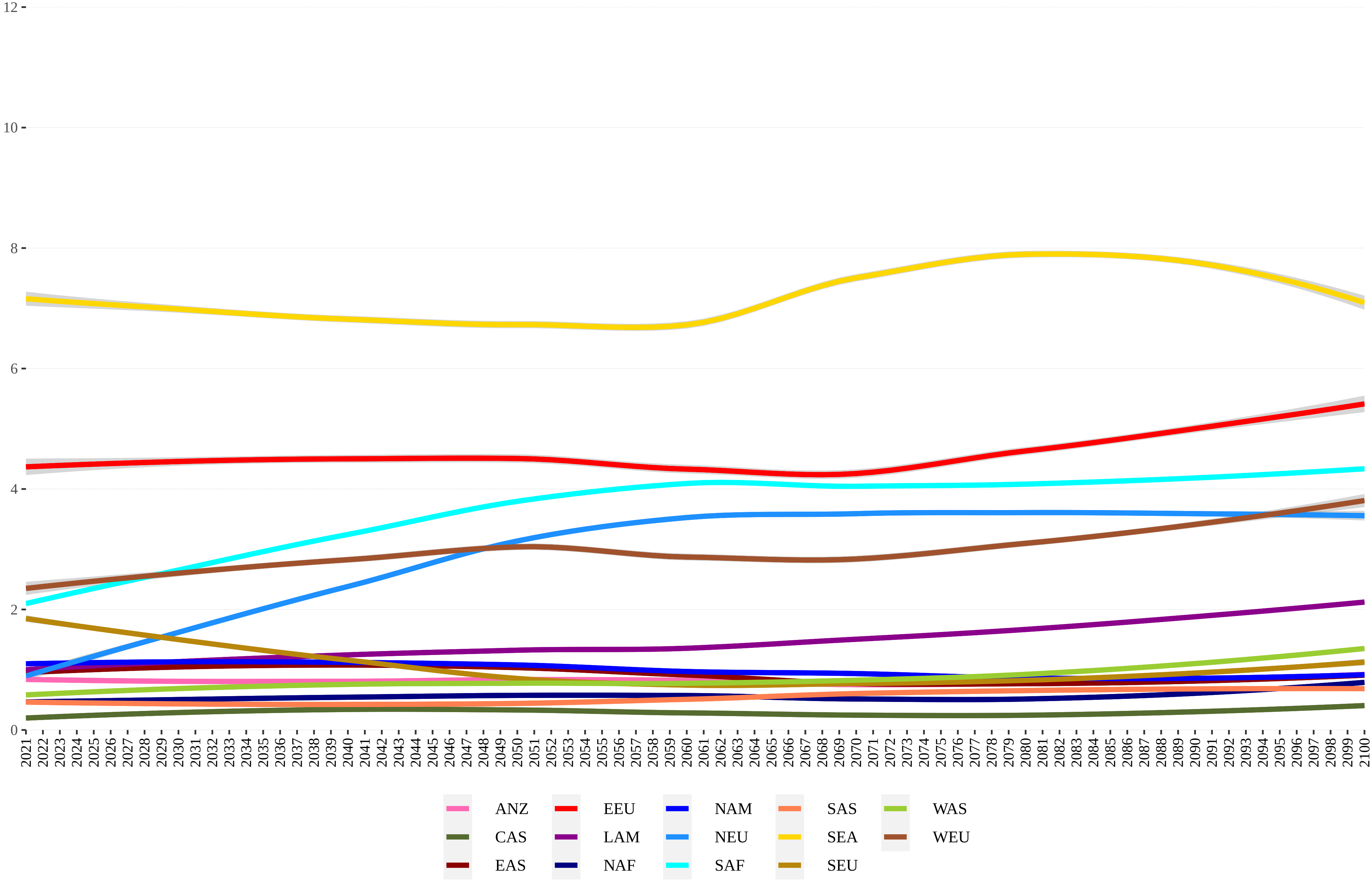
Average Annual Percentage Deviation from the Average Baseline Wind Speed



Source: Constructed by the Author using Data from ISIMIP (2022).

Extreme Wind Speeds compared to the Baseline (1961−1990) under SSP 5−8.5 across United Nations Regions from 2021 to 2100

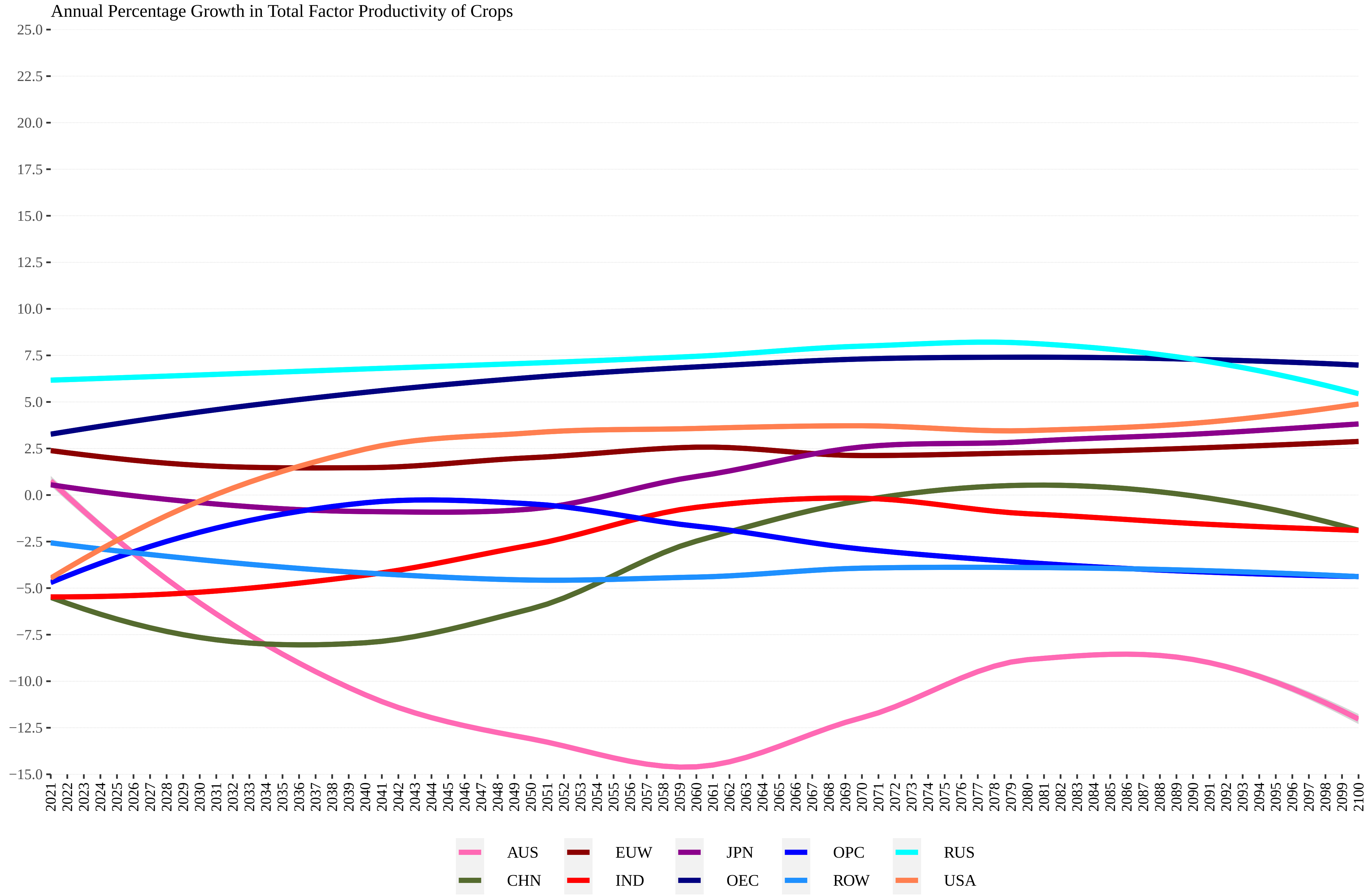
Average Annual Percentage Deviation from the Average Baseline Wind Speed



Source: Constructed by the Author using Data from ISIMIP (2022).

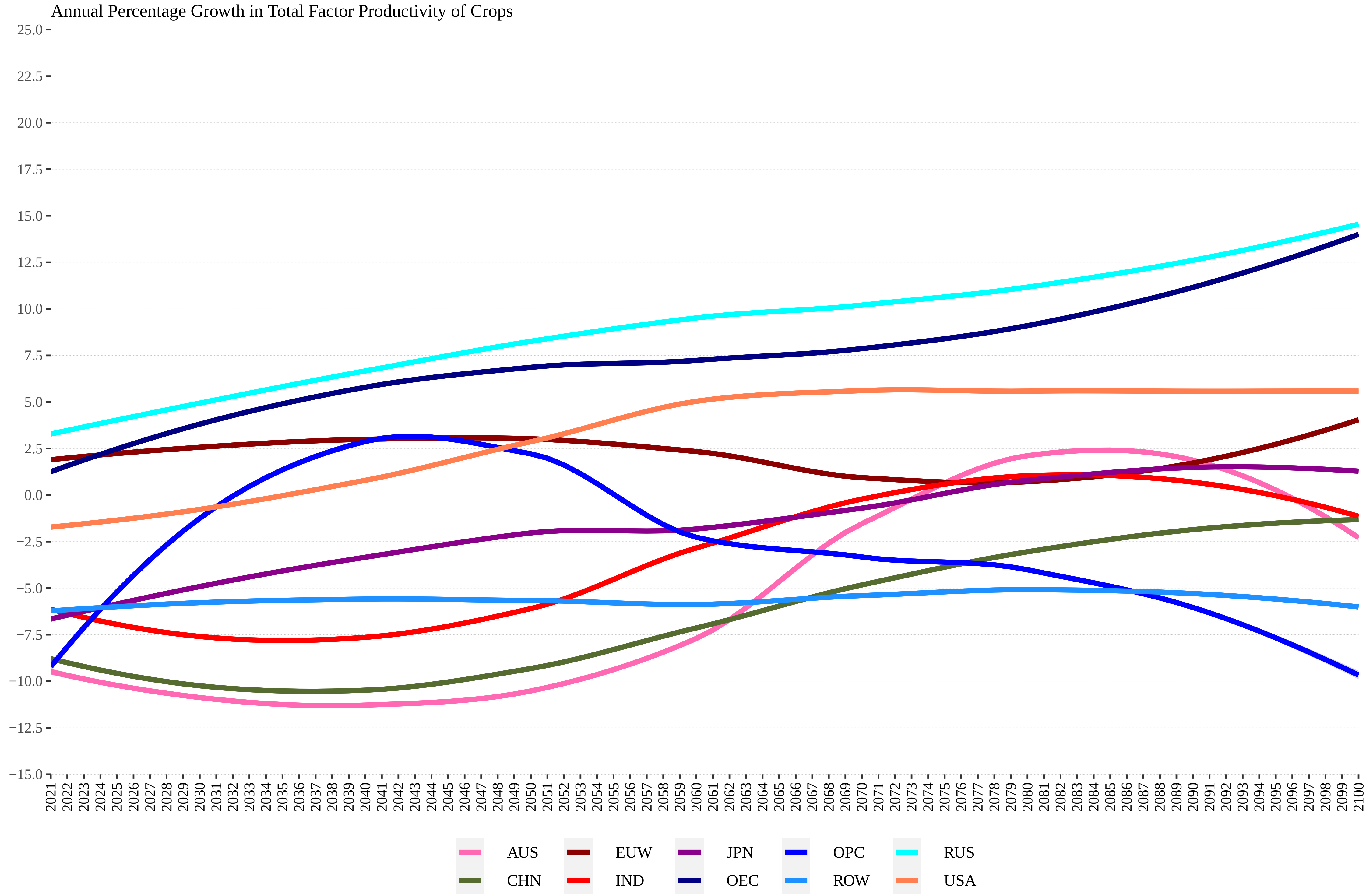
ANNEXURE 18: CROP PRODUCTION UNDER SSPS

Growth in Total Factor Productivity of Crops across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



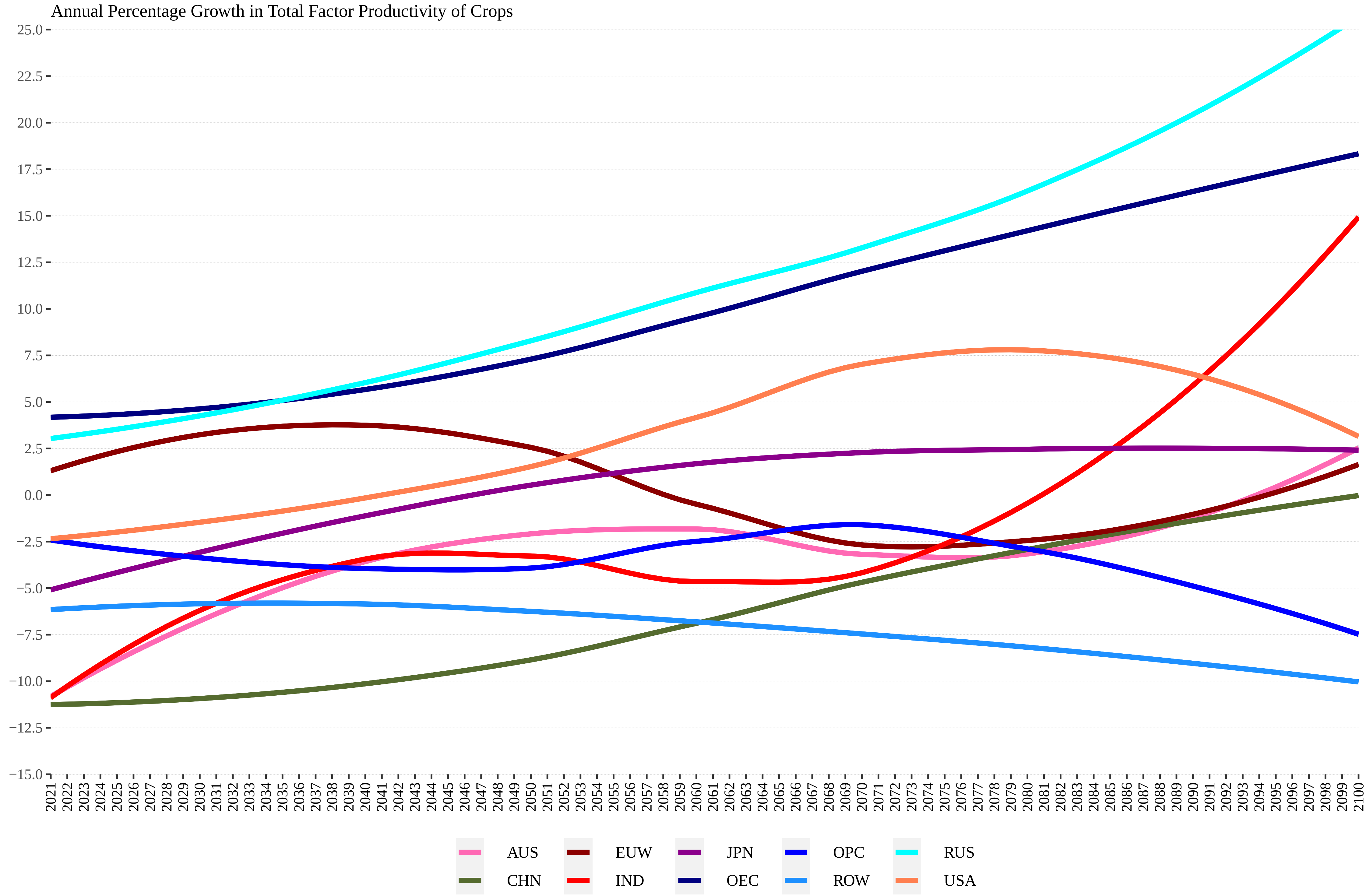
Source: Constructed by the Author.

Growth in Total Factor Productivity of Crops across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100

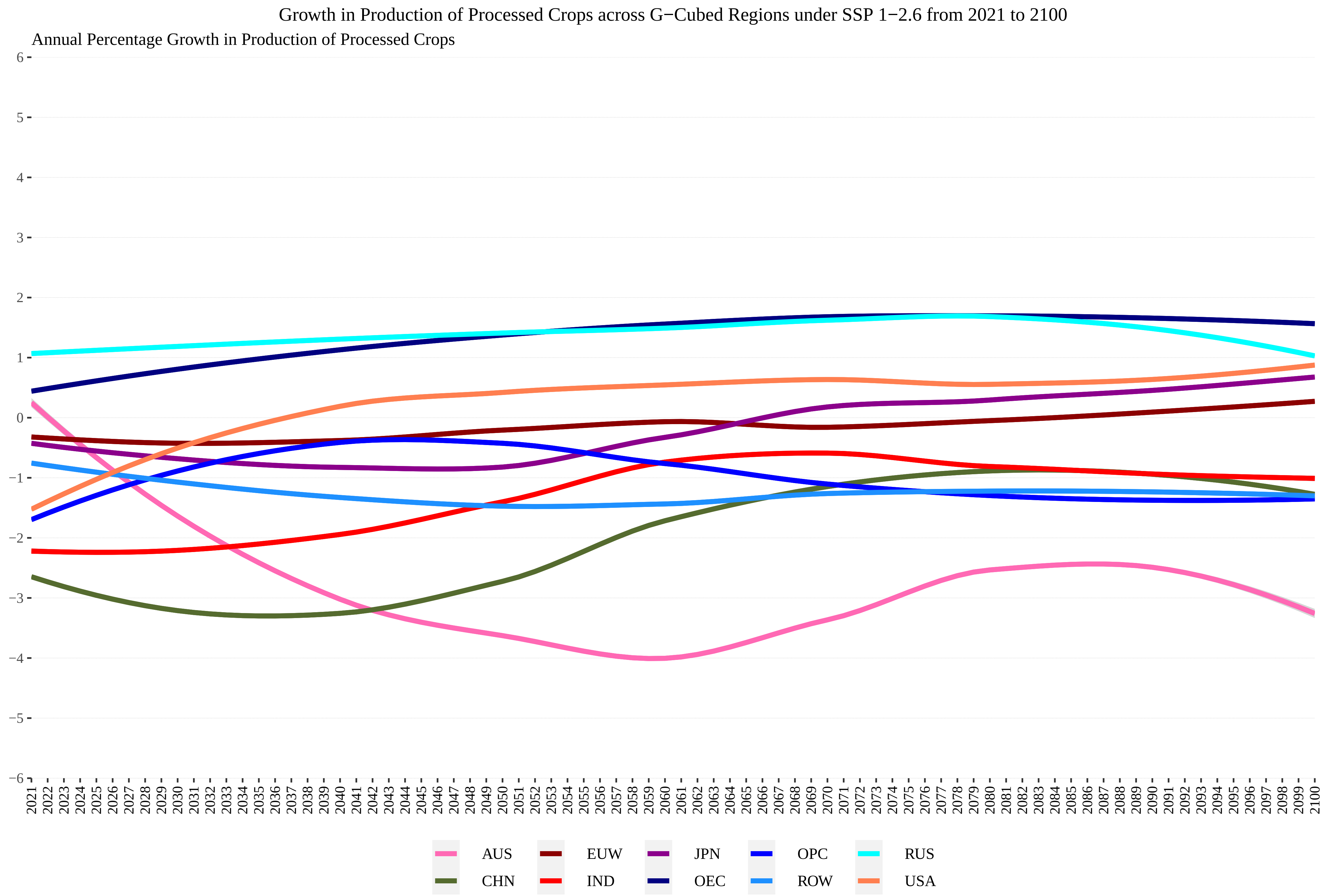


Source: Constructed by the Author.

Growth in Total Factor Productivity of Crops across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100

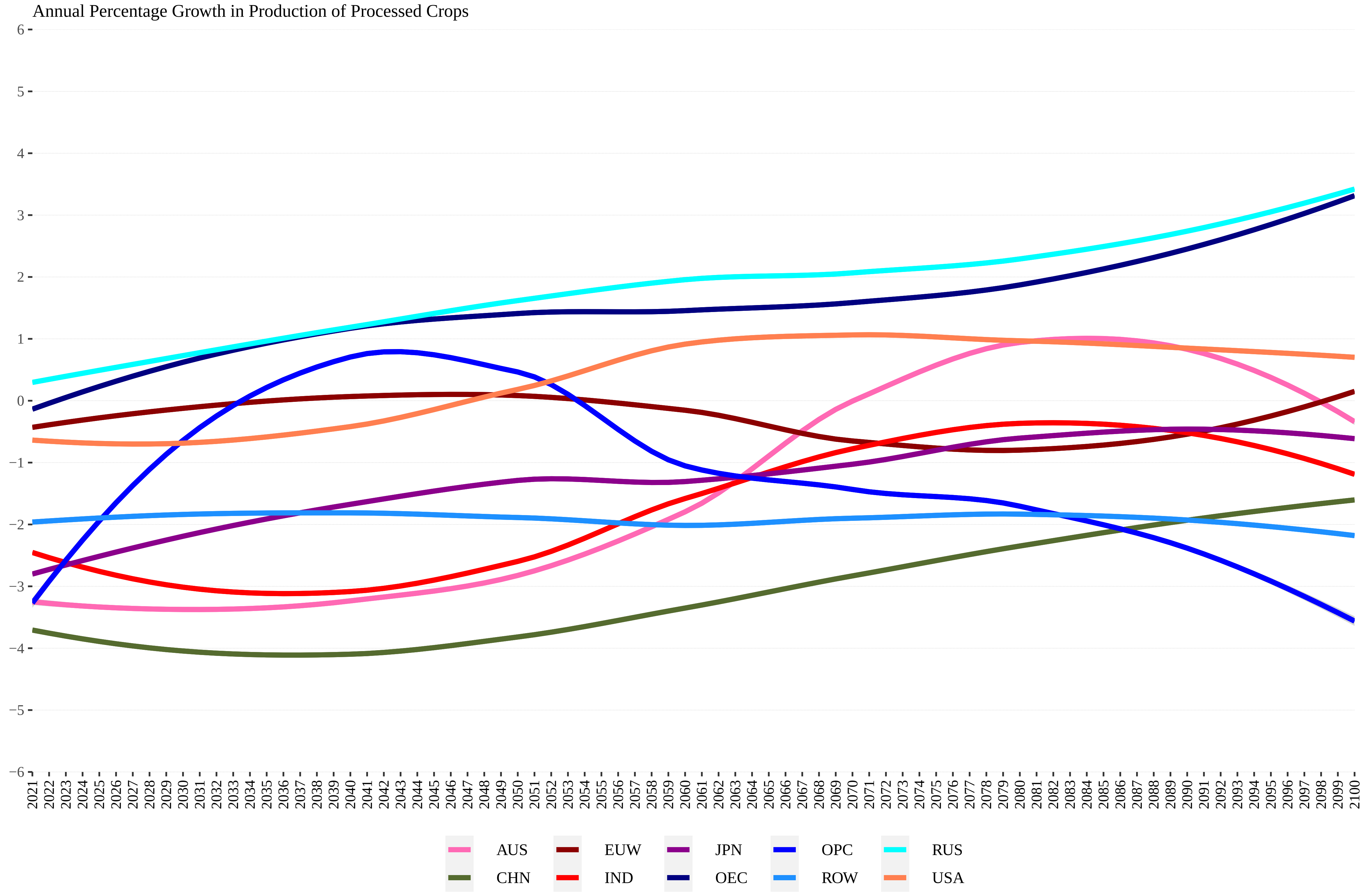


Source: Constructed by the Author.

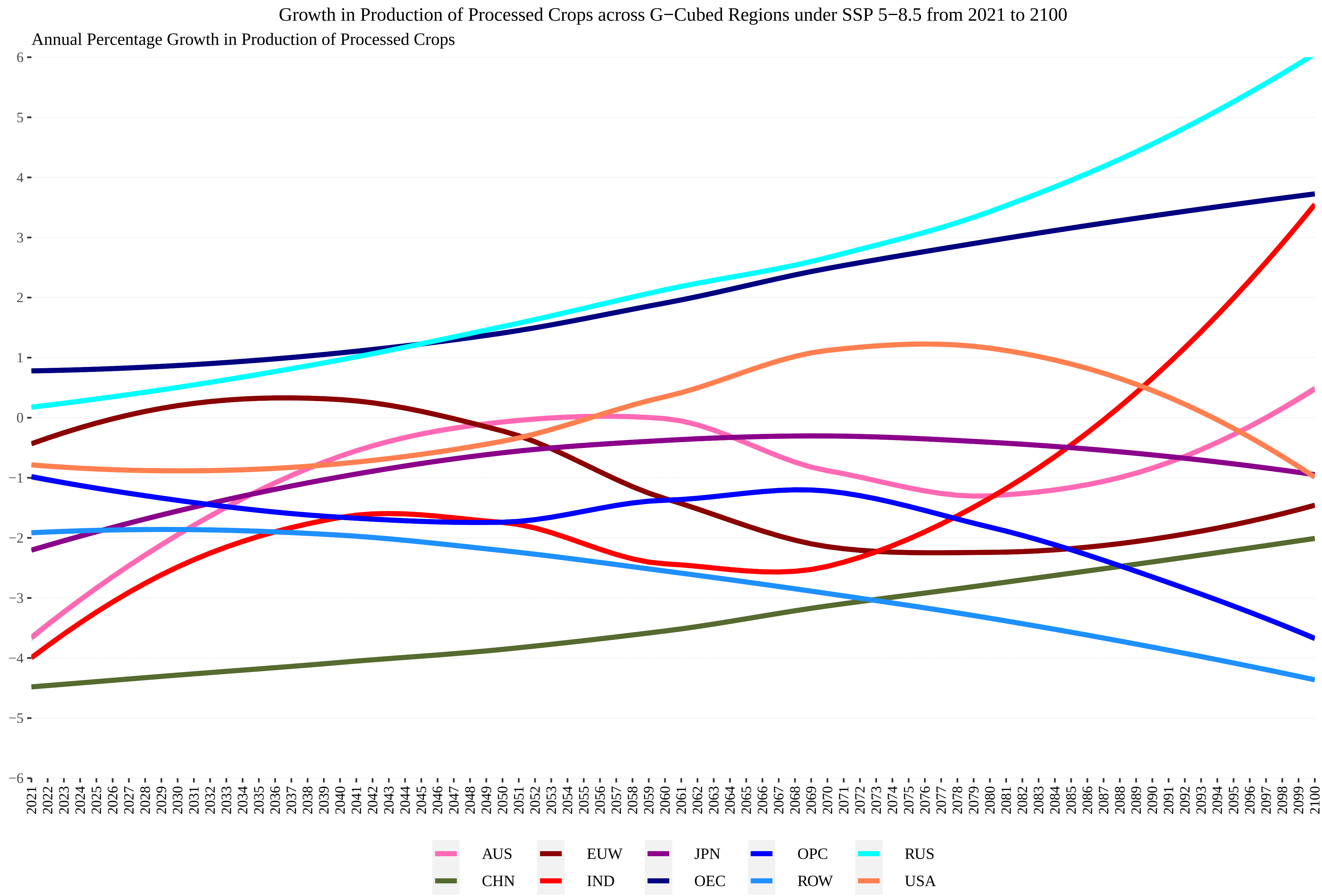


Source: Constructed by the Author.

