

# THE LANCET Planetary Health

## Supplementary appendix

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## **Supplementary Material**

Seasonality of mortality under climate change: a multicountry projection study

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## Detailed information on the analytical framework

The analytical framework is described below. Part of the statistical analysis is based on previously published methods, applied in a previous seasonality assessment<sup>1</sup> using the same dataset and then summarized in a recent tutorial.<sup>2</sup>

### Observed series:

Historical data on temperature and mortality were collected via the Multi-Country Multi-City (MCC) Collaborative Research Network (<http://mccstudy.lshtm.ac.uk/>). The dataset is composed of observed daily time series for daily mean temperature  $Temp. obs$  and mortality counts  $Mort. obs$  for all causes or non-external causes (the International Classification of Diseases (ICD): A00-R99 for 10th ICD and 001–799 for 9th ICD). The data covers 707 locations across 43 countries/areas in largely overlapping periods from 1 January 1969 to 31 December 2020.

### Modeled series:

The modeled data on daily mean temperature  $Temp. mod$  were collected for the period of 1969–2099 from the database developed in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP 3b). We selected four scenarios under the Shared Socioeconomic Pathways (SSP) within Phase 6 of the Coupled Model Intercomparison Project (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5),<sup>3,4</sup> representing a range of scenarios for climate change from mild (SSP1-2.6) to extreme (SSP5-8.5). The data under each scenario includes simulations from five general circulation models (GCMs), including GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. We extracted the modeled data for each MCC location by linking each location's coordinates with the corresponding GCM grid-cell from the simulation in 1969–2099. To preserve the trend and variability of the original data in the observed series, we recalibrated the  $Temp_{mod}$  series using the observed  $T_{obs}$  series and obtained  $Temp_{mod}^*$ .<sup>5</sup>

## Statistical analysis

### Projecting the daily mortality

We fitted a quasi-Poisson regression model to the observed mortality series  $Mort. obs$ :<sup>6</sup>

$$\log[E(Mort. obs_t)] = \alpha + cs(doy_t) + [LTT fn](t) + cb(Temp. obs_{t,l}) \quad (1)$$

Where  $Mort. obs_t$  is the mortality count on day  $t$  from the observed series;  $cs$  is a cyclic spline of day-of-year ( $doy$ ) on day  $t$  with 4 degrees of freedom ( $df$ ) to fit the baseline seasonality (that remaining after temperature effects were modelled);  $LTT fn$  is a natural cubic spline of the day  $t$  with 2  $df$  per decade to fit the long-term trend ( $LTT$ );  $cb$  is a bi-dimensional cross-basis function for the non-linear and delayed exposure-lag-response association of  $Mort. obs_t$  with the observed daily mean temperature  $Temp. obs_t$  up to 21 days, and  $l$  is the lag days. For the cross-basis function, a natural cubic spline for exposure-response curve with three internal knots placed at the 10th, 75th, and 90th percentiles of location-specific temperature distributions, and another natural cubic spline for lag-response curve with 21 days of lags with an intercept and three internal knots placed at equally spaced values in the log scale.<sup>6,7</sup>

Next, we obtained model parameters from the fitted model (1) and projected the daily mortality  $Mort. proj_{t^*}$  on day  $t^*$  from 2000 to 2099:

$$E(Mort. proj_{t^*}) = \exp\left(\hat{\alpha} + \hat{cs}(doy_{t^*}) + [\widehat{LTT fn}](t_{base}) + \widehat{cb}(Temp. mod_{t^*,l})\right) \quad (2)$$

Where  $Mort.proj_{t^*}$  is the projected daily mortality on day  $t^*$  from 2000 to 2099;  $\hat{a}$ ,  $\hat{cs}$ ,  $\widehat{LTT\ fn}$ , and  $\widehat{cb}$  are the model parameters obtained from the fitted model (1) above;  $doy_{t^*}$  is the day-of-year from 2000 to 2099;  $t_{base}$  is a baseline time value we set on a certain date to fix the  $LTT$ , and  $t_{base}$  can be different between locations, as the observation periods vary between locations;  $Temp.mod_{t^*}$  is the daily mean temperature from the recalibrated modelled series from 2000 to 2099. Here, by using the model parameter  $\widehat{cb}$  from the fitted model (1), we assumed a constant association between temperature and mortality and did not consider potential adaptation to changing climate. In addition, we also assumed the baseline seasonality  $\exp(\hat{cs}(doy_{t^*}))$  does not change from 2000 to 2099.

We computed  $Mort.proj_{t^*}$  for each location and combinations of GCMs and SSPs, and the average across five GCMs for each SSP ( $\overline{Mort.proj_{t^*}}$ ) was used for the seasonality assessment in the next step.

### Assessing seasonality

We fitted a cyclic spline of  $doy_{t^*}$  with 4  $df$  to the projected  $\overline{Mort.proj_{t^*}}$  to assess its seasonality for each location, by extending a method previously described.<sup>1,2</sup>

$$\log[E(\overline{Mort.proj_{t^*}})] = \alpha + cs(doy_{t^*}) \quad (3)$$

Where  $\overline{Mort.proj_{t^*}}$  is the average of projected daily mortality across five GCMs on day  $t^*$  from 2000 to 2099;  $cs$  is a cyclic spline of day-of-year ( $doy_{t^*}$ ) with 4  $df$  to fit the seasonality;  $doy_{t^*}$  ranges from 1 to 365 corresponding to 1 January through to 31 December for locations in the northern hemisphere and 1 July to 30 June of the following year for locations in the southern hemisphere. From the coefficients of  $cs(doy_{t^*})$ , we derived the log relative risk  $\beta_{doy}$  of mortality on each  $doy$  compared with the minimum mortality.

The coefficients of  $cs(doy_{t^*})$  from location-specific seasonality assessment were pooled by each climate zone (location nested within the country/area as random effects) and country/area (location as a random effect), respectively, using the multivariate meta-analysis.

The key features of seasonality include its shape, timings (peak and trough) and size (amplitude and impact):

- The shape can be estimated through the fitted seasonal curve from the regression model (3), and described by visual inspection.
- The  $doy$  with maximum and minimum mortality estimates were identified from the fitted seasonal curve as the peak and trough, respectively. The empirical confidence intervals (eCIs) for peak and trough were obtained through Monte Carlo simulations.<sup>8</sup>
- We summarized the size of seasonality by measuring the amplitude and estimating its impact on mortality. The amplitude was measured as the ratio of the maximum mortality estimate at peak day to the minimum mortality estimate at trough day (i.e. peak-to-trough ratio, PTR):  $PTR = \exp(\beta_{peak}/\beta_{trough})$ , and its 95% CI was obtained from the variance matrix of the estimated coefficients from the  $cs(doy_{t^*})$ . Then, we obtained the AF as:  $AF = \sum p_{doy}[1 - \exp(\beta_{doy})]$ , where  $p_{doy}$  is the percentage of cases on each  $doy$ . The eCIs for AF were estimated through Monte Carlo simulations.<sup>9</sup> Here, the AF estimates the fraction by which mortality would be reduced in a counterfactual scenario where mortality risk never rose above its seasonal trough.

We estimated the change in PTR and AF, denoted as  $d$ , by decades in comparison with 2000-09, respectively. The formular are as follows:  $d = \widehat{E}_{decade} - \widehat{E}_{2000-09}$  and  $SE(d) =$

$\sqrt{\widehat{SE}_{decade}^2 + \widehat{SE}_{2000-09}^2}$ , where  $\widehat{E}$  are the estimates of log(PTR) and AF in the future decades (from the 2010s to the 2100s) and the current decade (i.e., 2000-09), and  $\widehat{SE}$  are their respective standard

errors. We report the relative change in PTR by taking the exponentiation of the difference in  $\log(\text{PTR})$ .

#### References:

- 1 Madaniyazi L, Armstrong B, Chung Y, *et al.* Seasonal variation in mortality and the role of temperature: a multi-country multi-city study. *Int J Epidemiol* 2022; **51**: 122–33.
- 2 Madaniyazi L, Tobias A, Kim Y, Chung Y, Armstrong B, Hashizume M. Assessing seasonality and the role of its potential drivers in environmental epidemiology: a tutorial. *Int J Epidemiol* 2022; **51**: 1677–86.
- 3 Riahi K, van Vuuren DP, Kriegler E, *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 2017; **42**: 153–68.
- 4 O'Neill BC, Tebaldi C, van Vuuren DP, *et al.* The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci Model Dev* 2016; **9**: 3461–82.
- 5 Vicedo-Cabrera AM, Sera F, Gasparrini A. Hands-on Tutorial on a Modeling Framework for Projections of Climate Change Impacts on Health. *Epidemiology* 2019; **30**: 321–9.
- 6 Gasparrini A, Guo Y, Hashizume M, *et al.* Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 2015; **386**: 369–75.
- 7 Gasparrini A, Armstrong B, Kenward MG. Distributed lag non-linear models. *Stat Med* 2010; **29**: 2224–34.
- 8 Tobias A, Armstrong B, Gasparrini A. Brief report: Investigating uncertainty in the minimum mortality temperature. *Epidemiology* 2017; **28**: 72–6.
- 9 Gasparrini A, Leone M. Attributable risk from distributed lag models. *BMC Med Res Methodol* 2014; **14**, 55. <http://www.biomedcentral.com/1471-2288/14/55>.

**Table S1.** Peak\* (empirical 95% confidence intervals) by decades for each climatic zone under scenarios

Decades	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Tropical				
2000s	29 ( 222 , 72 )	29 ( 221 , 72 )	29 ( 221 , 72 )	29 ( 221 , 72 )
2010s	40 ( 226 , 218 )	37 ( 224 , 206 )	41 ( 227 , 221 )	35 ( 224 , 76 )
2020s	56 ( 243 , 236 )	52 ( 238 , 233 )	50 ( 236 , 232 )	51 ( 237 , 232 )
2030s	60 ( 249 , 240 )	60 ( 247 , 240 )	62 ( 254 , 241 )	66 ( 262 , 244 )
2040s	64 ( 263 , 241 )	65 ( 257 , 243 )	73 ( 263 , 250 )	73 ( 329 , 238 )
2050s	72 ( 278 , 245 )	72 ( 358 , 236 )	74 ( 5 , 235 )	79 ( 27 , 234 )
2060s	70 ( 264 , 247 )	77 ( 19 , 233 )	81 ( 60 , 147 )	86 ( 67 , 223 )
2070s	70 ( 267 , 246 )	80 ( 35 , 233 )	87 ( 71 , 229 )	94 ( 72 , 221 )
2080s	70 ( 280 , 245 )	83 ( 41 , 229 )	88 ( 69 , 149 )	87 ( 66 , 228 )
2090s	66 ( 263 , 244 )	86 ( 65 , 224 )	80 ( 58 , 225 )	82 ( 65 , 225 )
Arid				
2000s	9 ( 1 , 17 )	9 ( 1 , 17 )	9 ( 1 , 17 )	9 ( 1 , 17 )
2010s	9 ( 1 , 17 )	9 ( 1 , 17 )	9 ( 1 , 17 )	9 ( 1 , 17 )
2020s	9 ( 1 , 16 )	9 ( 1 , 17 )	9 ( 1 , 16 )	9 ( 364 , 17 )
2030s	9 ( 1 , 16 )	8 ( 364 , 17 )	8 ( 364 , 16 )	8 ( 364 , 16 )
2040s	9 ( 364 , 17 )	8 ( 364 , 16 )	8 ( 363 , 16 )	9 ( 364 , 16 )
2050s	8 ( 364 , 16 )	8 ( 363 , 16 )	9 ( 363 , 17 )	9 ( 363 , 17 )
2060s	8 ( 364 , 16 )	8 ( 363 , 16 )	9 ( 362 , 18 )	9 ( 223 , 18 )
2070s	8 ( 364 , 16 )	9 ( 363 , 18 )	9 ( 352 , 18 )	9 ( 215 , 18 )
2080s	8 ( 364 , 16 )	9 ( 362 , 17 )	9 ( 216 , 18 )	9 ( 212 , 16 )
2090s	8 ( 364 , 16 )	9 ( 360 , 17 )	9 ( 213 , 17 )	214 ( 211 , 14 )
Temperate				
2000s	18 ( 14 , 21 )	18 ( 14 , 21 )	17 ( 14 , 21 )	18 ( 14 , 21 )
2010s	18 ( 14 , 22 )	18 ( 14 , 22 )	18 ( 14 , 22 )	18 ( 15 , 22 )
2020s	18 ( 14 , 22 )	18 ( 15 , 22 )	17 ( 14 , 21 )	19 ( 15 , 23 )
2030s	18 ( 15 , 22 )	18 ( 15 , 22 )	19 ( 15 , 22 )	18 ( 15 , 22 )
2040s	18 ( 15 , 22 )	18 ( 14 , 22 )	17 ( 14 , 22 )	18 ( 14 , 22 )
2050s	18 ( 14 , 22 )	18 ( 14 , 22 )	18 ( 14 , 22 )	18 ( 14 , 21 )
2060s	18 ( 15 , 22 )	18 ( 14 , 22 )	19 ( 15 , 22 )	19 ( 15 , 23 )
2070s	18 ( 14 , 21 )	19 ( 15 , 23 )	18 ( 14 , 22 )	18 ( 212 , 22 )
2080s	18 ( 14 , 22 )	18 ( 14 , 21 )	18 ( 213 , 22 )	214 ( 211 , 19 )
2090s	18 ( 15 , 22 )	18 ( 15 , 22 )	214 ( 211 , 22 )	214 ( 212 , 215 )
Continental				
2000s	22 ( 15 , 31 )	22 ( 15 , 31 )	22 ( 15 , 31 )	22 ( 15 , 31 )
2010s	22 ( 15 , 32 )	22 ( 16 , 32 )	22 ( 15 , 32 )	23 ( 17 , 32 )
2020s	22 ( 15 , 33 )	22 ( 16 , 32 )	22 ( 16 , 32 )	23 ( 16 , 32 )

2030s	22 ( 16 , 31 )	22 ( 15 , 33 )	23 ( 16 , 32 )	23 ( 17 , 32 )
2040s	21 ( 15 , 30 )	20 ( 14 , 30 )	21 ( 14 , 31 )	21 ( 15 , 30 )
2050s	21 ( 15 , 30 )	21 ( 15 , 31 )	20 ( 13 , 30 )	21 ( 14 , 30 )
2060s	22 ( 15 , 31 )	21 ( 15 , 30 )	22 ( 14 , 32 )	21 ( 14 , 31 )
2070s	20 ( 13 , 31 )	21 ( 14 , 31 )	20 ( 13 , 31 )	19 ( 210 , 29 )
2080s	21 ( 14 , 30 )	21 ( 14 , 31 )	20 ( 214 , 30 )	211 ( 206 , 26 )
2090s	22 ( 15 , 32 )	21 ( 14 , 30 )	19 ( 208 , 30 )	212 ( 207 , 24 )

\*The *day – of – year* with maximum mortality estimates were identified from the fitted seasonal curve as the peak. The empirical confidence intervals (eCIs) for peak and trough were obtained through Monte Carlo simulations. These estimates are obtained by pooling location-specific estimates for each climate zone. We removed Feb 29 from the datasets and took values from 1 to 365 to represent the day-of-year, corresponding to 1 January through 31 December for locations in the northern hemisphere and 1 July to 30 June of the following year for locations in the southern hemisphere.



**Table S2.** Trough\* (empirical 95% confidence intervals) by decades for each climatic zone scenarios

Decades	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Tropical				
2000s	142 ( 342 , 316 )	142 ( 341 , 315 )	142 ( 343 , 316 )	142 ( 342 , 316 )
2010s	144 ( 338 , 320 )	143 ( 337 , 320 )	144 ( 337 , 321 )	143 ( 338 , 319 )
2020s	147 ( 335 , 326 )	146 ( 335 , 325 )	145 ( 334 , 324 )	146 ( 334 , 325 )
2030s	147 ( 335 , 326 )	147 ( 335 , 326 )	148 ( 335 , 327 )	151 ( 338 , 331 )
2040s	313 ( 136 , 125 )	149 ( 336 , 329 )	338 ( 160 , 155 )	331 ( 151 , 148 )
2050s	324 ( 145 , 139 )	323 ( 146 , 117 )	325 ( 146 , 137 )	338 ( 269 , 151 )
2060s	330 ( 150 , 147 )	336 ( 157 , 153 )	339 ( 239 , 153 )	342 ( 290 , 1 )
2070s	327 ( 147 , 144 )	336 ( 279 , 148 )	345 ( 302 , 1 )	348 ( 261 , 3 )
2080s	326 ( 146 , 141 )	336 ( 275 , 148 )	343 ( 256 , 2 )	343 ( 232 , 2 )
2090s	320 ( 141 , 135 )	344 ( 284 , 38 )	334 ( 232 , 2 )	334 ( 236 , 1 )
Arid				
2000s	255 ( 140 , 268 )	255 ( 141 , 268 )	255 ( 140 , 269 )	255 ( 141 , 268 )
2010s	258 ( 138 , 271 )	258 ( 137 , 271 )	259 ( 135 , 272 )	258 ( 137 , 271 )
2020s	262 ( 133 , 274 )	262 ( 135 , 274 )	263 ( 131 , 275 )	263 ( 130 , 275 )
2030s	266 ( 129 , 277 )	266 ( 125 , 277 )	266 ( 124 , 277 )	267 ( 124 , 278 )
2040s	267 ( 125 , 278 )	269 ( 120 , 279 )	270 ( 117 , 280 )	273 ( 118 , 283 )
2050s	268 ( 123 , 279 )	271 ( 116 , 281 )	275 ( 113 , 284 )	279 ( 113 , 288 )
2060s	268 ( 122 , 280 )	274 ( 114 , 284 )	280 ( 112 , 289 )	283 ( 109 , 292 )
2070s	268 ( 122 , 279 )	277 ( 113 , 287 )	283 ( 109 , 292 )	124 ( 100 , 294 )
2080s	267 ( 121 , 278 )	279 ( 110 , 288 )	125 ( 102 , 293 )	120 ( 96 , 298 )
2090s	266 ( 123 , 278 )	281 ( 111 , 290 )	121 ( 97 , 297 )	116 ( 301 , 298 )
Temperate				
2000s	256 ( 225 , 263 )	256 ( 238 , 263 )	256 ( 240 , 264 )	256 ( 239 , 263 )
2010s	262 ( 252 , 268 )	261 ( 251 , 268 )	261 ( 250 , 268 )	262 ( 236 , 268 )
2020s	266 ( 258 , 271 )	267 ( 257 , 272 )	264 ( 254 , 270 )	268 ( 258 , 273 )
2030s	271 ( 264 , 276 )	272 ( 265 , 277 )	272 ( 264 , 276 )	273 ( 267 , 278 )
2040s	273 ( 265 , 278 )	276 ( 270 , 280 )	276 ( 269 , 280 )	279 ( 273 , 283 )
2050s	274 ( 267 , 279 )	278 ( 272 , 282 )	282 ( 276 , 286 )	285 ( 279 , 288 )
2060s	276 ( 270 , 280 )	281 ( 276 , 285 )	286 ( 281 , 290 )	290 ( 286 , 293 )
2070s	275 ( 268 , 279 )	285 ( 279 , 288 )	289 ( 283 , 292 )	292 ( 288 , 295 )
2080s	274 ( 267 , 278 )	285 ( 280 , 288 )	292 ( 287 , 295 )	296 ( 292 , 299 )
2090s	272 ( 264 , 276 )	287 ( 281 , 290 )	295 ( 290 , 298 )	299 ( 295 , 302 )
Continental				
2000s	215 ( 193 , 224 )	215 ( 193 , 224 )	215 ( 193 , 224 )	215 ( 193 , 224 )
2010s	215 ( 189 , 228 )	215 ( 190 , 228 )	215 ( 191 , 230 )	214 ( 188 , 230 )
2020s	216 ( 180 , 239 )	216 ( 183 , 240 )	217 ( 184 , 241 )	216 ( 182 , 246 )

