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Impact of Physical Climate Risks on Financial Assets

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Abstract

Climate change poses substantial risks to global socioeconomic stability. The financial sector of the economy could be affected by climate risks both independent of the real sector and due to the linkages with the real sector. Understanding these linkages is crucial not only to prevent the vulnerability of the financial sector to climate risks but also to effectively utilize the financial markets to raise finance for mitigation and adaptation efforts. This paper explores the impacts of physical climate risks on the risk premia of financial assets. We employ a range of climate indicators representative of chronic and extreme climate risks and a mix of panel regressions, machine learning, and local projections to examine the contemporaneous and persistent effects of physical climate risks on financial assets. We also investigate the exposure of different economic subsectors and assets to physical climate risks. We observe that employing a suite of climate indicators enriches the understanding of the impacts of physical climate risks on financial assets. Most of these pathways align with the impacts on the real sector of the economy via sectoral productivity. The physical climate risks could have persistent effects for several years, both at the aggregate and sectoral levels. Different assets could experience similar effects, although safer assets could reduce the exposure of asset portfolios to climate risks.

Keywords

climate change, financial markets, econometrics, machine learning, local projections

JEL Classification

C51, C53, C54, C55, C68, F41, Q51, Q54

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IMPACT OF PHYSICAL CLIMATE RISKS ON FINANCIAL ASSETS

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ABSTRACT

Climate change poses substantial risks to global socioeconomic stability. The financial sector of the economy could be affected by climate risks both independent of the real sector and due to the linkages with the real sector. Understanding these linkages is crucial not only to prevent the vulnerability of the financial sector to climate risks but also to effectively utilize the financial markets to raise finance for mitigation and adaptation efforts. This paper explores the impacts of physical climate risks on the risk premia of financial assets. We employ a range of climate indicators representative of chronic and extreme climate risks and a mix of panel regressions, machine learning, and local projections to examine the contemporaneous and persistent effects of physical climate risks on financial assets. We also investigate the exposure of different economic subsectors and assets to physical climate risks. We observe that employing a suite of climate indicators enriches the understanding of the impacts of physical climate risks on financial assets. Most of these pathways align with the impacts on the real sector of the economy via sectoral productivity. The physical climate risks could have persistent effects for several years, both at the aggregate and sectoral levels. Different assets could experience similar effects, although safer assets could reduce the exposure of asset portfolios to climate risks.

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1 INTRODUCTION

Climate change challenges global socioeconomic stability. The risks posed by climate change can be classified as physical and transition risks. The physical climate risks, including chronic changes in temperature and precipitation as well as extreme climate-related events, such as droughts, floods, heat and coldwaves, storms, and wildfires, disrupt economic activities, damage physical assets and infrastructure, and reduce labor and sectoral productivity. The transition risks arise from policy changes to act on climate change, technological developments, and preference changes for consumption and investment during the transition to a low-carbon economy.

The impacts of physical and transition risks of climate change on the real sector of the economy could spill over to the financial sector of the economy. Those impacts could also result in feedback effects, magnifying the impact on the real sector. Transmission channels, via which the real impacts could spill over to the financial sector, include changes in asset values, returns on assets, income, savings, wealth, and investment. Such effects are additional to the direct effects on the firms, institutions, and markets providing financial services to the real sector of the economy. The direct effects include readjustments to the demand for financial services, operational risks, costs, and losses, as well as market, credit, and regulatory risks (Zhou et al. 2023; Grippa et al. 2019).

Asset prices are a significant source of the impacts of climate risks on the financial sector. They affect all aforementioned transmission channels of climate risks to the financial sector. From a theoretical perspective, the price of an asset reflects the present value of its expected future returns. Physical and transition climate risks could affect both the useful life and the potential of the asset to generate returns.[2] Given the role of perceptions and expectations in financial markets, the physical and transition risks could trigger asset revaluations even without tangible damage to the underlying physical assets. As asset prices create linkages within the financial sector, such as between the financial markets and institutions, the impacts of climate risks on assets could also give rise to systemic risks by affecting financial stability via contagion, which leads to such events considered as a "Green Swan" or a "Climate Minsky Moment" (Ojea-Ferreiro et al. 2022; Bolton et al. 2020; Carney 2015).

A resilient financial sector is fundamental to facilitating global economic activities. Disruptions to economic activities from climate risks and the necessity to mobilize finance to facilitate the transition and empower adaptation and mitigation efforts further increase the demand for a resilient financial sector to enable within- and across-border financial flows. Thus, the resilient operation of the global financial sector while managing the direct impacts of climate risks on itself is crucial in addressing climate change. The increasing

[2] For example, impacts on the physical assets of a coal mining firm from an extreme weather event could reduce the attractiveness of the firm's shares, as their fundamental value is attached to the potential of the firm to generate revenue and profits using its physical assets. Even without physical climate risks, a policy decision to transition to a low-carbon economy could also reduce the useful life of the physical assets and their potential to contribute to firm operations. Household assets (such as real estate and vehicles) could also be vulnerable to climate risks similarly.

awareness, interest, and actions of central banks and financial regulators to proactively manage climate risks is encouraging (Boissinot et al. 2016).

A central challenge to financial regulators in reducing the exposure of the financial sector to both physical and transition risks while preventing sudden changes in financial valuations is determining the price differential between high- and low-carbon-intensive assets. Such price differentials, referred to as a carbon discount or a green premium, could help understand investor preferences and sentiments towards decarbonization and be used in various fiscal and monetary policy instruments to drive decarbonization alongside other instruments, such as carbon prices and emission trading systems (Intoni et al. 2023; Alessi et al. 2020, 2019).

Within a given country, as both risky and risk-free assets could be vulnerable to systematic climate risks, the fluctuation in the risk premia of risky assets compared to risk-free assets could explain the unsystematic exposure of risky assets. Such risk premia could differentiate high- and low-carbon-intensive sectors when considering the physical risks of climate change and transition policies for decarbonization. However, globally, as the systematic exposure of countries to climate risks varies, additional country-specific risk premia could exist (Nag et al. 2021).

Existing research attempts to quantify the risk premia using various approaches. The research belongs to two main philosophical schools. Purely forward-looking approaches assume that the existing asset values have not priced in climate risks and engage in hypothetical simulations to illustrate how costly asset price adjustments could be (e.g., Christos & Anastasios 2019). Backward-looking approaches assume that the current asset values have partially priced in climate risks but acknowledge that much larger adjustments may occur depending on the scale and speed of the transition policies (e.g., Faccini et al. 2023; Sautner et al. 2023).

The existing research is also distinguishable based on the source of climate risks they focus on. One body of literature explores how the risk premia for different assets could change in response to transition risks as investor (and broader) awareness of climate transition policies increases (Li et al. 2023; Agliardi & Agliardi 2021). Although still limited, the literature on assessing the responsiveness of the risk premia in response to physical risks is relatively more prevalent. Most of these studies are event studies focusing on the aggregate stock market indices in developed countries with limited findings about sector-specific effects (Tay 2023). Bua et al. (2022) illustrate that investment portfolios are responsive to physical risks of economic significance using a text-based analysis. Fernando et al. (2020), using panel regressions, demonstrate that returns from equity markets have been sensitive to the occurrence of historical climate-related extreme events, and even without additional or incremental climate risks, the recurrence of those historical events alone in the future could result in significant economic losses under the Representative Concentration Pathways. All strands of research agree that increasing intensity and frequency of physical climate risks are negatively associated with asset prices, and transition risks could increase the risk premia for carbon-intensive assets.

This paper makes four main contributions to the emerging literature on the impacts of physical climate risks on financial assets. Firstly, it illustrates the heterogeneous impacts of a range of both chronic and extreme climate risks on equity risk premia. Secondly, it provides evidence of the persistence of the heterogeneous impacts of physical climate risks. Thirdly, using Australia as a case study, it illustrates the persistent impacts of physical climate risks on 20 economic sectors. Fourthly, it estimates the impacts of different physical risks on several assets. The rest of the paper is organized as follows. Section 2 discusses the data used and the empirical approaches. Section 3 discusses the results from the empirical estimations. Section 4 concludes by outlining the implications and future directions for research.

2 EMPIRICAL ESTIMATIONS

We conduct four analyses to explore the impacts of climate risks on financial markets: (1) The contemporaneous impact of physical climate risks on equity risk premia; (2) The persistent impact of physical climate risks on equity risk premia; (3) The persistent impact of physical climate risks on sectoral equity risk premia, and (4) The persistent impact of physical climate risks on risk premia on different assets. We employ datasets with different country, sectoral, and temporal coverage for these analyses and penalized regressions and local projections as methods.

2.1 Financial Data

Despite efforts to use the same dataset consistently across all analyses, the sample size differs due to limitations associated with the financial data, mainly with respect to the country and time coverage. Table 1 presents the various financial datasets used in this paper and their sources.

Table 1: Financial Data and Sources

	Source	Data	Country Coverage	Temporal Coverage
1	Reuters Refinitiv Datastream (2020)	Performance of Global Stock Markets	71	1990-2020
2	FRED by the Federal Reserve Bank of St. Louis (2023)	1. Global Data on Long-term Government Bonds 2. Chicago Board Options Exchange (CBOE) Volatility Index	36	1990-2020
3	World Development Indicators by the World Bank (2023)	1. Current Account Balance as a Proportion of GDP 2. Public Debt as a Proportion of GDP 3. GDP per Capita Growth 4. GDP Growth	266	1990-2020
4	Australian Stock Exchange (2023)	Stock Market Performance of the 100 Leading Companies representing 19 subsectors considered in the ASX 200 Index	1	2000-2020
5	Jorda et al. (2017)	1. Returns on Equity 2. Returns on Real Estate 3. Returns on Bonds and Bills 4. Combined Returns on Equity and Real Estate 5. Combined Returns on Bonds, Bills, Equity and Real Estate	18	1870-2020

Source: Constructed by the Author.

2.2 Climate Variables and Indicators

2.2.1 Climate Data

We use historical data on six climate variables: Mean Temperature, Maximum Temperature, Minimum Temperature, Precipitation, Relative Humidity, and Wind Speed. We obtain the historical gridded monthly data for the first four variables from the Climate Research Unit of the University of East Anglia (2022) for the period from 1961 to 2020[3] 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 Earth System Model of the Geophysical Fluid Dynamics Library as reported by the Intersectoral Impact Model Intercomparison Project (Potsdam Institute for Climate Impact Research 2022). We then aggregate the gridded data for 256 countries recognized in the Database of Global Administrative Areas (GADM) (2022). We use the climate variables at monthly and annual frequencies to construct ten physical climate risk indicators indicative of three chronic and seven extreme climate risks, following the approach in Fernando (2023).

2.2.2 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 2 summarizes the climate indicators constructed and used in this paper.

Our approaches to constructing the indicators of extreme temperature conditions are similar to those of Lai and Dzombak (2019). We use the Standardized Precipitation Index (SPI) developed by McKee et al. (1993) to identify precipitation-related extreme conditions. Following the insights in the literature[4] using indicators of extreme conditions, our indicators relate to heat and cold waves, droughts, extreme precipitation events, and storms.[5,6]

The indicators of extreme temperature conditions evaluate how the monthly maximum (or minimum) temperature of a given month has deviated from the 90^{th} and 10^{th} percentiles of the historical baseline distribution (1961-90) of monthly maximum (or minimum) temperatures. Assuming the maximum temperature of a day would be experienced during the day, a maximum temperature exceeding the 90^{th} percentile of the baseline maximum temperature distribution indicates a month with warmer days on average, and a maximum temperature experienced below the 10^{th} percentile of the baseline maximum

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[3] 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.

[4] Russo et al. (2014) use short-term indicators of extreme temperature 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.

[5] The indicators of extreme conditions should not, however, be interpreted as indicators of extreme events. The occurrence of extreme events depends on a complex set of other factors, including local weather conditions and land-use management practices, which are not captured by the above indicators of extreme conditions.

[6] See Fernando (2023) for an illustration and a discussion of the average behavior of the historical climate indicators for 15 United Nations regions from 1991 to 2020.

temperature distribution indicates a month with colder days on average. Similarly, assuming the minimum temperature of a day would be experienced during the night, a minimum temperature exceeding the 90th percentile of the baseline minimum temperature distribution indicates a month with warmer nights on average, and a minimum temperature experienced below the 10th percentile of the baseline minimum temperature distribution indicates a month with colder nights on average. We construct these short-term extreme temperature indicators for each month for each country and obtain the annual average percentage deviation of the maximum (or minimum) temperatures from the 90th and 10th percentiles of the historical baseline distribution (1961-90).

Table 2: 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 of the baseline period (1961–90).	^{0}C
2	Precipitation	Percentage change in annual total precipitation compared to the mean annual total precipitation of the baseline period (1961–90).	%
3	Relative Humidity	Change in the mean annual relative humidity compared to the mean annual relative humidity of the baseline period (1961–90).	%
Extreme Climate Indicators			
4	MaxTemp90P	In a given year, the average percentage change of the monthly maximum temperature from the 90th percentile of the baseline (1961–90) 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 baseline (1961–90) 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 baseline (1961–90) 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 baseline (1961-90) monthly minimum temperature distribution.	%
8	Extremely Dry Conditions	In a given year, the average percentage deviation of the SPI index from -2 (SPI Index < -2 indicates Extreme Dry conditions).	%
9	Extremely Wet Conditions	In a given year, the average percentage deviation of the SPI index from 2 (SPI Index > 2 indicates Extreme Wet conditions).	%
10	Extremely Windy Conditions	In a given year, the average percentage change of the monthly maximum wind speed from the 90th percentile of the baseline (1961-90) monthly maximum wind speed distribution.	%

Source: Constructed by the Author, following Fernando (2023) and Fernando and Lepore (2023).