Growth in Production of Processed Crops across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100



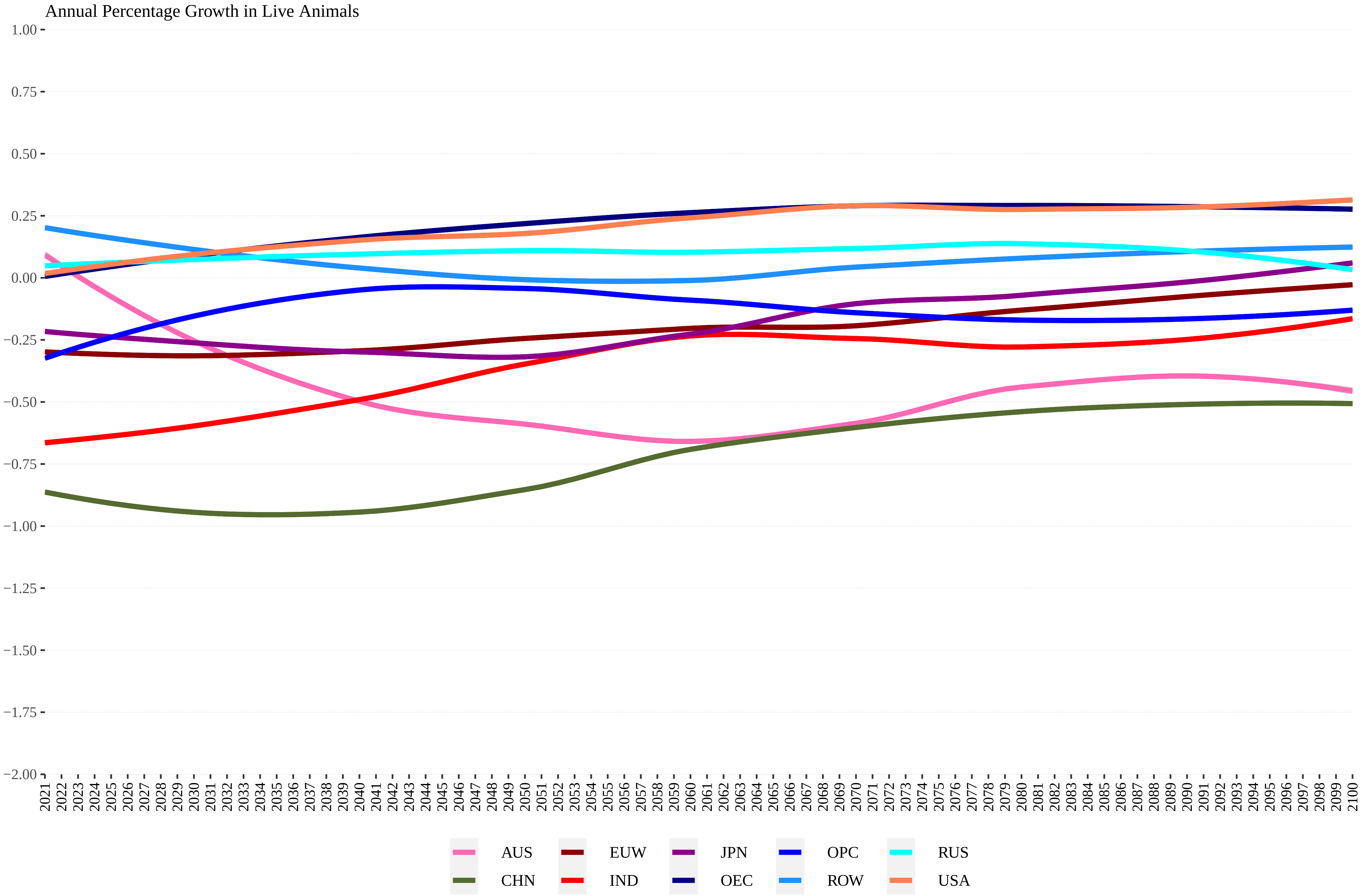
Source: Constructed by the Author.



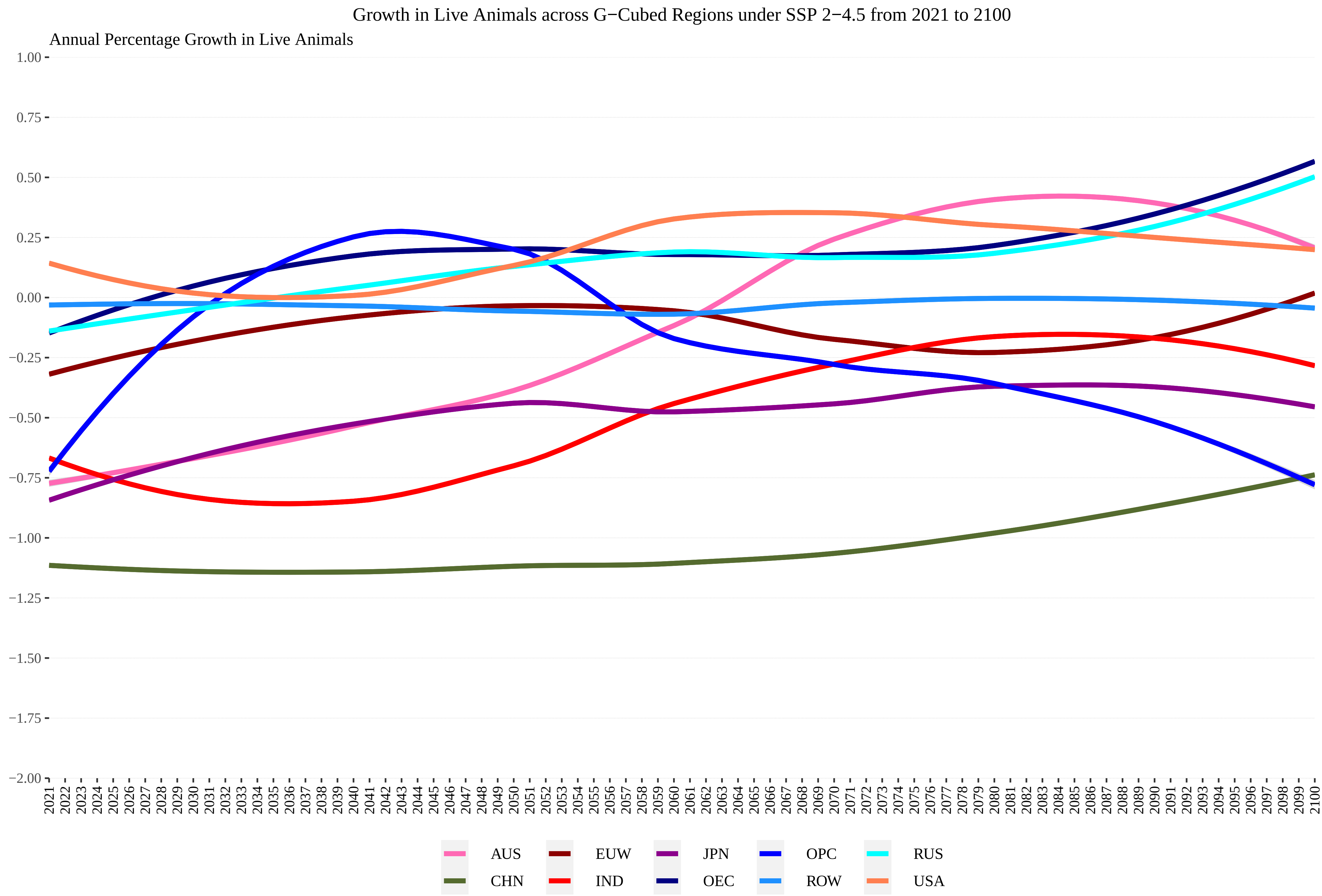
Source: Constructed by the Author.

ANNEXURE 19: LIVESTOCK PRODUCTION UNDER SSPS

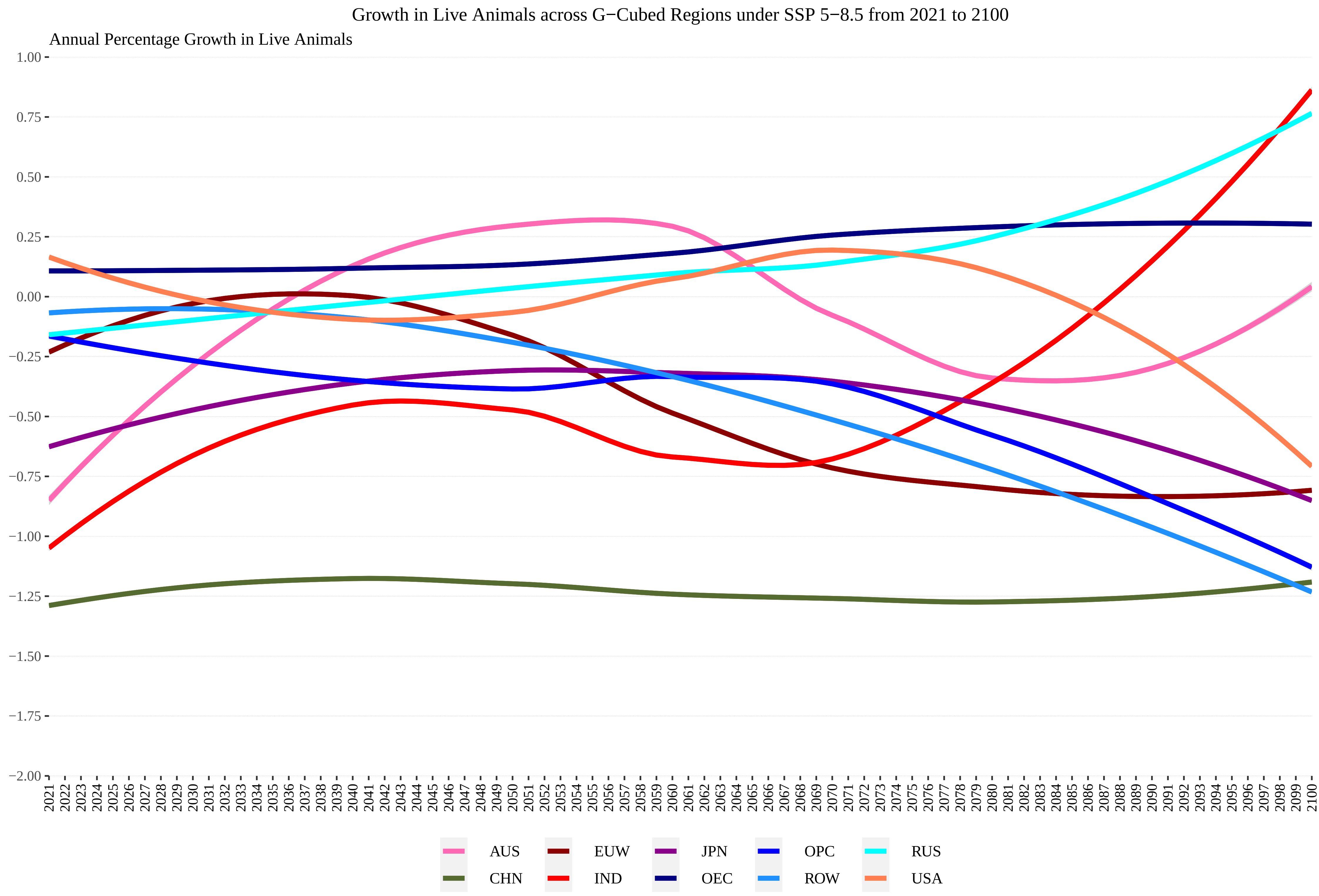
Growth in Live Animals across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



Source: Constructed by the Author.

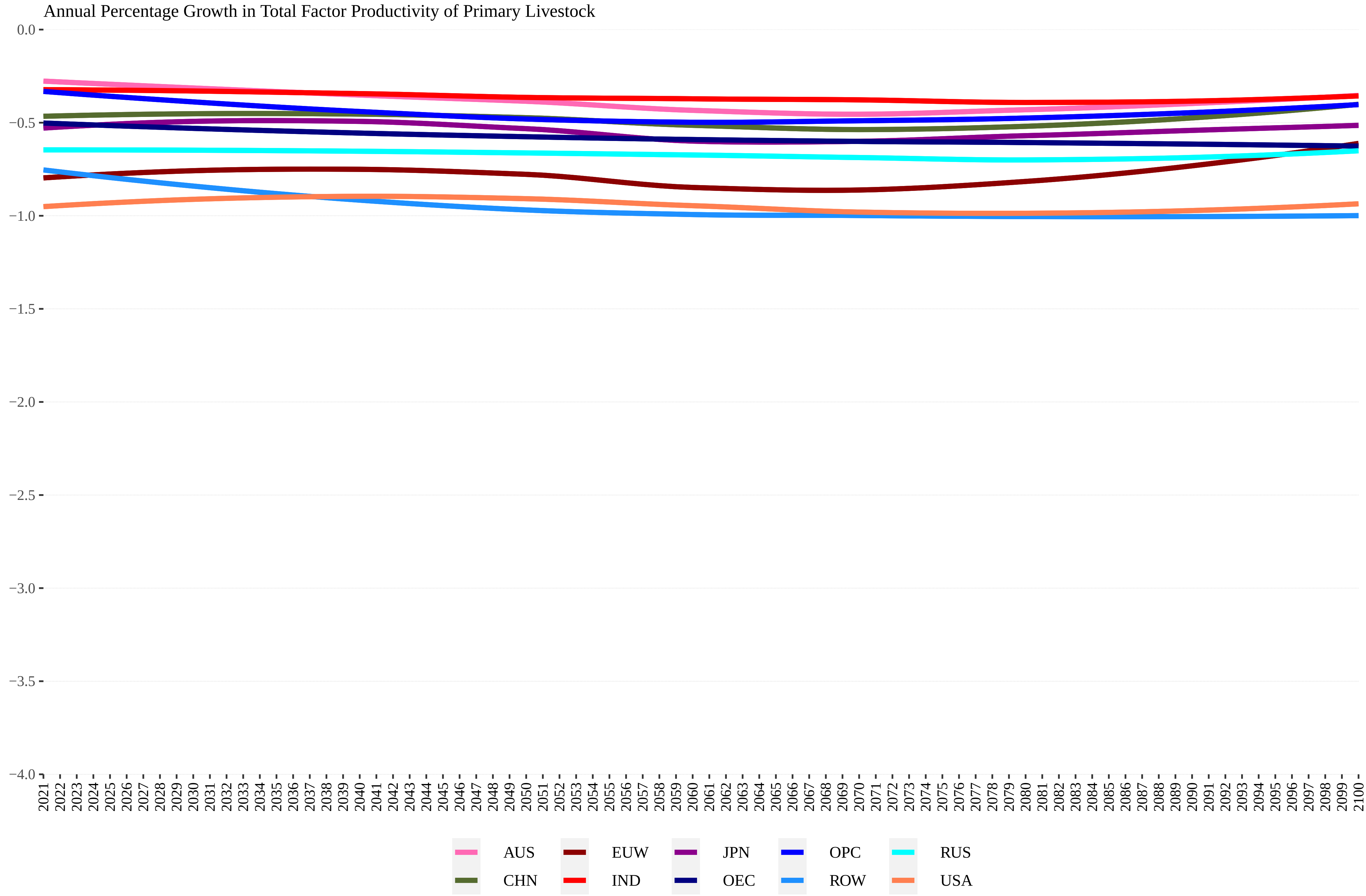


Source: Constructed by the Author.



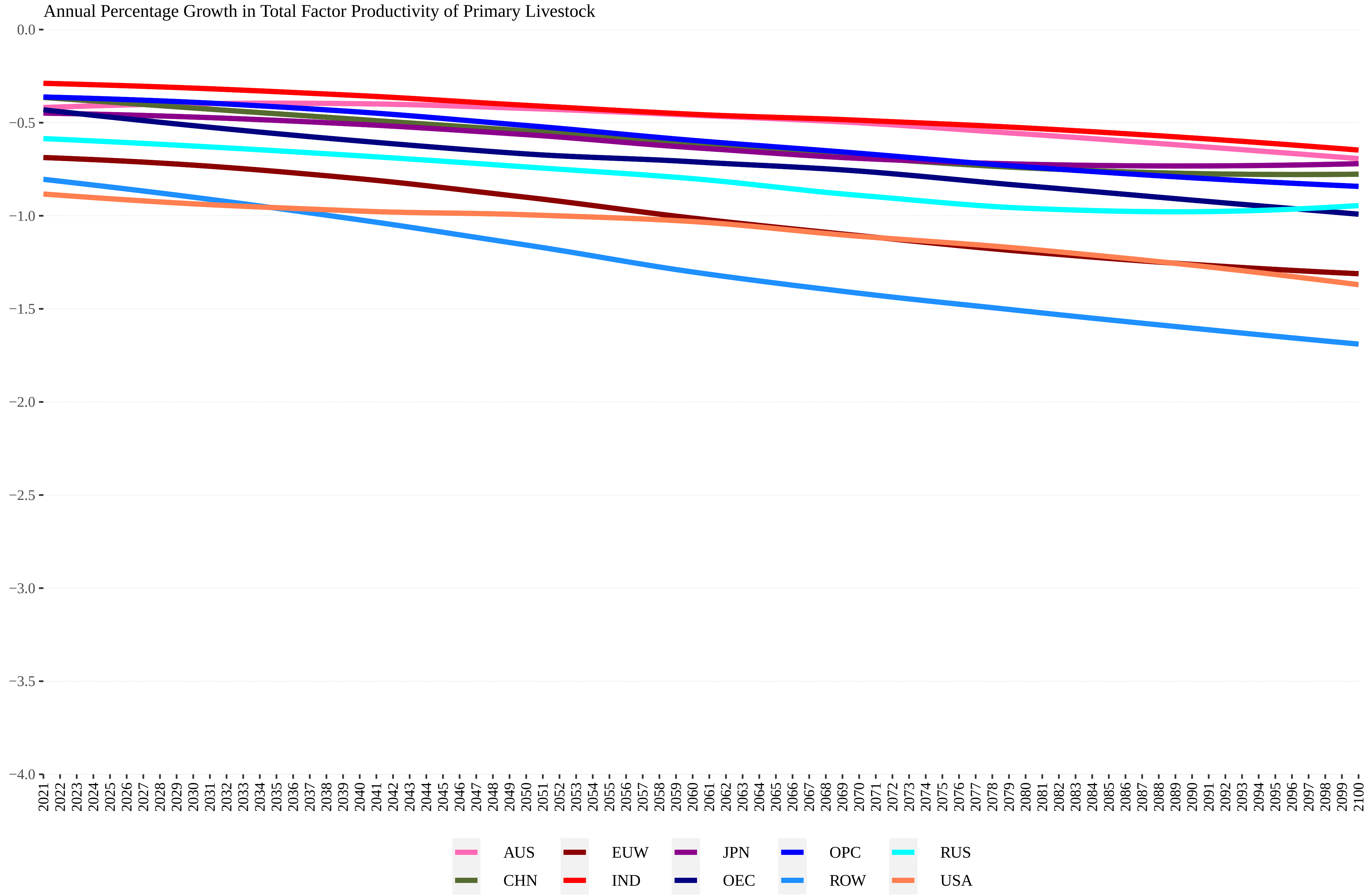
Source: Constructed by the Author.

Growth in Total Factor Productivity of Primary Livestock across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



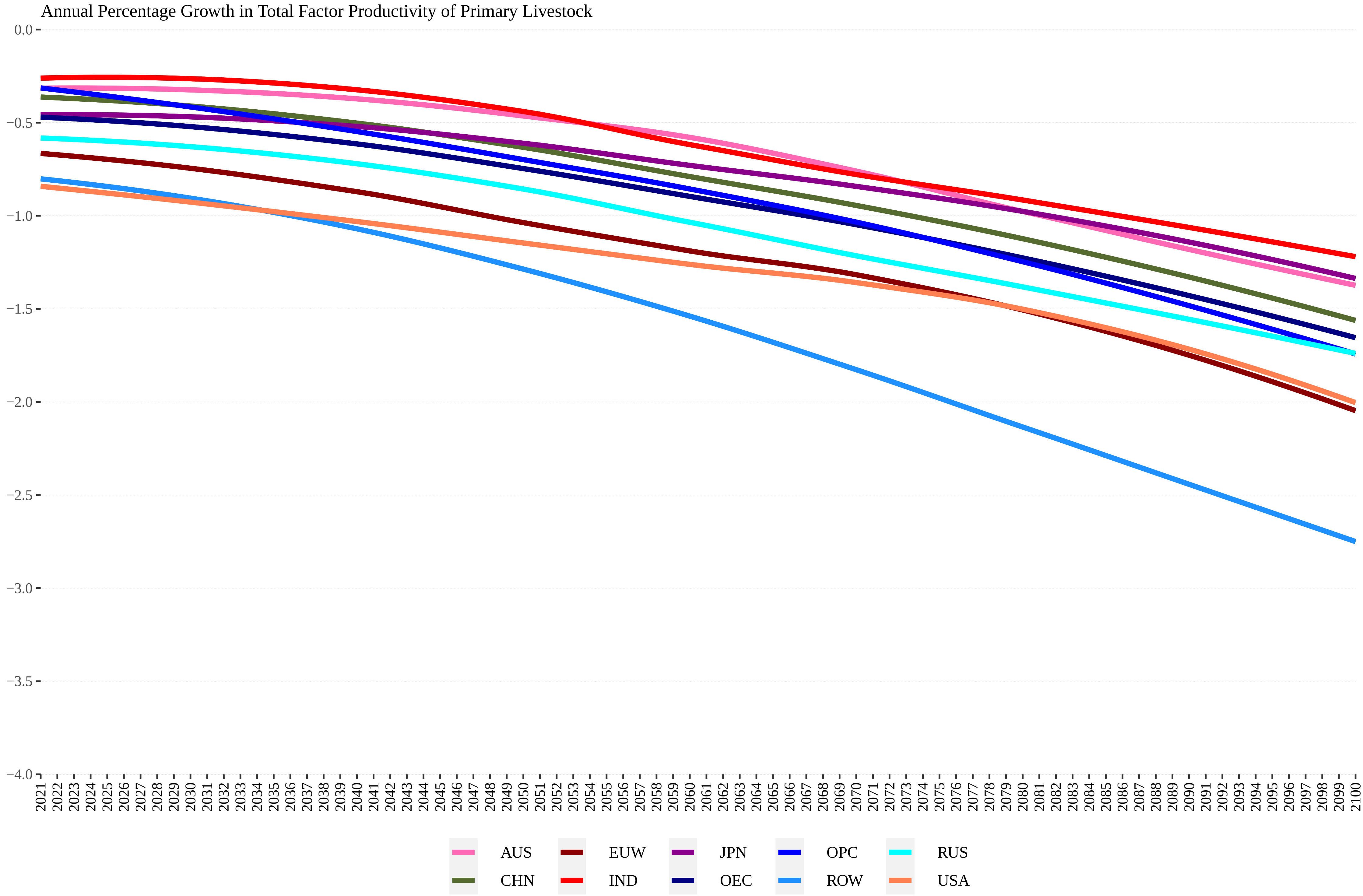
Source: Constructed by the Author.

Growth in Total Factor Productivity of Primary Livestock across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100



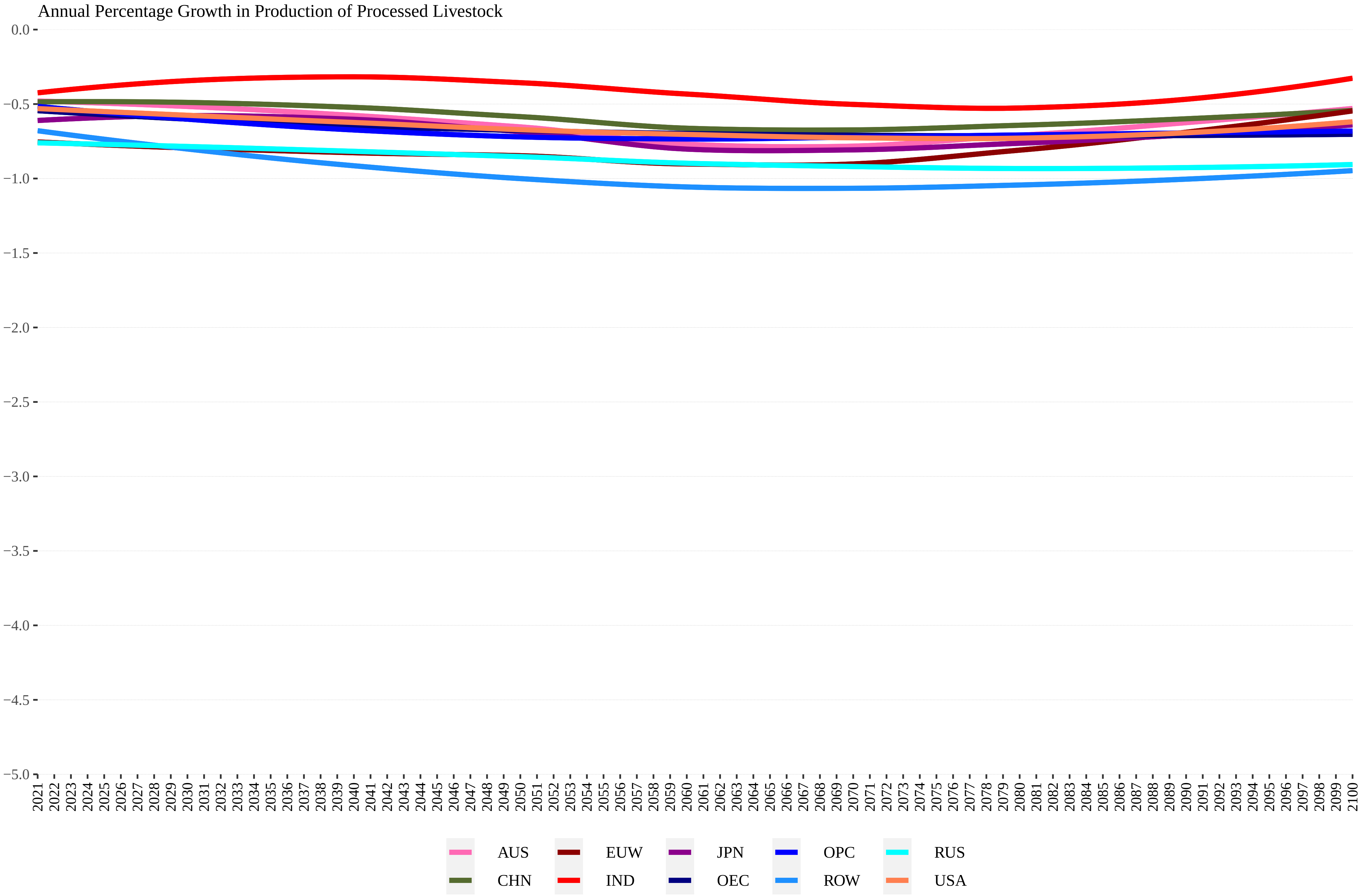
Source: Constructed by the Author.

Growth in Total Factor Productivity of Primary Livestock across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100

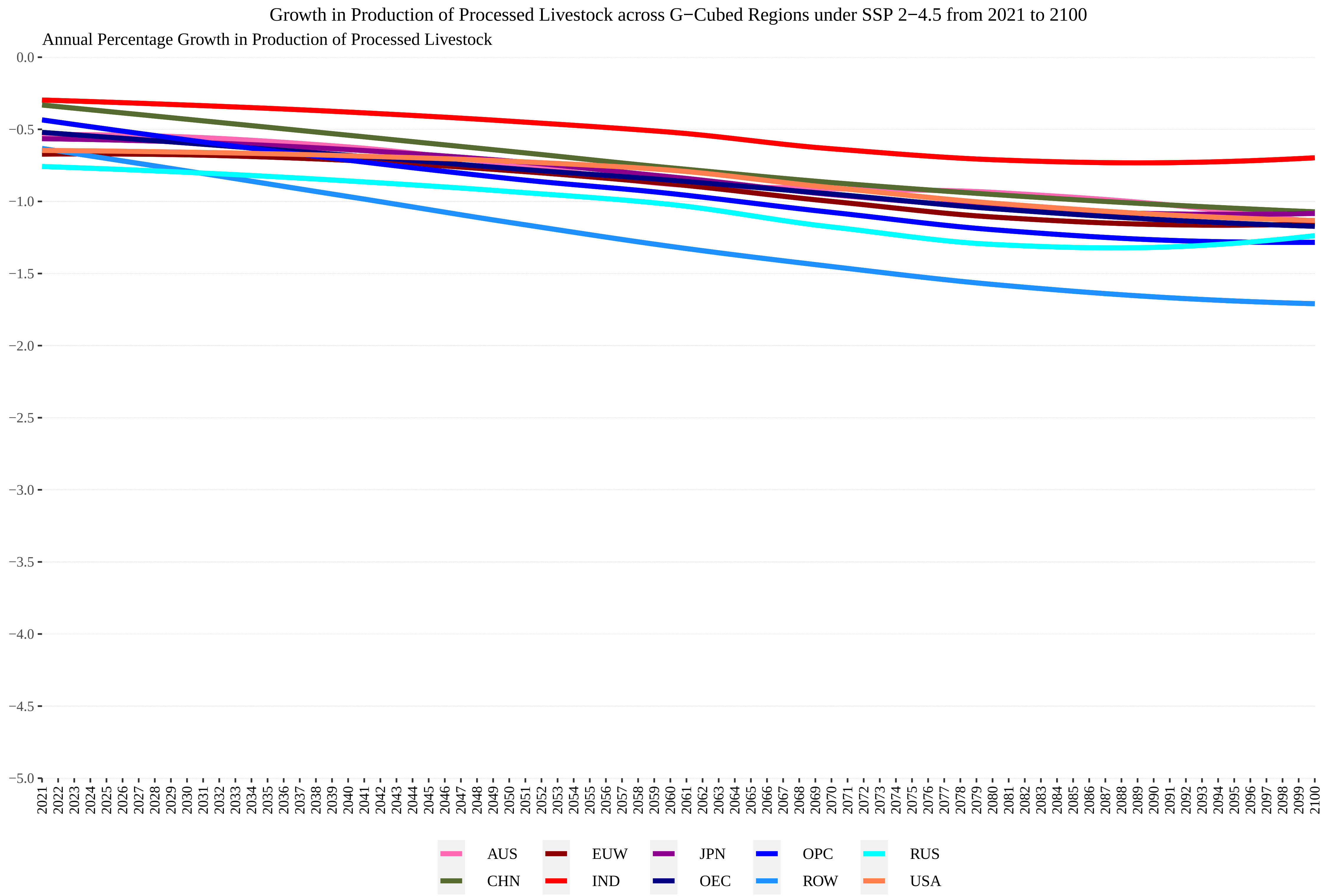


Source: Constructed by the Author.