2030s	229 ( 175 , 258 )	235 ( 174 , 260 )	225 ( 175 , 255 )	238 ( 171 , 263 )
2040s	248 ( 171 , 267 )	253 ( 174 , 269 )	244 ( 167 , 266 )	260 ( 165 , 274 )
2050s	243 ( 170 , 264 )	258 ( 165 , 273 )	266 ( 163 , 278 )	277 ( 163 , 286 )
2060s	246 ( 165 , 265 )	264 ( 163 , 277 )	277 ( 157 , 285 )	287 ( 267 , 293 )
2070s	247 ( 166 , 267 )	273 ( 161 , 282 )	284 ( 253 , 290 )	291 ( 279 , 296 )
2080s	243 ( 170 , 263 )	278 ( 160 , 286 )	289 ( 277 , 294 )	295 ( 286 , 300 )
2090s	243 ( 169 , 264 )	280 ( 163 , 288 )	293 ( 282 , 298 )	298 ( 289 , 303 )

\*The *day – of – year* with minimum mortality estimates were identified from the fitted seasonal curve as the trough. The empirical confidence intervals (eCIs) for peak and trough were obtained through Monte Carlo simulations. These estimates are obtained by pooling location-specific estimates for each climate zone. We removed Feb 29 from the datasets and took values from 1 to 365 to represent the day-of-year, corresponding to 1 January through 31 December for locations in the northern hemisphere and 1 July to 30 June of the following year for locations in the southern hemisphere.

**Table S3.** Peak-to-trough ratio (95% confidence intervals) by decades for each climatic zone under scenarios

Decades	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
<b>Arid</b>				
2000s	1.19 ( 1.11 , 1.29 )	1.19 ( 1.11 , 1.29 )	1.19 ( 1.11 , 1.29 )	1.19 ( 1.11 , 1.29 )
2010s	1.18 ( 1.1 , 1.27 )	1.18 ( 1.1 , 1.27 )	1.18 ( 1.1 , 1.27 )	1.18 ( 1.1 , 1.27 )
2020s	1.17 ( 1.09 , 1.26 )	1.17 ( 1.09 , 1.26 )	1.18 ( 1.1 , 1.26 )	1.17 ( 1.09 , 1.26 )
2030s	1.17 ( 1.09 , 1.25 )	1.17 ( 1.09 , 1.26 )	1.17 ( 1.09 , 1.25 )	1.17 ( 1.08 , 1.25 )
2040s	1.17 ( 1.09 , 1.25 )	1.16 ( 1.08 , 1.25 )	1.16 ( 1.08 , 1.25 )	1.16 ( 1.08 , 1.24 )
2050s	1.16 ( 1.08 , 1.25 )	1.16 ( 1.07 , 1.24 )	1.15 ( 1.07 , 1.24 )	1.15 ( 1.07 , 1.23 )
2060s	1.16 ( 1.08 , 1.25 )	1.15 ( 1.07 , 1.24 )	1.15 ( 1.07 , 1.23 )	1.14 ( 1.06 , 1.23 )
2070s	1.16 ( 1.08 , 1.25 )	1.15 ( 1.07 , 1.24 )	1.14 ( 1.06 , 1.23 )	1.14 ( 1.09 , 1.19 )
2080s	1.16 ( 1.08 , 1.25 )	1.15 ( 1.07 , 1.23 )	1.14 ( 1.09 , 1.19 )	1.14 ( 1.09 , 1.19 )
2090s	1.16 ( 1.08 , 1.25 )	1.14 ( 1.07 , 1.23 )	1.14 ( 1.09 , 1.19 )	1.14 ( 0.96 , 1.36 )
<b>Continental</b>				
2000s	1.21 ( 1.17 , 1.25 )	1.21 ( 1.17 , 1.25 )	1.21 ( 1.17 , 1.25 )	1.21 ( 1.17 , 1.25 )
2010s	1.19 ( 1.16 , 1.22 )	1.2 ( 1.16 , 1.23 )	1.19 ( 1.16 , 1.22 )	1.19 ( 1.16 , 1.23 )
2020s	1.18 ( 1.15 , 1.21 )	1.18 ( 1.16 , 1.21 )	1.18 ( 1.16 , 1.21 )	1.18 ( 1.16 , 1.21 )
2030s	1.17 ( 1.15 , 1.2 )	1.17 ( 1.14 , 1.19 )	1.17 ( 1.15 , 1.2 )	1.17 ( 1.14 , 1.19 )
2040s	1.17 ( 1.14 , 1.2 )	1.16 ( 1.14 , 1.19 )	1.16 ( 1.13 , 1.18 )	1.15 ( 1.13 , 1.18 )
2050s	1.16 ( 1.14 , 1.18 )	1.15 ( 1.13 , 1.18 )	1.15 ( 1.12 , 1.17 )	1.14 ( 1.12 , 1.17 )
2060s	1.16 ( 1.14 , 1.19 )	1.15 ( 1.12 , 1.18 )	1.14 ( 1.12 , 1.17 )	1.14 ( 1.11 , 1.17 )
2070s	1.16 ( 1.13 , 1.19 )	1.15 ( 1.12 , 1.17 )	1.14 ( 1.11 , 1.17 )	1.15 ( 1.11 , 1.18 )
2080s	1.16 ( 1.14 , 1.19 )	1.15 ( 1.12 , 1.17 )	1.14 ( 1.11 , 1.17 )	1.16 ( 1.06 , 1.27 )
2090s	1.17 ( 1.14 , 1.19 )	1.14 ( 1.12 , 1.17 )	1.14 ( 1.11 , 1.17 )	1.22 ( 1.08 , 1.38 )
<b>Temperate</b>				
2000s	1.22 ( 1.18 , 1.26 )	1.22 ( 1.18 , 1.26 )	1.22 ( 1.18 , 1.26 )	1.22 ( 1.18 , 1.26 )
2010s	1.21 ( 1.17 , 1.24 )	1.21 ( 1.17 , 1.25 )	1.21 ( 1.17 , 1.24 )	1.21 ( 1.17 , 1.25 )
2020s	1.2 ( 1.17 , 1.24 )	1.2 ( 1.17 , 1.24 )	1.2 ( 1.17 , 1.24 )	1.21 ( 1.17 , 1.24 )
2030s	1.2 ( 1.17 , 1.24 )	1.2 ( 1.16 , 1.23 )	1.2 ( 1.16 , 1.23 )	1.2 ( 1.16 , 1.23 )
2040s	1.2 ( 1.16 , 1.23 )	1.2 ( 1.16 , 1.23 )	1.19 ( 1.16 , 1.22 )	1.19 ( 1.16 , 1.22 )
2050s	1.19 ( 1.16 , 1.22 )	1.19 ( 1.16 , 1.22 )	1.18 ( 1.16 , 1.21 )	1.19 ( 1.16 , 1.22 )
2060s	1.2 ( 1.16 , 1.23 )	1.19 ( 1.16 , 1.22 )	1.18 ( 1.16 , 1.21 )	1.18 ( 1.15 , 1.22 )
2070s	1.19 ( 1.16 , 1.23 )	1.19 ( 1.16 , 1.22 )	1.18 ( 1.15 , 1.22 )	1.19 ( 1.16 , 1.22 )
2080s	1.19 ( 1.16 , 1.23 )	1.19 ( 1.16 , 1.22 )	1.18 ( 1.15 , 1.21 )	1.22 ( 1.13 , 1.32 )
2090s	1.2 ( 1.16 , 1.23 )	1.19 ( 1.15 , 1.22 )	1.19 ( 1.11 , 1.27 )	1.31 ( 1.18 , 1.44 )
<b>Tropical</b>				
2000s	1.04 ( 1 , 1.08 )	1.04 ( 1 , 1.08 )	1.04 ( 1 , 1.08 )	1.04 ( 1 , 1.08 )
2010s	1.04 ( 1 , 1.07 )	1.03 ( 1 , 1.07 )	1.03 ( 1 , 1.07 )	1.04 ( 1 , 1.07 )

2020s	1.03 ( 0.99 , 1.06 )	1.03 ( 1 , 1.06 )	1.03 ( 1 , 1.06 )	1.03 ( 1 , 1.06 )
2030s	1.02 ( 0.99 , 1.06 )	1.03 ( 0.99 , 1.07 )	1.03 ( 0.99 , 1.07 )	1.03 ( 0.99 , 1.08 )
2040s	1.03 ( 0.97 , 1.09 )	1.03 ( 0.98 , 1.08 )	1.03 ( 0.98 , 1.09 )	1.04 ( 0.99 , 1.1 )
2050s	1.03 ( 0.97 , 1.09 )	1.04 ( 0.99 , 1.09 )	1.04 ( 0.99 , 1.1 )	1.05 ( 1 , 1.11 )
2060s	1.03 ( 0.97 , 1.09 )	1.05 ( 1 , 1.11 )	1.08 ( 1.02 , 1.14 )	1.11 ( 1.03 , 1.18 )
2070s	1.02 ( 0.97 , 1.08 )	1.06 ( 1 , 1.12 )	1.12 ( 1.06 , 1.19 )	1.12 ( 1.03 , 1.22 )
2080s	1.03 ( 0.98 , 1.08 )	1.06 ( 1 , 1.12 )	1.13 ( 1.04 , 1.23 )	1.14 ( 1.04 , 1.24 )
2090s	1.02 ( 0.97 , 1.08 )	1.08 ( 1.02 , 1.14 )	1.15 ( 1.04 , 1.26 )	1.16 ( 1.05 , 1.27 )

The peak-to-trough ratio is the ratio of the maximum mortality estimate at peak day to the minimum mortality estimate at trough day. These estimates are obtained by pooling location-specific estimates for each climate zone. We removed Feb 29 from the datasets and took values from 1 to 365 to represent the day of year, corresponding to 1 January through 31 December for locations in the northern hemisphere and 1 July to 30 June of the following year for locations in the southern hemisphere.

**Table S4.** Attributable fraction (95% empirical confidence intervals) by decades for each climatic zone under scenarios

Period	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
<b>Arid</b>				
2000s	0.06 ( 0.04 , 0.09 )	0.06 ( 0.04 , 0.09 )	0.06 ( 0.04 , 0.09 )	0.06 ( 0.04 , 0.09 )
2010s	0.05 ( 0.04 , 0.09 )	0.05 ( 0.04 , 0.09 )	0.05 ( 0.04 , 0.09 )	0.05 ( 0.04 , 0.08 )
2020s	0.05 ( 0.03 , 0.08 )	0.05 ( 0.03 , 0.08 )	0.05 ( 0.04 , 0.08 )	0.05 ( 0.03 , 0.08 )
2030s	0.05 ( 0.03 , 0.08 )	0.05 ( 0.03 , 0.08 )	0.05 ( 0.03 , 0.08 )	0.05 ( 0.03 , 0.08 )
2040s	0.05 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )
2050s	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )
2060s	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.09 )
2070s	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.09 )	0.05 ( 0.03 , 0.09 )
2080s	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.09 )	0.05 ( 0.03 , 0.1 )
2090s	0.05 ( 0.03 , 0.08 )	0.04 ( 0.03 , 0.08 )	0.05 ( 0.03 , 0.1 )	0.06 ( 0.03 , 0.11 )
<b>Continental</b>				
2000s	0.08 ( 0.06 , 0.09 )	0.08 ( 0.06 , 0.09 )	0.08 ( 0.06 , 0.09 )	0.08 ( 0.06 , 0.09 )
2010s	0.07 ( 0.06 , 0.08 )	0.07 ( 0.06 , 0.08 )	0.07 ( 0.06 , 0.08 )	0.07 ( 0.06 , 0.08 )
2020s	0.07 ( 0.06 , 0.08 )	0.07 ( 0.06 , 0.08 )	0.06 ( 0.06 , 0.08 )	0.06 ( 0.06 , 0.08 )
2030s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.05 ( 0.05 , 0.07 )
2040s	0.05 ( 0.05 , 0.07 )	0.05 ( 0.05 , 0.06 )	0.05 ( 0.04 , 0.07 )	0.05 ( 0.04 , 0.06 )
2050s	0.05 ( 0.05 , 0.06 )	0.05 ( 0.04 , 0.06 )	0.05 ( 0.04 , 0.06 )	0.05 ( 0.04 , 0.06 )
2060s	0.05 ( 0.05 , 0.06 )	0.05 ( 0.04 , 0.06 )	0.05 ( 0.04 , 0.06 )	0.05 ( 0.04 , 0.07 )
2070s	0.05 ( 0.04 , 0.07 )	0.05 ( 0.04 , 0.06 )	0.05 ( 0.04 , 0.07 )	0.06 ( 0.04 , 0.09 )
2080s	0.05 ( 0.05 , 0.07 )	0.05 ( 0.04 , 0.06 )	0.06 ( 0.04 , 0.08 )	0.08 ( 0.05 , 0.1 )
2090s	0.05 ( 0.05 , 0.07 )	0.05 ( 0.04 , 0.06 )	0.07 ( 0.05 , 0.09 )	0.09 ( 0.05 , 0.12 )
<b>Temperate</b>				
2000s	0.07 ( 0.06 , 0.08 )	0.07 ( 0.06 , 0.08 )	0.07 ( 0.06 , 0.08 )	0.07 ( 0.06 , 0.08 )
2010s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )
2020s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )
2030s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )
2040s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )
2050s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.07 ( 0.05 , 0.08 )
2060s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.07 )	0.07 ( 0.05 , 0.08 )	0.07 ( 0.06 , 0.09 )
2070s	0.06 ( 0.05 , 0.07 )	0.06 ( 0.05 , 0.08 )	0.07 ( 0.06 , 0.08 )	0.08 ( 0.06 , 0.1 )
2080s	0.06 ( 0.05 , 0.07 )	0.07 ( 0.05 , 0.08 )	0.08 ( 0.06 , 0.09 )	0.09 ( 0.07 , 0.11 )
2090s	0.06 ( 0.05 , 0.07 )	0.07 ( 0.05 , 0.08 )	0.08 ( 0.06 , 0.1 )	0.11 ( 0.08 , 0.14 )
<b>Tropical</b>				
2000s	0.02 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )
2010s	0.02 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )

2020s	0.01 ( 0.01 , 0.04 )	0.01 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.04 )
2030s	0.01 ( 0.01 , 0.04 )	0.01 ( 0.01 , 0.04 )	0.01 ( 0.01 , 0.04 )	0.01 ( 0.01 , 0.04 )
2040s	0.01 ( 0.01 , 0.04 )	0.01 ( 0.01 , 0.04 )	0.01 ( 0.01 , 0.05 )	0.02 ( 0.01 , 0.05 )
2050s	0.01 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.05 )	0.02 ( 0.01 , 0.05 )	0.03 ( 0.01 , 0.06 )
2060s	0.01 ( 0.01 , 0.04 )	0.02 ( 0.01 , 0.05 )	0.04 ( 0.02 , 0.07 )	0.05 ( 0.03 , 0.09 )
2070s	0.01 ( 0.01 , 0.04 )	0.03 ( 0.01 , 0.06 )	0.06 ( 0.04 , 0.09 )	0.06 ( 0.03 , 0.11 )
2080s	0.01 ( 0.01 , 0.04 )	0.03 ( 0.01 , 0.07 )	0.06 ( 0.03 , 0.11 )	0.07 ( 0.03 , 0.12 )
2090s	0.01 ( 0.01 , 0.04 )	0.04 ( 0.02 , 0.07 )	0.07 ( 0.03 , 0.12 )	0.08 ( 0.04 , 0.15 )

The attributable fraction estimates the fraction by which mortality would be reduced in a counterfactual scenario where mortality risk never rose above its seasonal trough. These estimates are obtained by pooling location-specific estimates for each climate zone. We removed Feb 29 from the datasets and took values from 1 to 365 to represent the day of year, corresponding to 1 January through 31 December for locations in the northern hemisphere and 1 July to 30 June of the following year for locations in the southern hemisphere.