The indicators of extreme precipitation conditions evaluate how monthly precipitation patterns for a given country have changed compared to the historical baseline distribution (1961-90). SPI is one such statistical indicator widely used in meteorology to identify dry and wet conditions. SPI compares the total precipitation observed at a particular location during a period of n months with the long-term rainfall distribution for the same period at the same location. SPI is calculated monthly for a moving window of n months, where n indicates the rainfall accumulation period, typically 1, 3, 6, 9, 12, 24, or 48 months (European Commission 2013). Following the procedure in McKee et al. (1993), we calculate the monthly SPI for all the countries. We then obtain the percentage deviation of those values from Extremely Dry and

Wet Conditions, defined as SPI values lower than -2 and higher than 2, respectively.[7] We use the annual average of the monthly values to obtain the indicators.

2.3 Empirical Estimations

2.3.1 Contemporaneous Impacts of Physical Climate Risks on Equity Risk Premia

We assess the monthly returns from investments in equity markets against those from long-term government bonds as a proxy for risk-free assets to construct a series of risk premia on equity investments. The monthly movement of the main stock market index in 71 countries, as reported by the Reuters Refinitiv Datastream Database (2021), is used to approximate the monthly returns to equity investments. The data is available from the initial establishment of stock markets in the respective countries, which goes back to the 1950s for certain countries. However, the long-term government bond yields are available only for 36 countries from the FRED Database of the St. Louis Federal Reserve Bank (2023). Therefore, we obtain a balanced sample of monthly equity premia for 29 countries[8] from 1990 to 2020. The annual equity premia for the sample are obtained by averaging the monthly equity premia, as the climate indicators have been calculated at an annual frequency.

The first analysis investigates how physical climate risks, discussed in Section 2.2, have historically affected equity risk premia contemporaneously. There, we encounter two challenges. Firstly, some of the climate indicators are linked to the same distributions, although their methods of construction are independent.[9] Secondly, we have a considerably higher number of climate indicators as predictors. Accordingly, accounting for collinearity and retaining the features are central to our estimations. Therefore, we estimate a regularized panel regression model, the Ridge regression model, illustrated in Equation 1,[10] where Y_{ij} refers to the average annual change in risk premia in the country i and year j, and X_{kij} refers to the individual climate indicators in Table 2.

Equation 1: Panel Regression Model for the Estimation of the Contemporaneous Impacts of Physical Climate Risks on Equity Risk Premia

$$Y_{ij} = \beta_0 + \sum_{k=1}^{n} \beta_k * X_{ijk} + \gamma_i + \delta_j + \varepsilon_{ij}$$

We include country- and year-specific fixed effects (γ_i and δ_j respectively) to control for unobserved time-invariant heterogeneities, such as those in climate indicators, and any additional unobserved time-variant

[7] Following McKee et al. (1993), World Meteorological Organization (2012) defines SPI ranges as below: Extremely wet: SPI > 2; Very wet: 1.5 < SPI < 1.99; Moderately wet: 1.0 < SPI < 1.49; Near Normal: -0.99 < SPI 0.99; Moderately Dry: -1.0 < SPI < -1.49; Severely Dry: -1.5 < SPI < -1.99; Extremely Dry: SPI < -2.

[8] The ISO codes of the countries are AUS, BEL, CAN, CHE, CHL, CZE, DEU, ESP, FIN, FRA, GBR, GRC, HUN, IRL, ISR, ITA, JPN, KOR, MEX, NLD, NOR, NZL, POL, PRT, RUS, SVK, TUR, USA, and ZAF.

[9] For example, while a chronic climate indicator could measure the deviation in mean temperature in a given year from baseline, an extreme climate 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, yet the method of construction enables identifying mean vs. extreme values.

[10] See Fernando and Lepore (2023) for a detailed introduction to penalized regression models and how they help overcome certain limitations of conventional regression models.

effects. These fixed effects also account for the impact of any time-variant and/or time-invariant historical climate adaptation measures on equity markets.[11]

2.3.2 Persistent Impacts of Physical Climate Risks on Equity Risk Premia

The second analysis examines the persistent impacts of individual physical climate risks on equity risk premia. For this, we use the same dataset as in the first analysis. We employ local projection models (Jorda et al. 2005) for each climate indicator with additional controls to investigate these effects for up to five periods (*h*=[0,5]). The general model estimated for a given climate indicator is presented in Equation 2, where Y_{ij} refers to the average annual change in risk premia in the country i and year j, X_{ijk} refers to the individual climate indicators in Table 2 and G_{j-1} and N_{ij-1} refers to a vector of additional controls.

Equation 2: Local Projections Model for the Estimation of the Persistent Impacts of Physical Climate Risks on Equity Risk Premia

$$Y_{ij+h} - Y_{ij-1} = \beta_0 + \beta_k * X_{ijk} + \eta G_{j-1} + \theta N_{ij-1} + \gamma_i + \delta_j + \varepsilon_{ij+h}$$

The additional controls include global (G_{j-1}) and national (N_{ij-1}) factors. The lagged values of these factors are used to avoid potential endogeneities. The national factors include the annual growth in GDP, GDP per capita, current account balance as a proportion of GDP, and public debt as a proportion of GDP. The global factors include the growth in the long-term US government bond returns and the volatility index of the Chicago Board Options Exchange. Similar to the first analysis, we include country- and year-specific fixed effects (γ_i and δ_j respectively) to account for unobserved time-invariant and time-variant heterogeneities.

2.3.3 Persistent Impacts of Physical Climate Risks on Sectoral Equity Risk Premia

The third analysis explores the heterogeneous responses of sectoral equity risk premia to physical climate risks. Although stock market performance data for listed companies worldwide is available from open-source databases, such as Yahoo Finance, mapping those companies to their principal sector in which they operate is difficult. However, we use a dataset covering 100 of the 200 companies from the ASX 200 Index of the Australian Stock Exchange (2023). These companies represent 20 subsectors.[12] The monthly opening and closing prices of the stocks from 2000 to 2020 are available. We calculate the monthly returns from investments in equity markets for each subsector. We calculate the monthly variation in equity risk premia

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[11] The objective of the empirical estimation in this paper is not to comprehensively explain the fluctuation of equity risk premia but to estimate their sensitivity to physical climate risks. Therefore, the omitted variables (that could contribute to explaining equity risk premia movements) could affect the estimates only to the extent they are correlated with the climate indicators. As climate risks are largely exogenous, we assume the omitted variables do not significantly affect the current estimates.

[12] The subsectors (with the number of companies in brackets) are Banks (6), Capital Goods (3), Commercial and Professional Services (5), Consumer Discretionary Distribution and Retail (3), Consumer Services (6), Consumer Staples Distribution and Retail (2), Energy (3), Equity Real Estate Investment Trusts (REITs) (9), Financial Services (6), Food, Beverage and Tobacco (2), Health Care Equipment and Services (6), Insurance (4), Materials (15), Media & Entertainment (3), Pharmaceuticals, Biotechnology & Life Sciences (1), Real Estate Management & Development (1), Software & Services (3), Telecommunication Services (2), Transportation (5), Utilities (3), and Unallocated (12). The analysis excludes the 12 firms that are unallocated to a sector and the nine firms from the REITs due to the relatively short time span of the data.

for each subsector by assessing the monthly returns from long-term Australian government bonds (from the first analysis in Section 2.3.1) against the monthly equity returns. We then average them to obtain their annual variation, as the climate indicators and other control variables are available at an annual frequency.

The local projection model estimated for five periods (*h*=[0,5]) in each subsector for each indicator is presented in Equation 3, where Y_j refers to the average annual change in sectoral risk premia in Australia in year j, X_{kj} refers to the individual climate indicators in Table 2 and G_{j-1} and N_{j-1} refers to a vector of additional controls.

Equation 3: Local Projections Model for the Estimation of the Persistent Impacts of Physical Climate Risks on Australian Sectoral Equity Risk Premia

$$Y_{j+h} - Y_{j-1} = \beta_0 + \beta_k * X_{jk} + \eta G_{j-1} + \theta N_{ij-1} + \delta_j + \varepsilon_{j+h}$$

Similar to the second analysis (Section 2.3.2), the additional controls include global (G_{j-1}) and Australian (N_{j-1}) and factors. The lagged values of these factors are used to avoid potential endogeneities. The Australian factors include the annual growth in GDP, GDP per capita, current account balance as a proportion of GDP, and public debt as a proportion of GDP. The global factors include the growth in the long-term US government bond returns and the volatility index of the Chicago Board Options Exchange. We control for the year-specific fixed effects (δ_j) to account for unobserved time-variant heterogeneities.

2.3.4 Persistent Impacts of Physical Climate Risks on Risk Premia of Alternative Assets

The fourth analysis examines the heterogeneous responses of risk premia for different assets and asset groups to physical climate risks discussed in Section 2.2. We use the dataset compiled by Jorda et al. (2017) covering the annual performance of several assets across 18 countries[13] from 1870 to 2020. The assets covered in the dataset are treasury bills, government bonds, equity, and housing. The dataset also defines several asset groupings as Safe Assets, which include treasury bills and government bonds; Risky Assets, which include equity and housing; and Total Assets, which include all the assets. We calculate the risk premia for different assets and asset groups by comparing their returns against the group of safe assets. We estimate the local projection models for two assets (equity and real estate) and two asset groups (Risky and Total Assets) for each climate indicator for the 18 countries from 1990 to 2020. The general form of the model estimated for five periods (*h*=[0,5]) is presented in Equation 4, where Y_{ij} refers to the annual change in risk premia of each asset in the country i in year j, X_{ijk} refers to the individual climate indicators in Table 2 and G_{j-1} and N_{ij-1} refers to vectors of additional controls.

Equation 4: Local Projections Model for the Estimation of the Persistent Impacts of Physical Climate Risks on Different Assets

$$Y_{ij+h} - Y_{ij-1} = \beta_0 + \beta_k * X_{ijk} + \eta G_{j-1} + \theta N_{ij-1} + \gamma_i + \delta_j + \varepsilon_{ij+h}$$

[13] The ISO codes of the countries are AUS, BEL, CAN, CHE, DEU, DNK, ESP, FIN, FRA, GBR, IRL, ITA, JPN, NLD, NOR, PRT, SWE, and USA.

Similar to the second and third analyses, we control for global (G_{j-1}) and national (N_{ij-1}) factors in the estimations. The lagged values of these factors are used to avoid potential endogeneities. The national factors include the annual growth in GDP, GDP per capita, current account balance as a proportion of GDP, and public debt as a proportion of GDP. The global factors include the growth in the long-term US government bond returns and the volatility index of the Chicago Board Options Exchange. We control for the country and year-specific fixed effects (γ_i and δ_j respectively) to account for unobserved time-invariant and time-variant heterogeneities.

3 RESULTS & DISCUSSION

3.1 Contemporaneous Impacts of Physical Climate Risks on Equity Risk Premia

Figure 1 presents the contemporaneous impacts of physical climate risks on equity risk premia. These estimates reflect the average historical responsiveness of equity risk premia to contemporaneous physical climate risks. Among the chronic physical risks, increases in relative humidity could increase the equity risk premia by about two basis points. In contrast, rising mean temperature could reduce the equity risk premia by about 17 basis points.

From the extreme physical risks, Extremely Warm Conditions during the Night and Extremely Dry and Wet conditions could increase the equity risk premia by about four to nine basis points. Increases in Extremely Warm Conditions during the Day and Extremely Windy Conditions could reduce the equity risk premia by about three to four basis points. The other extreme physical risks have minimal effects on equity risk premia.

All countries in the sample considered for this analysis generally experience cold winters and prefer warm conditions. Therefore, the increases in mean temperature and Extremely Warm Conditions during the Day could favor them and improve firm performance in those countries. Hence, the equity risk premia may reduce in response to these conditions.

However, this observation may not hold for temperature ranges beyond those experienced historically. Furthermore, the equity risk premia at the country level may best be interpreted as the aggregate impact on all sectors. The individual sectors may experience heterogeneous impacts that are much different from those observed at the country level. Section 3.3 explores some of these heterogeneous impacts using a sample of Australian economic sectors. All other chronic and extreme risks increase the equity risk premia for the countries in the sample.

3.2 Persistent Impacts of Physical Climate Risks on Equity Risk Premia

Figure 2 presents the variation in equity risk premia for five years after an impulse response, equivalent to a unit standard deviation, for each physical climate risk discussed in Section 2.2. Similar to the results from the first analysis (Section 3.1), the increase in mean temperature could initially reduce the equity risk premia. However, the mean temperature could increase the equity risk premia for the next three years before the shock dissipates. The relative humidity also has initial effects similar to the first analysis (Section 3.1) and then fluctuates minimally before the shock dissipates.