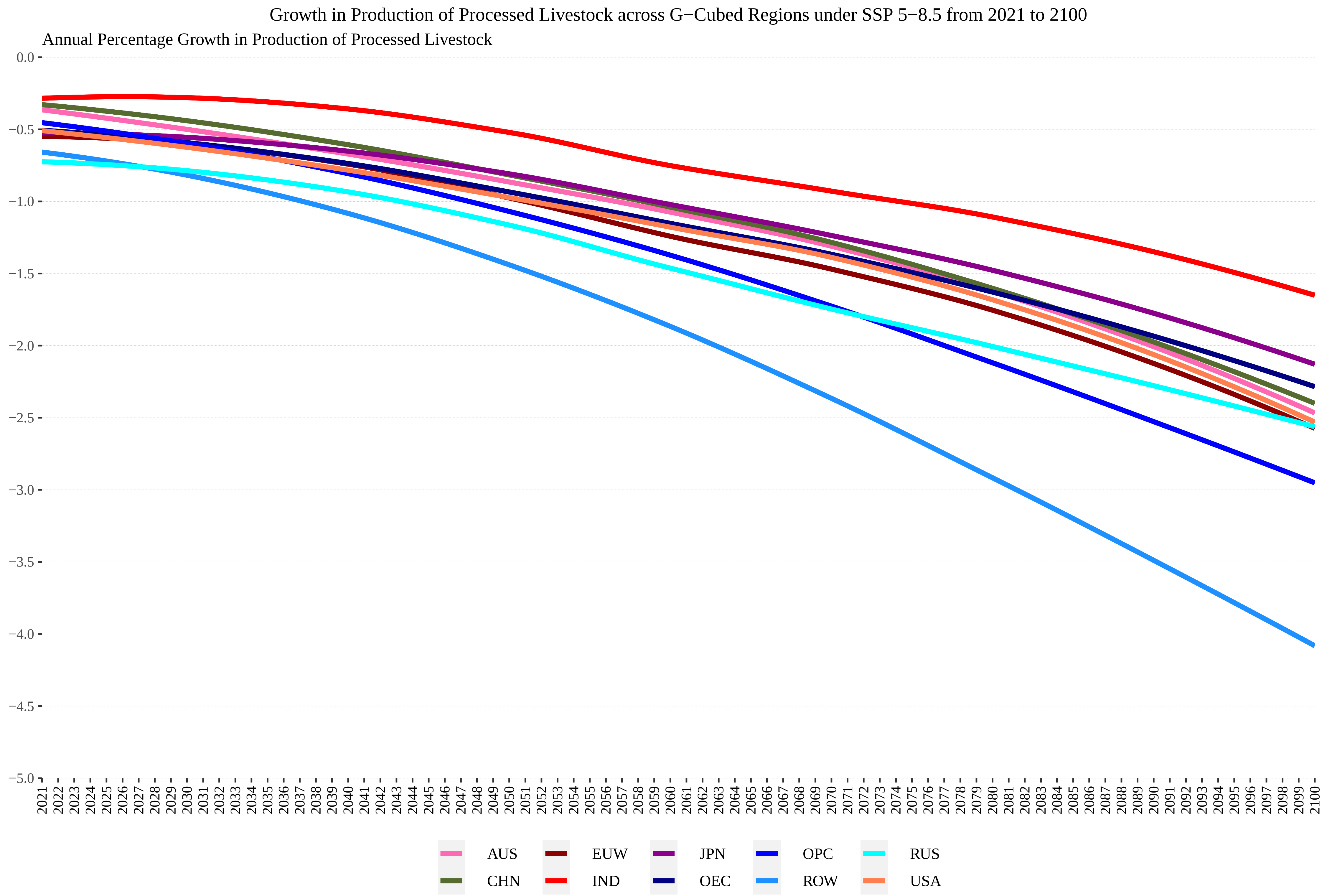
Growth in Production of Processed Livestock across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



Source: Constructed by the Author.

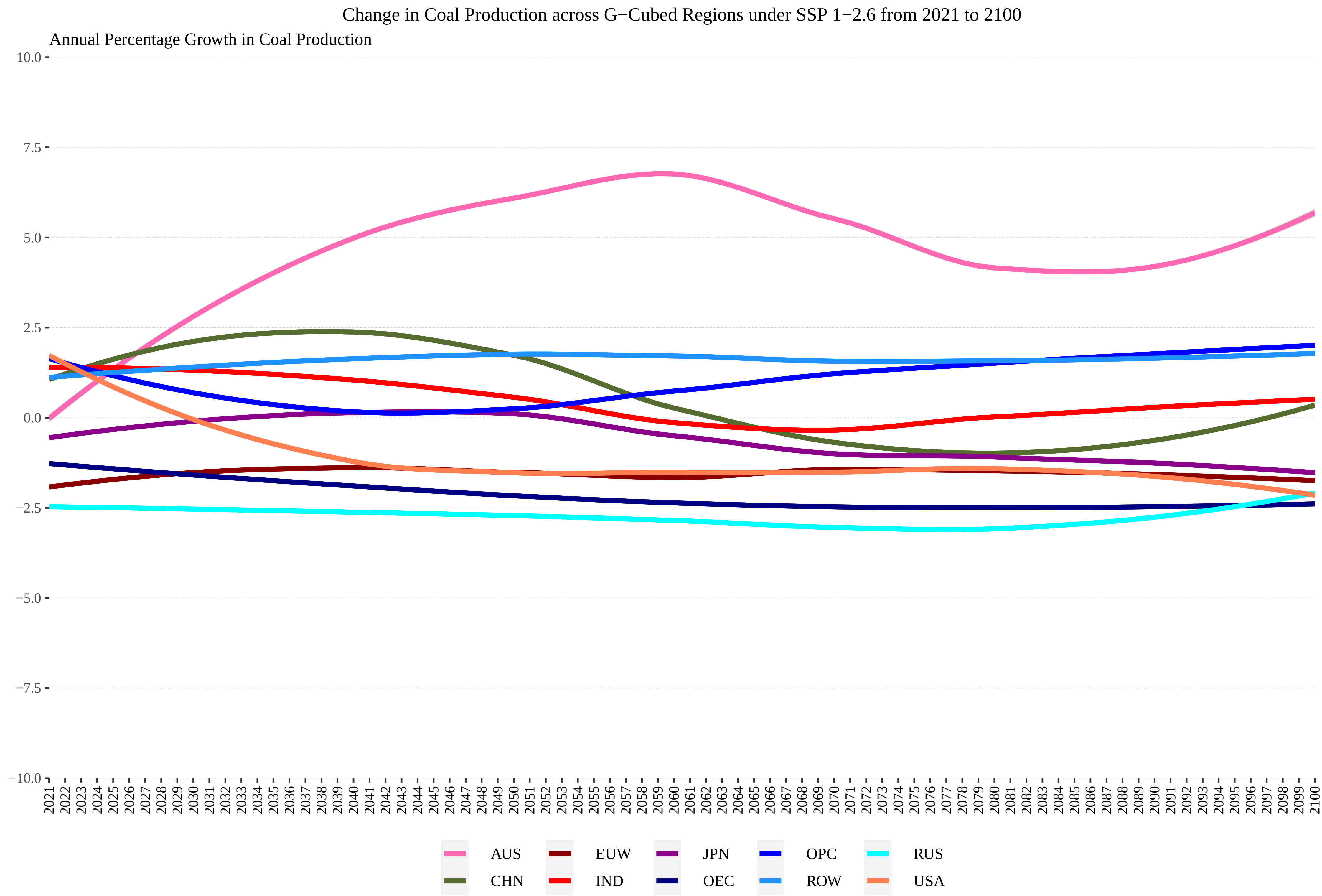


Source: Constructed by the Author.

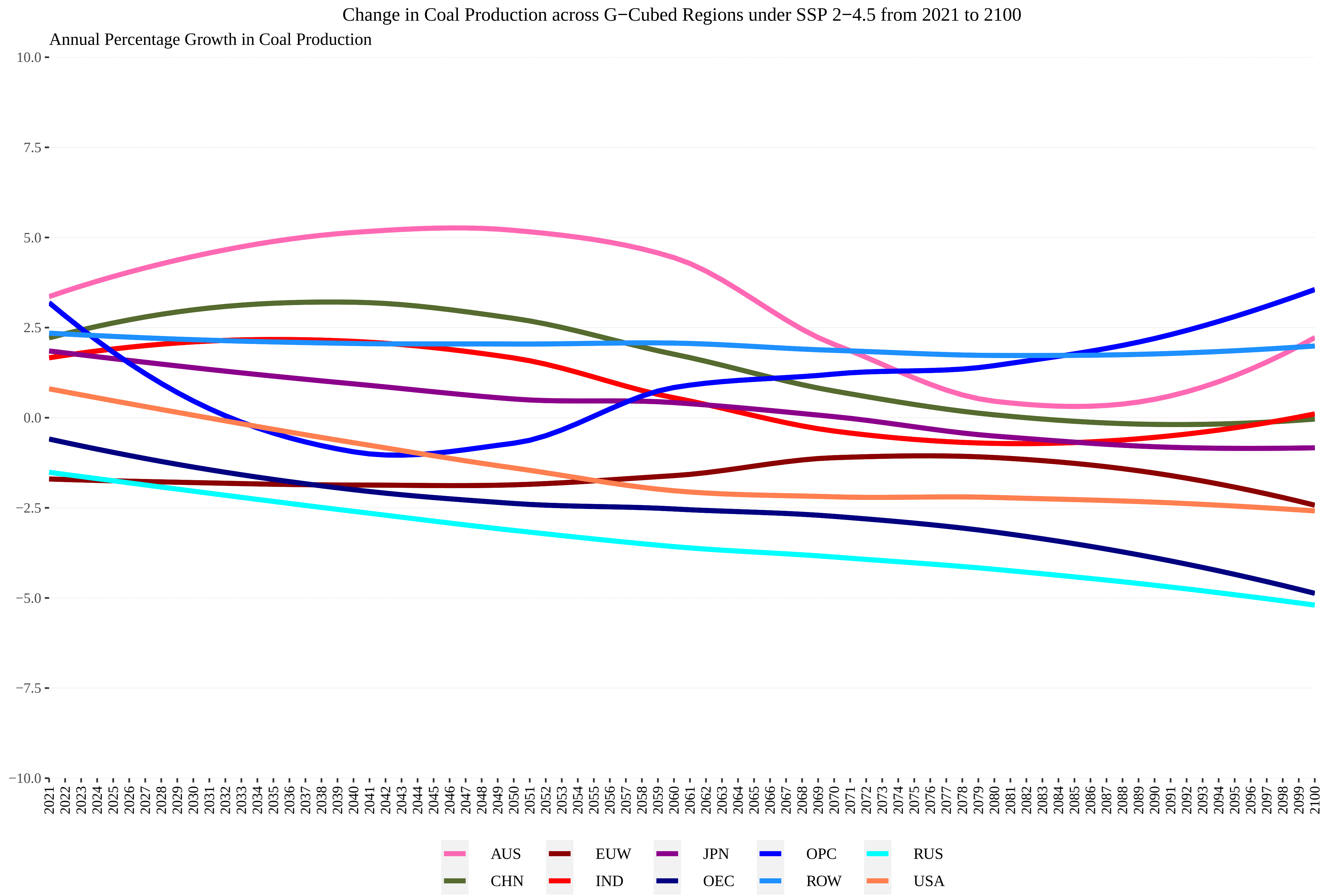


Source: Constructed by the Author.

ANNEXURE 20: ENERGY PRODUCTION FROM NON-RENEWABLE RESOURCES UNDER SSPS

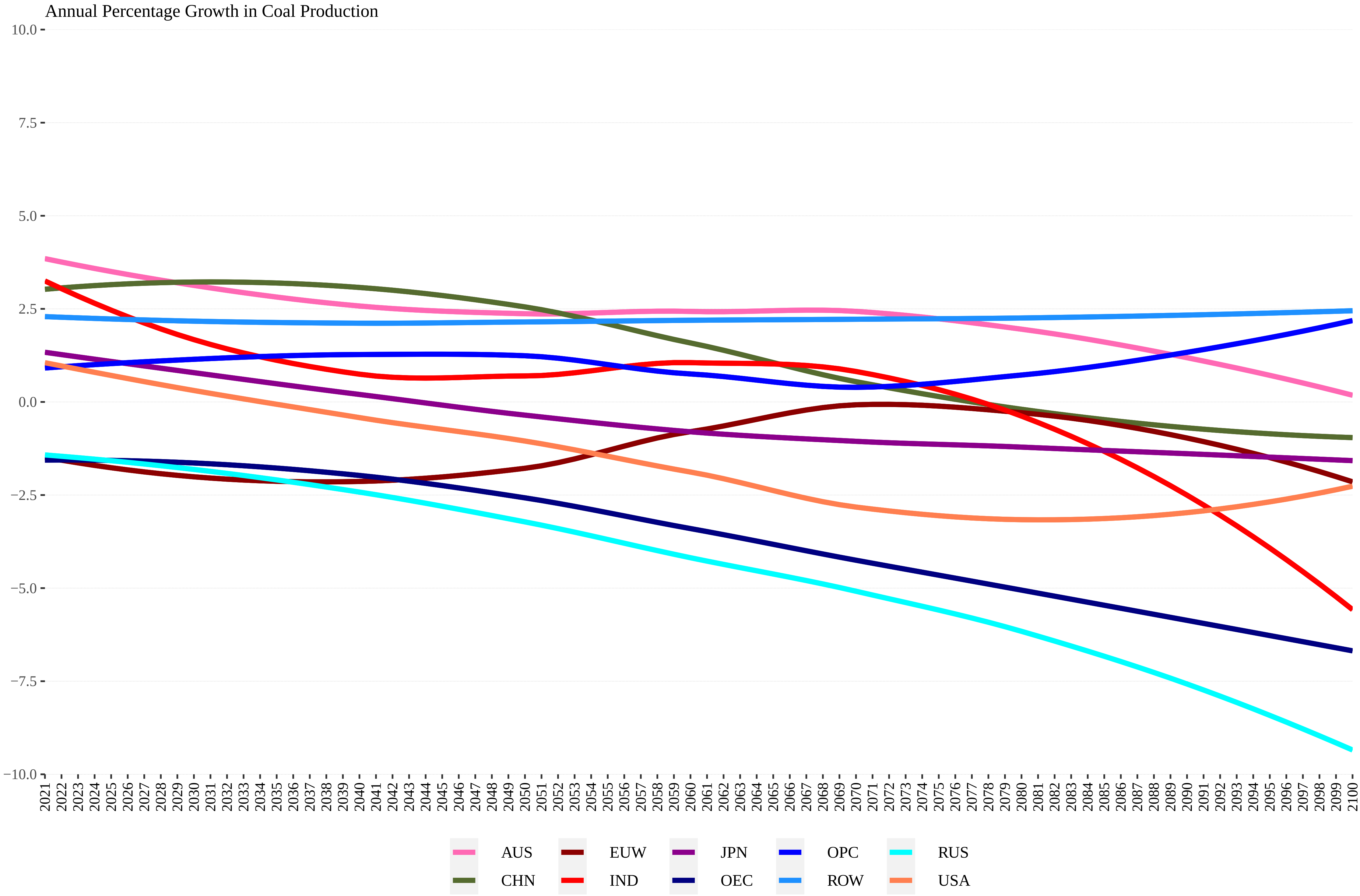


Source: Constructed by the Author.

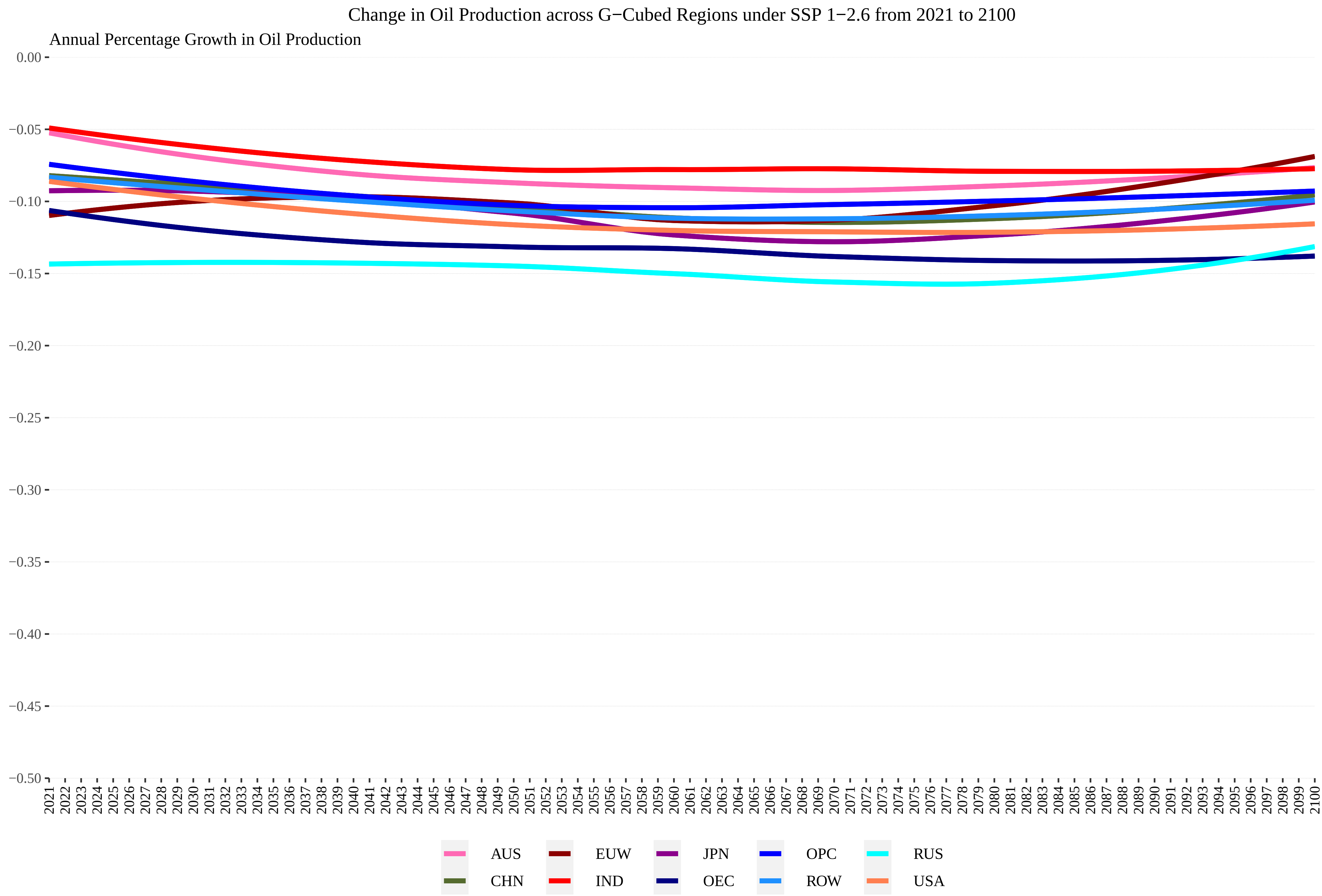


Source: Constructed by the Author.

Change in Coal Production across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100



Source: Constructed by the Author.



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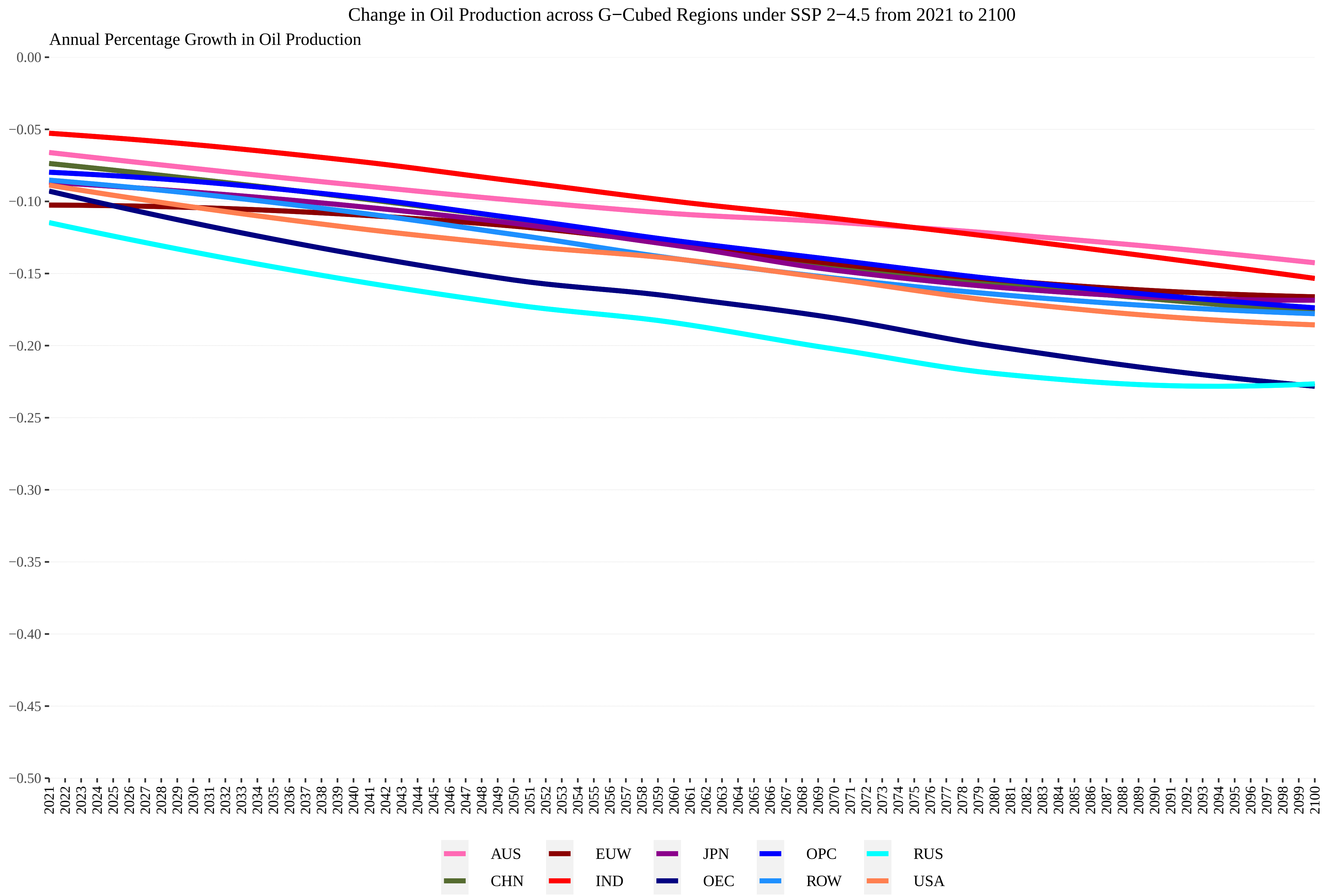
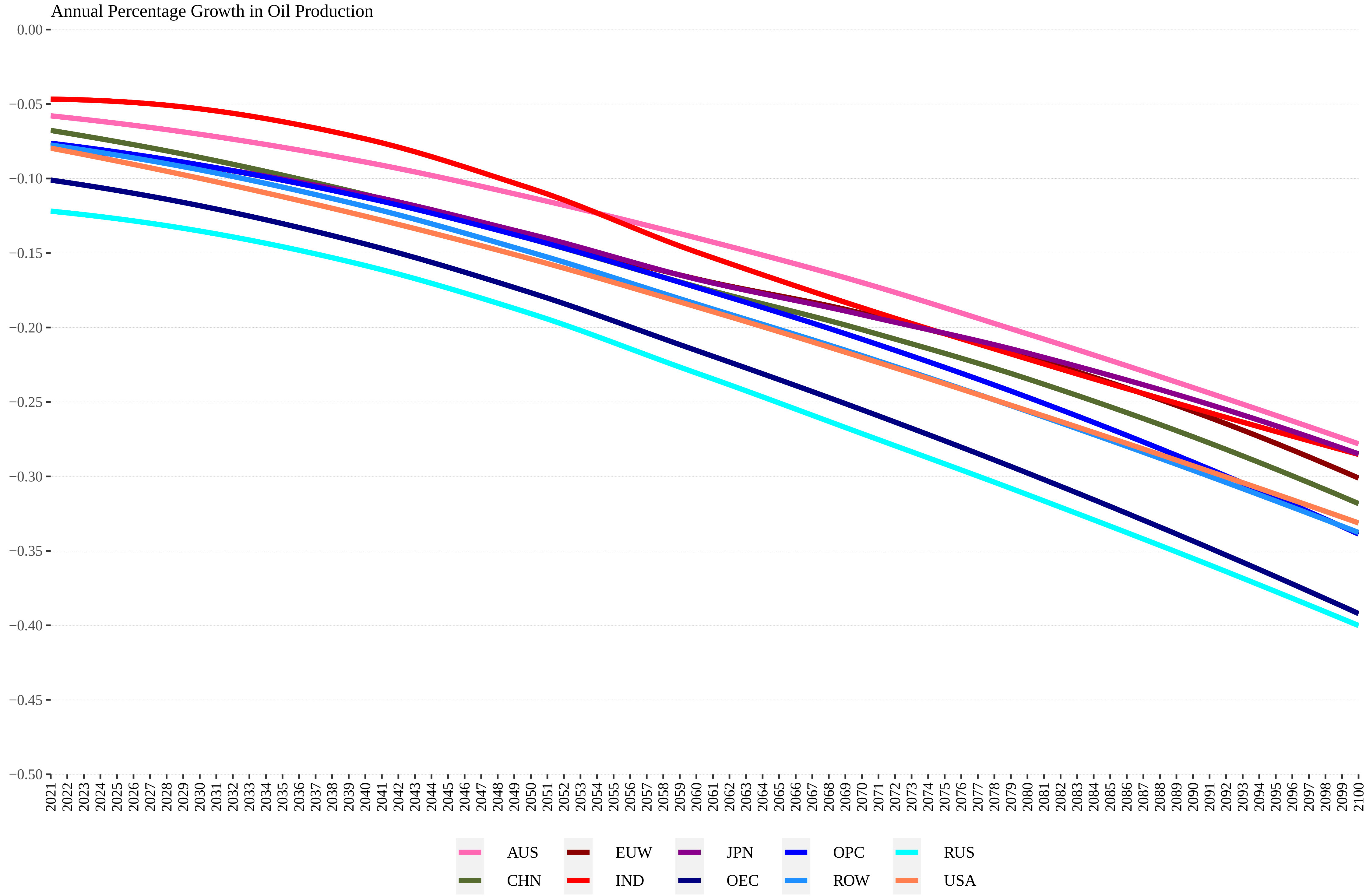
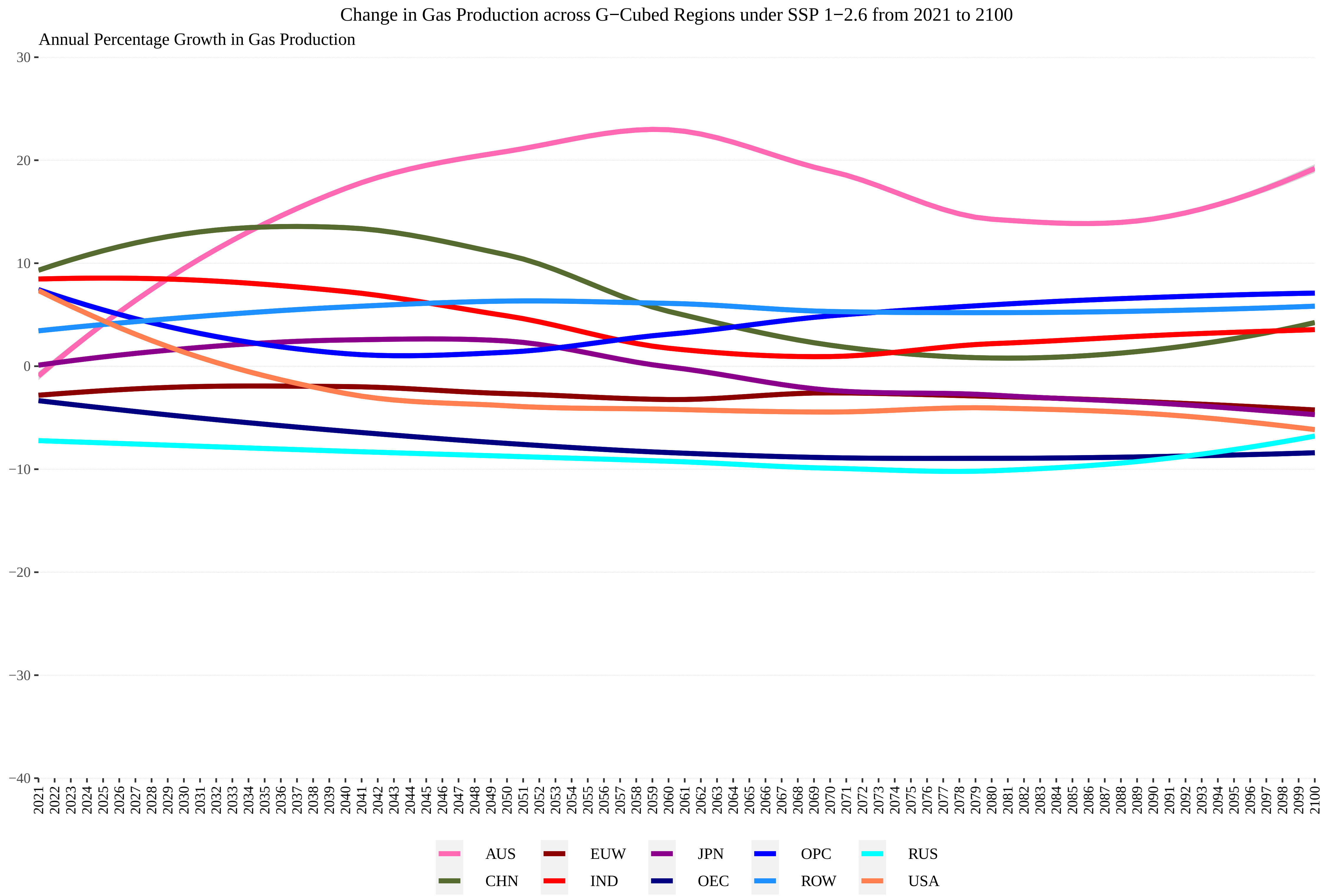


Source: Constructed by the Author.