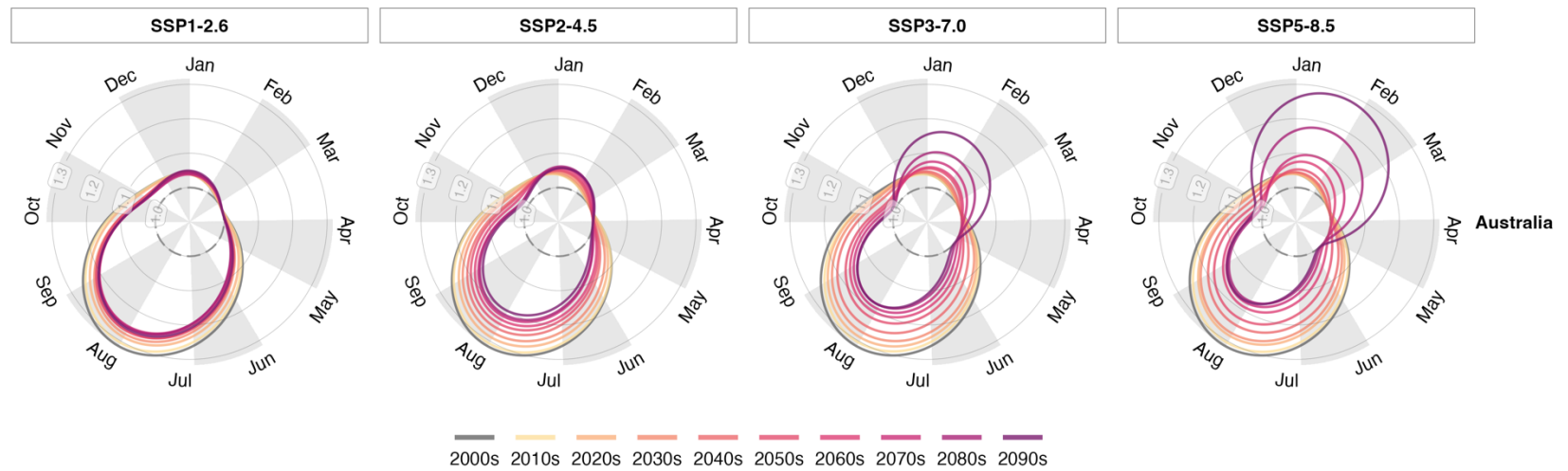
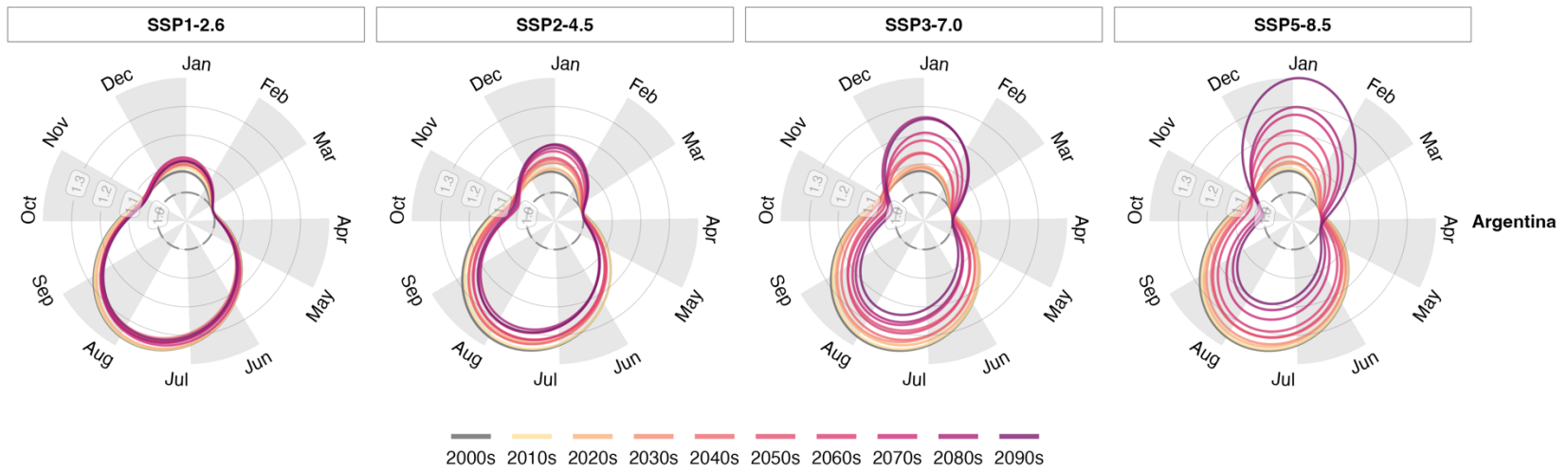
**Figure S1.** Shape of seasonality of mortality in each country/area from the 2000s to 2090s under four scenarios

The seasonality is computed as the relative risk of mortality estimates at each day-of-year  $i$  to minimum mortality estimates at the trough day for each country/ area:

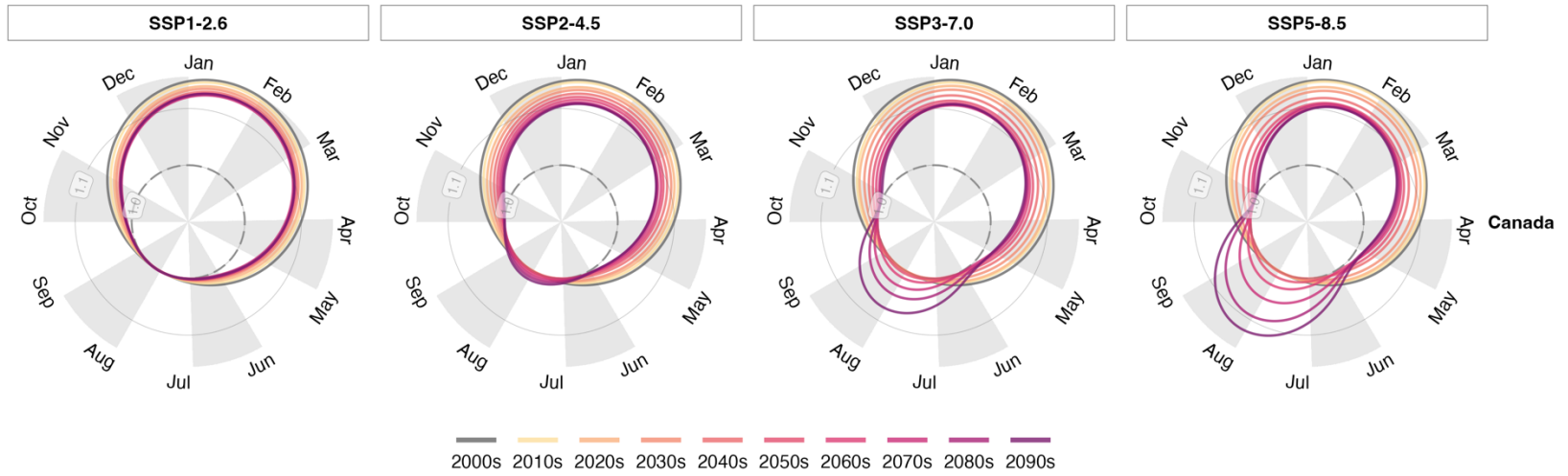
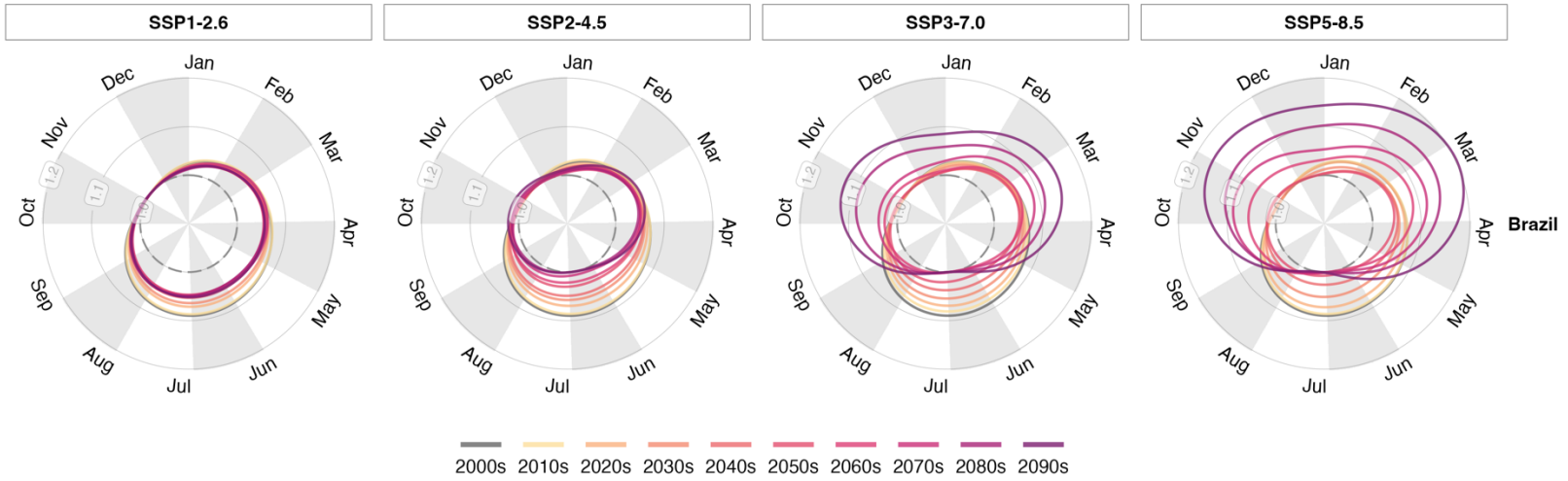
$$\text{Relative risk} = \text{Mortality estimate at day } i \text{ of year } i / \text{Minimum mortality estimate at the trough}$$

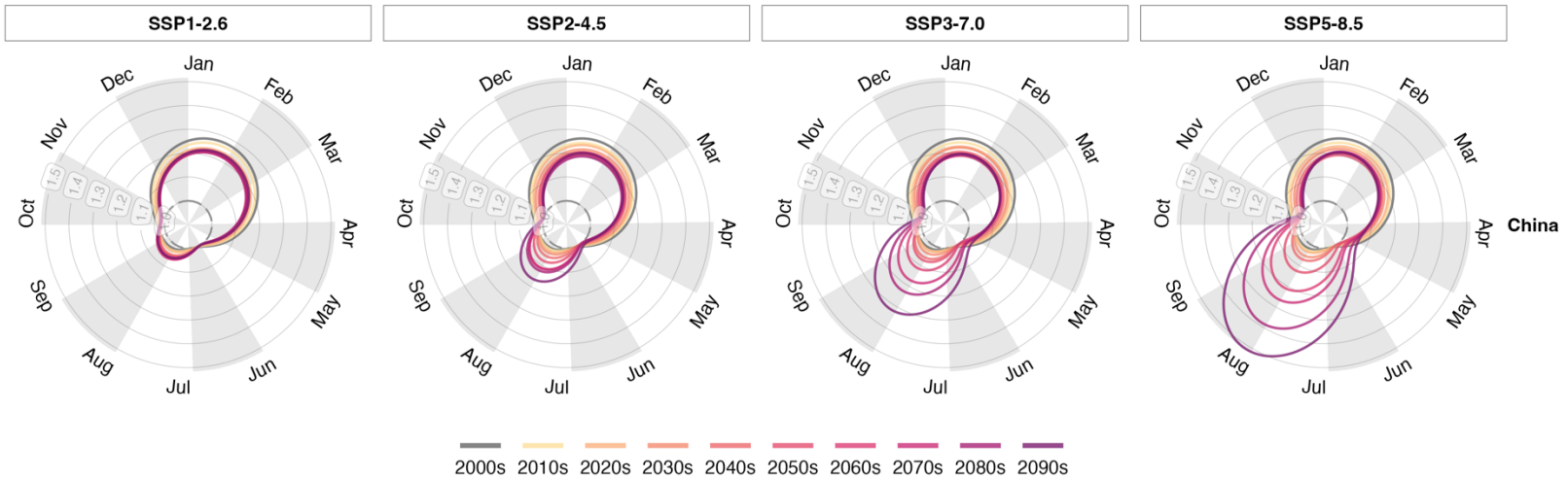
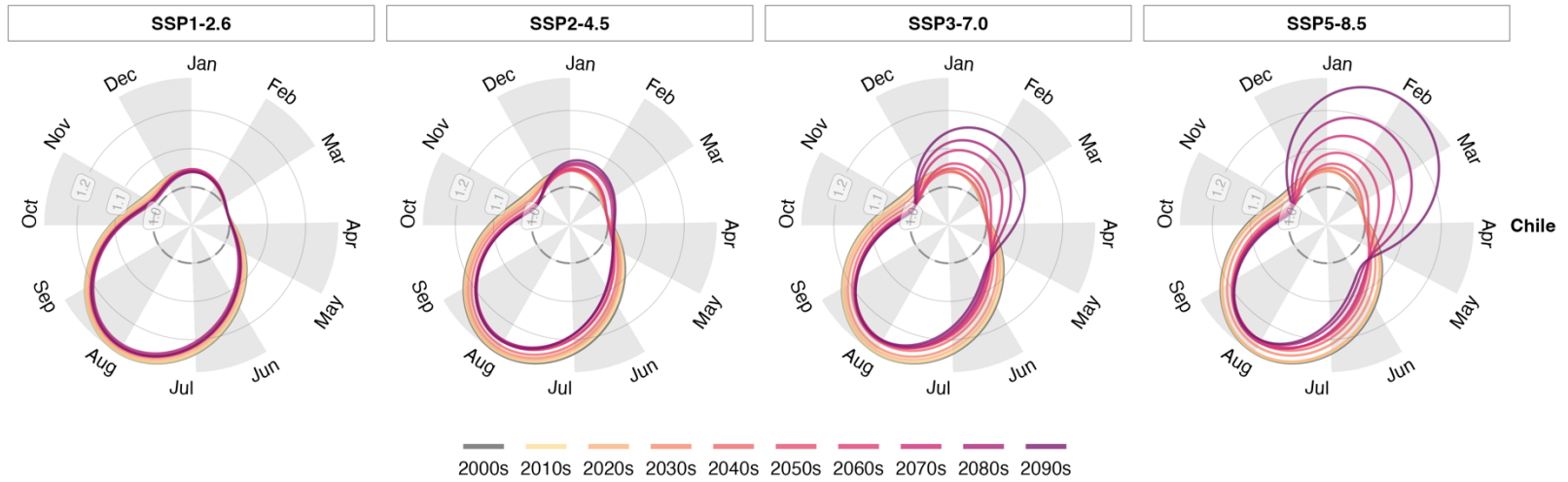
These estimates are obtained by pooling location-specific estimates for each country/area. We removed Feb 29 from the datasets. When reporting results at the country/area level, we took values from 1 to 365 to represent the day-of-year, corresponding to 1 January through 31 December for locations in both hemispheres. Note that the scales are different in each row, as the relative risk varies substantially between countries.

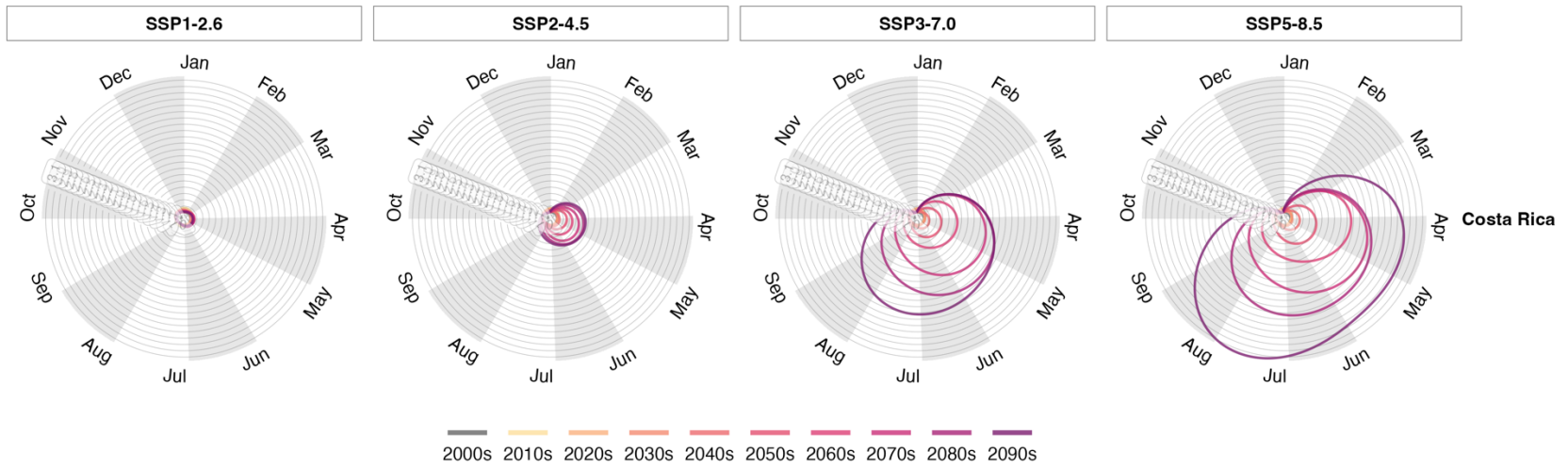
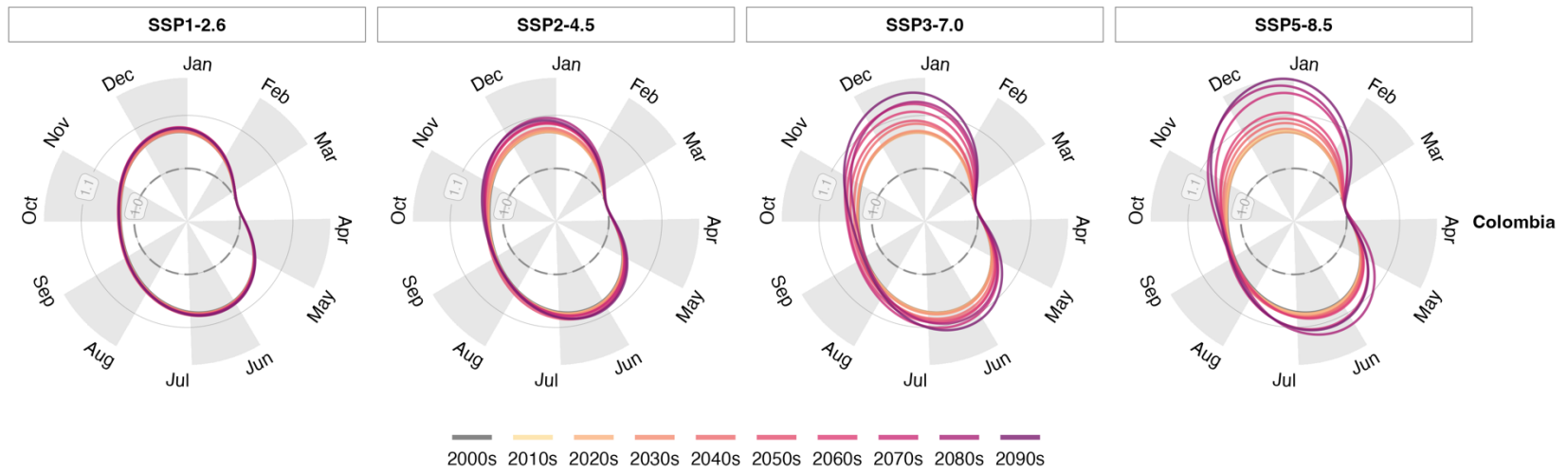
**Note:** The two polar locations in Peru were included when pooling the results for Peru.