Extremely Warm Conditions during the Day and Night could initially reduce the equity risk premia, potentially due to the nature of the countries in the sample generally experiencing cold conditions and preferring warm conditions. Extremely Dry, Wet, and Windy conditions increase the equity risk premia immediately. Extremely Windy Conditions could have persistent increasing effects on equity risk premia. Precipitation and Extremely Cold Conditions have minimal impacts on equity risk premia changes.

The responsiveness of equity risk premia in the first year under the second analysis is similar to the results from the first analysis (Section 3.1). Similarities exist with respect to the directionality and the magnitude of the responsiveness. These similarities confirm the potential of the Ridge regressions to handle correlated confounders together and determine the independent effects of the individual confounders.

3.3 Persistent Impacts of Physical Climate Risks on Sectoral Equity Risk Premia

Figures 3 to 12 illustrate the responsiveness of sectoral equity risk premia to an impulse response, equivalent to a unit standard deviation, for each physical climate risk, discussed in Section 2.2. Out of the chronic risks covered in Figures 3 to 5, the sectoral equity risk premia variations are minimal in response to precipitation and relative humidity changes. Most of the sectors experience initial declines in equity risk premia. A rise in relative humidity could increase the equity risk premia for sectors such as capital goods, materials, and utilities, potentially due to the adverse effects of relative humidity on the labor force. Increases in mean temperature have more substantial contemporaneous and persistent effects on sectoral equity risk premia than precipitation and relative humidity. Almost all sectors experience an increase in risk premia, with the Consumer Discretionary sector having the highest effect, exceeding five percentage points towards the mid-term. Different from other sectors, Software and Services experience a reduction in risk premia, possibly as it is minimally exposed to adverse heat and becomes an attractive option for investment compared to the other sectors.

Figures 6 to 9 present the responsiveness of sectoral equity risk premia to short-term extreme temperature conditions. The responsiveness of equity risk premia to all those conditions is stronger than chronic risks. Extremely Cold Conditions during the Night (Figure 9) have the lowest effect among the four extreme temperature indicators. Equity risk premia for Banks, and Consumer Discretionary, Distribution, and Retail tend to increase in response to them in the medium term, exceeding three percentage points. Extremely Warm Conditions during the Night (Figure 8) have the second lowest effects. The same sectors as before experience the highest increase in equity risk premia, exceeding five percentage points in the medium term.

The equity risk premia for Australian subsectors are more responsive to extreme temperature conditions during the day. All subsectors experience more substantial adjustments when faced with extreme temperature conditions during the day (Figures 4 and 6) than at night. Banks, Capital Goods, and Consumer Discretionary, Distribution, and Retail experience the strongest persistent rise in equity risk premia, which could exceed 20 percentage points towards the fifth year in response to a shock occurring in the first year.

Amidst the capital reallocation, Software and Services and Telecommunication Services persistently experience a decline in equity risk premia.

Figures 10 to 12 illustrate the responsiveness of sectoral equity risk premia to Extremely Dry, Wet, and Windy Conditions. Extremely Wet Conditions (Figure 11) have the lowest relative impact among the three risks. Commercial and Professional Services demonstrate the strongest increases in equity risk premia in response to Extremely Wet Conditions. The same sectors are also the most vulnerable to Extremely Windy Conditions (Figure 12). Extremely Dry Conditions (Figure 10) affect the equity risk premia the most. Consumer Services, Energy, and Transportation could experience persistently elevated equity risk premia in the medium term as their economic activities are more exposed to physical climate risks. However, amidst the capital reallocation, certain sectors, such as Banks and Capital Goods, could attract capital and experience a declining equity risk premia.

The directionality of the impacts of physical climate risks on sectoral equity risk premia generally agrees with that on sectoral productivity.[14] This alludes to the fact that investors account for the changes in sectoral productivity and, hence, marginal returns to capital in their investment decisions. This also confirms the active linkages between the real and financial sectors of the economy through equity prices.

3.4 Persistent Impacts of Physical Climate Risks on Risk Premia of Alternative Assets

Figures 13 to 16 present the responsiveness of the risk premia for risky assets and asset groups to an impulse response, equivalent to a unit standard deviation, of the physical climate risks. The responsiveness of the equity risk premia to most physical climate risks in Figure 13 is quite similar to the patterns observed in Figure 2. The equity risk premia persistently increase in response to mean temperature rise to above ten basis points by the fourth year. The responses are also volatile for Extremely Warm Conditions during the Day and Night and Extremely Dry, Wet, and Windy Conditions, with a ceiling of five basis points.

Changes in real estate risk premia in response to physical climate risks are summarized in Figure 14. The range of responses is generally lower compared to equity investments. However, the responses are more volatile, mainly due to the rise in mean temperature. Extremely Warm Conditions during the Day and Night and Extremely Wet and Windy Conditions trigger a surge in real estate risk premia, while the real estate risk premia could decline in response to Extremely Dry Conditions. This reflects the disproportionate effects of extreme events, such as floods and storms, on physical establishments compared to droughts.

Figure 15 presents the responsiveness of the risk premia of an equity and real estate asset portfolio to physical climate risks. The risk premia of such a portfolio could persistently increase with the rise in mean temperature potentially exceeding two basis points by the fourth year. Extremely Wet Conditions could also have similar persistence. Extremely Dry and Windy Conditions could reduce the risk premia of such a

[14] Fernando and Lepore (2023) provide a detailed discussion on the different impact pathways of physical climate risks on the total factor productivity of different sectors and estimates of the responsiveness of sectoral productivity to physical climate risks.

portfolio. Risk premia respond with a lag to Extremely Warm Conditions during the Day and Night, and the shock dissipates towards the fifth year since the initiation.

Figure 16 indicates how the risk premia of a portfolio with risky and safe assets would respond to physical climate risks. Notably, its response patterns are quite similar to those of Figure 15, and the magnitude of the responses is slightly lower due to the inclusion of safe assets in the portfolio. This observation indicates that investments in risky assets are more responsive to physical climate risks compared to safe assets, and the risky assets would determine the performance of even a balanced portfolio of risky and safe assets.

4 CONCLUSION

Climate change challenges global socioeconomic stability. The impacts of climate risks on the real sector of the economy could easily spill over into the financial sector and create feedback that magnifies the economic consequences of climate change. Ensuring resilient financial markets and institutions is fundamental to reducing the risks of climate change via mitigation and adaptation efforts, as well as potential financial contagion from unmitigated climate risks.

Asset prices are a fundamental source of climate-related financial risks. Their behavior presents insights into the perceptions and expectations of investors and the differential returns between high- and low-carbon-intensive assets, which could help design alternative supplementary policy instruments to drive decarbonization. An emerging body of literature attempts to detect whether such a greenium exists. This study contributes to this research by investigating the contemporaneous and persistent impacts of a range of physical climate risks on equity risk premia. We also examine the sectoral heterogeneity of these effects and how they could change across different asset classes.

The results illustrate that both chronic and extreme physical risks could trigger changes in equity risk premia. The persistent effects of the physical risks could be much larger than the immediate effects. Chronic temperature changes and extremely dry, wet, and windy conditions could significantly increase equity risk premia. An analysis of the sectoral heterogeneity of the impacts of the physical climate risks reveals that sectors involving manufacturing and trading operations, such as Consumer Discretionary Distribution and Retail, Capital Goods, Energy, Utilities, and Transportation, are generally more vulnerable to physical climate risks. Software and Services are an attractive last resort when capital is reallocated from exposed sectors. Analysis of the responsiveness of different assets reveals that real estate assets could be less vulnerable to chronic physical risks compared to equity holdings. However, real estate assets are notably exposed to changes in extremely wet and windy conditions.

The insights from this paper could be further enriched by relaxing some of the constraints with current data. Future research could attempt to use more disaggregated sectoral data. Notably, analyzing the energy sector to identify the differential impacts of physical climate risks on the equity risk premia could help uncover a greenium between the renewable and non-renewable sectors, independent of unannounced and unanticipated transition policies. Expanding the dataset to include additional countries, particularly developing countries with developed equity markets, could further enrich the understanding of the geographical heterogeneities in asset valuations. Portfolio-level analyses, where data is available, could utilize climate indicators and empirical methodologies in this paper to analyze how sensitive investors are to different physical climate risks.

References

Agliardi, E. & Agliardi, R. 2021. Pricing Climate-related Risks in the Bond Market. *Journal of Financial Stability,* 54, pp.1-9.

Alessi, L., Ossola, E. & Panzica, R. 2019. 'The Greenium Matters: Evidence on the Pricing of Climate Risk'. 2019/12. Joint Research Centre of the European Commission. Luxembourg.

Alessi, L., Ossola, E. & Panzica, R. 2020. 'The Greenium Matters: Greenhouse Gas Emissions, Environmental Disclosures, and Stock Prices'. 2020/418. Center for European Studies.

Ali, S., Khalid, B., Akhter, A., Islam, A. & Adnan, S. 2020. Analyzing the Occurrence of Floods and Droughts in Connection with Climate Change in Punjab Province, Pakistan. *Natural Hazards,* 103, pp.2533-59.

Australian Stock Exchange. 2023. *ASX Price Data* [Online]. Australian Stock Exchange. Available: https://www.asx.com.au/connectivity-and-data/information-services/price-data [Accessed 10 November 2023].

Bee-Hoong, T. Climate Change and Stock Market: A Review. IOP Conference Series: Earth and Environmental Science, 2023. IOP Publishing, 1-10.

Bhunia, P., Das, P. & Maiti, R. 2020. Meteorological Drought Study through SPI in Three Drought Prone Districts of West Bengal, India. *Earth Systems and Environment,* 4, pp.43-55.

Boissinot, J., Huber, D. & Lame, G. 2016. Finance and Climate: The Transition to a Low-Carbon and Climate-Resilient Economy from a Financial Sector Perspective. *OECD Journal: Financial Market Trends,* 2015/1, pp.1-17.

Bolton, P., Despres, M., Da Silva, L. A. P., Samama, F. & Svartzman, R. 2020. *The Green Swan: Central Banking and Financial Stability in the Age of Climate Change,* Basel, Bank for International Settlements and Bank of France.

Bua, G., Kapp, D., Ramella, F. & Rognone, L. 2022. 'Transition versus Physical Climate Risk Pricing in European Financial Markets: A Text-based Approach'. 2677. European Central Bank. Frankfurt.

Carney, M. 2015. 'Breaking the Tragedy of the Horizon–Climate Change and Financial Stability'. Bank of England. London.

Climate Research Unit of the University of East Anglia. 2022. *High-Resolution Gridded Datasets (and Derived Products)* [Online]. Norwich: Climate Research Unit of the University of East Anglia. Available: https://crudata.uea.ac.uk/cru/data/hrg/ [Accessed 20 August 2022].

Database of Global Administrative Areas. 2022. *GADM Maps and Data* [Online]. Database of Global Administrative Areas. Available: https://gadm.org/ [Accessed 20 August 2022].

Datastream International 2021. Thomson Reuters Datastream.

Ekwezuo, C. & Ezeh, C. 2020. Regional Characterisation of Meteorological Drought and Floods over West Africa. *Sustainable Water Resources Management,* 6.

Faccini, R., Matin, R. & Skiadopoulos, G. 2023. Dissecting Climate Risks: Are They Reflected in Stock Prices? *Journal of Banking & Finance,* 155, pp.1-25.

Federal Reserve Bank of St. Louis. 2023. *FRED Economic Data* [Online]. Federal Reserve Bank of St. Louis. Available: https://fred.stlouisfed.org/ [Accessed 10 November 2023].

Fernando, R. 2023. Global Economic Consequences Arising from the Impacts of Physical Climate Risks on Agriculture and Energy. *26th Annual Conference on Global Economic Analysis.* Bordeaux: Global Trade Analysis Project.

Fernando, R. & Lepore, C. 2023. 'Global Economic Impacts of Physical Climate Risks'. IMF Working Papers No. 2023/183. The International Monetary Fund. Washington DC.

Golian, S., Mazdiyasni, O. & AghaKouchak, A. 2015. Trends in Meteorological and Agricultural Droughts in Iran. *Theoretical and Applied Climatology,* 119, pp.679-88.

Grippa, P., Schmittmann, J. & Suntheim, F. 2019. Climate Change and Financial Risk. *Finance & Development*, p.26.

Hu, X., Zhu, B., Lin, R., Li, X., Zeng, L. & Zhou, S. 2024. How does Greenness Translate into Greenium? Evidence from China's Green Bonds. *Energy Economics,* 133, pp.1-14.

Intonti, M., erlenga, L., Ferri, G., De Leonardis, M. & Starace, G. 2023. The "Greenium" in Green Bonds: How Did It Change with COVID-19? *Sustainability,* 15, pp.1-17.

Jordà, Ò. 2005. Estimation and Inference of Impulse Responses by Local Projections. *American Economic Review,* 95, pp.161-82.

Jordà, Ò., Schularick, M. & Taylor, A. M. (eds.) 2017. *Macrofinancial History and the New Business Cycle Facts,* Chicago: University of Chicago Press.

Karydas, C. & Xepapadeas, A. 2019. 'Pricing Climate Change Risks: CAPM with Rare Disasters and Stochastic Probabilities'. CER-ETH Working Paper Series No. 19. ETH Zurich, Center of Economic Research. Zurich.

Lai, Y. & Dzombak, D. 2019. Use of Historical Data to Assess Regional Climate Change. *Journal of Climate,* 32, pp.4299-320.