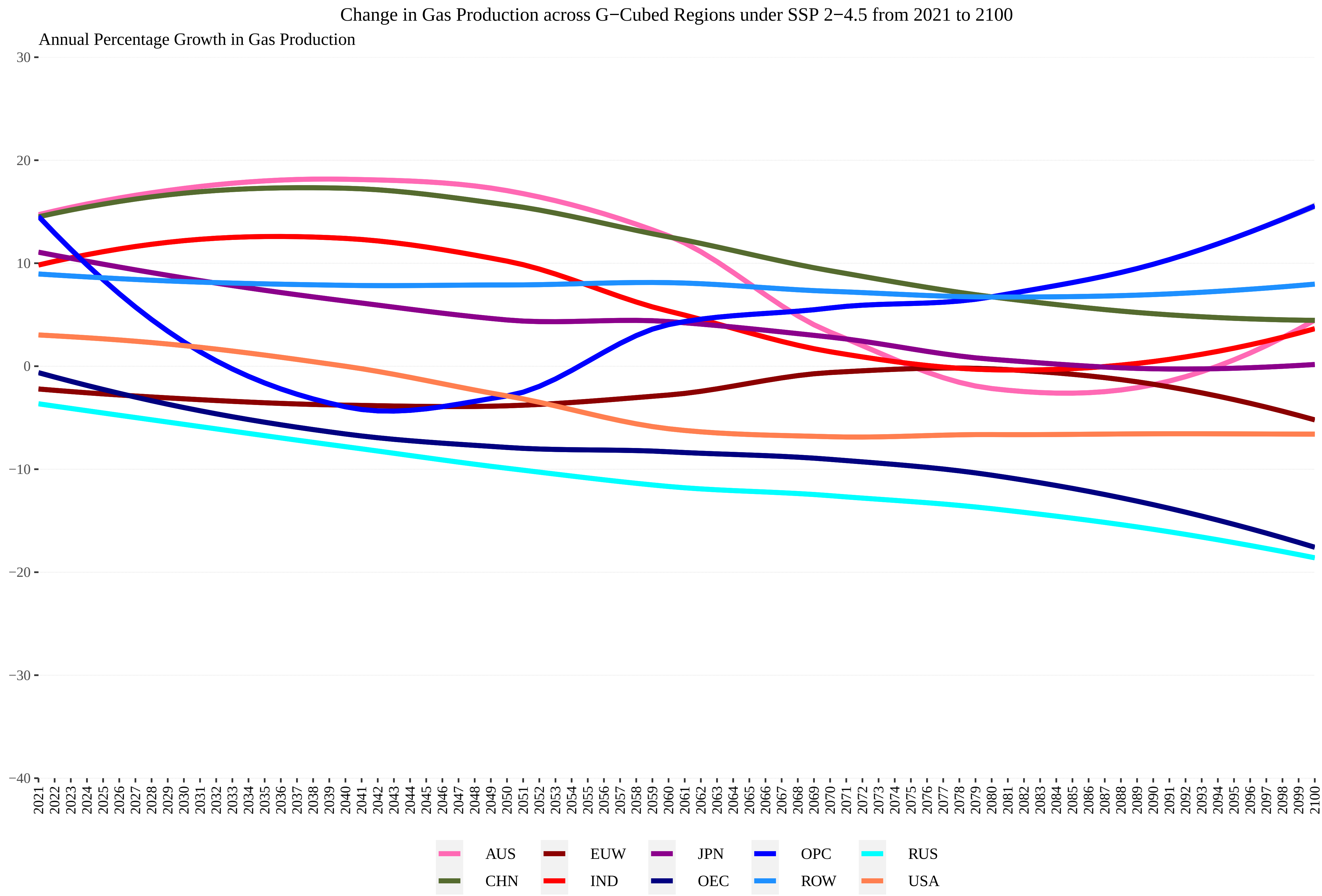
Change in Oil Production across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100



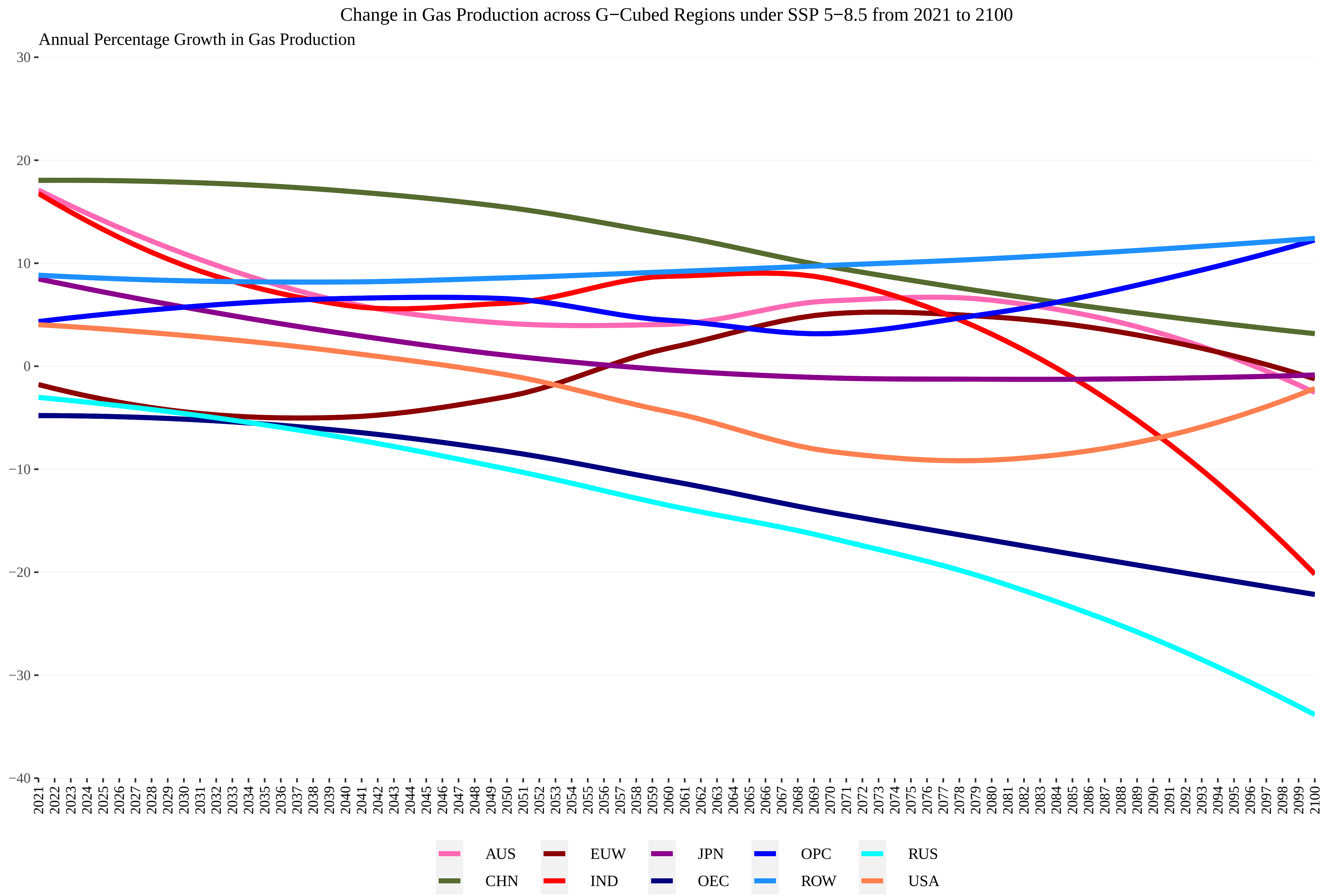
Source: Constructed by the Author.



Source: Constructed by the Author.

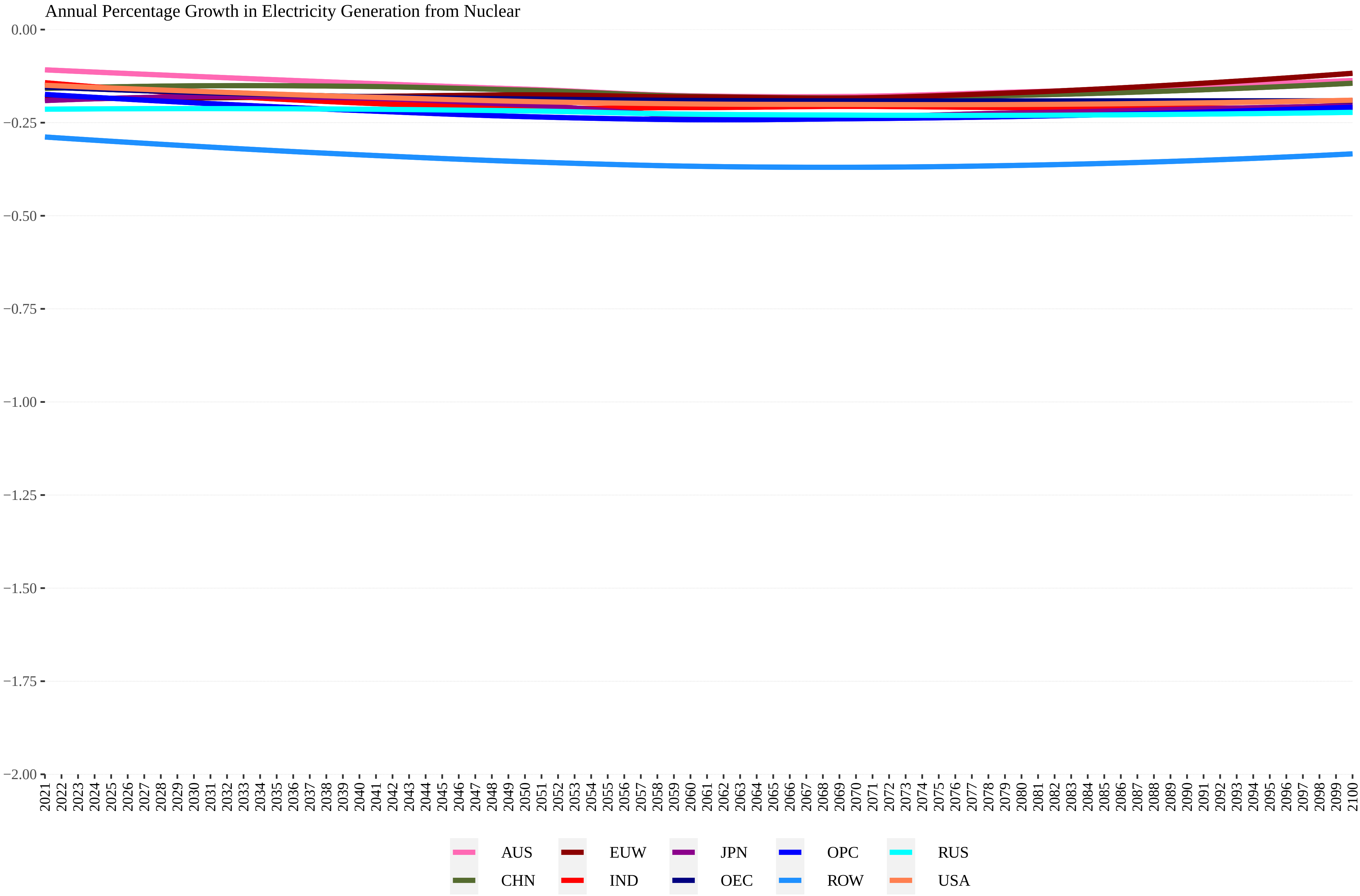


Source: Constructed by the Author.



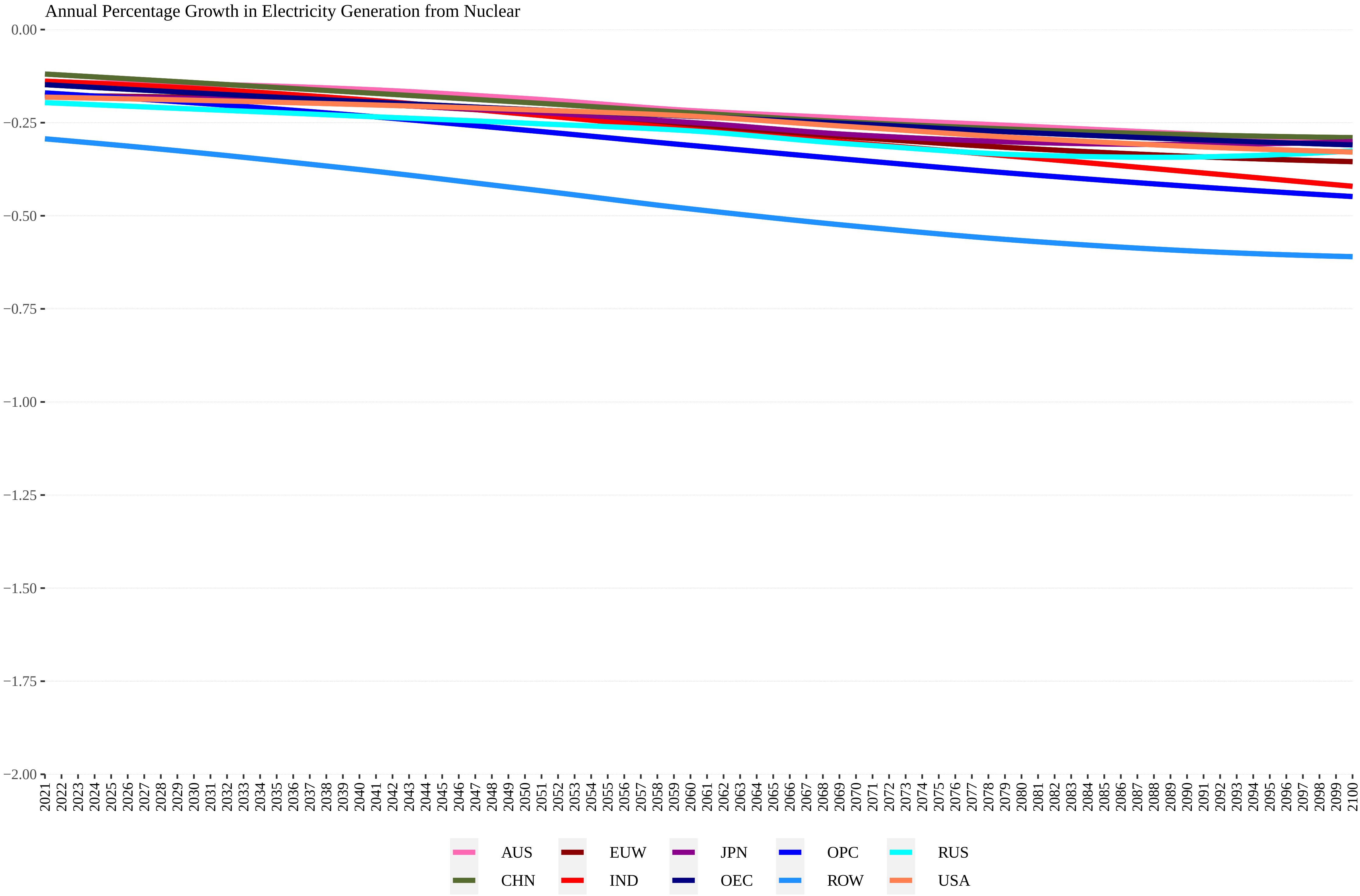
Source: Constructed by the Author.

Change in Electricity Generation from Nuclear across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



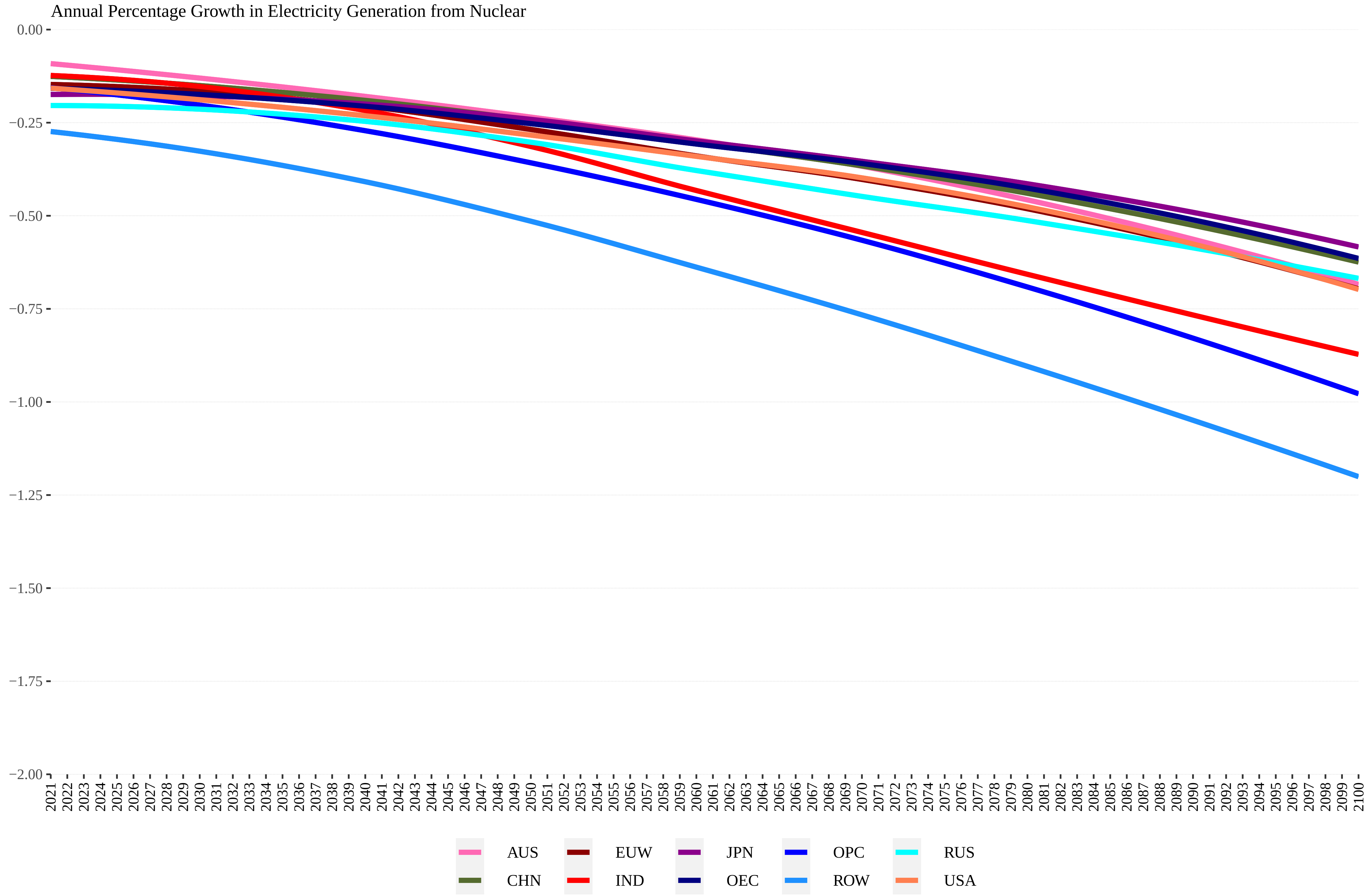
Source: Constructed by the Author.

Change in Electricity Generation from Nuclear across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100



Source: Constructed by the Author.

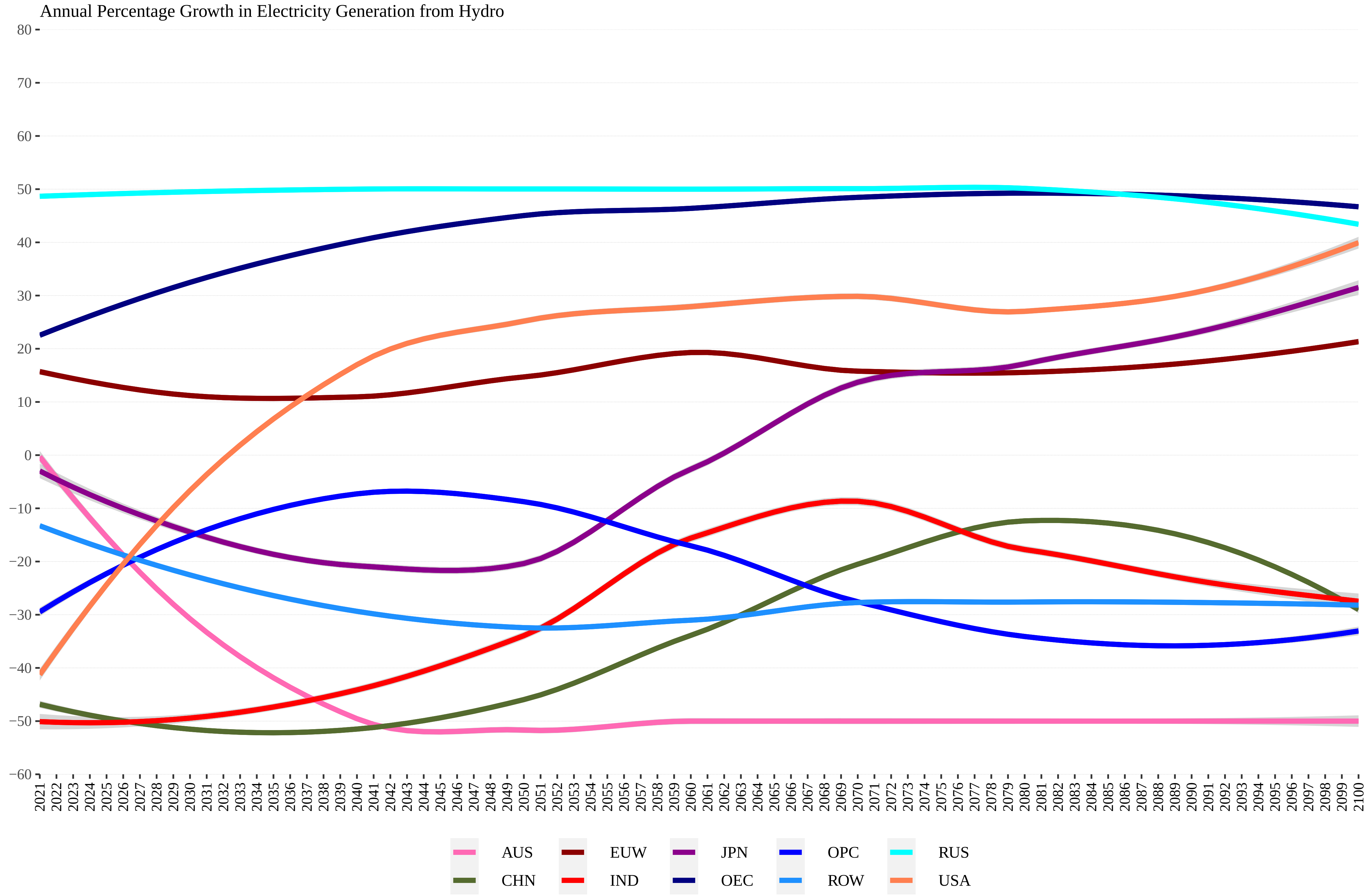
Change in Electricity Generation from Nuclear across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100



Source: Constructed by the Author.

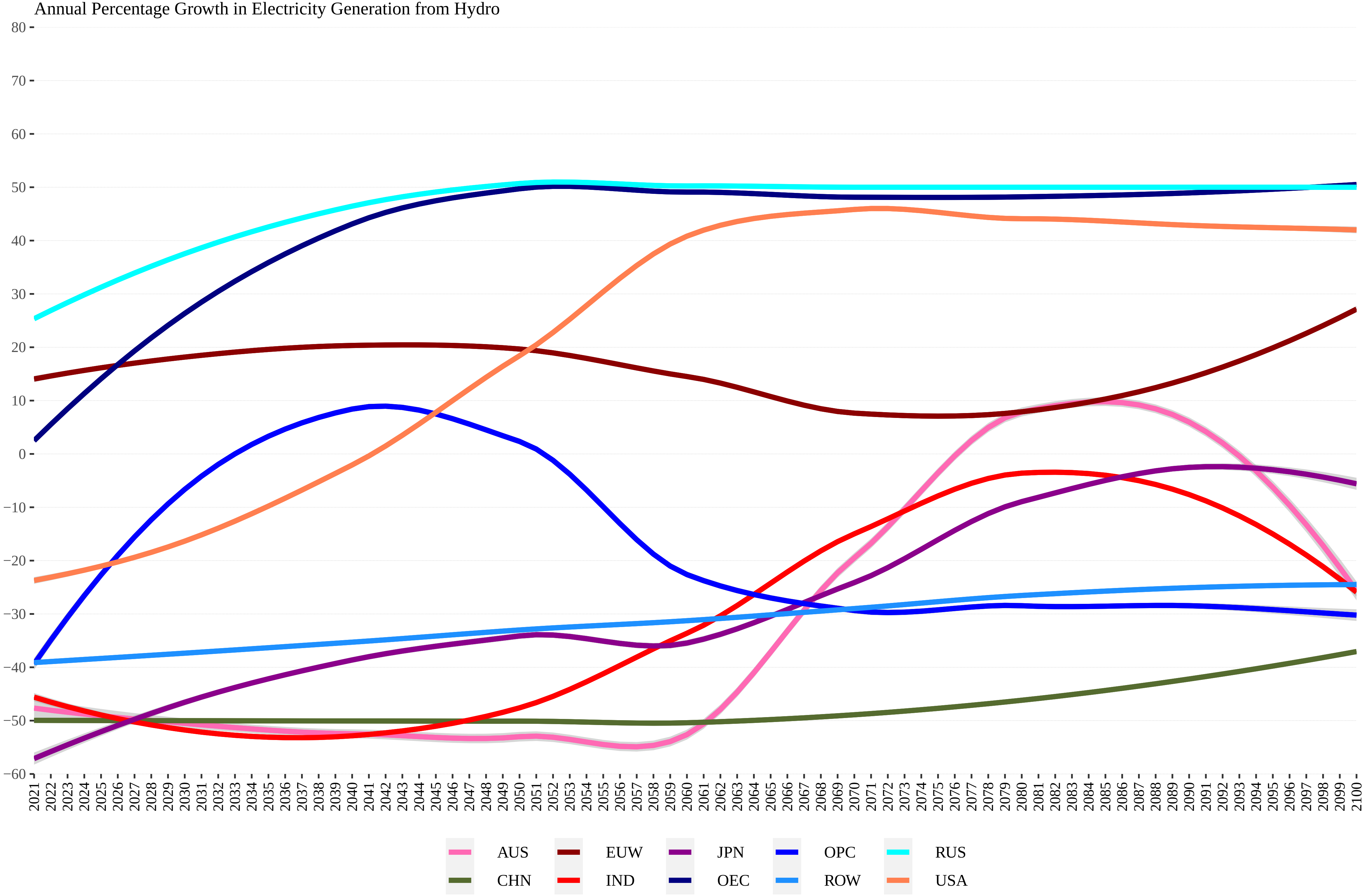
ANNEXURE 21: ELECTRICITY GENERATION FROM RENEWABLE RESOURCES UNDER SSPS

Change in Electricity Generation from Hydro across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100

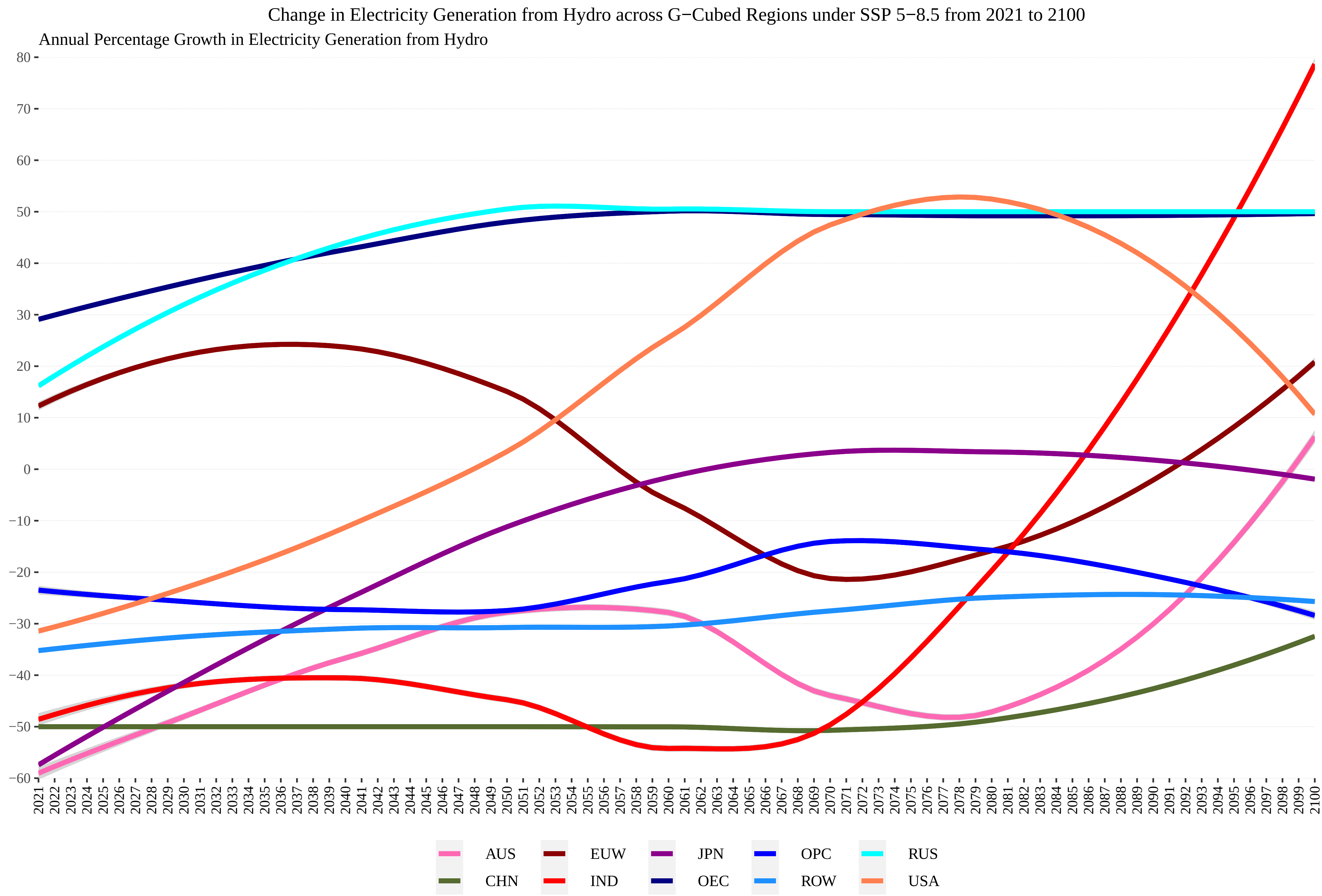


Source: Constructed by the Author.