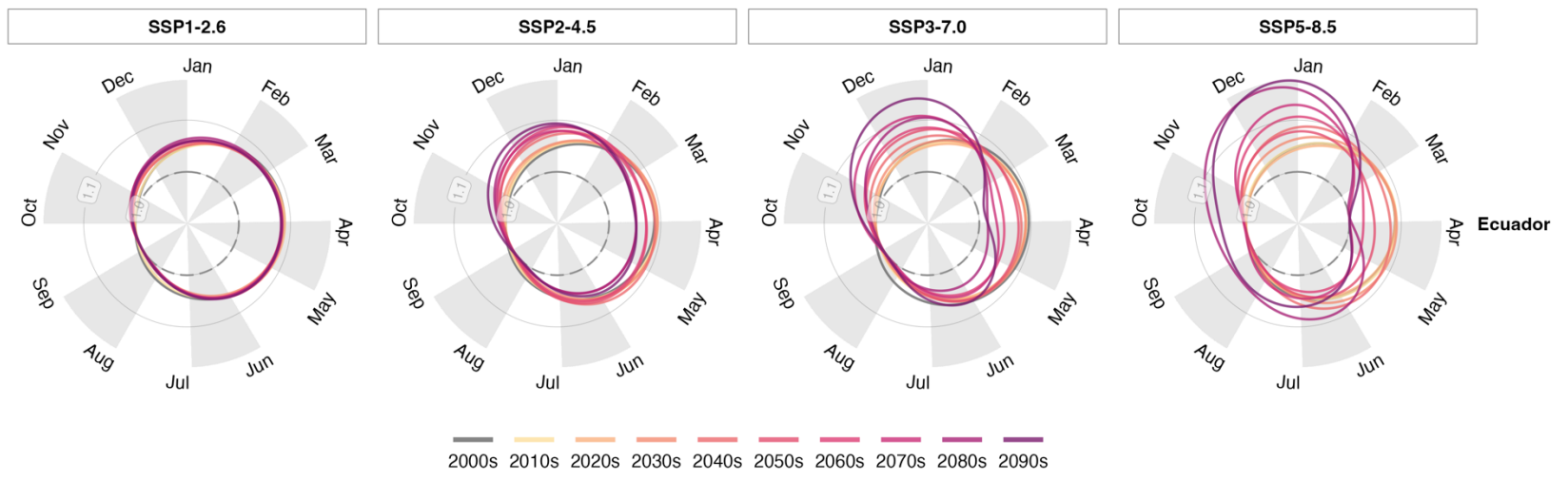
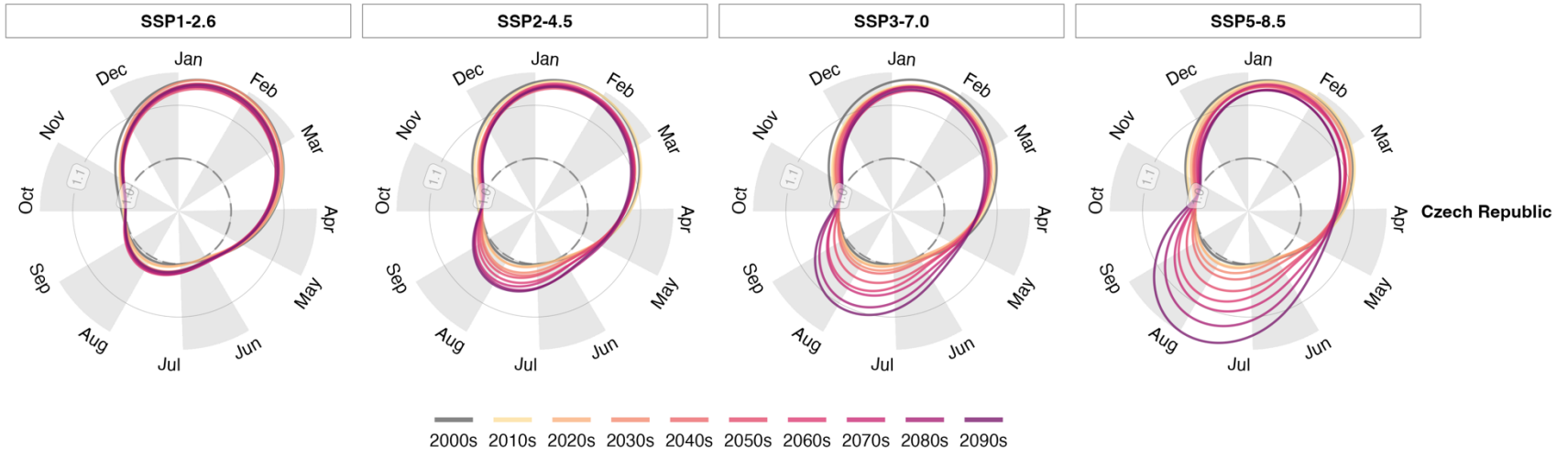


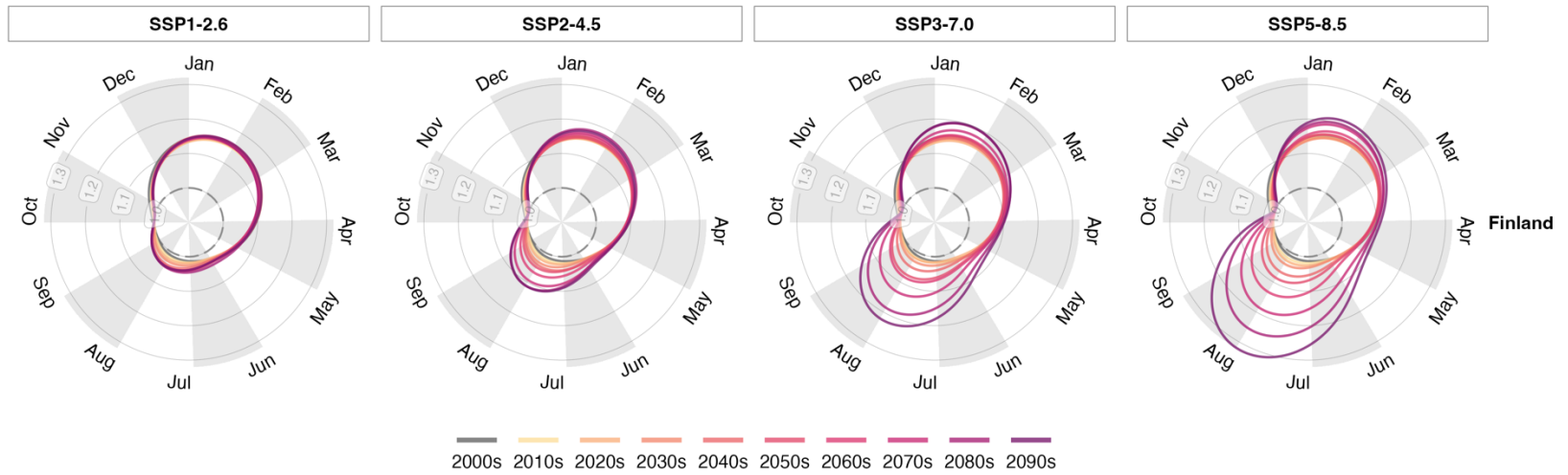
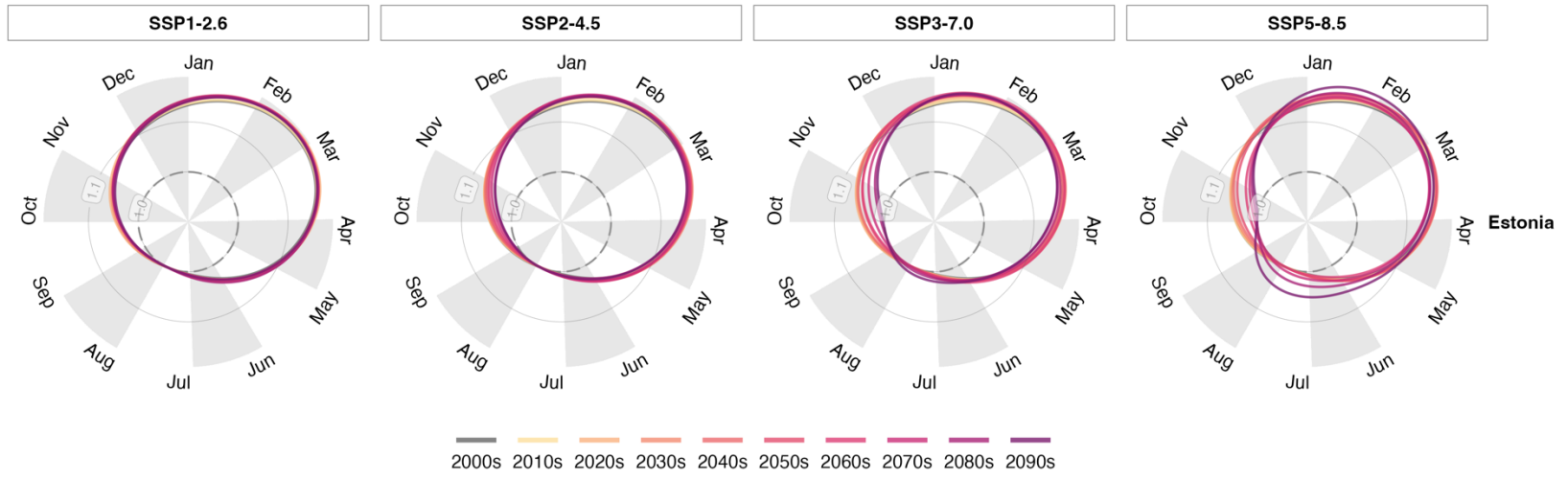


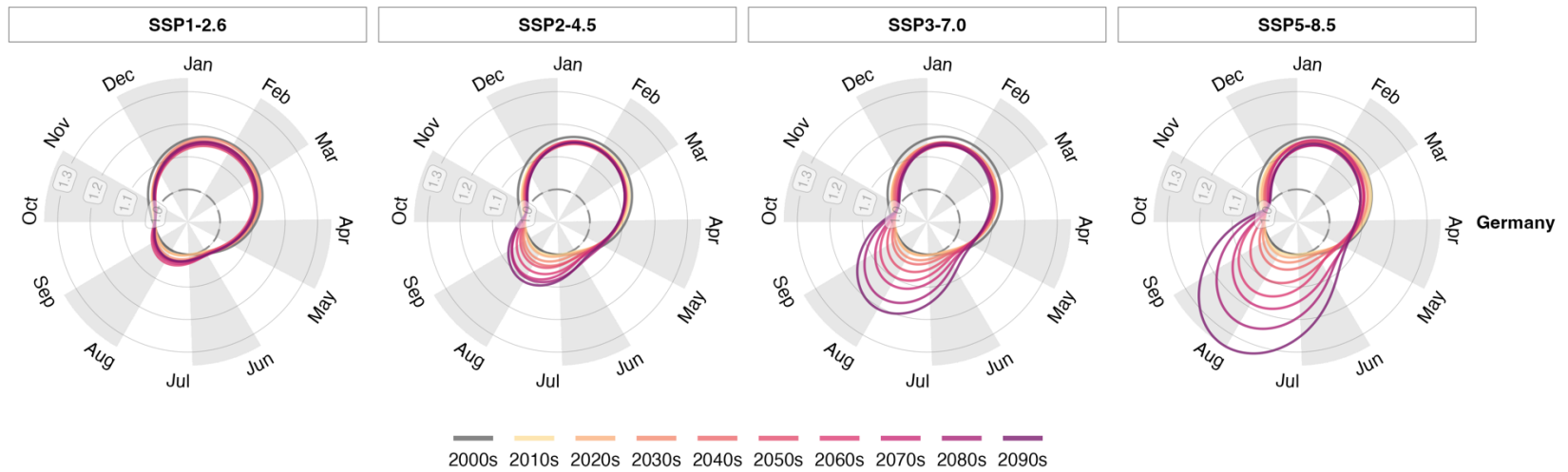
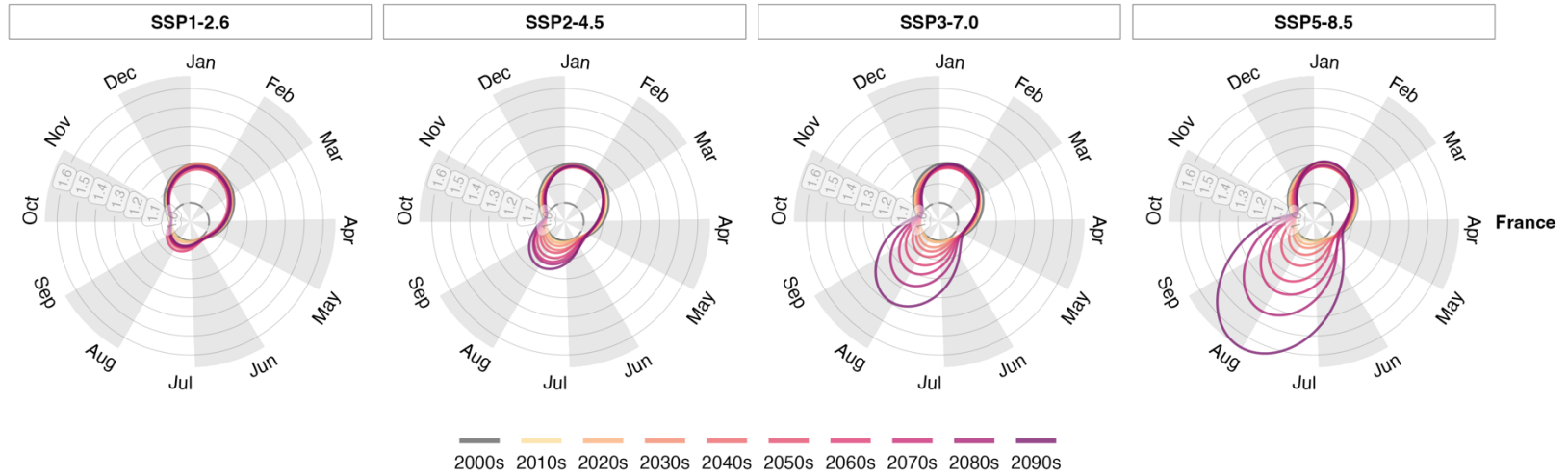


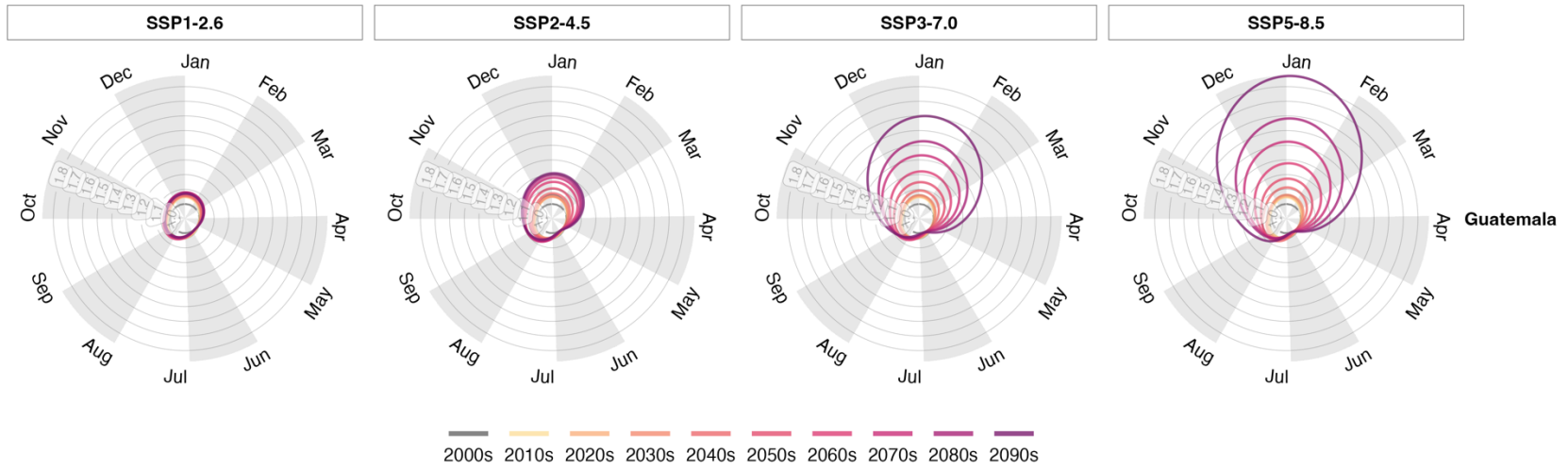
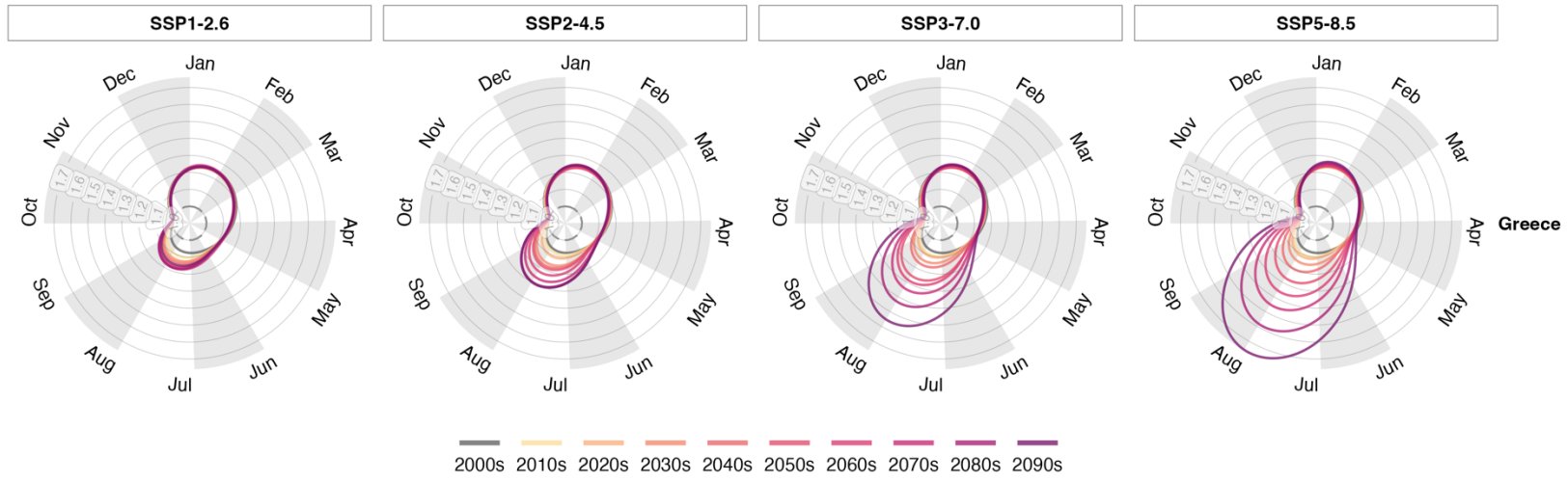