Li, B., Wang, B. & Yu, J. 2023. 'The Emerging Greenium'. The Brookings Institution. Washington DC.

Manatsa, D., Mukwada, G., Siziba, E. & Chinyanganya, T. 2010. Analysis of Multidimensional Aspects of Agricultural Droughts in Zimbabwe Using the Standardized Precipitation Index (SPI). *Theoretical and Applied Climatology,* 102, pp.287-305.

McKee, T., Doesken, N. & Kleist, J. The Relationship of Drought Frequency and Duration to Time Scales. 8th Conference on Applied Climatology, 1993. 179-83.

Nag, S., Chakrabarty, S. P. & Basu, S. 2021. From Carbon-Transition Premium to Carbon-Transition Risk. *arXiv,* 2107.06518, pp.1-25.

Ojea Ferreiro, J., Reboredo, J. C. & Ugolini, A. 2022. 'The Impact of Climate Transition Risks on Financial Stability: A Systemic Risk Approach'. 2022/1. Joint Research Centre of the European Commission. Brussels.

Potsdam-Institute for Climate Impact Research. 2022. *Intersectoral Impact Model Intercomparison Project (ISIMIP)* [Online]. Potsdam-Institute for Climate Impact Research. Available: https://data.isimip.org/ [Accessed 20 October 2022].

Russo, S., Dosio, A., Graversen, R., Sillmann, J., Carrao, H., Dunbar, M., Singleton, A., Montagna, P., Barbola, P. & Vogt, J. 2014. Magnitude of Extreme Heat Waves in Present Climate and Their Projection in a Warming World. *Journal of Geophysical Research-Atmospheres,* 119, pp.12500-12.

Sautner, Z., Van Lent, L., Vilkov, G. & Zhang, R. 2023. Pricing Climate Change Exposure. *Management Science,* 69, pp.7540-61.

Wang, Z. & Cao, L. 2011. Analysis on Characteristics of Droughts and Floods of Zhengzhou City based on SPI in Recent 60 Years. *Journal of North China Institute of Water Conservancy and Hydroelectric Power,* 6, pp.1-14.

World Bank. 2021. *GDP Growth (Annual %)* [Online]. The World Bank. Available: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG [Accessed 10 November 2023].

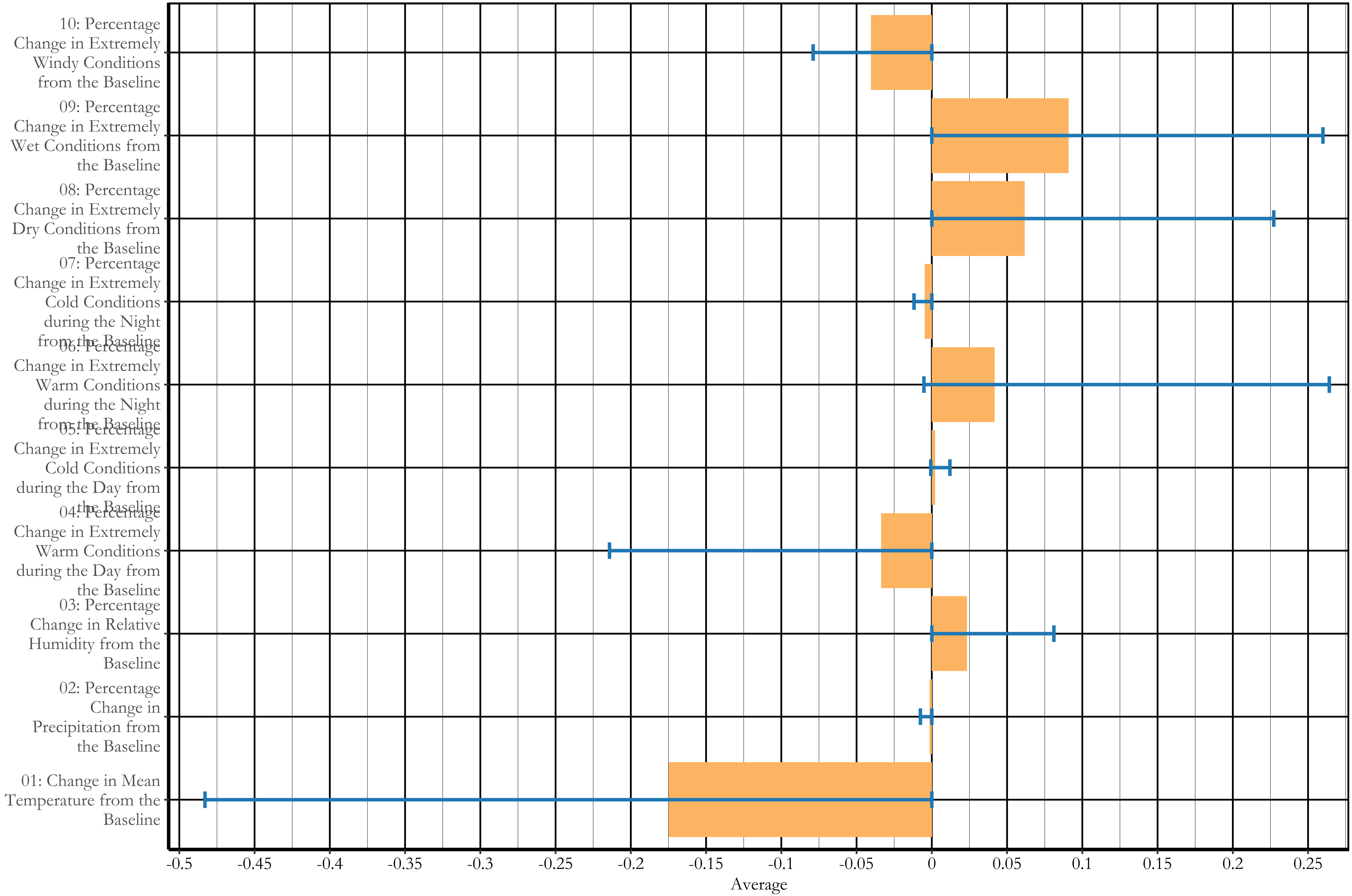
World Bank. 2023. *World Development Indicators* [Online]. The World Bank. Available: https://datatopics.worldbank.org/world-development-indicators/ [Accessed 10 November 2023].

World Meteorological Organization 2012. 'Standardized Precipitation Index: User Guide'. World Meteorological Organization. Geneva.

World Meteorological Organization 2017. 'WMO Guidelines on the Calculation of Climate Normals'. World Meteorological Organization. Geneva.

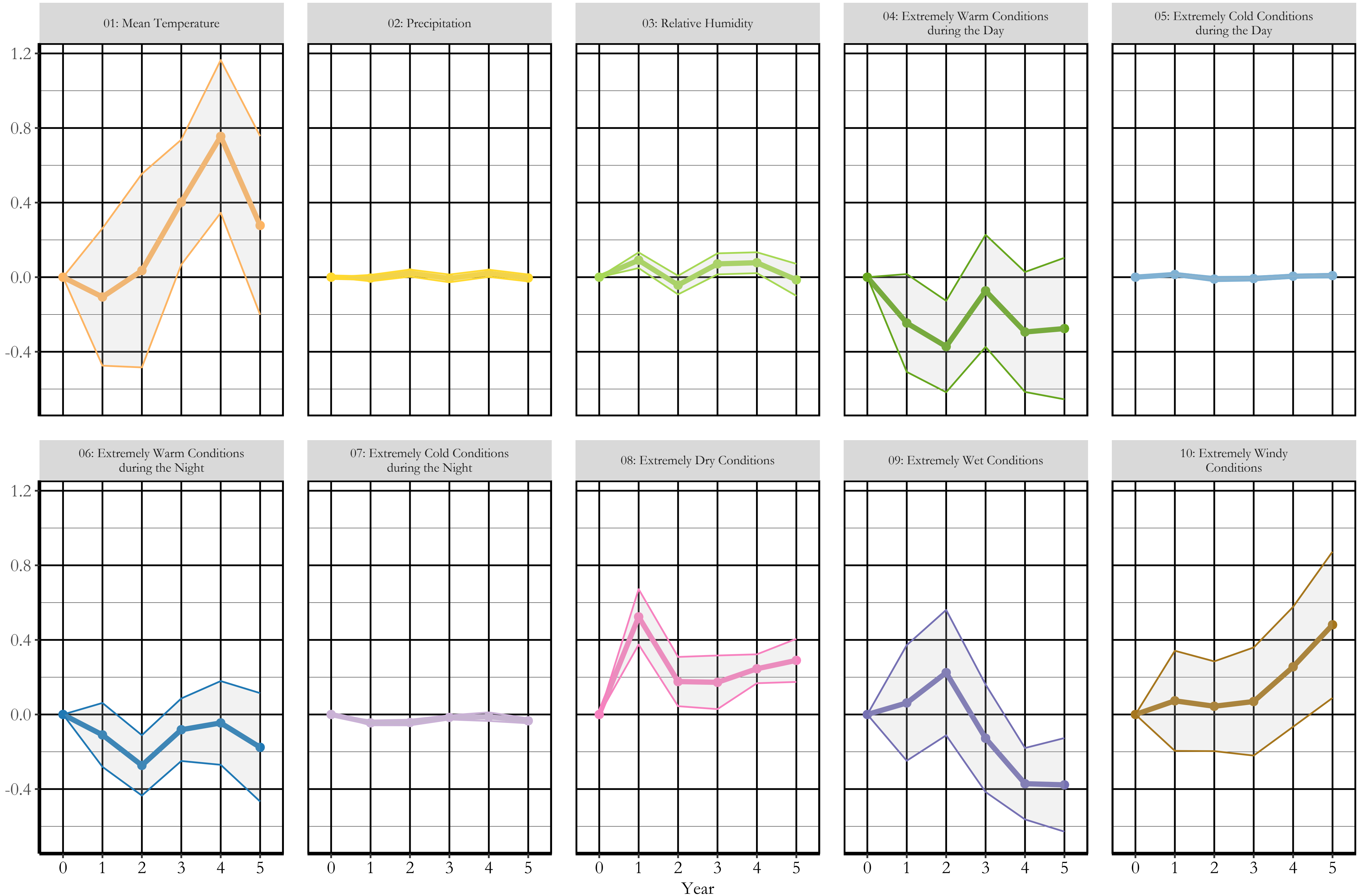
Zhou, F., Endendijk, T. & Botzen, W. W. 2023. A Review of the Financial Sector Impacts of Risks Associated with Climate Change. *Annual Review of Resource Economics,* 15, pp.233-56.

Figure 1: Contemporaneous Responsiveness of Equity Risk Premia to Physical Climate Risks (Percentage Points)



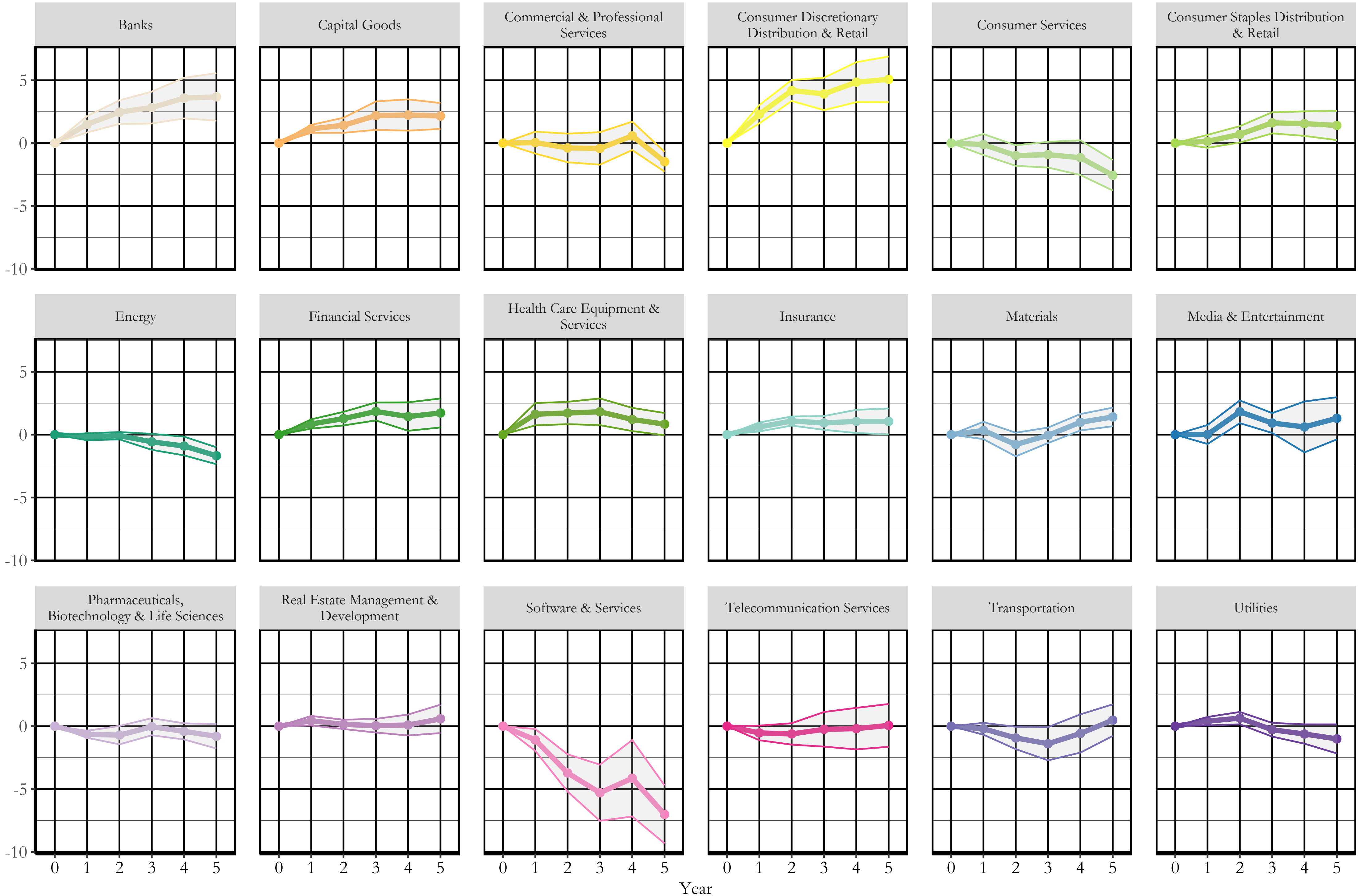
Source: Author's Calculations.