Change in Electricity Generation from Hydro across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100

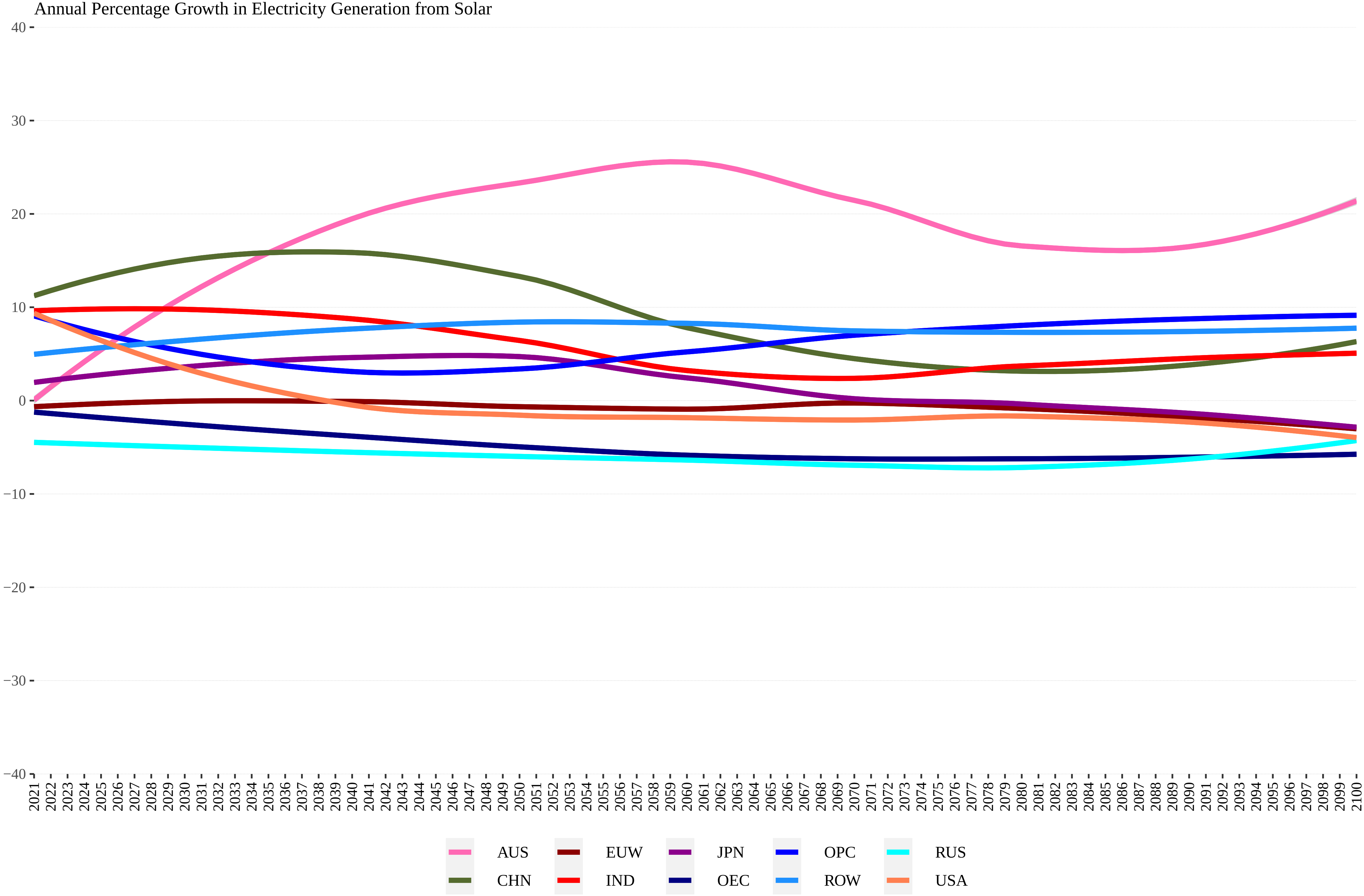


Source: Constructed by the Author.



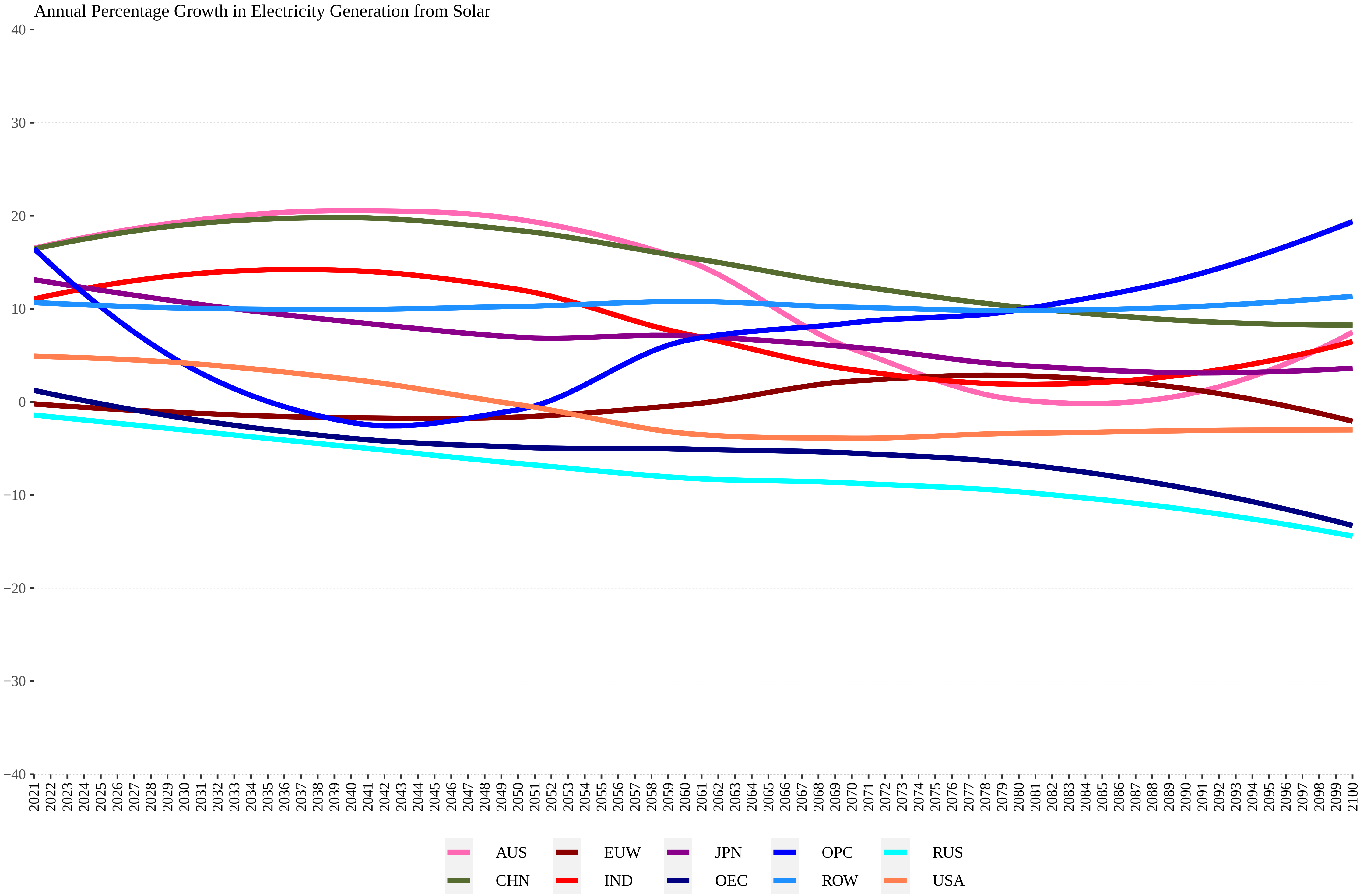
Source: Constructed by the Author.

Change in Electricity Generation from Solar across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100

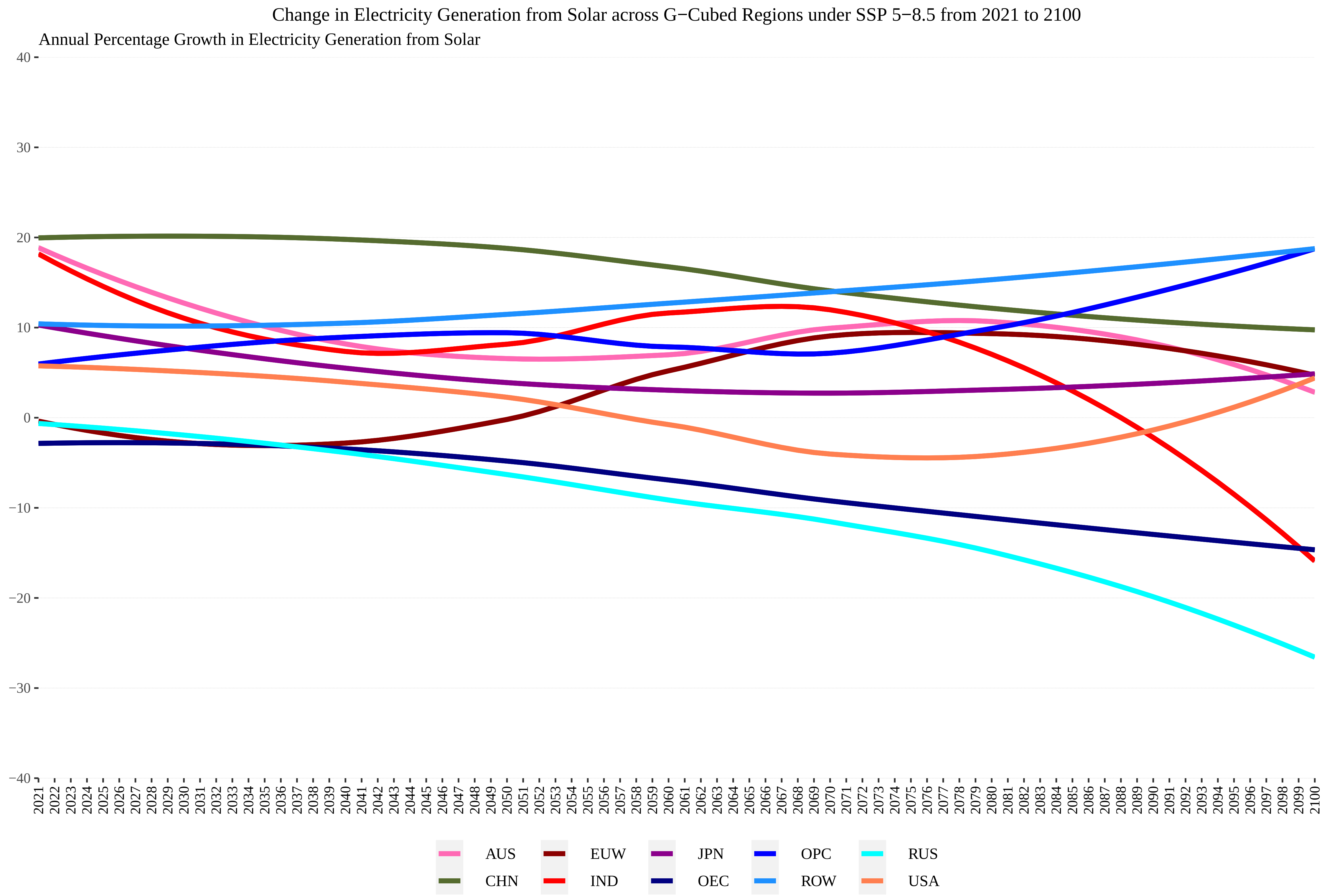


Source: Constructed by the Author.

Change in Electricity Generation from Solar across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100

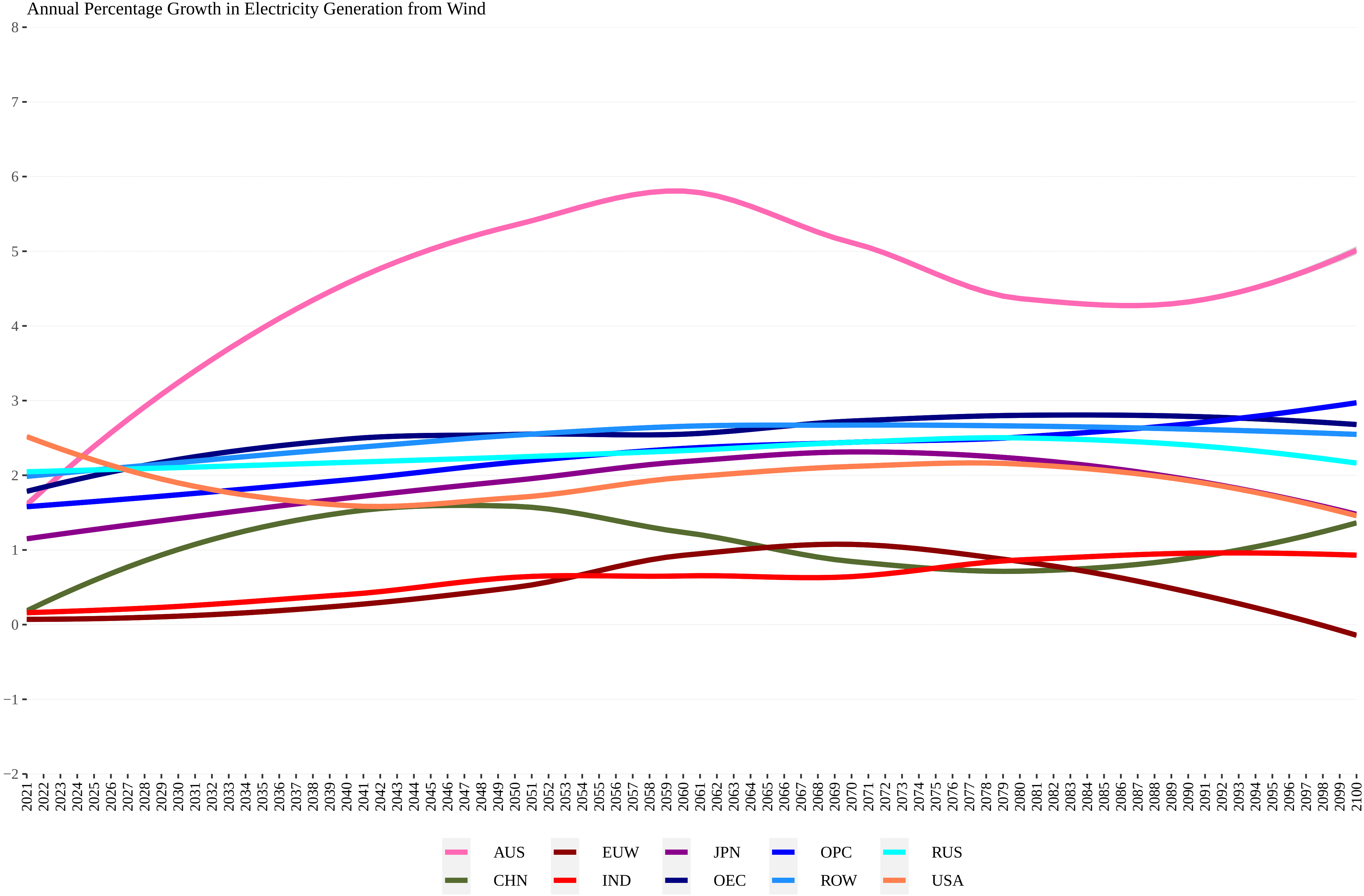


Source: Constructed by the Author.

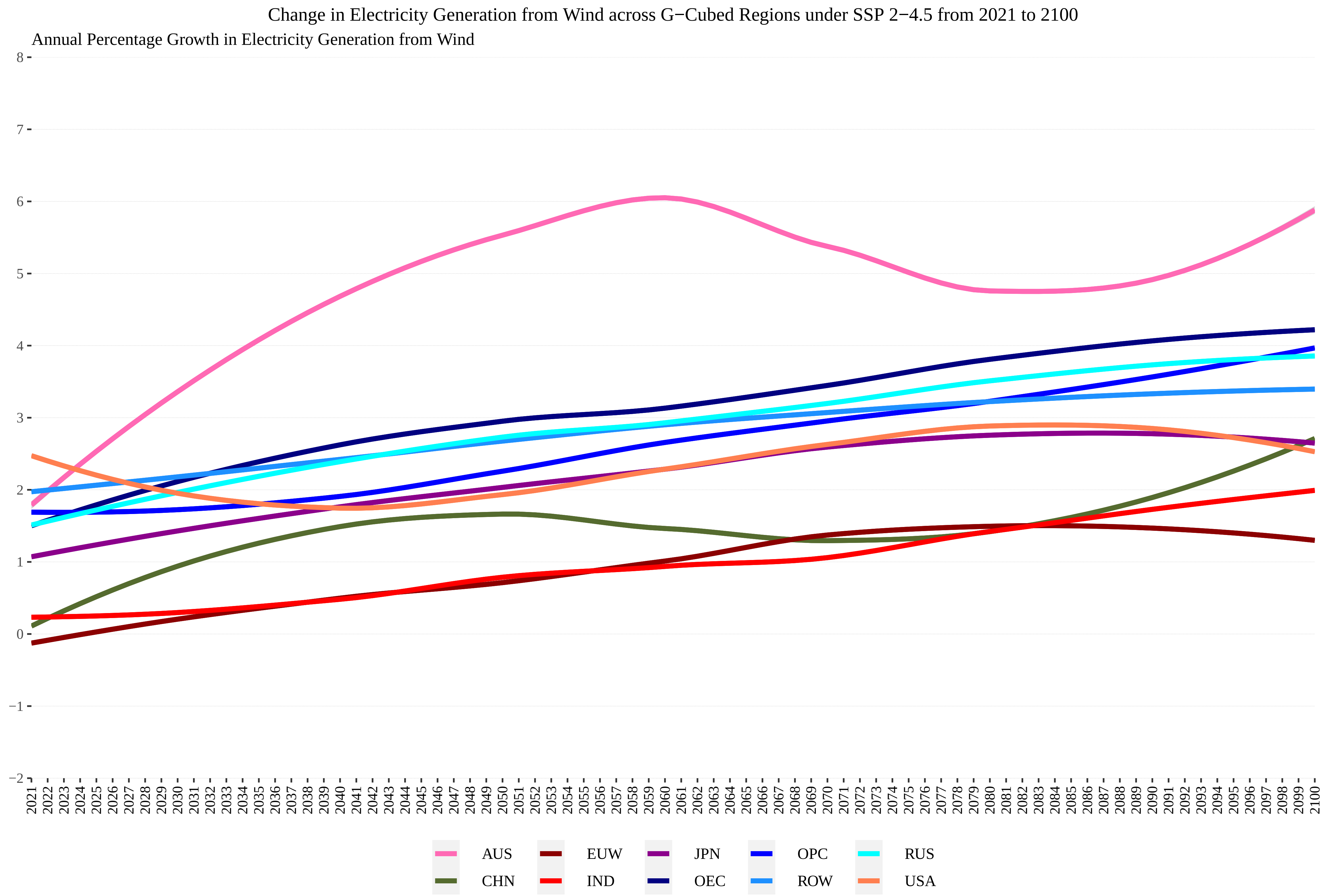


Source: Constructed by the Author.

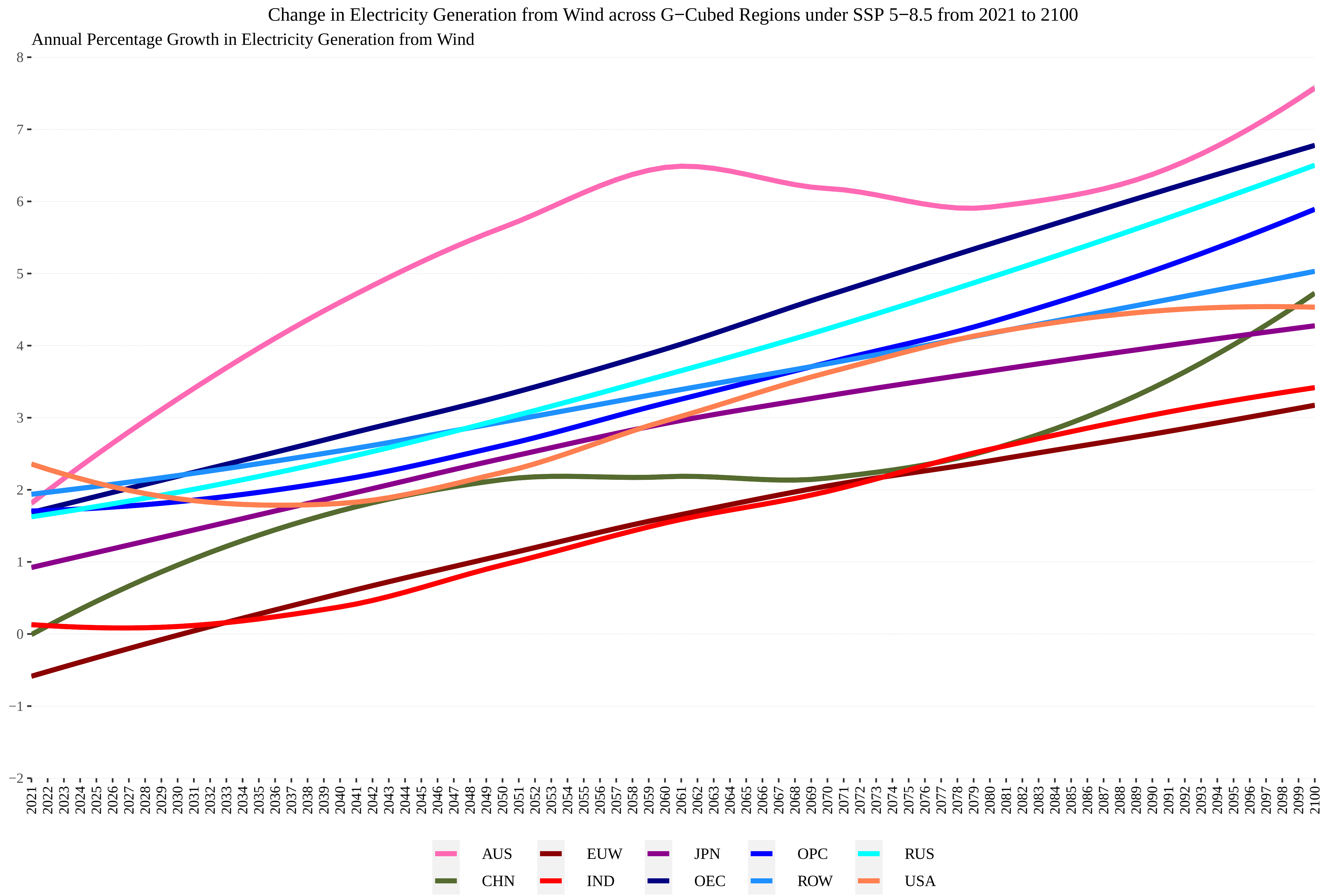
Change in Electricity Generation from Wind across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



Source: Constructed by the Author.

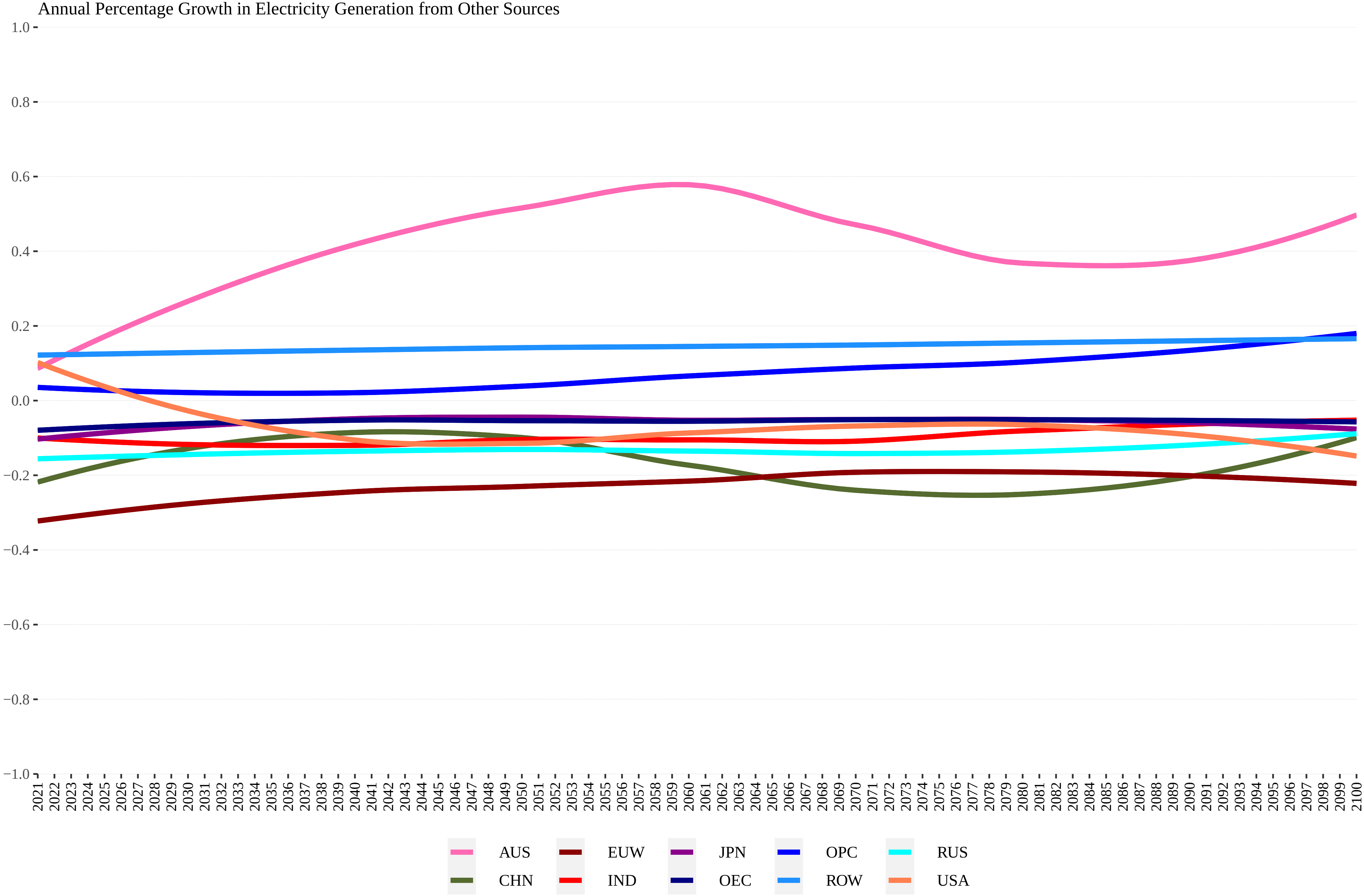


Source: Constructed by the Author.