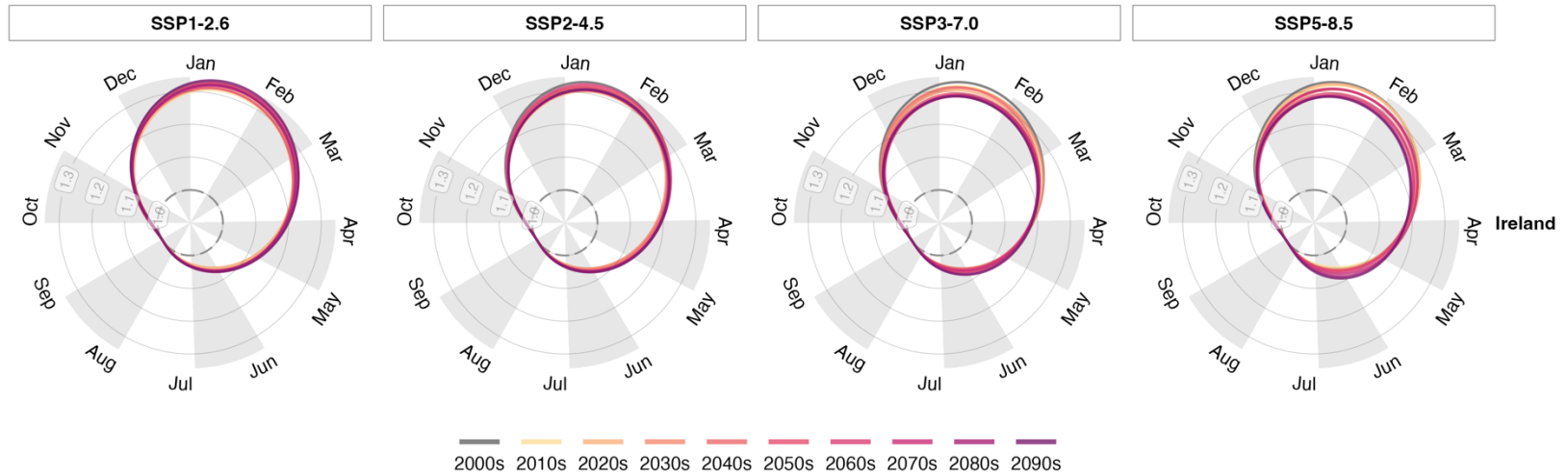
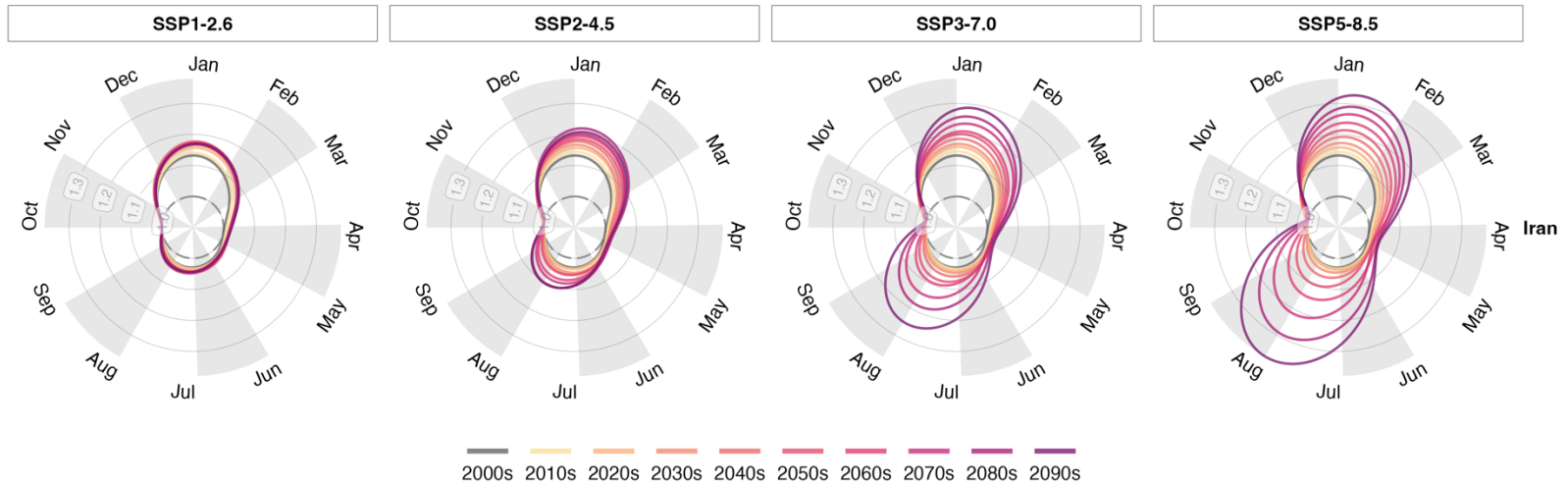




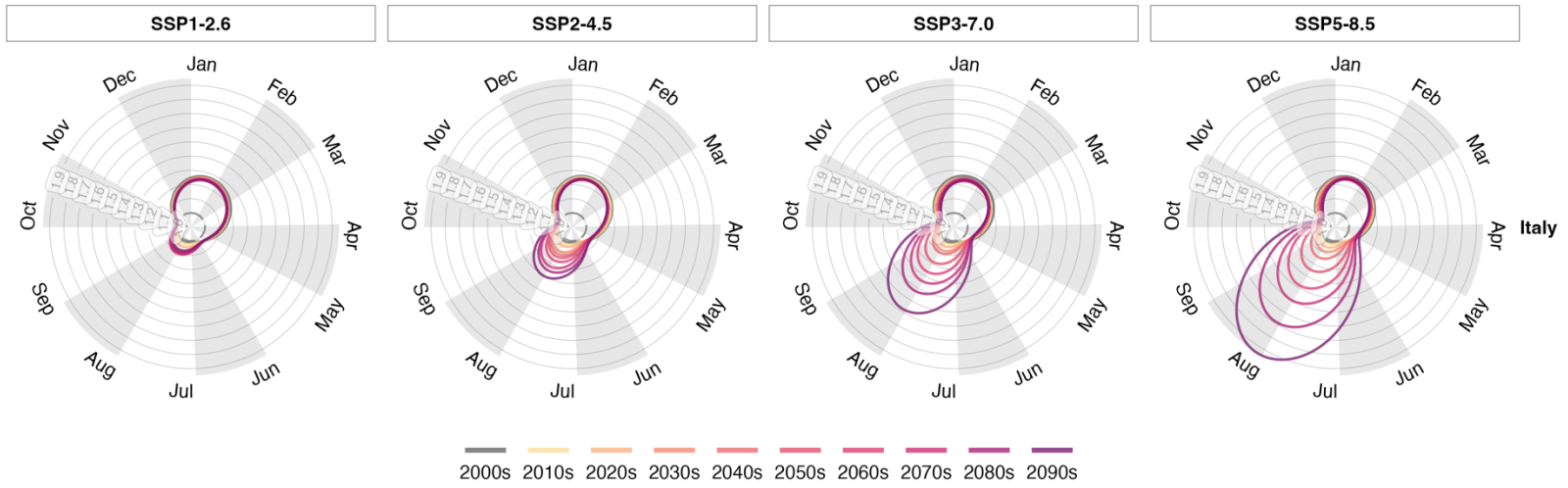
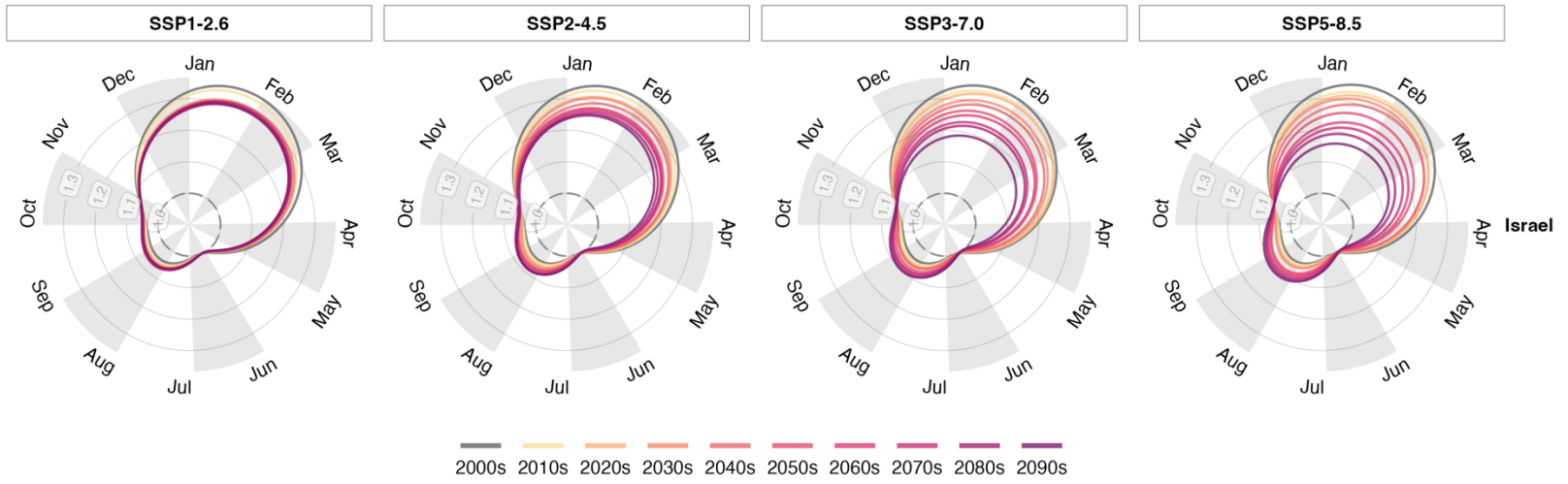


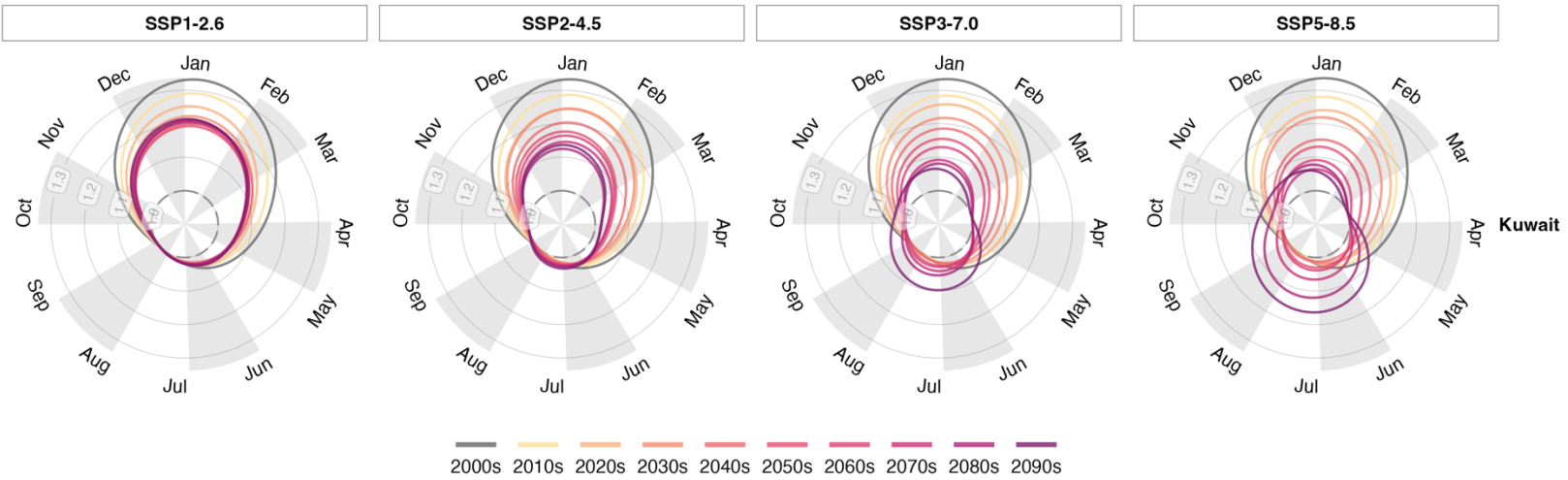
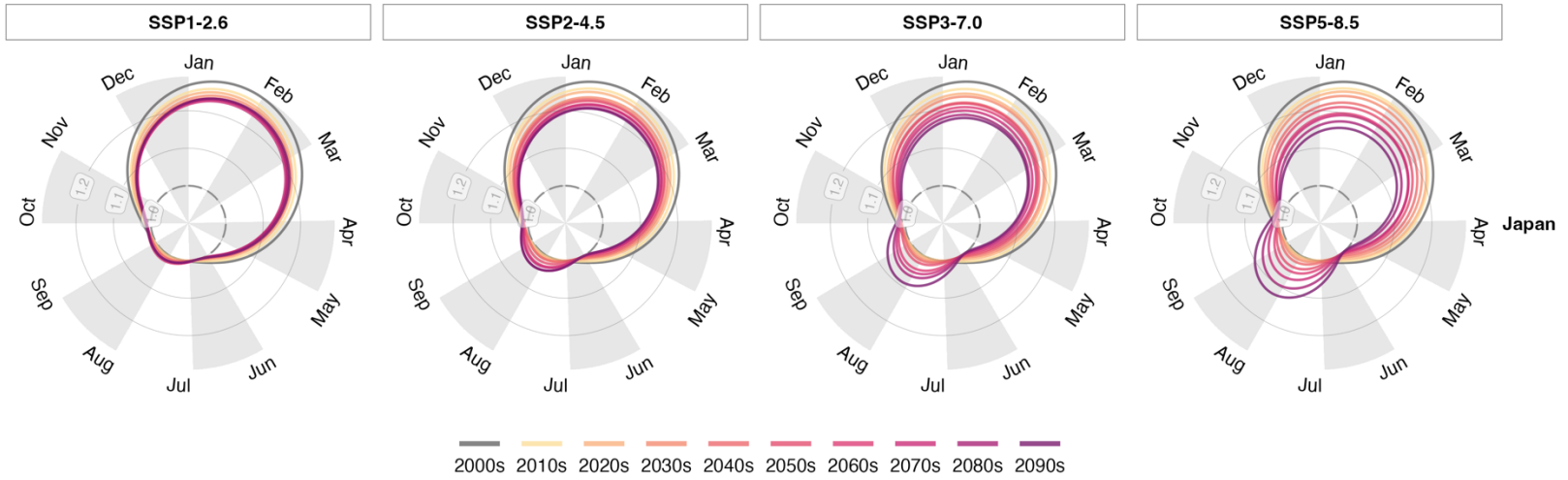