Figure 2: Annual Impulse Responses of Equity Risk Premia to Physical Climate Risks (Percentage Points)



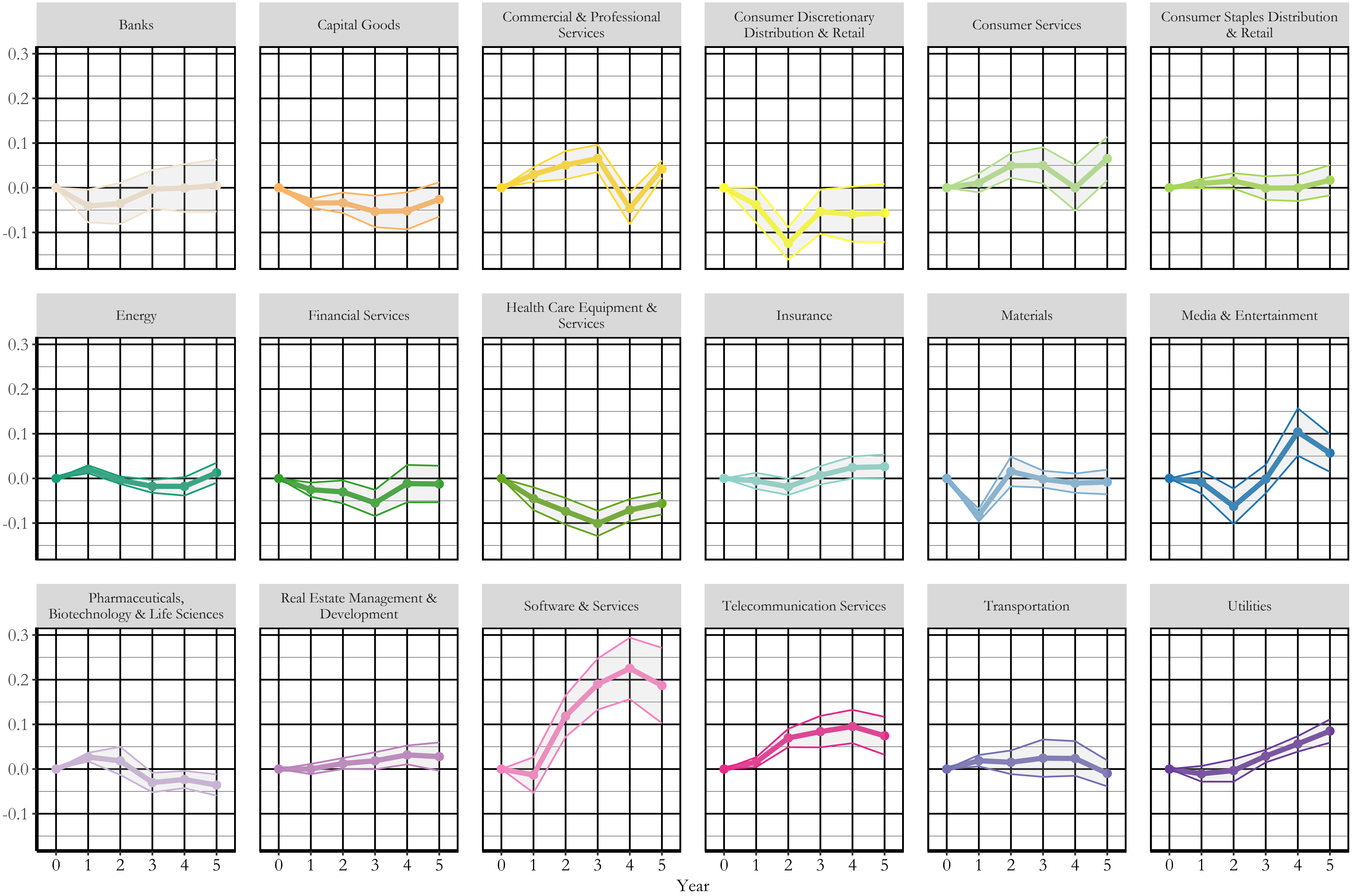
Source: Author's Calculations.

Figure 3: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 01: Mean Temperature



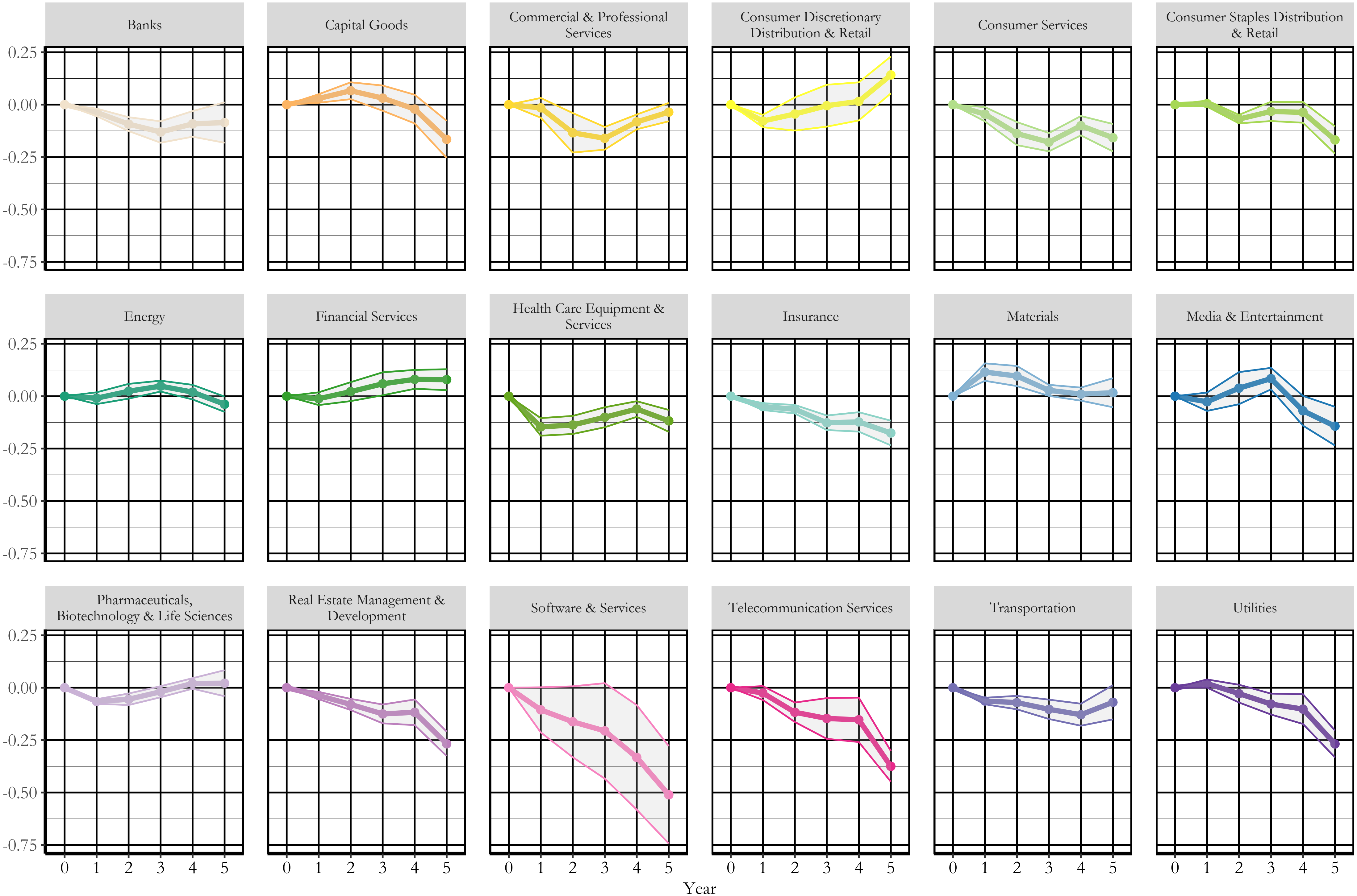
Source: Author's Calculations.

Figure 4: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 02: Precipitation



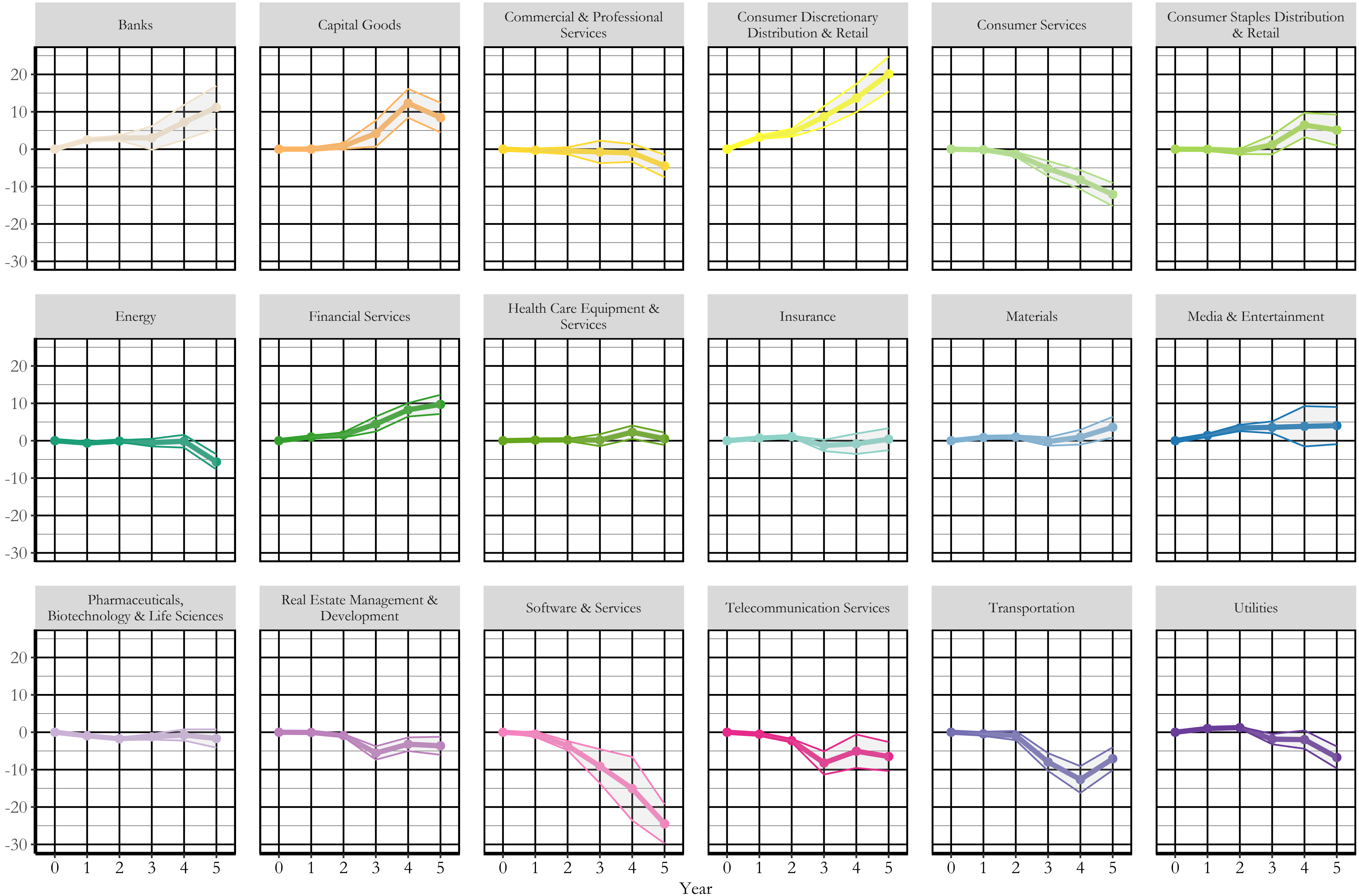
Source: Author's Calculations.