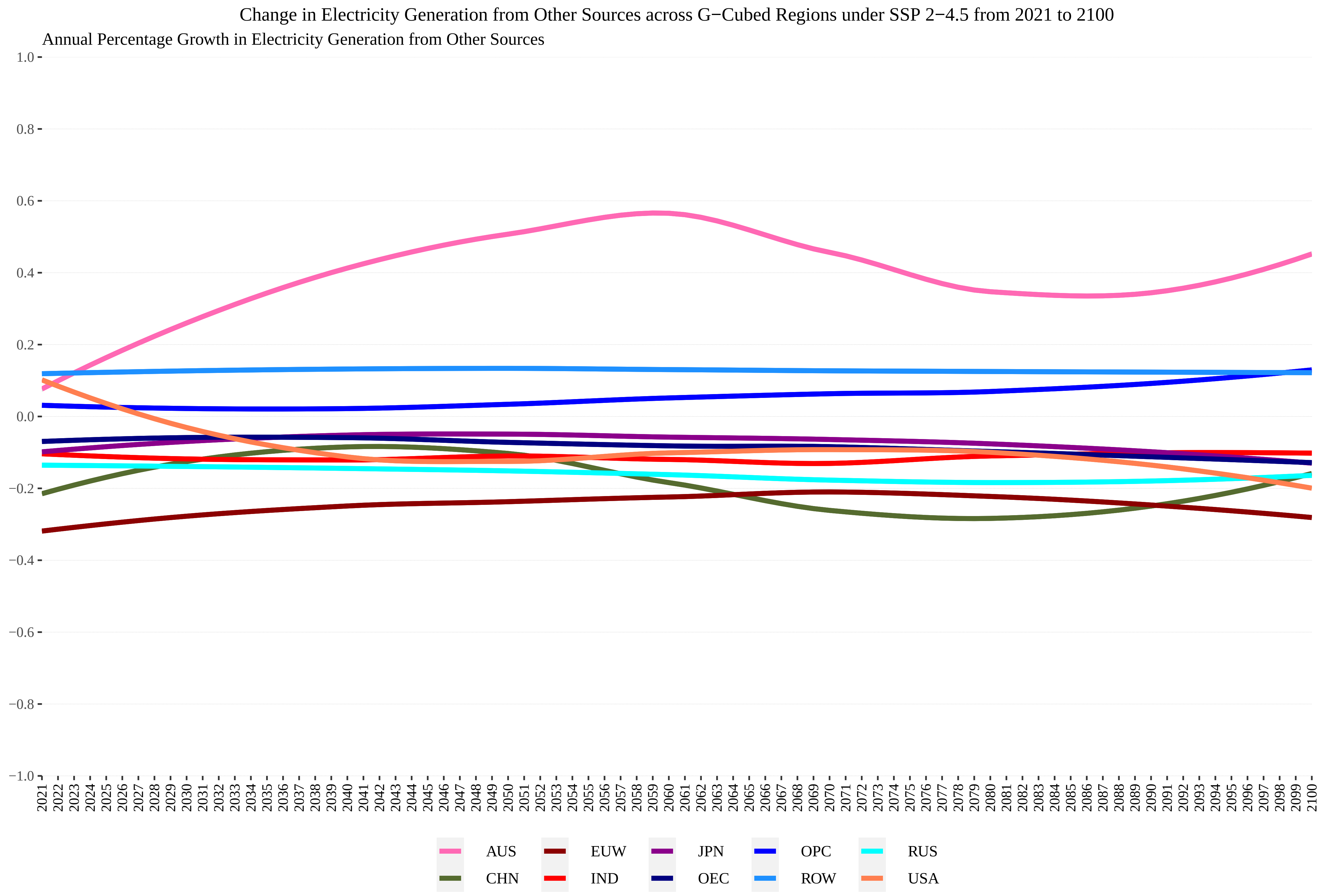


Source: Constructed by the Author.

Change in Electricity Generation from Other Sources across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



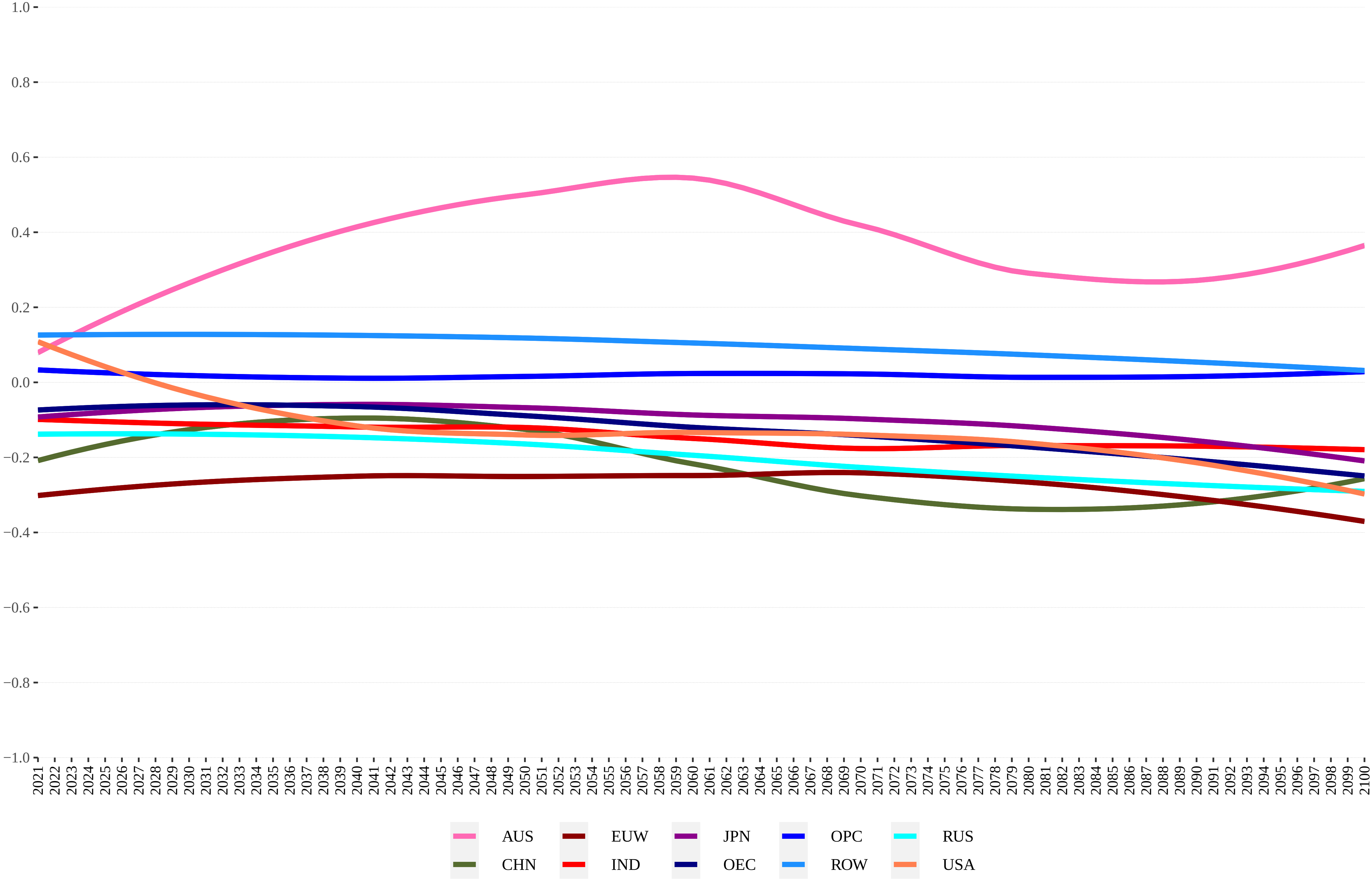
Source: Constructed by the Author.



Source: Constructed by the Author.

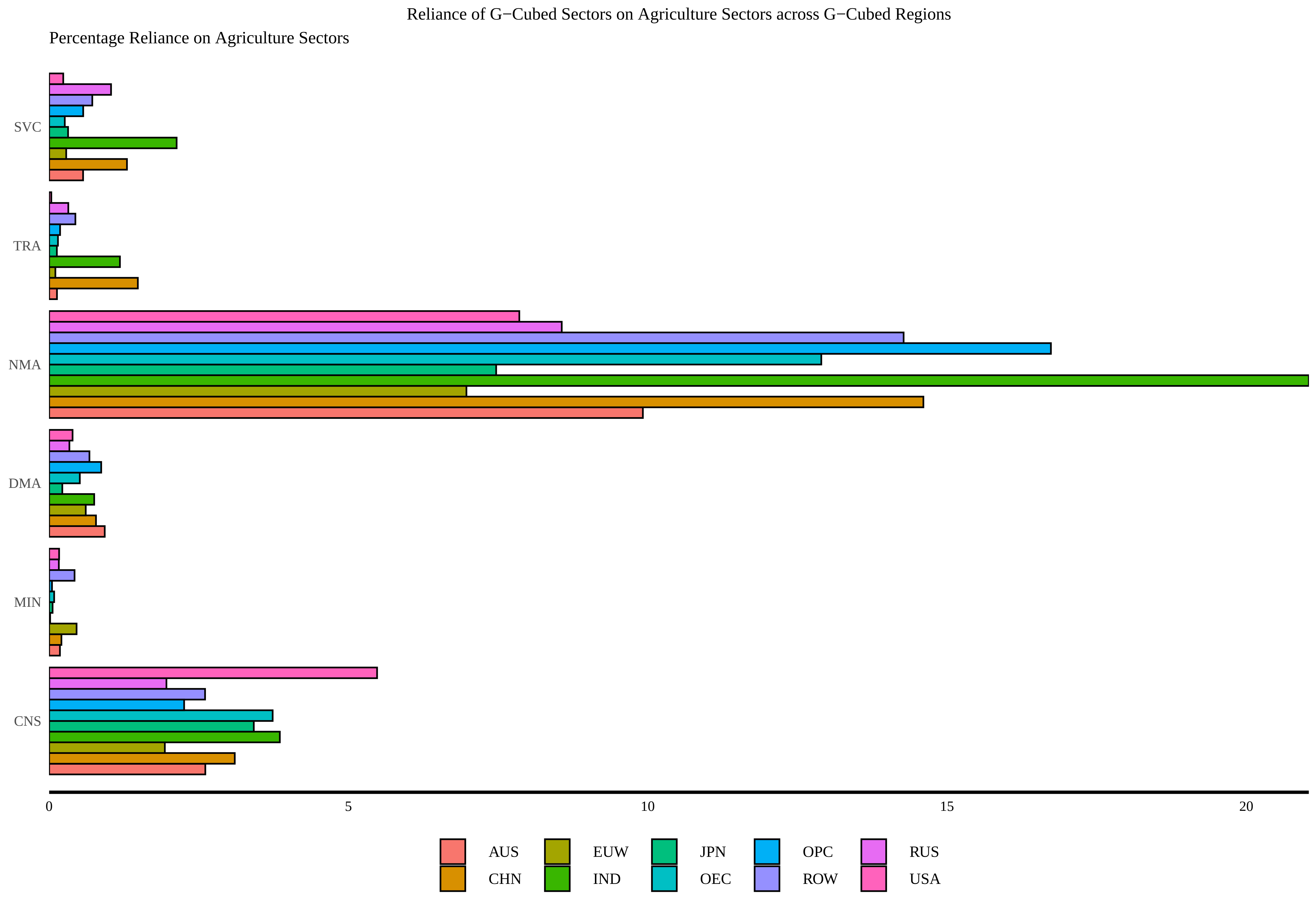
Change in Electricity Generation from Other Sources across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100

Annual Percentage Growth in Electricity Generation from Other Sources



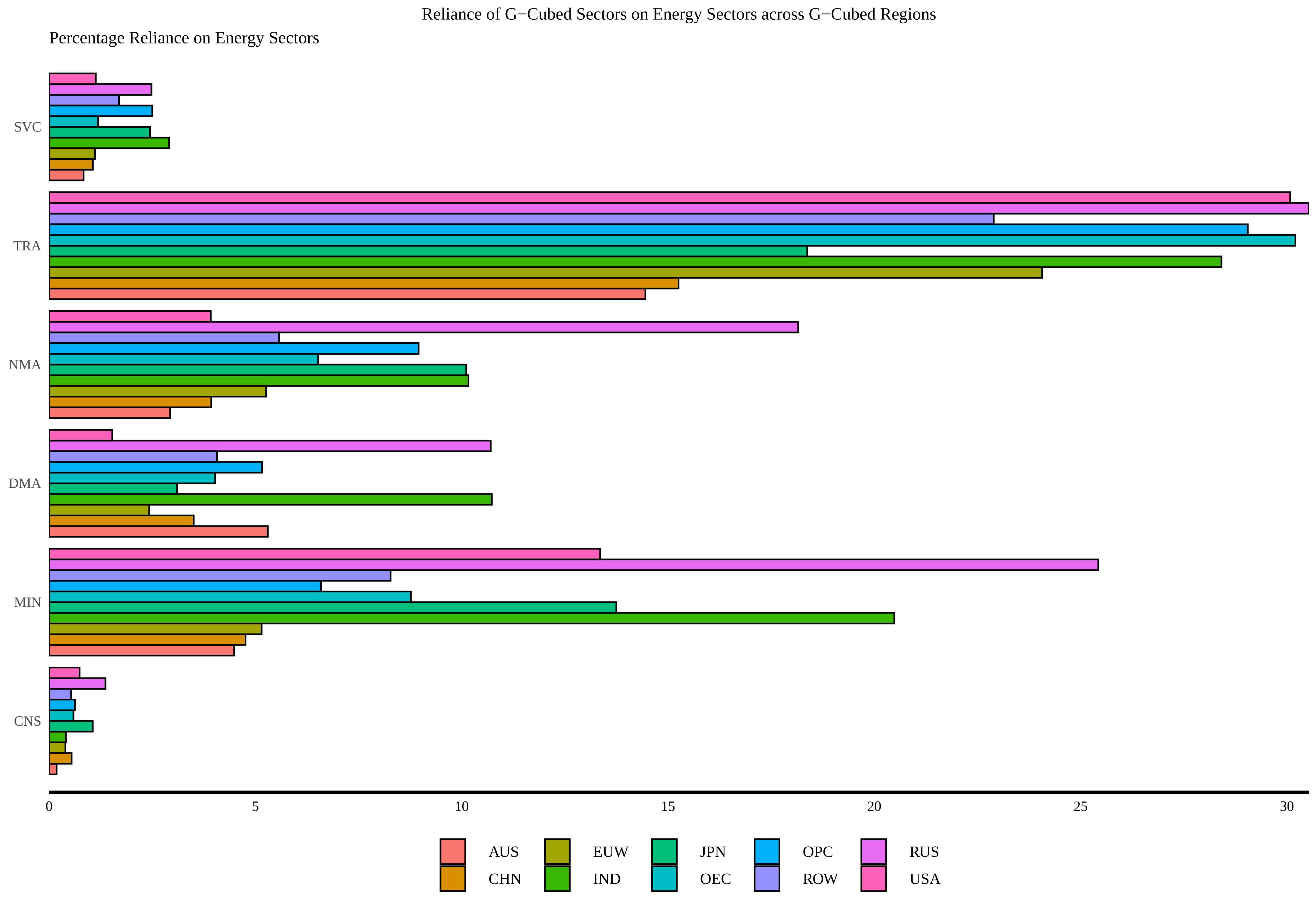
Source: Constructed by the Author.

ANNEXURE 22: SECTOR RELIANCE ON AGRICULTURE



Source: G−Cubed (GGG20J_v164). SVC − Services, TRA − Transportation, NMA − Non−durable Manufacturing, DMA − Durable Manufacturing, MIN − Mining, CNS − Construction

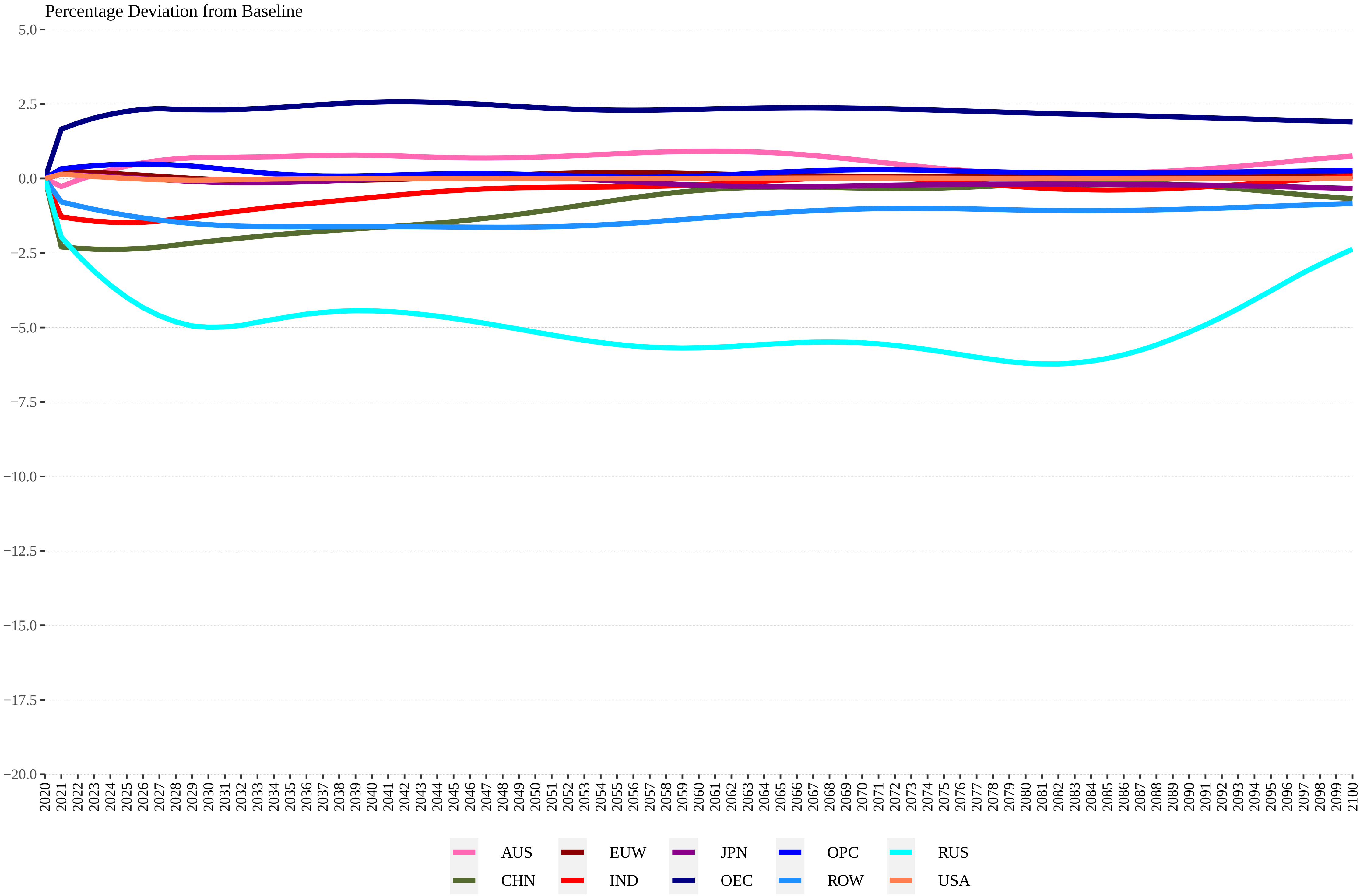
ANNEXURE 23: SECTOR RELIANCE ON ENERGY



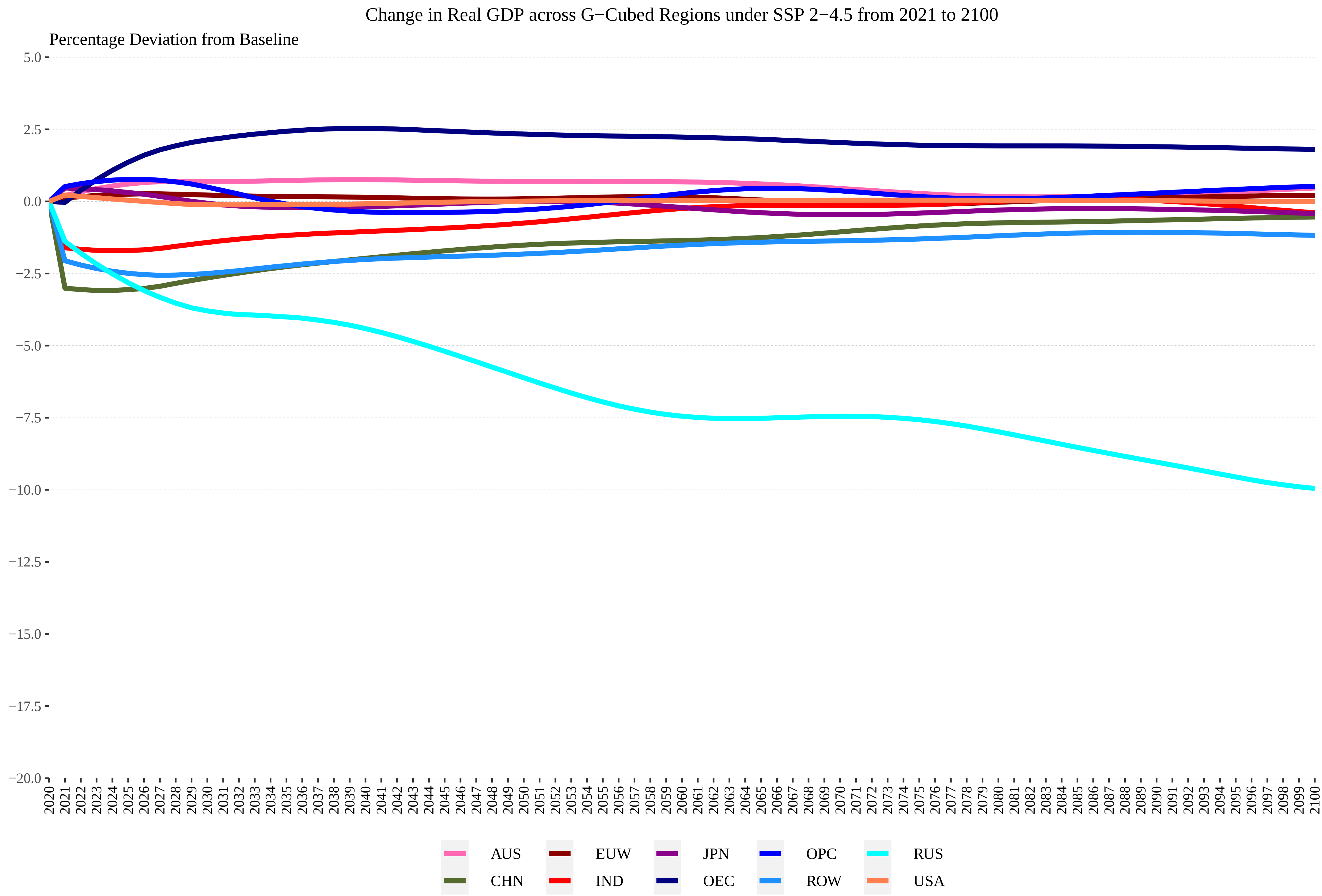
Source: G−Cubed (GGG20J_v164). SVC − Services, TRA − Transportation, NMA − Non−durable Manufacturing, DMA − Durable Manufacturing, MIN − Mining, CNS − Construction

ANNEXURE 24: DYNAMIC RESULTS FROM G-CUBED SIMULATIONS

Change in Real GDP across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100

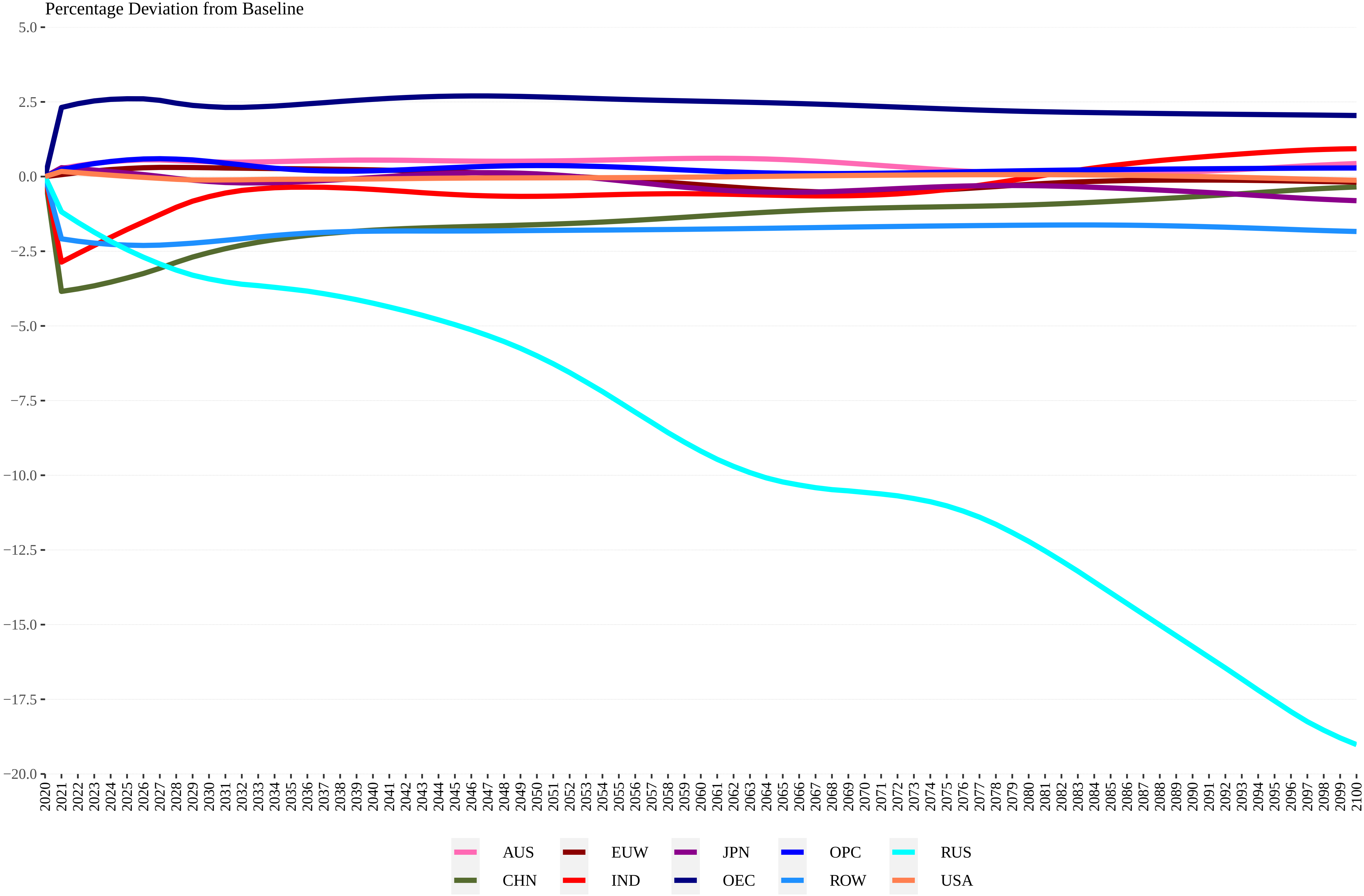


Source: G−Cubed Simulations (GGG20J_v164).