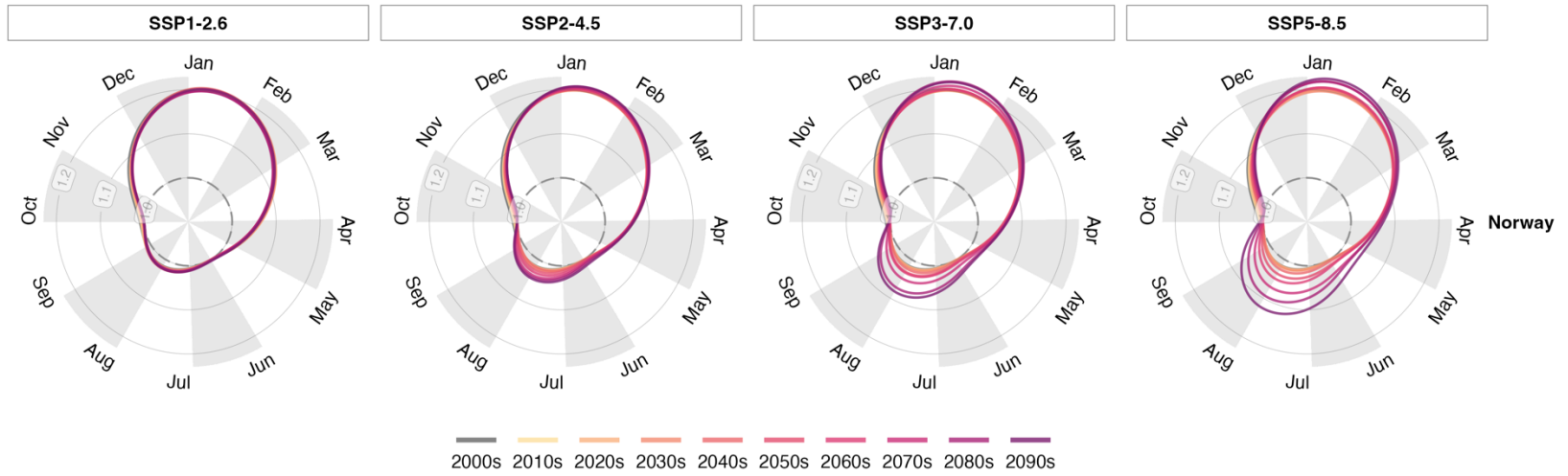
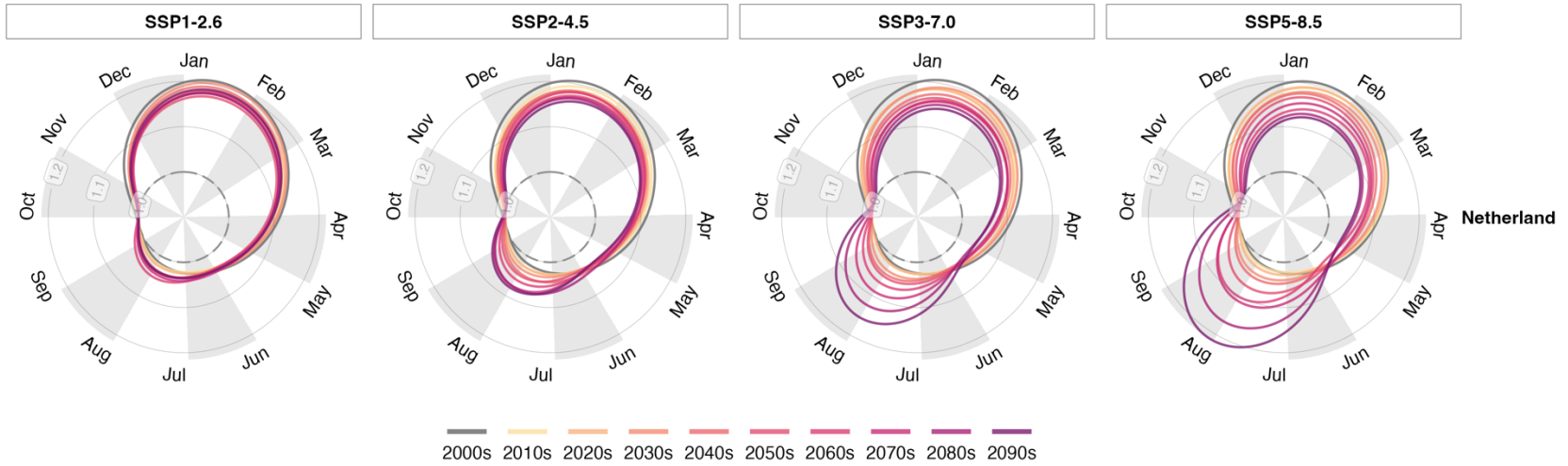


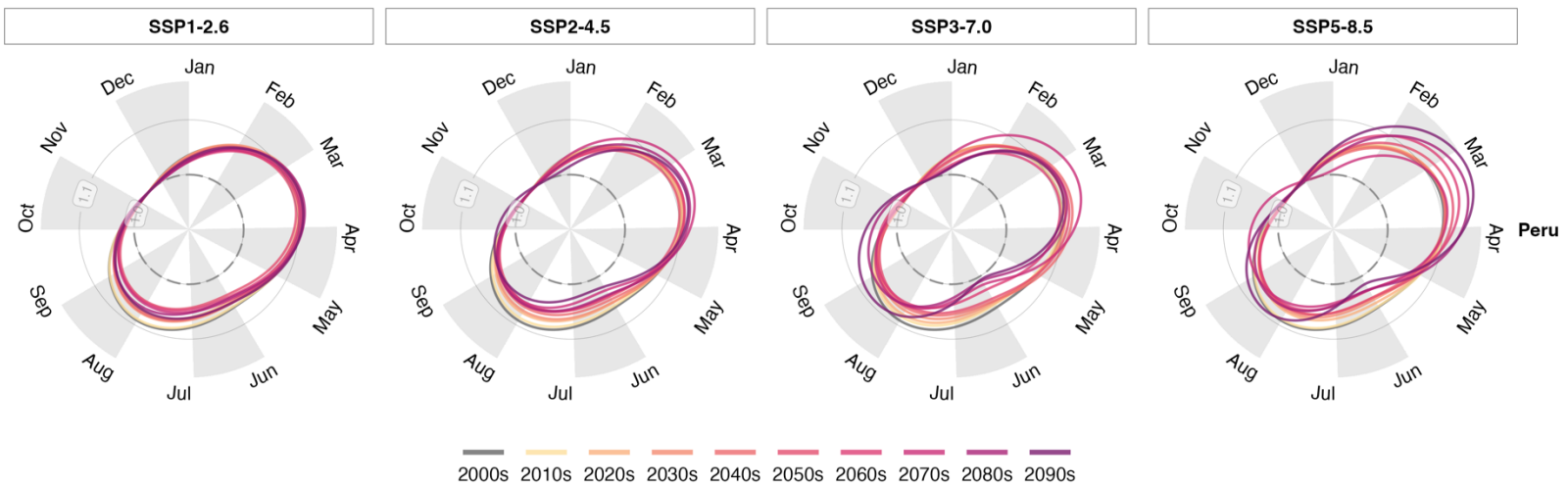
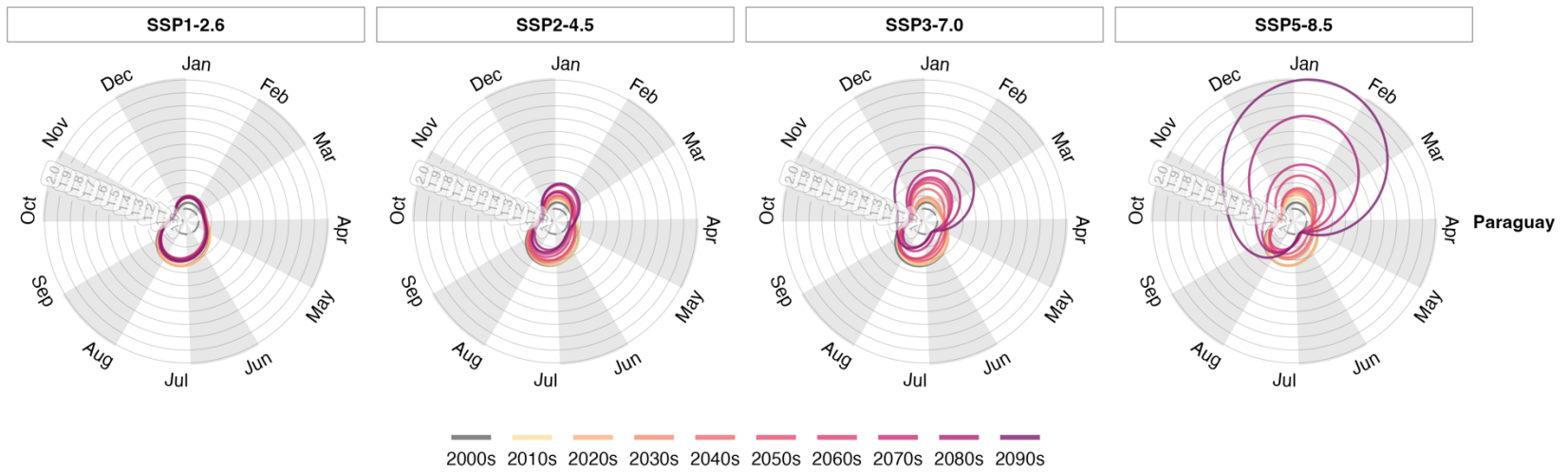


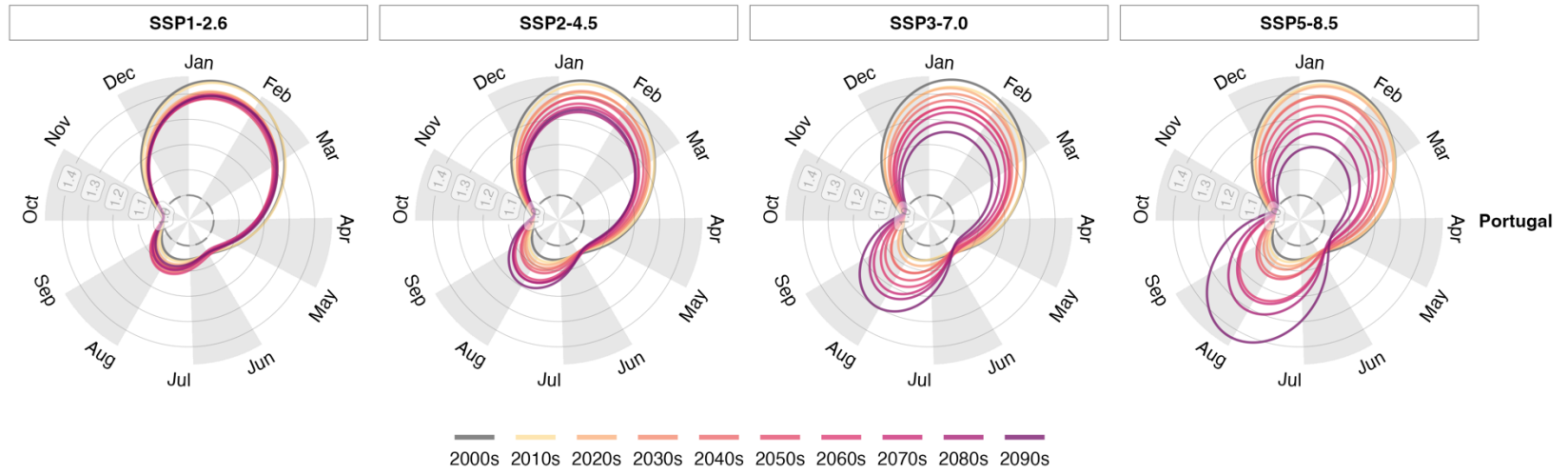
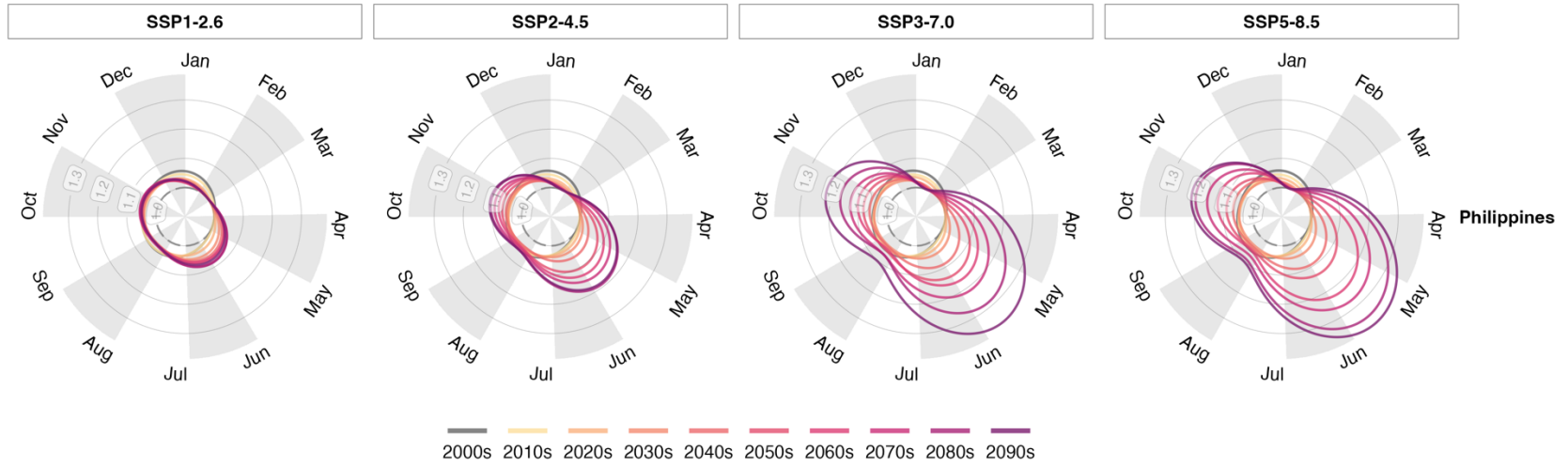


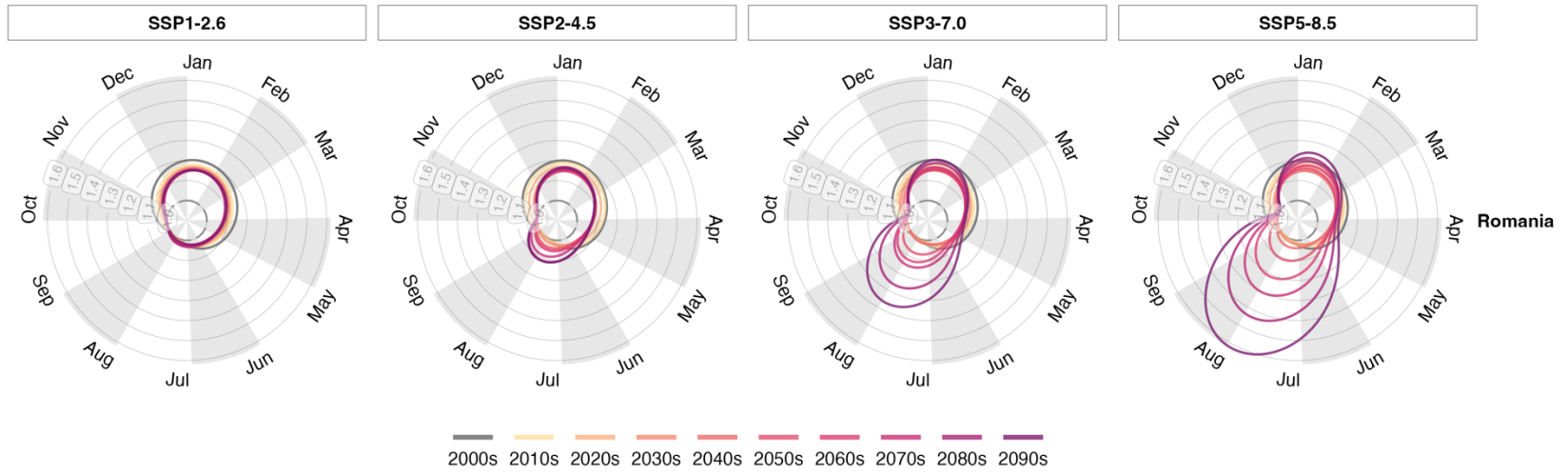
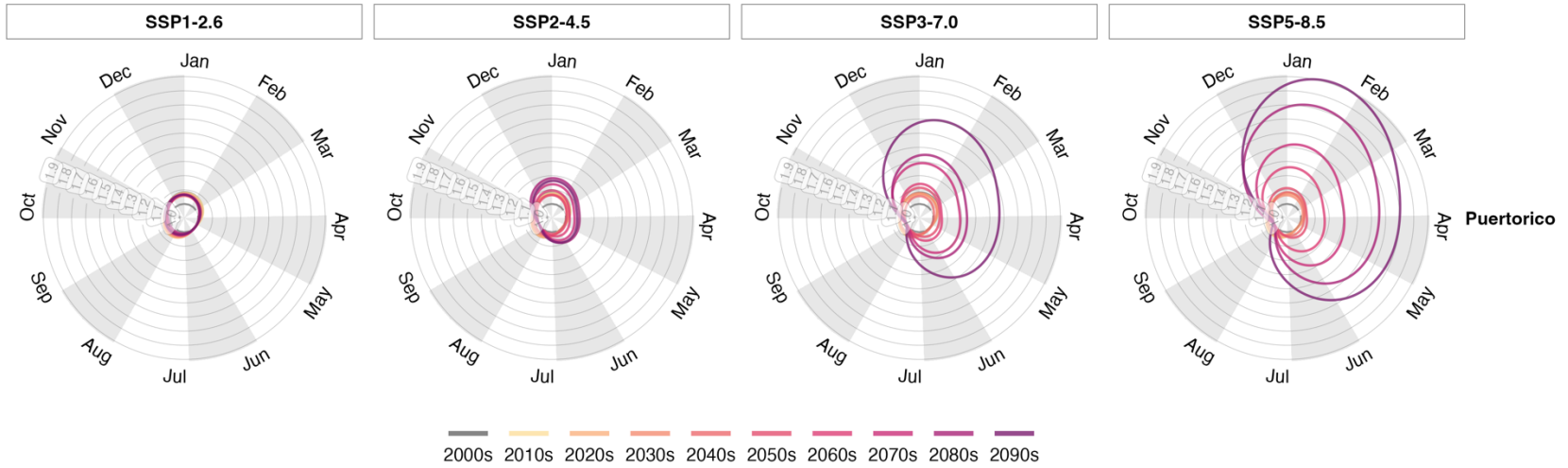