Figure 5: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 03: Relative Humidity



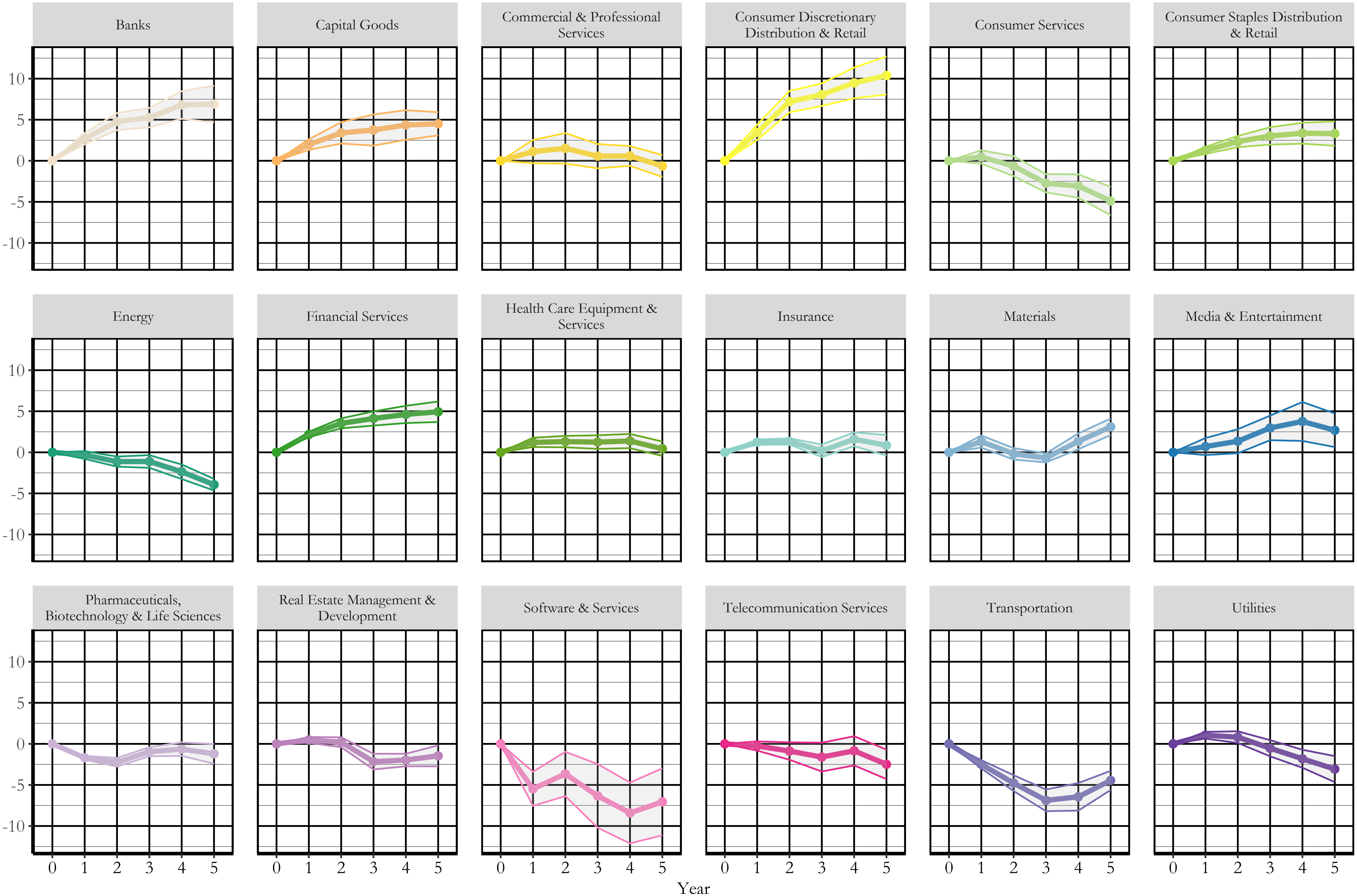
Source: Author's Calculations.

Figure 6: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 04: Extremely Warm Conditions during the Day



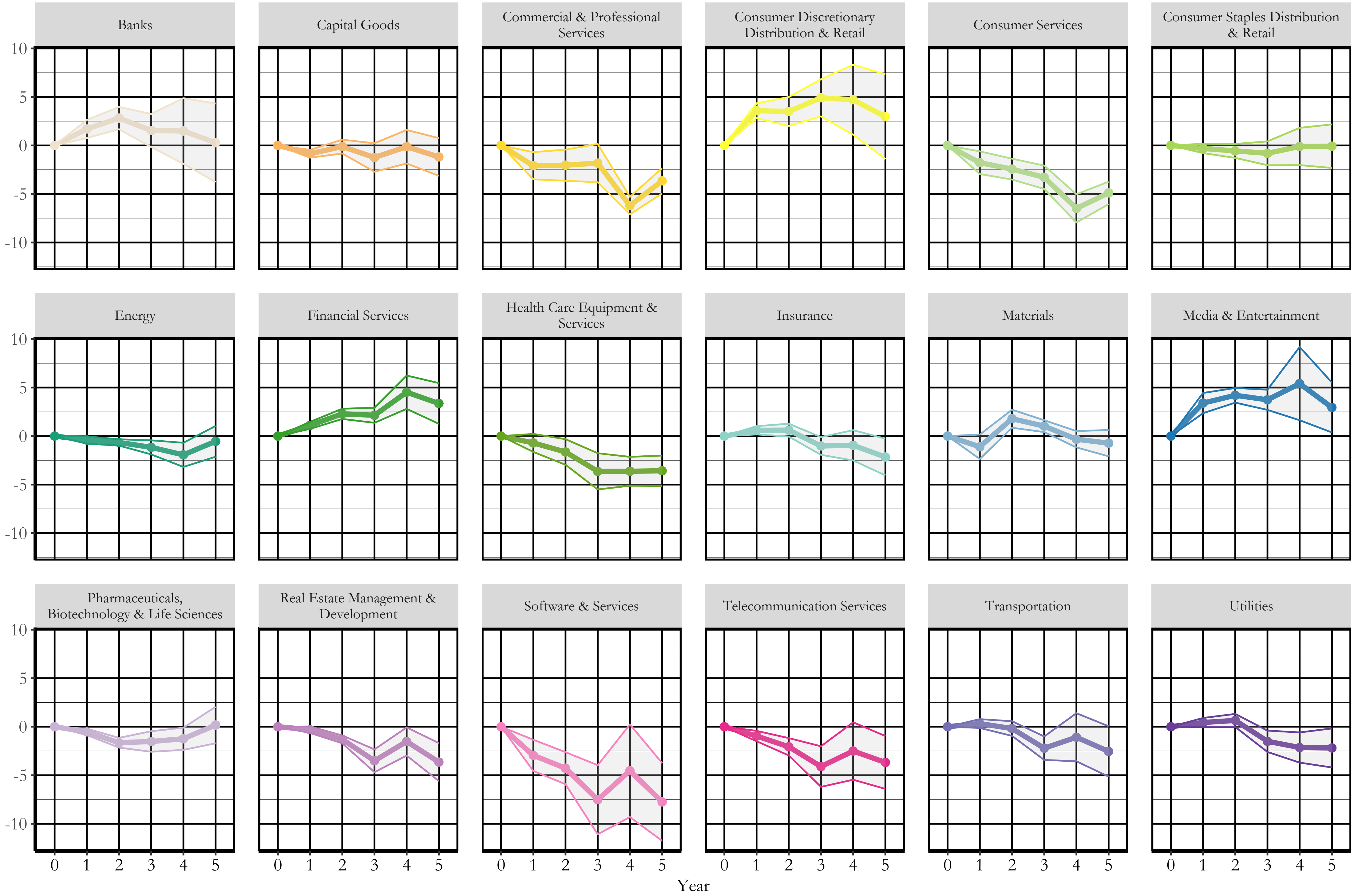
Source: Author's Calculations.

Figure 7: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 05: Extremely Cold Conditions during the Day



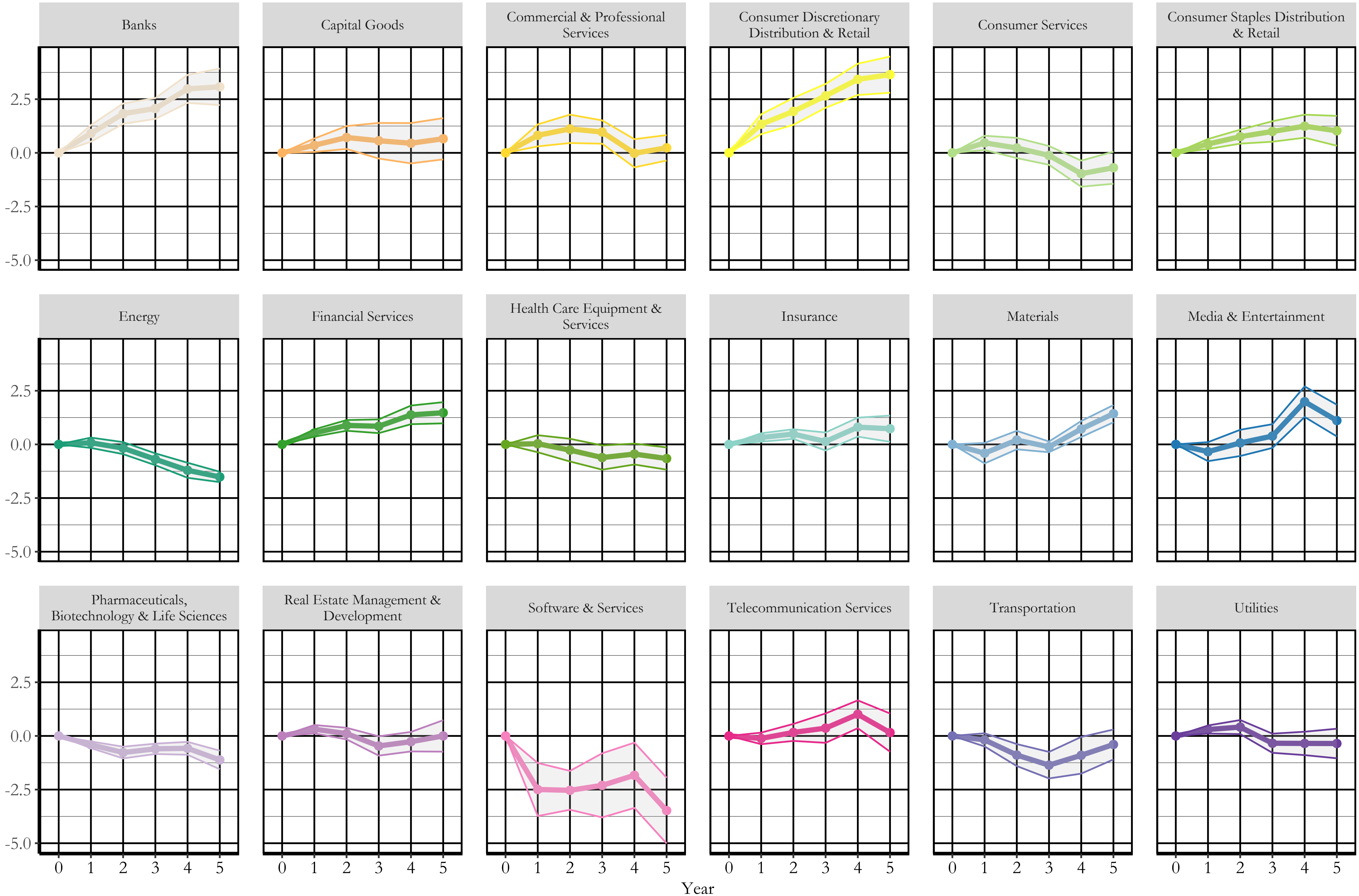
Source: Author's Calculations.