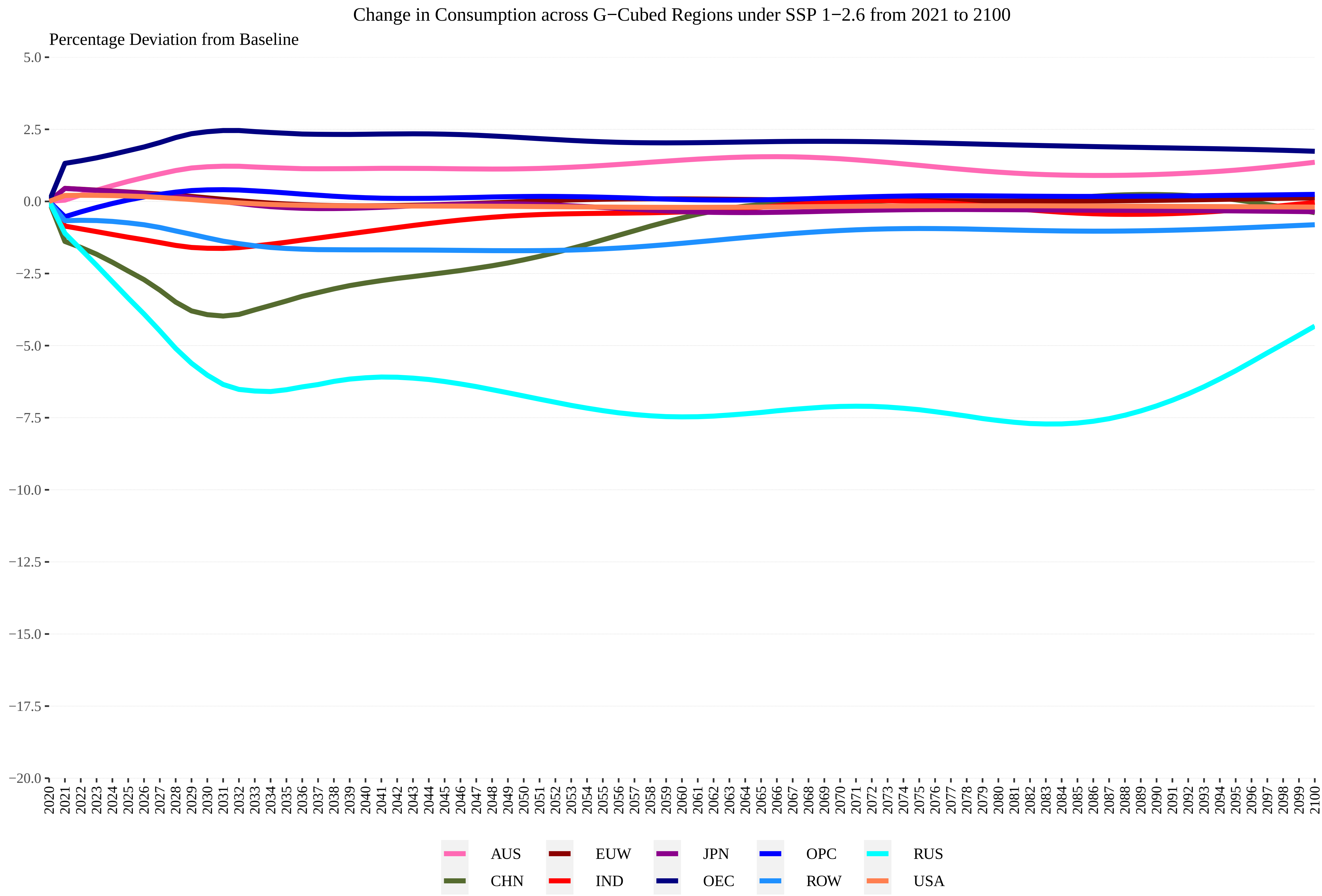


Source: G−Cubed Simulations (GGG20J_v164).

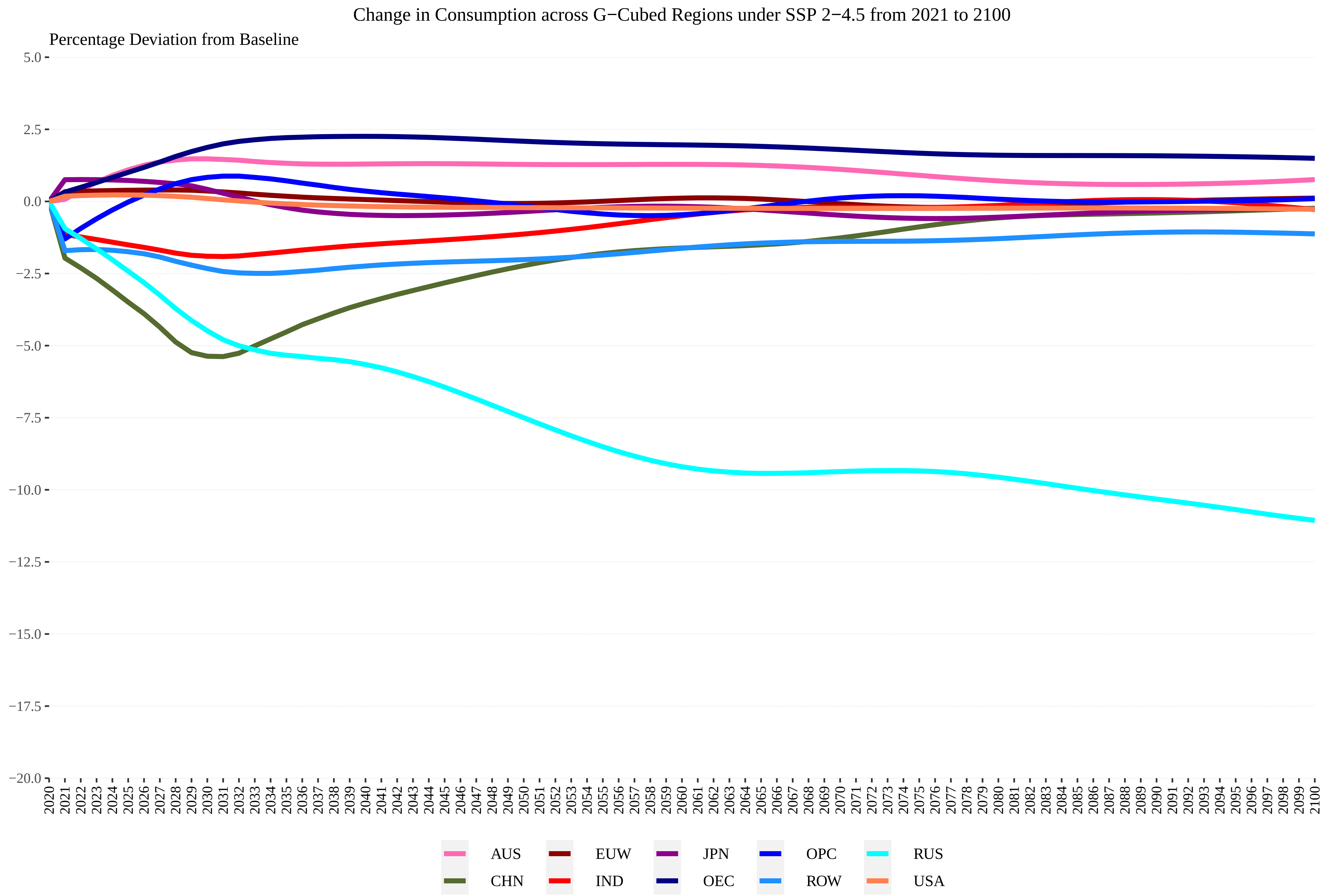
Change in Real GDP across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100



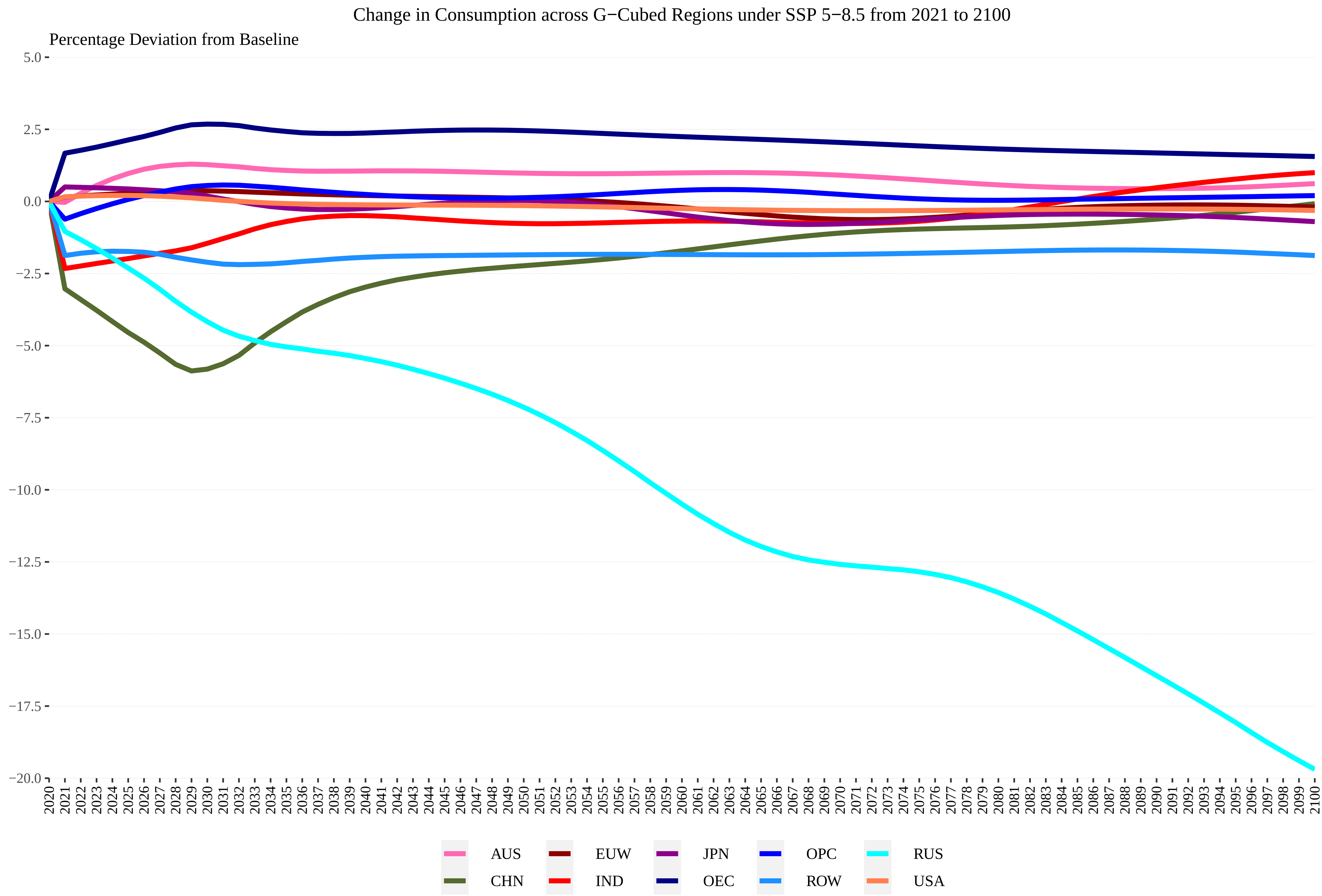
Source: G−Cubed Simulations (GGG20J_v164).



Source: G−Cubed Simulations (GGG20J_v164).

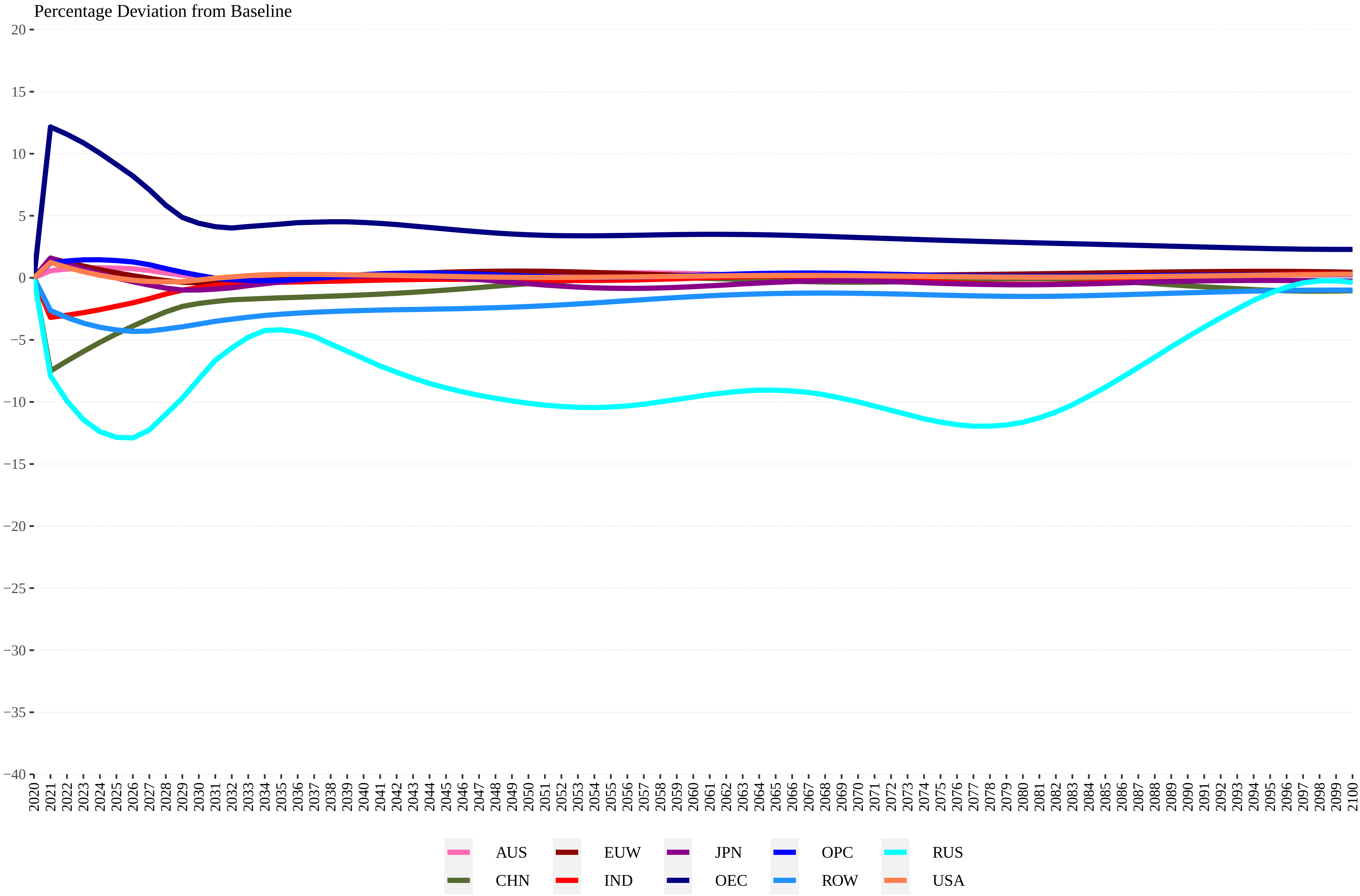


Source: G−Cubed Simulations (GGG20J_v164).



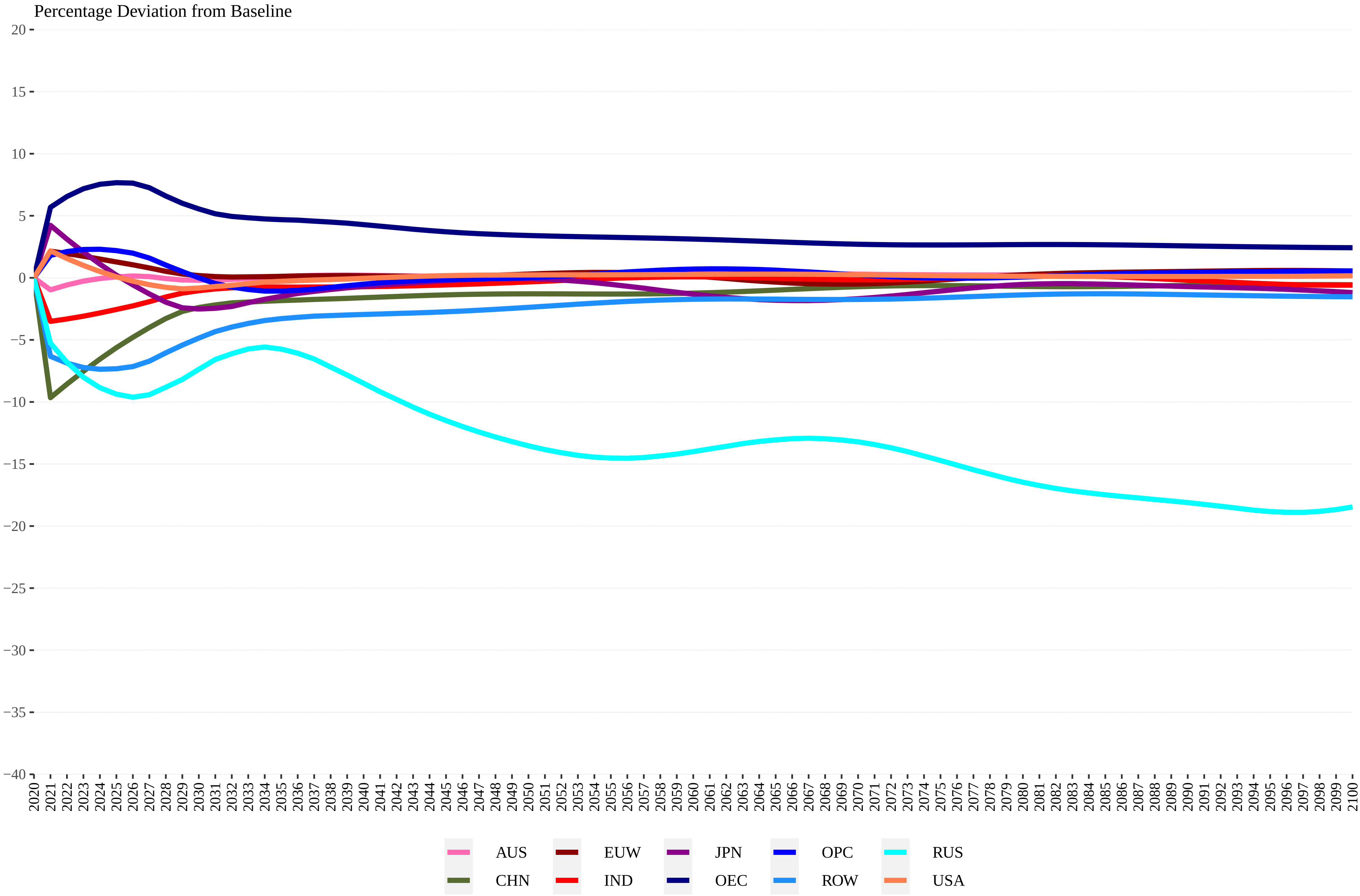
Source: G−Cubed Simulations (GGG20J_v164).

Change in Investment across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



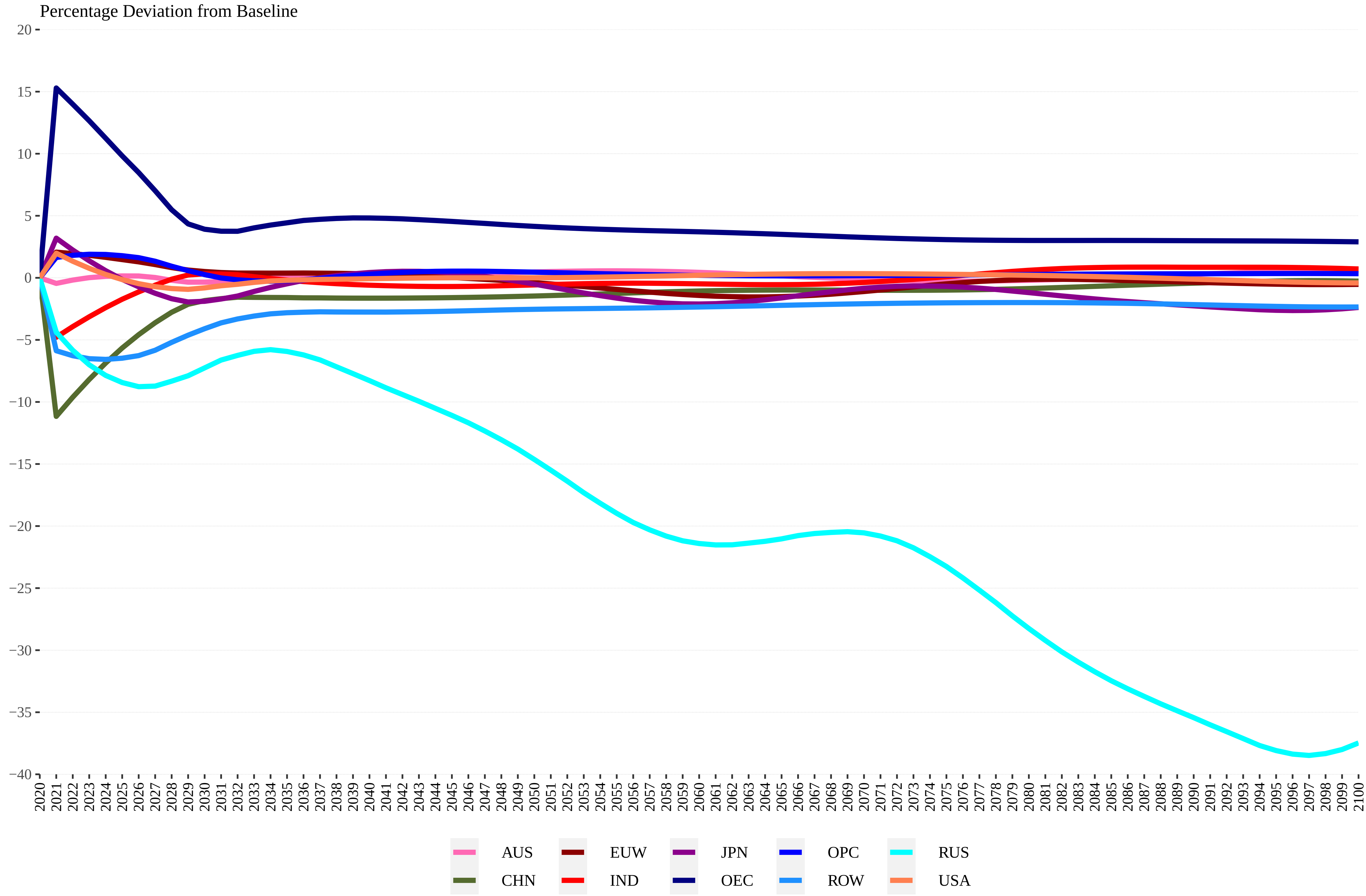
Source: G−Cubed Simulations (GGG20J_v164).

Change in Investment across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100

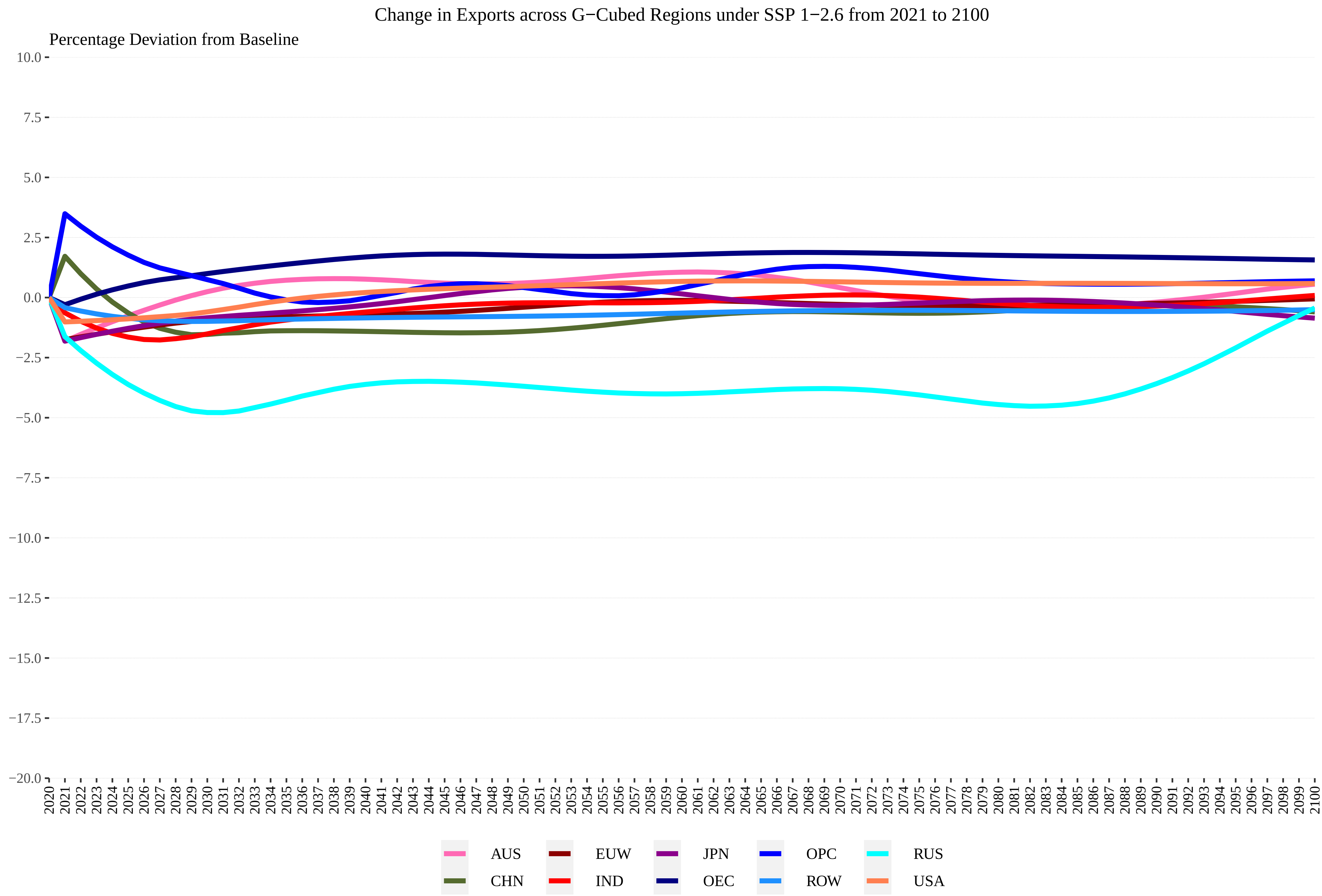


Source: G−Cubed Simulations (GGG20J_v164).