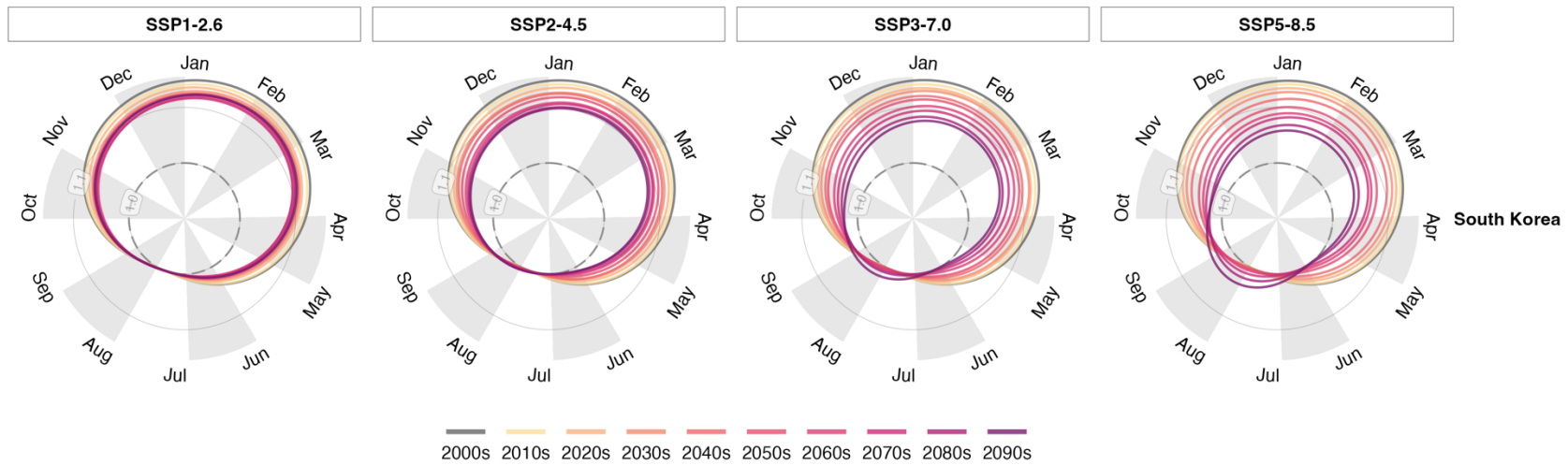
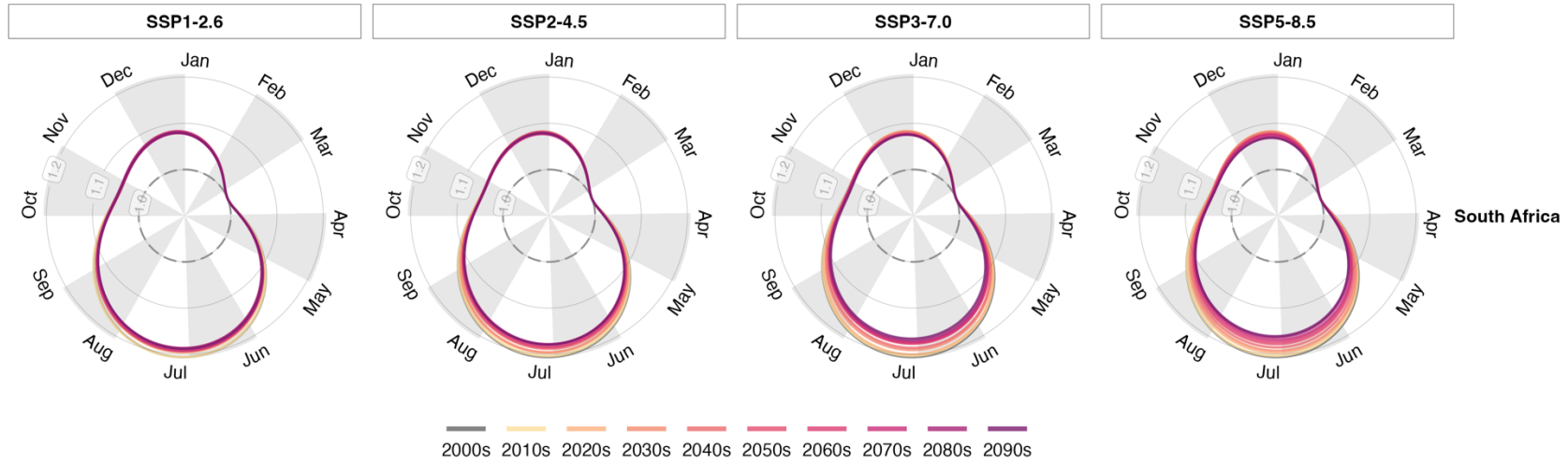




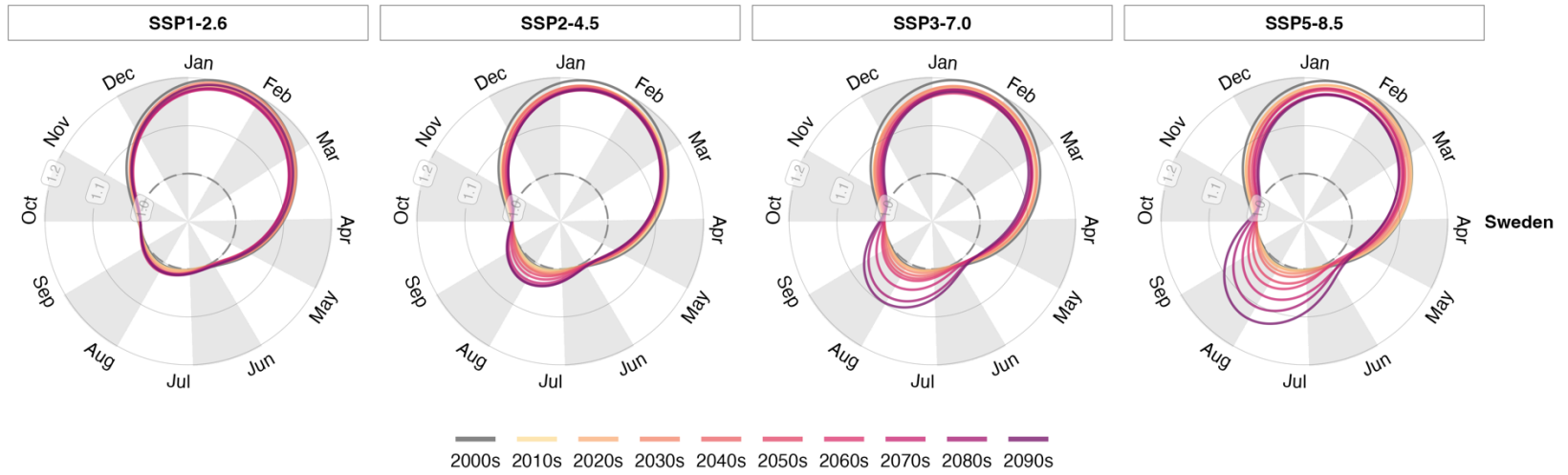
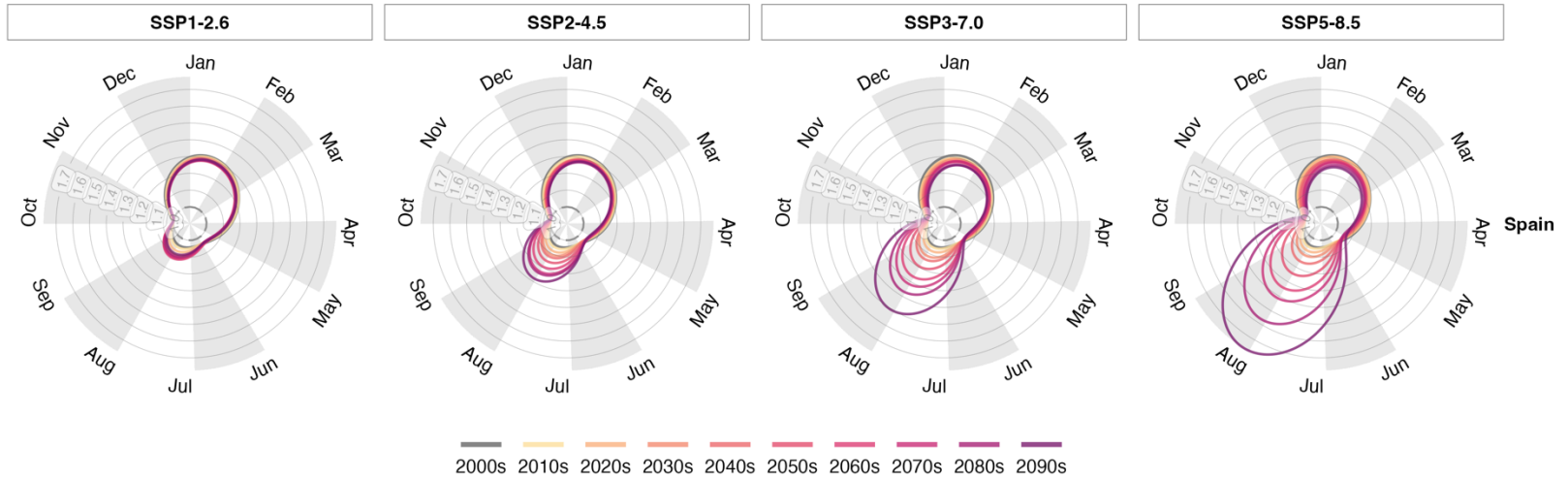


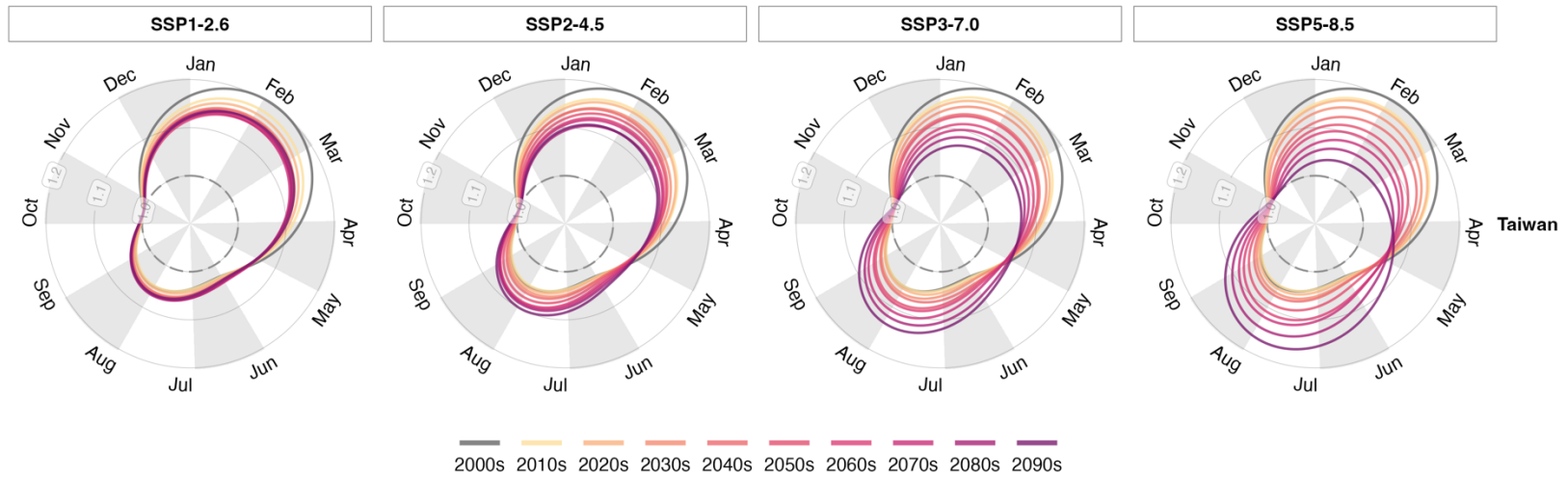
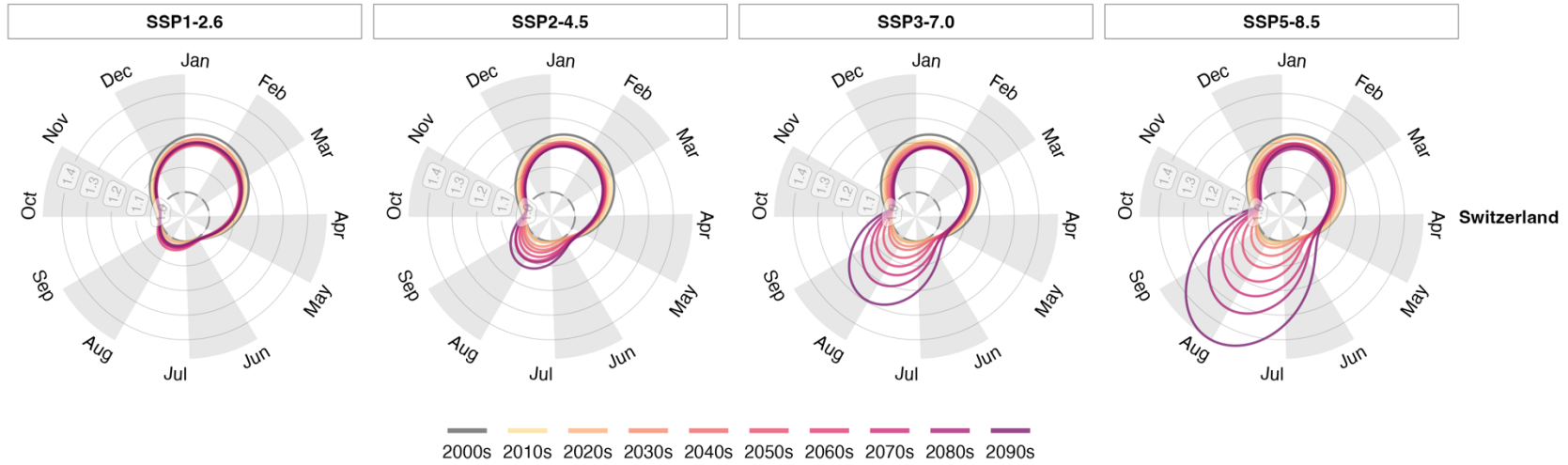


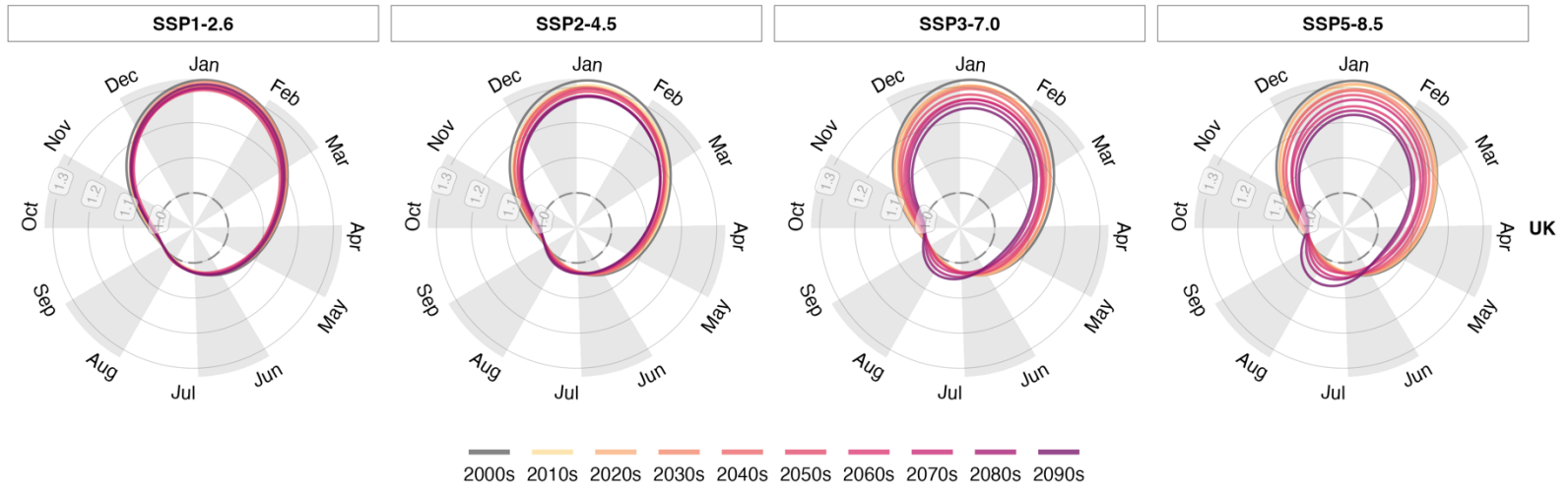
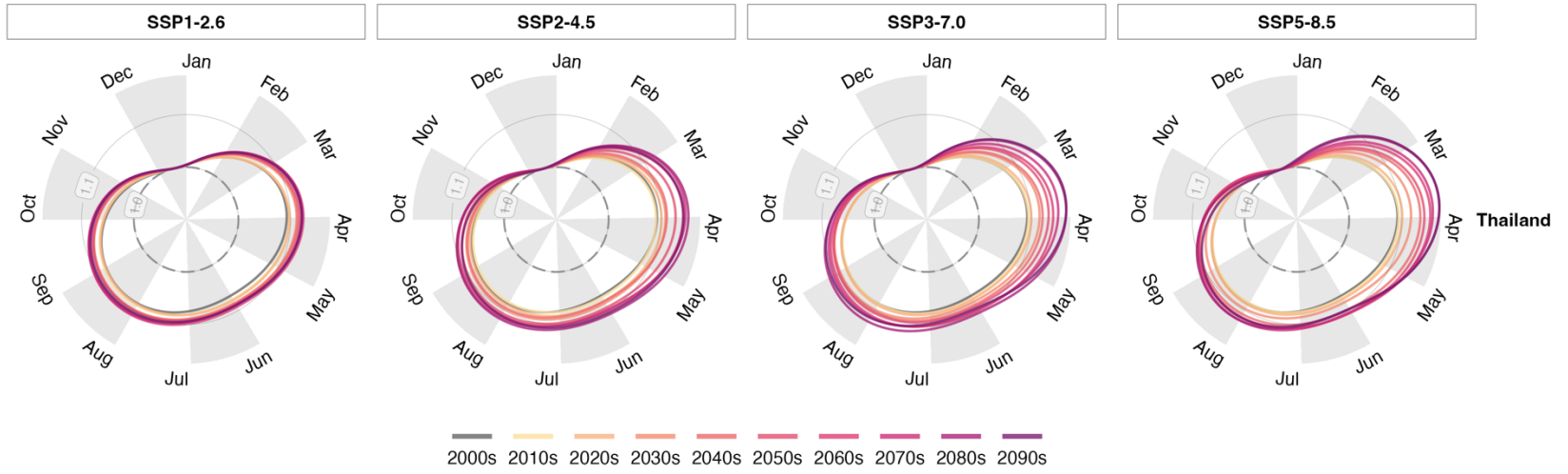