Figure 8: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 06: Extremely Warm Conditions during the Night



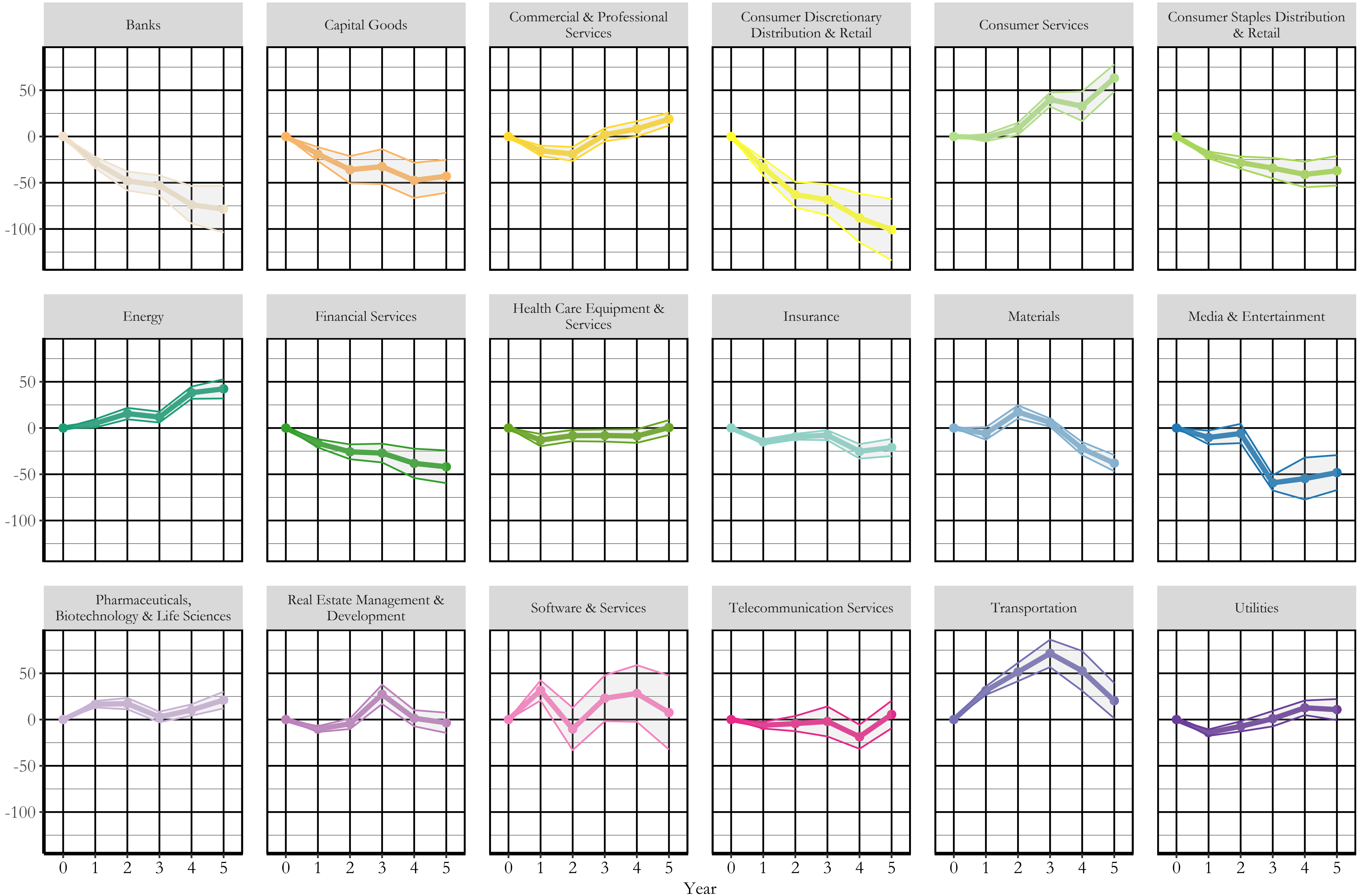
Source: Author's Calculations.

Figure 9: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 07: Extremely Cold Conditions during the Night



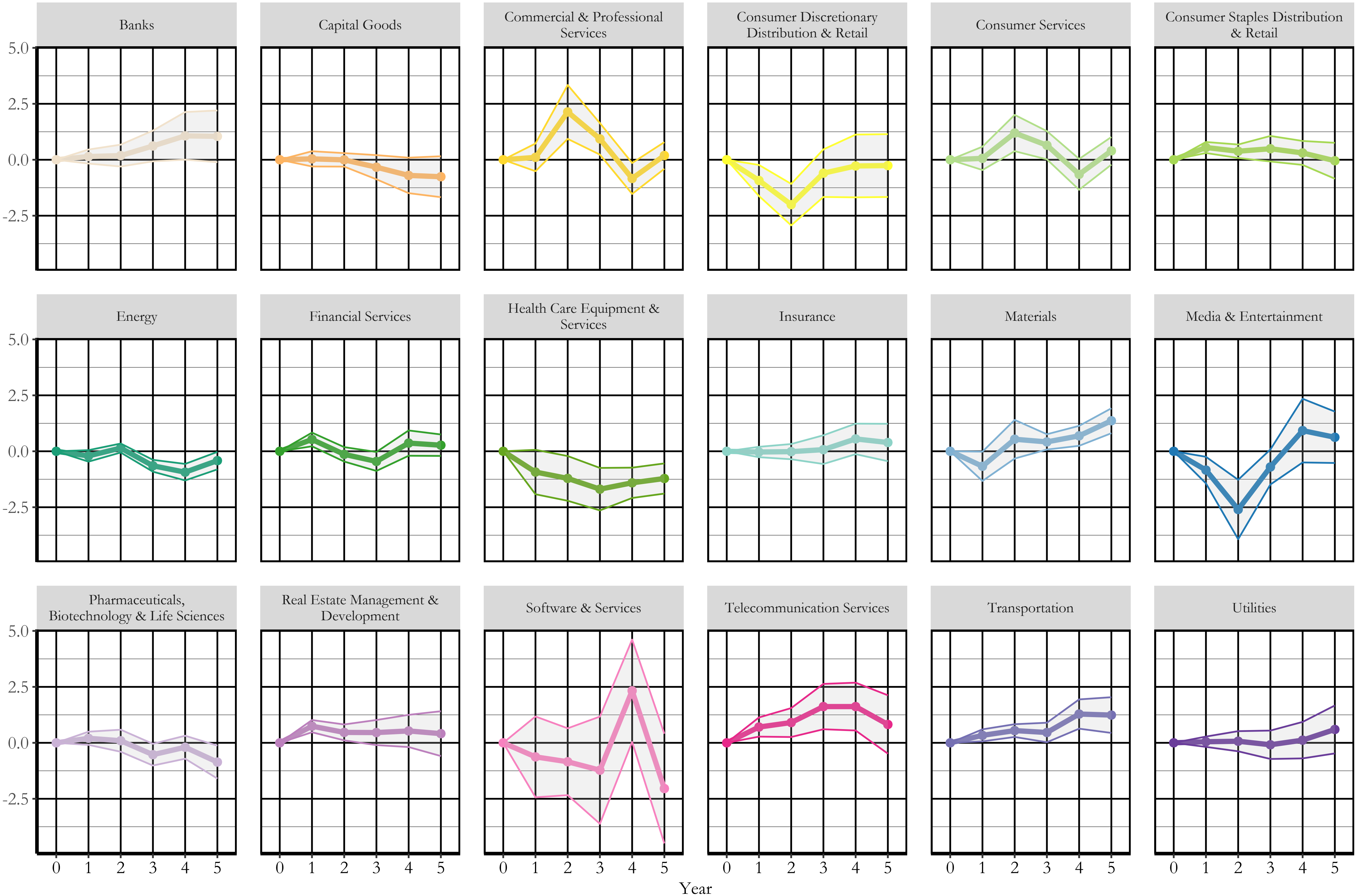
Source: Author's Calculations.

Figure 10: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 08: Extremely Dry Conditions



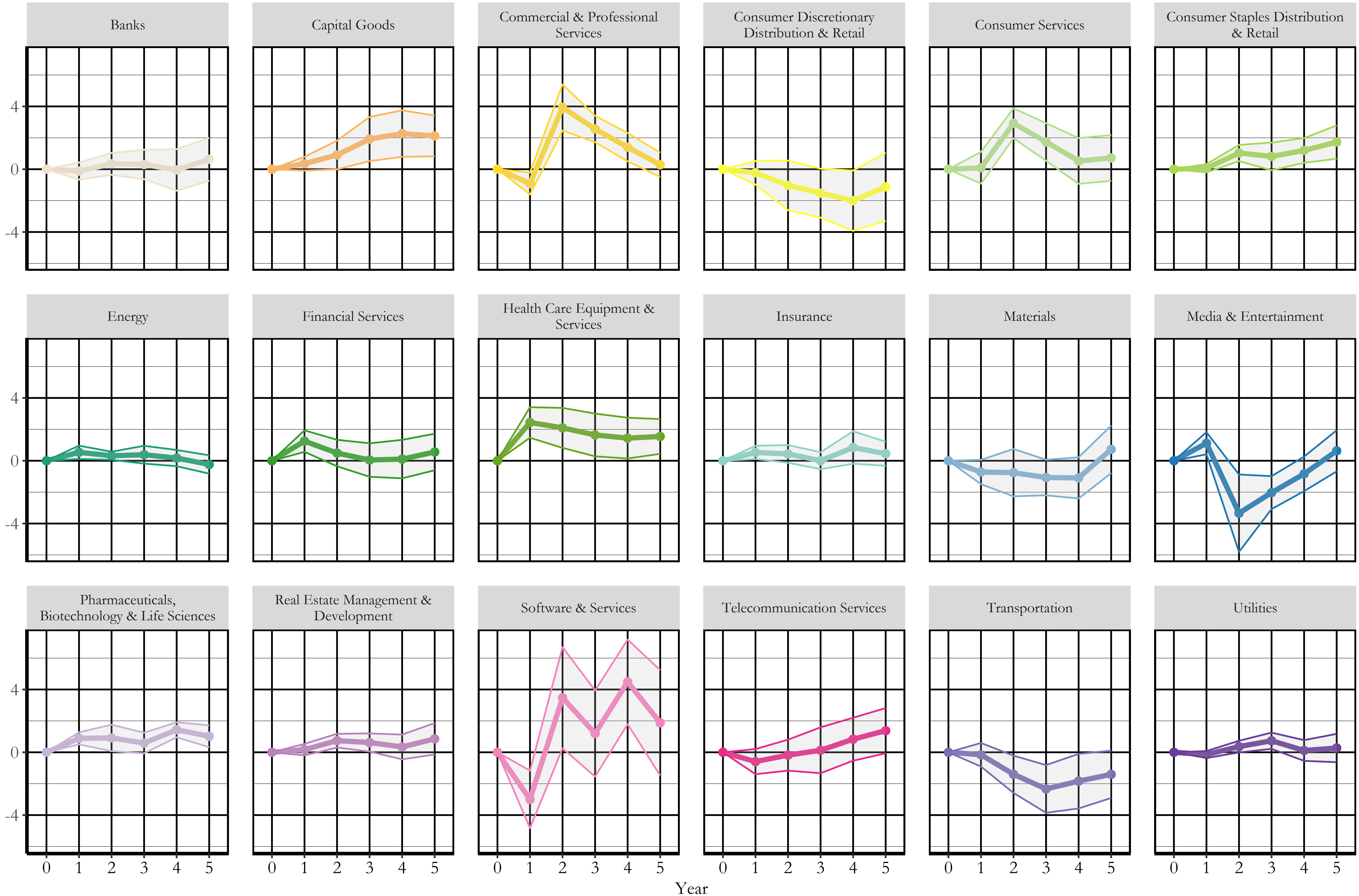
Source: Author's Calculations.

Figure 11: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 09: Extremely Wet Conditions



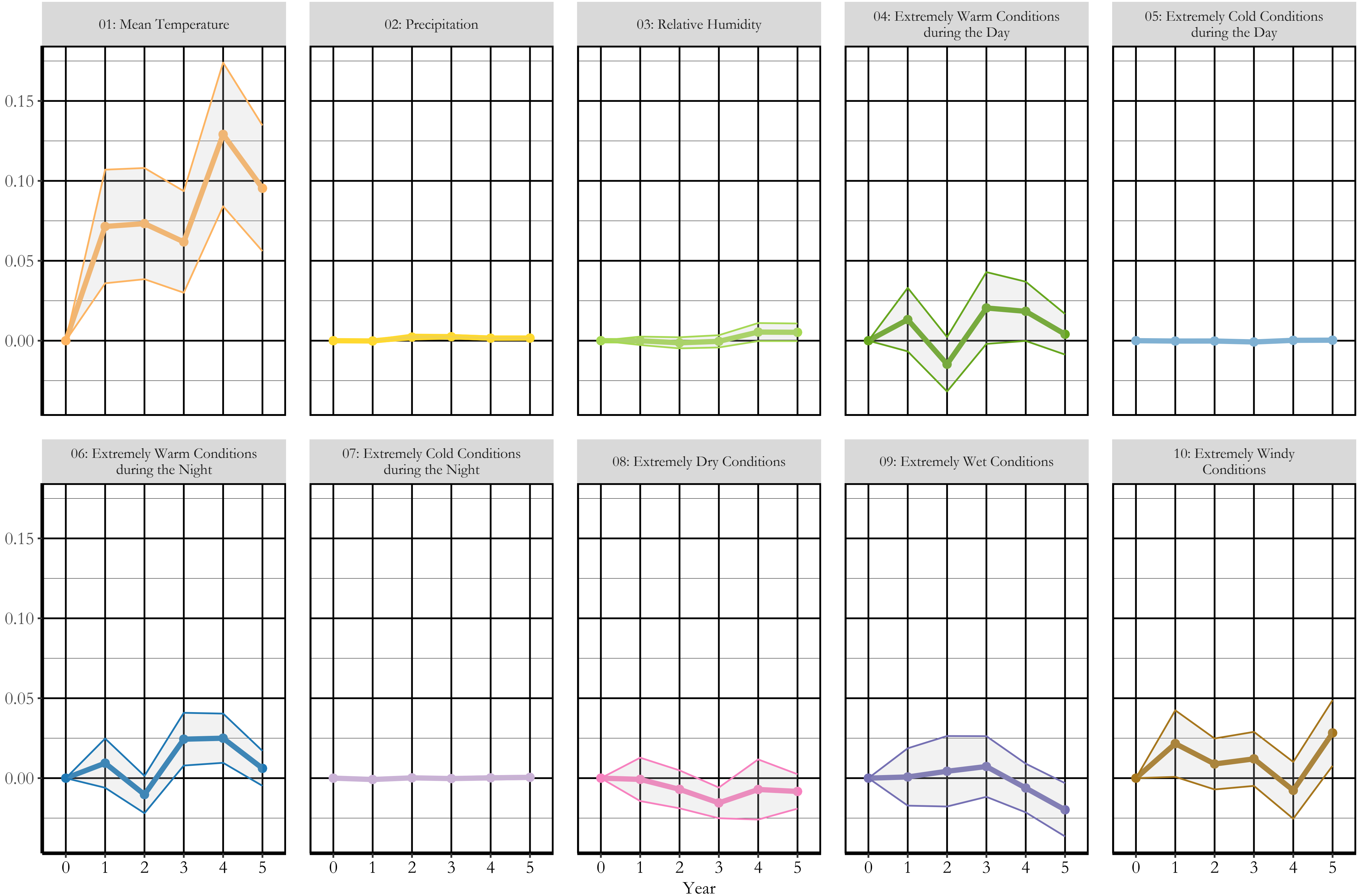
Source: Author's Calculations.