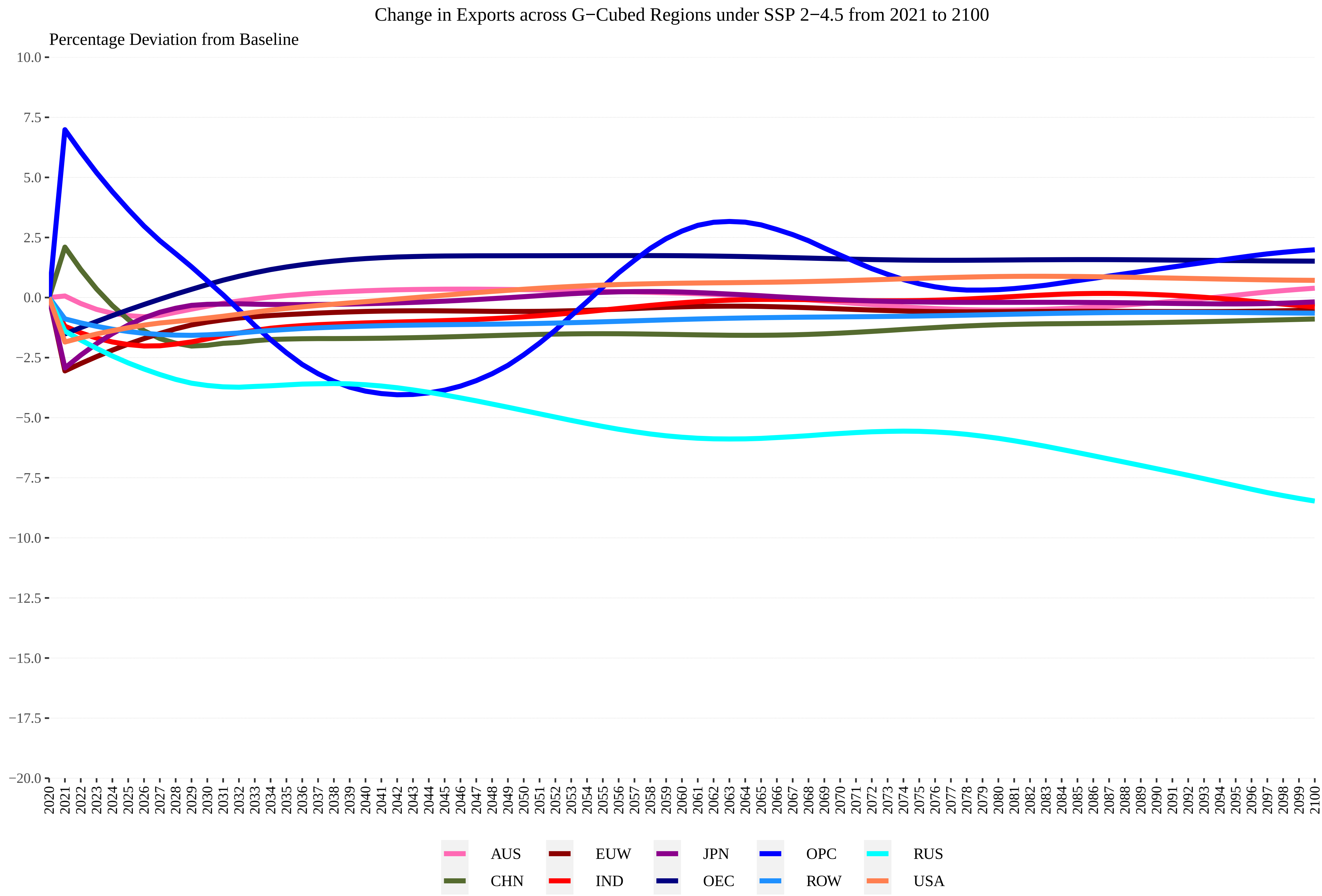
Change in Investment across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100



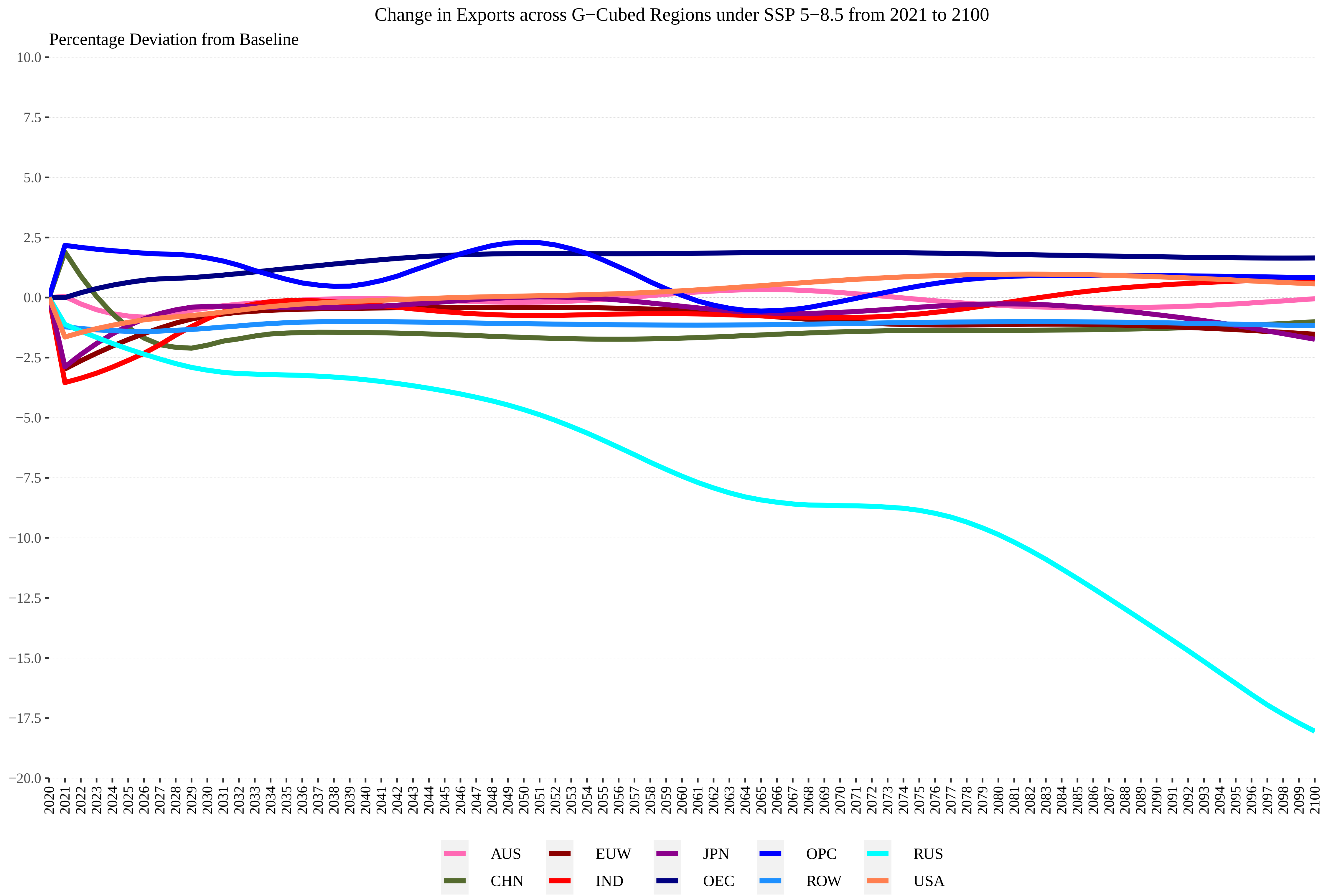
Source: G−Cubed Simulations (GGG20J_v164).



Source: G−Cubed Simulations (GGG20J_v164).

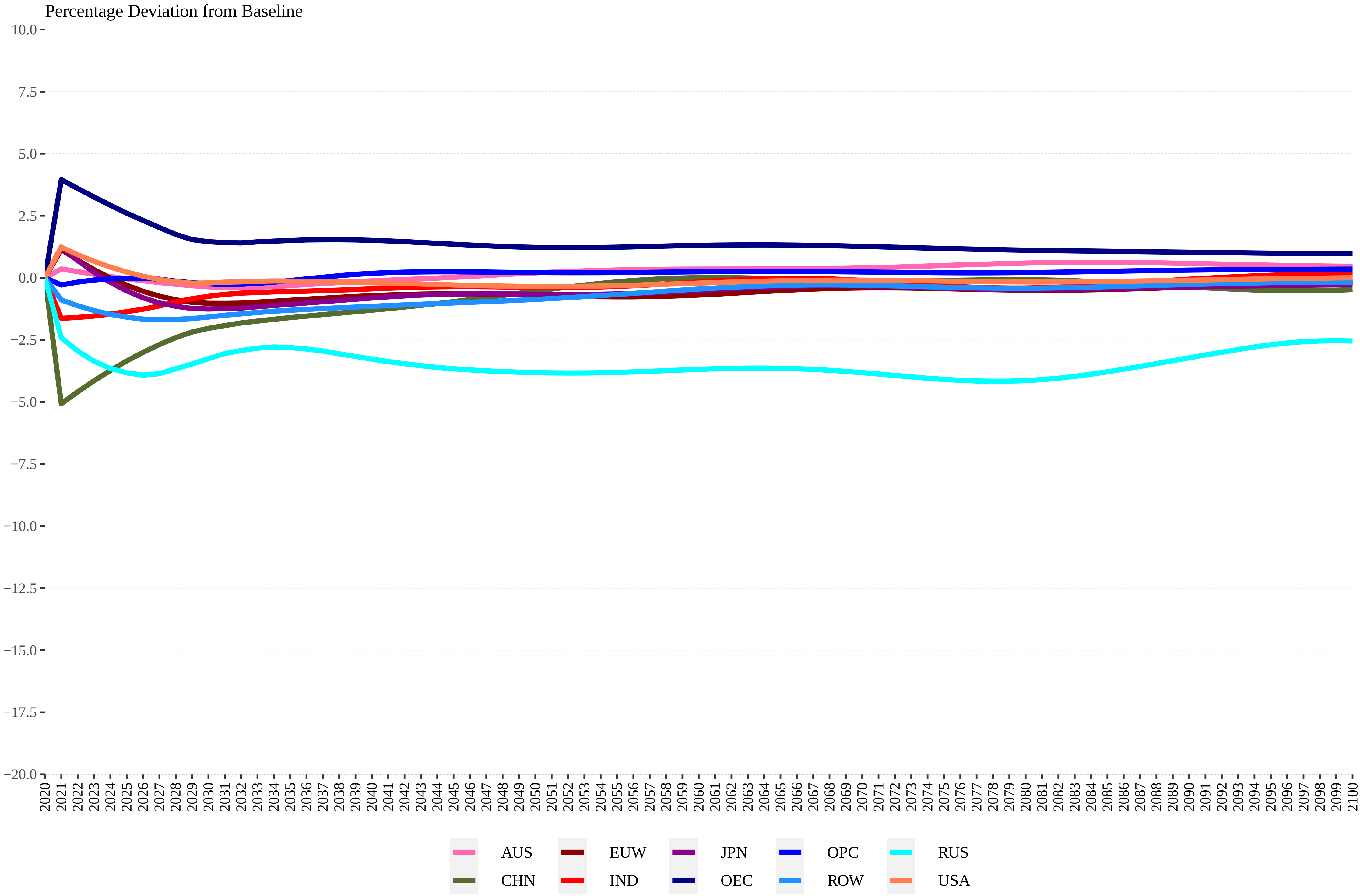


Source: G−Cubed Simulations (GGG20J_v164).

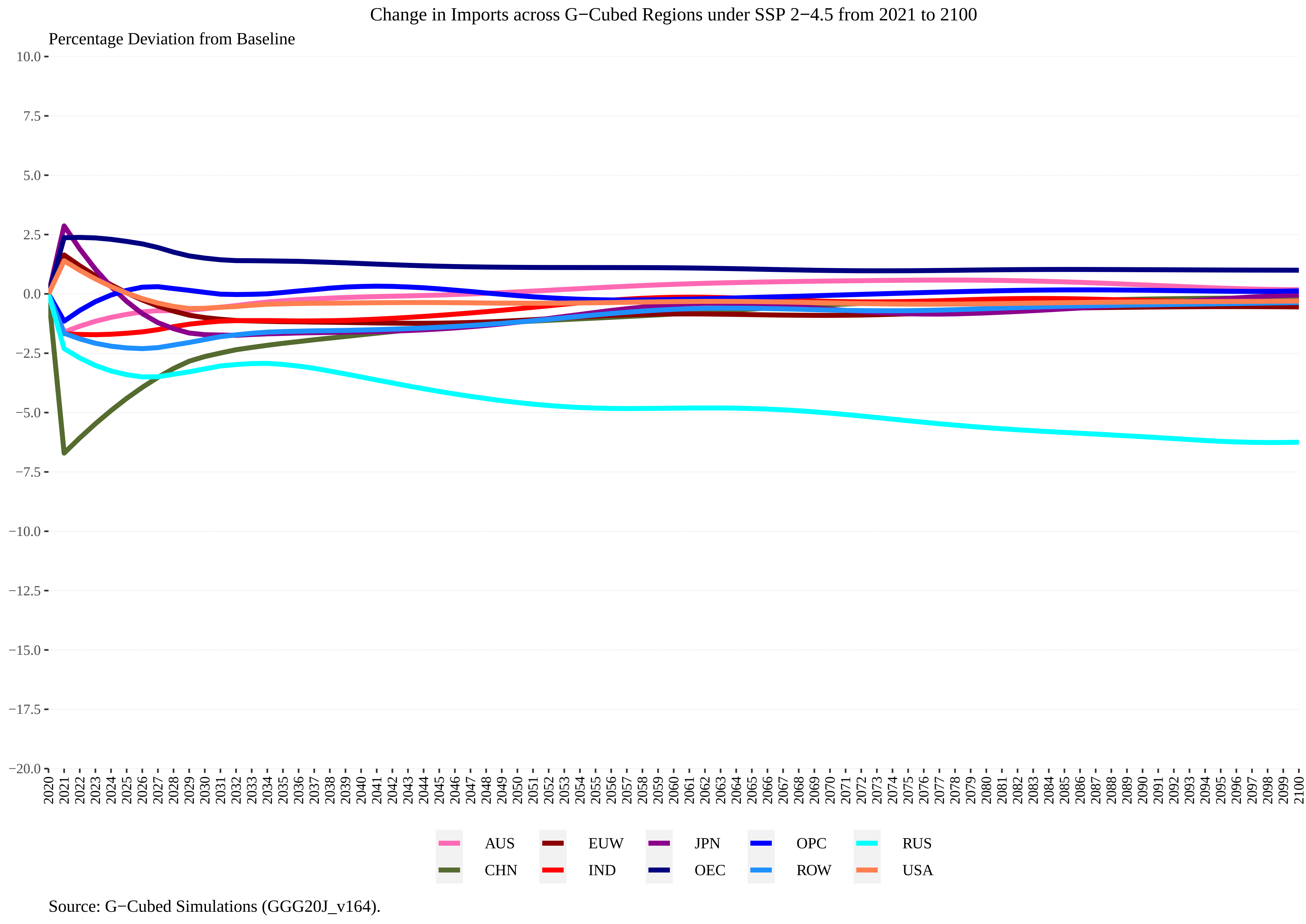


Source: G−Cubed Simulations (GGG20J_v164).

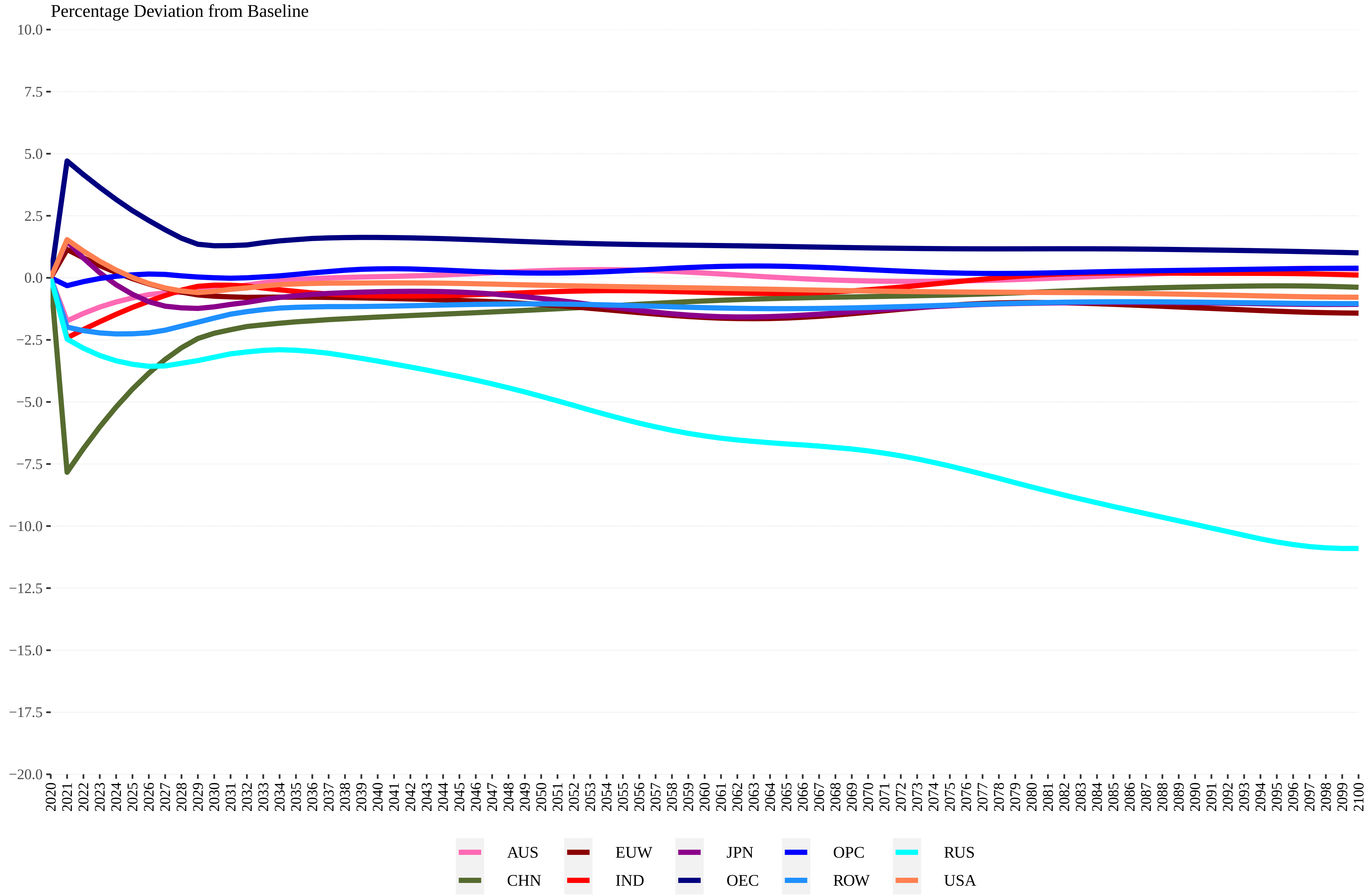
Change in Imports across G−Cubed Regions under SSP 1−2.6 from 2021 to 2100



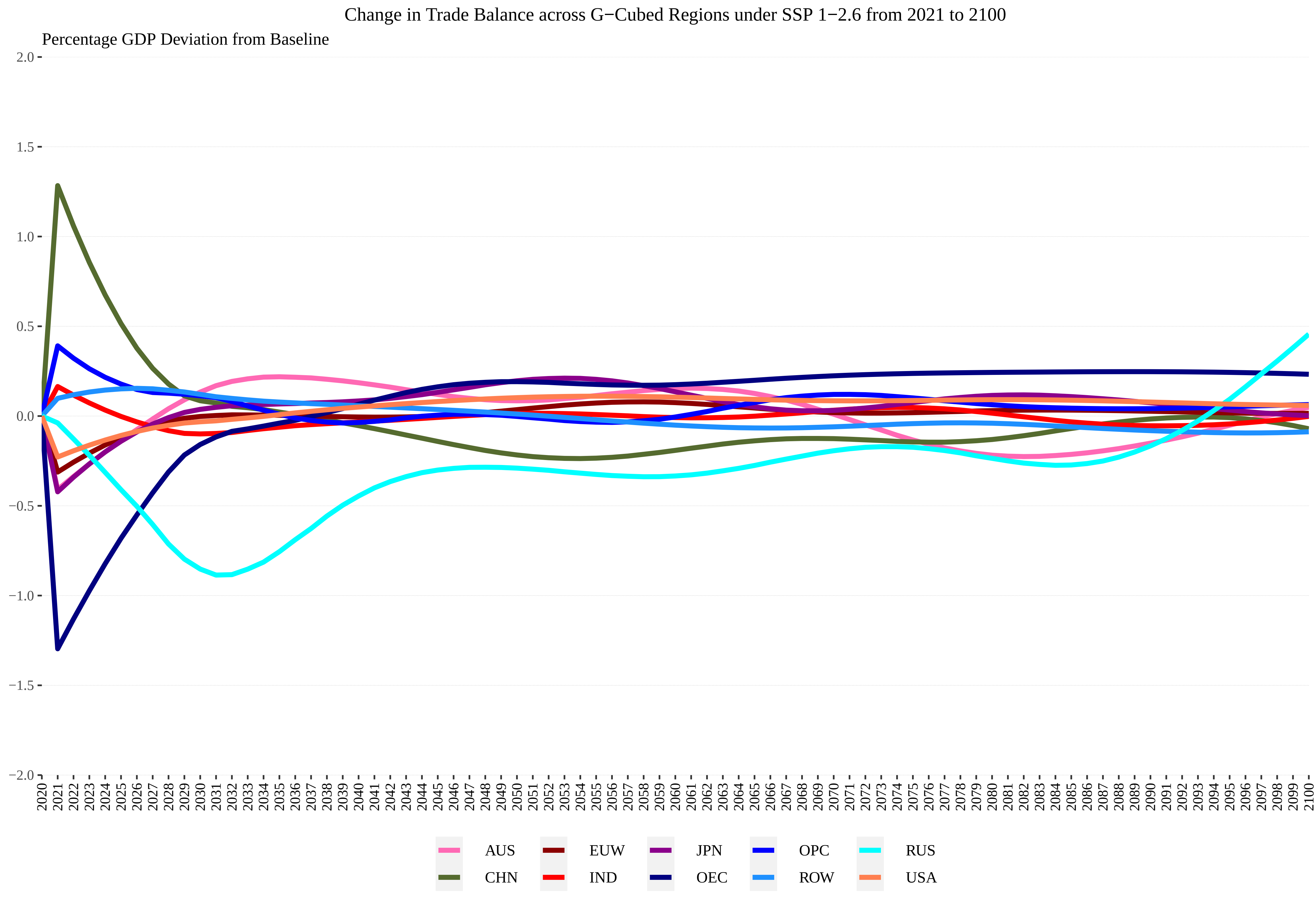
Source: G−Cubed Simulations (GGG20J_v164).


Change in Imports across G−Cubed Regions under SSP 2−4.5 from 2021 to 2100
Percentage Deviation from Baseline
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
−12.5
−15.0
−17.5
−20.0
2020
2030
2040
2050
2060
2070
2080
2090
2100
AUS
CHN
EUW
IND
JPN
OEC
OPC
ROW
RUS
USA
Source: G−Cubed Simulations (GGG20J_v164).

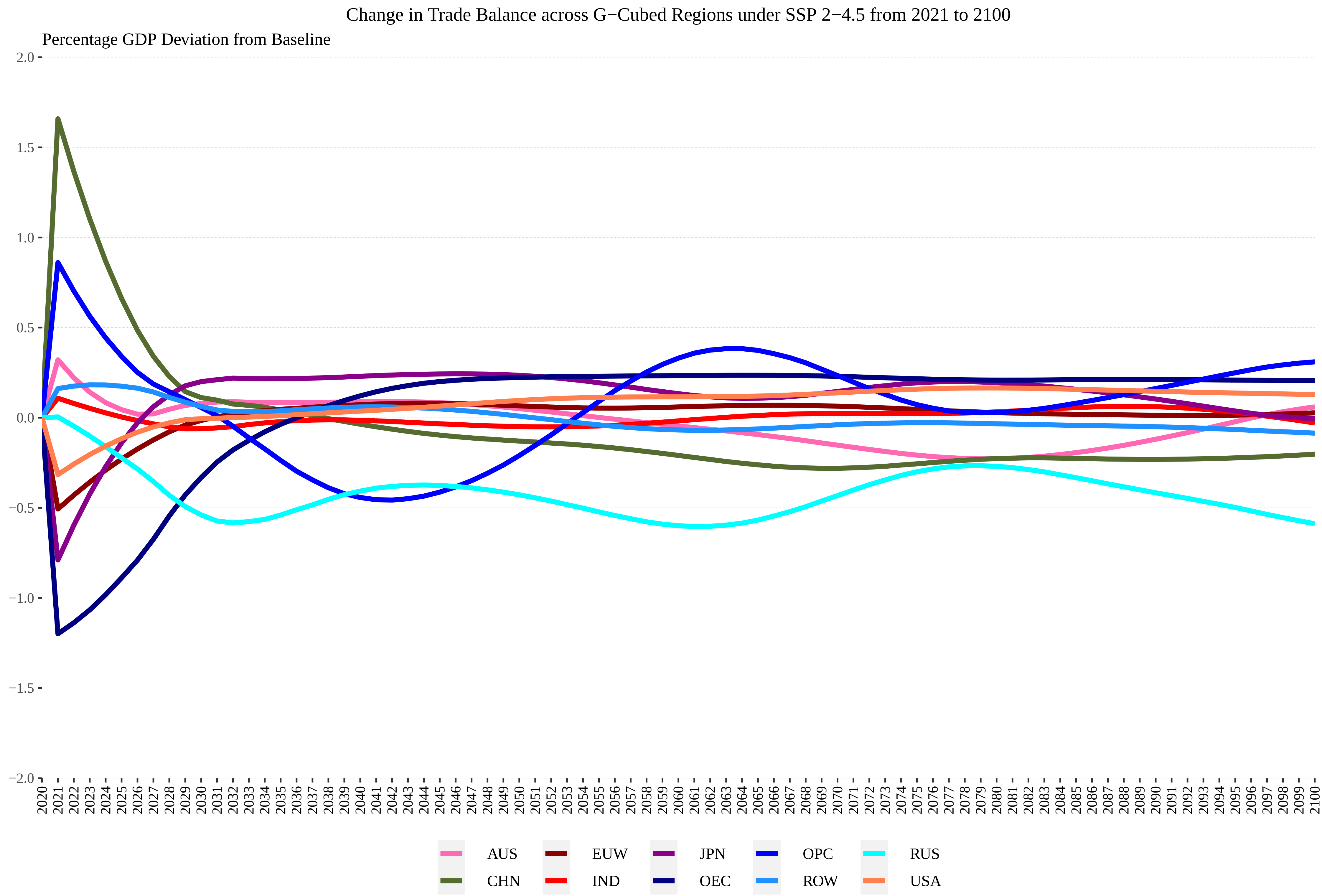
Change in Imports across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100



Source: G−Cubed Simulations (GGG20J_v164).

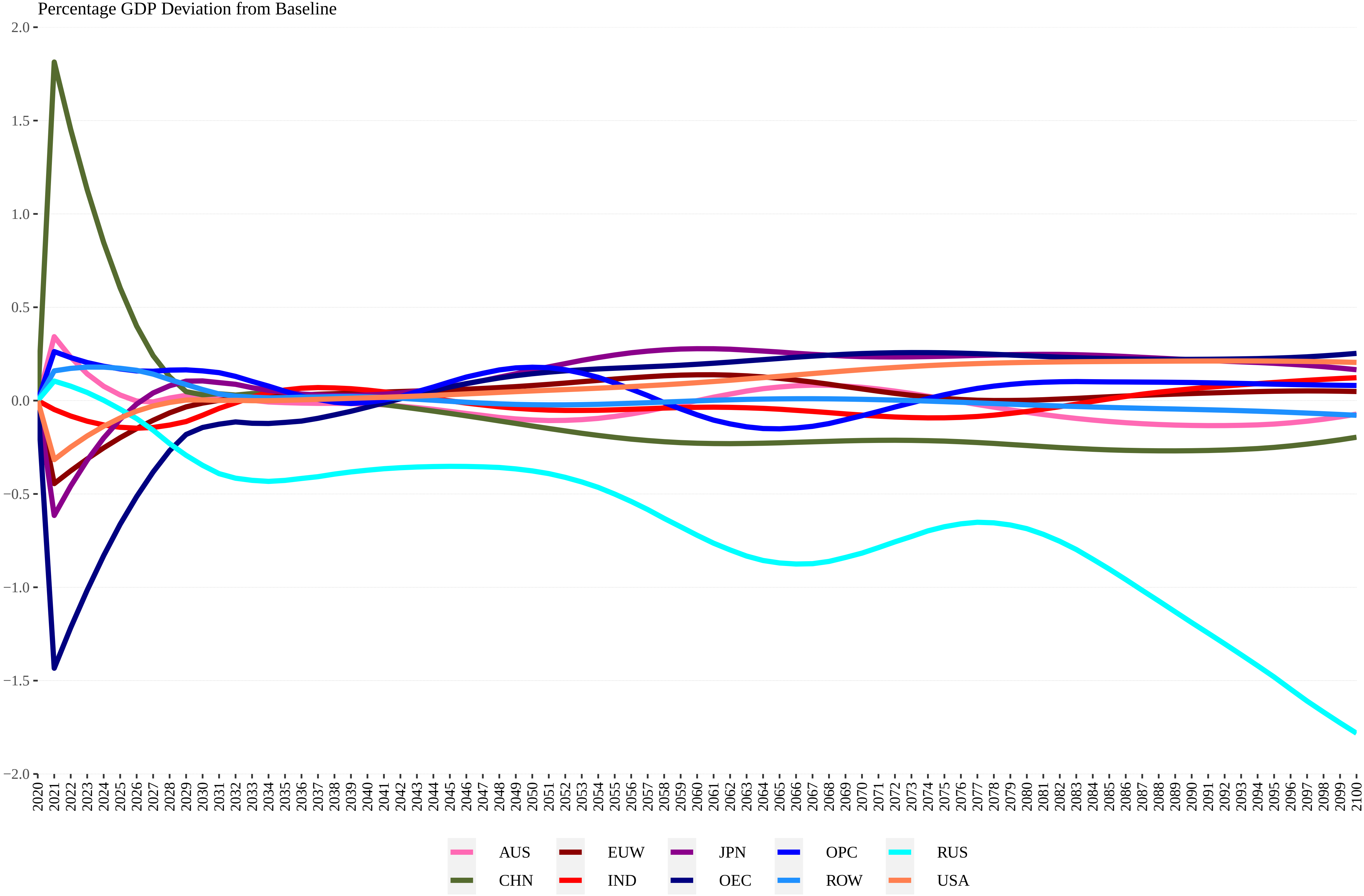


Source: G−Cubed Simulations (GGG20J_v164).



Source: G−Cubed Simulations (GGG20J_v164).

Change in Trade Balance across G−Cubed Regions under SSP 5−8.5 from 2021 to 2100



Source: G−Cubed Simulations (GGG20J_v164).