Figure 12: Annual Impulse Responses of Australian Sectoral Equity Risk Premia to Physical Climate Risks (Percentage Points): 10: Extremely Windy Conditions



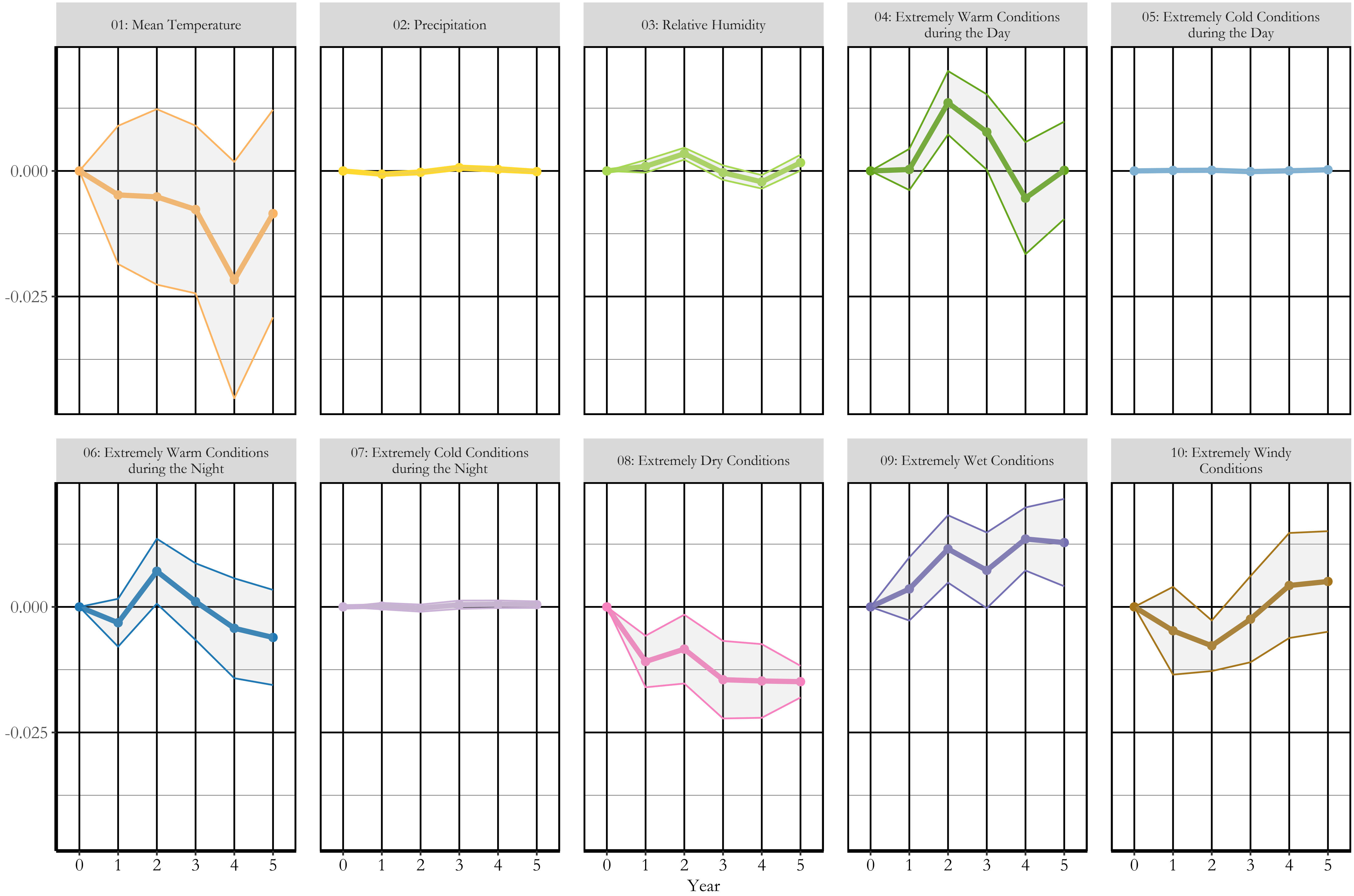
Source: Author's Calculations.

Figure 13: Annual Impulse Responses to Physical Climate Risks (Percentage Points): 01: Changes in Equity Premia



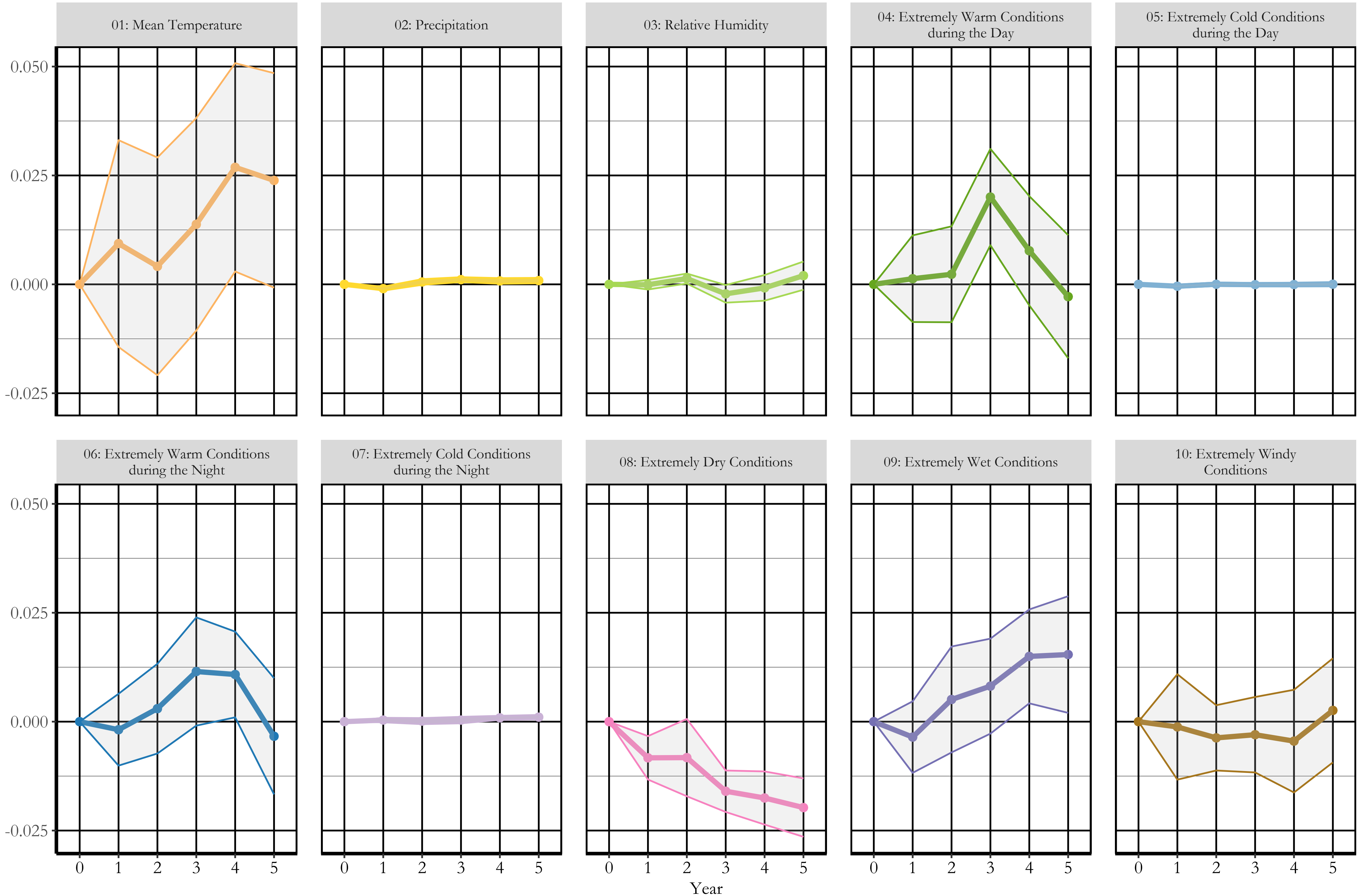
Source: Author's Calculations.

Figure 14: Annual Impulse Responses to Physical Climate Risks (Percentage Points): 02: Changes in Real Estate Premia



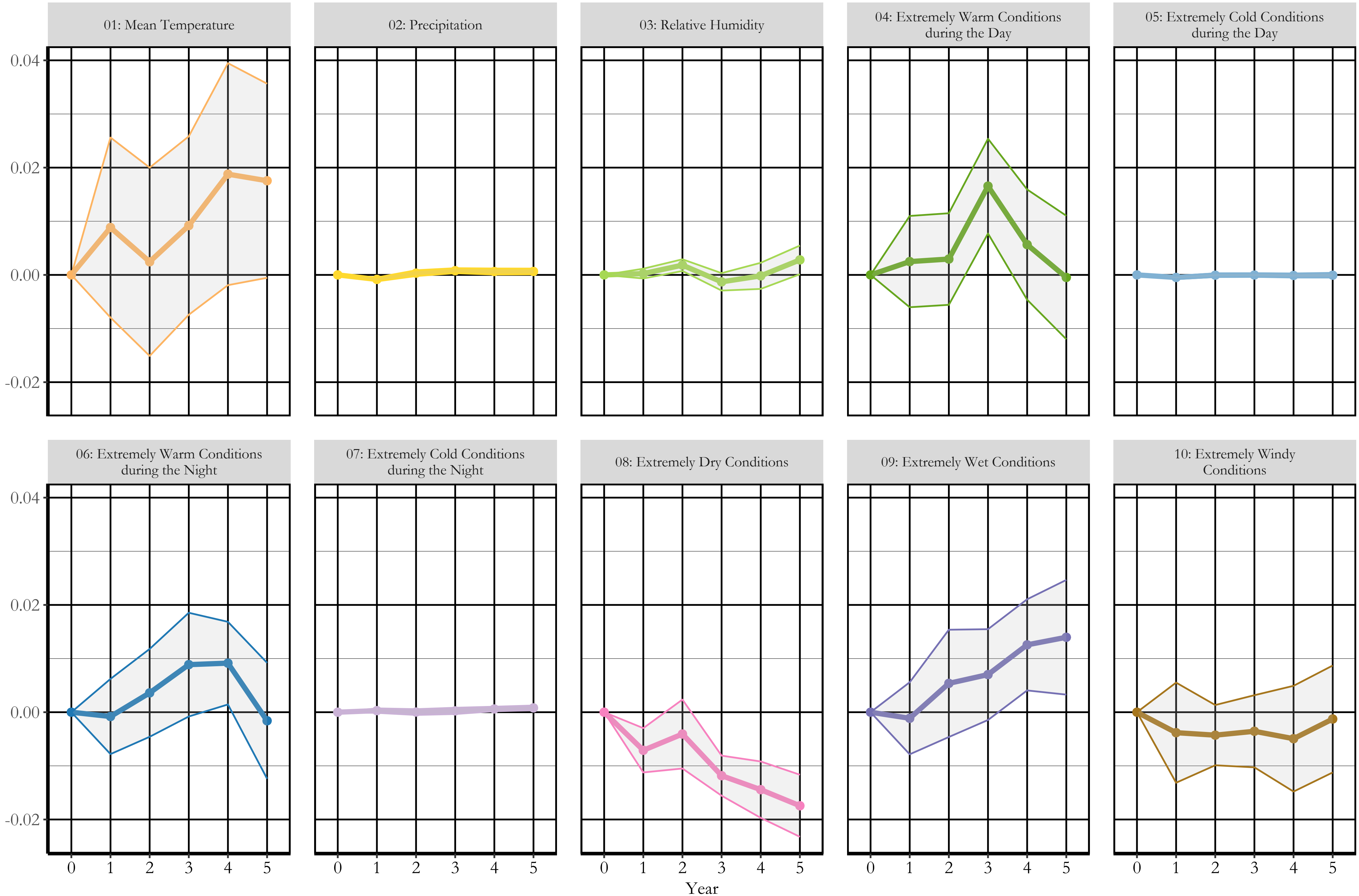
Source: Author's Calculations.

Figure 15: Annual Impulse Responses to Physical Climate Risks (Percentage Points): 03: Combined Changes in Premia on Equity and Real Estate



Source: Author's Calculations.

Figure 16: Annual Impulse Responses to Physical Climate Risks (Percentage Points): 04: Combined Changes in Premia on All Investments (including Bonds, Bills, Equity, and Real Estate)



Source: Author's Calculations.