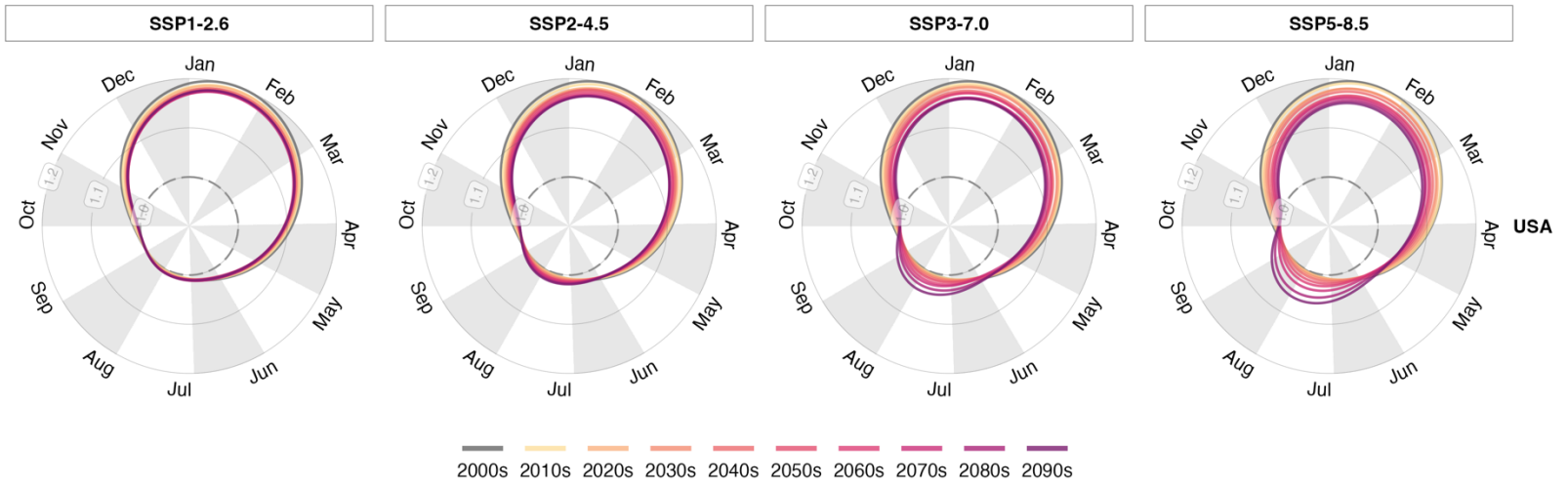
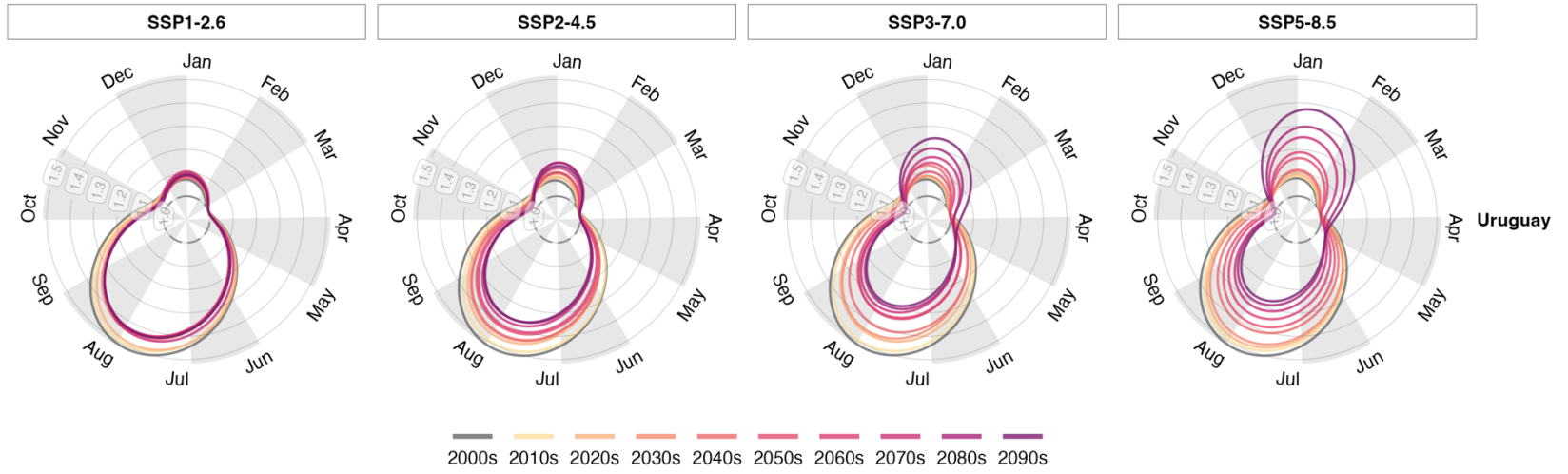


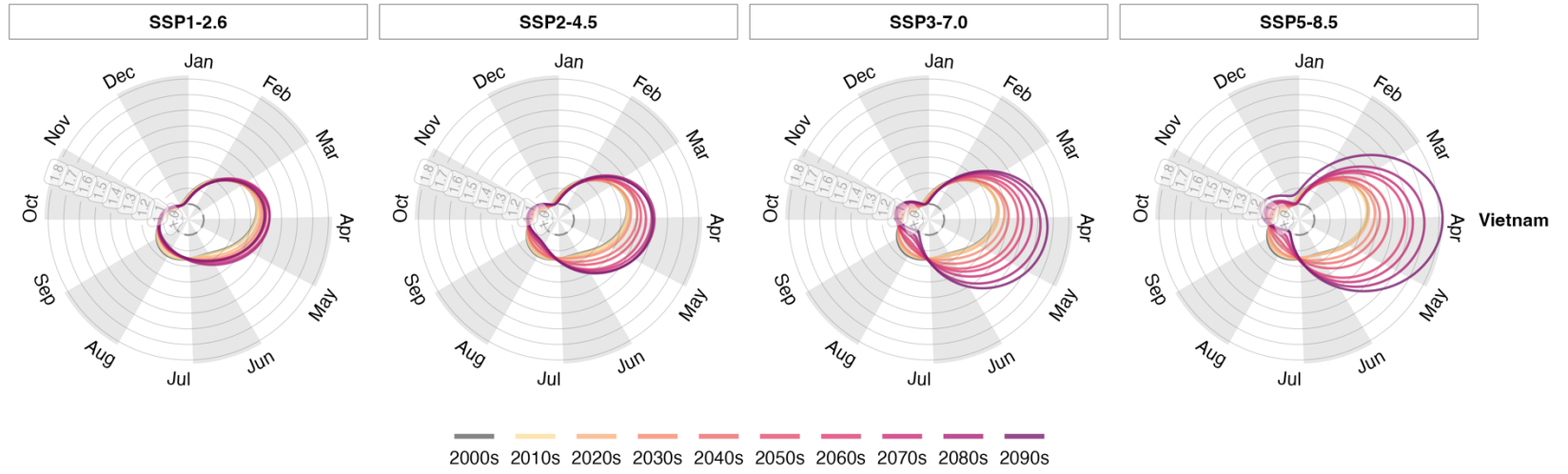












**Figure S2.** Temporal changes in the size of seasonality by country/area under four scenarios

The graph shows the difference in peak-to-trough ratio (PTR) and attributable fraction (AF) by decade compared with the 2000s in each country/area.

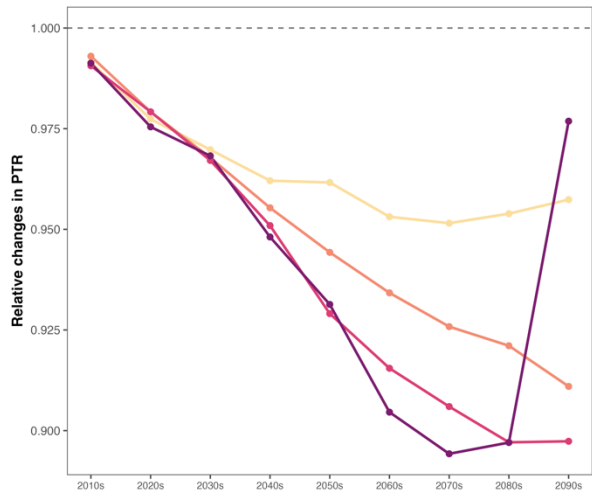
Change in PTR and AF is calculated as the ratio of PTR and the absolute difference in AF by decade compared with the 2000s, respectively.

The colour of the lines represents different scenarios.

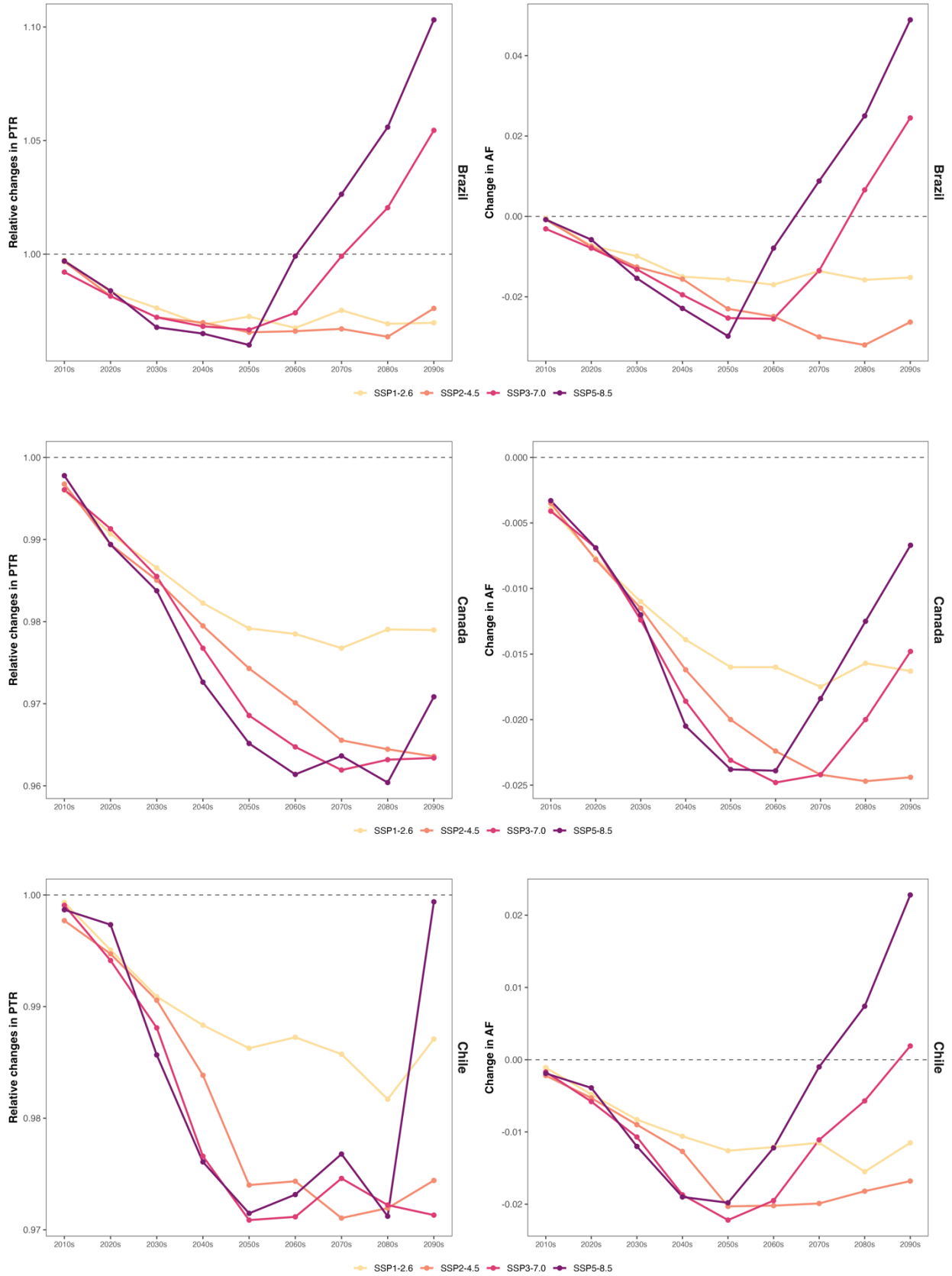
**Note:** The two polar locations in Peru were included when pooling the results for Peru.



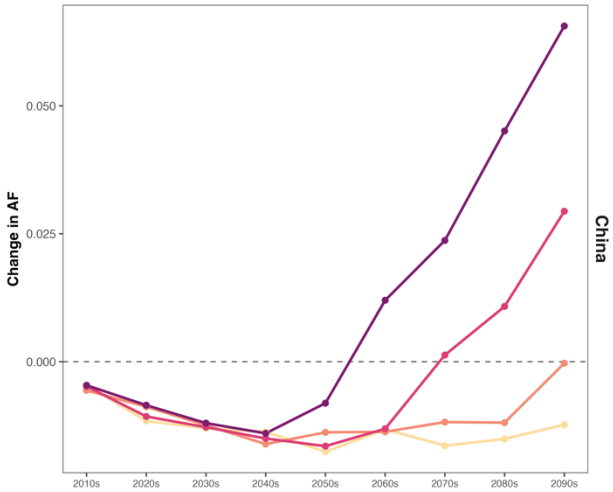
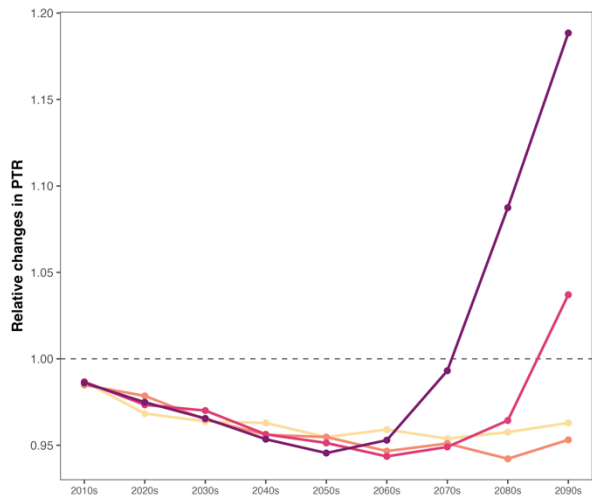
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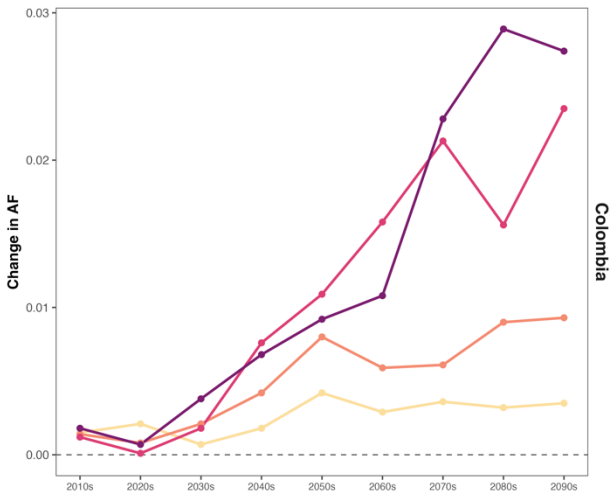
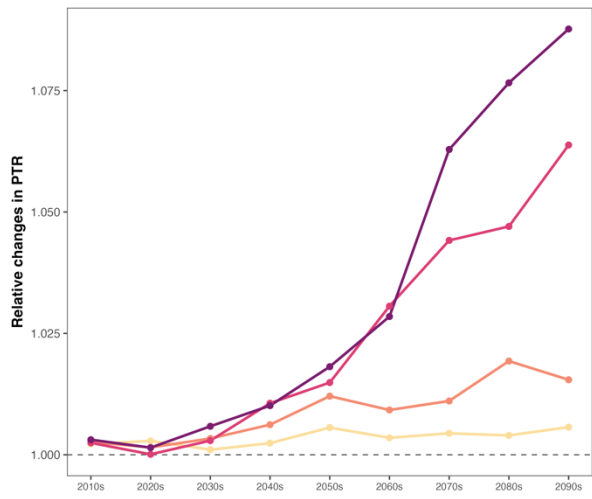
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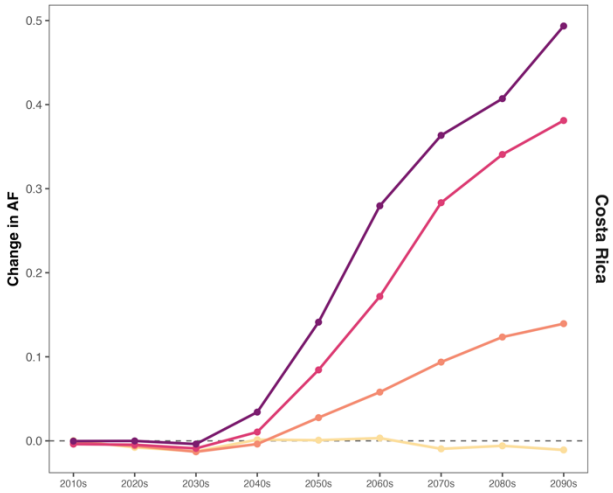
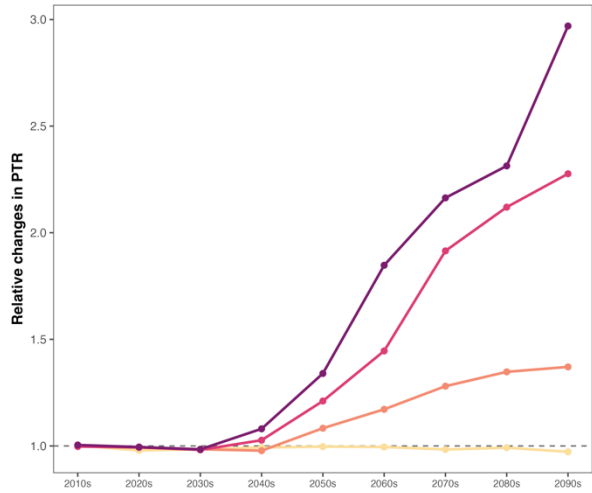




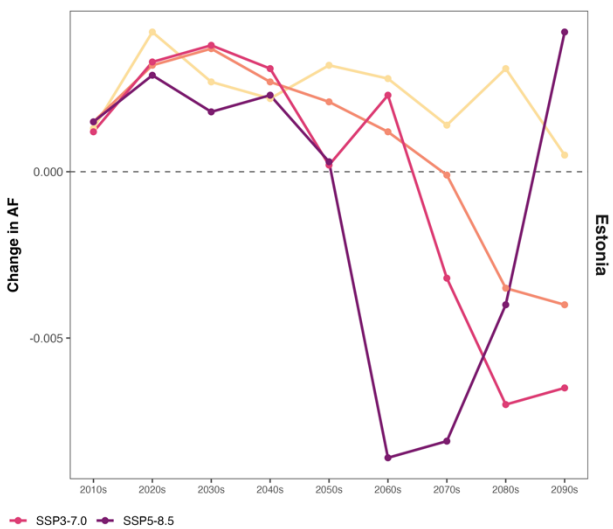
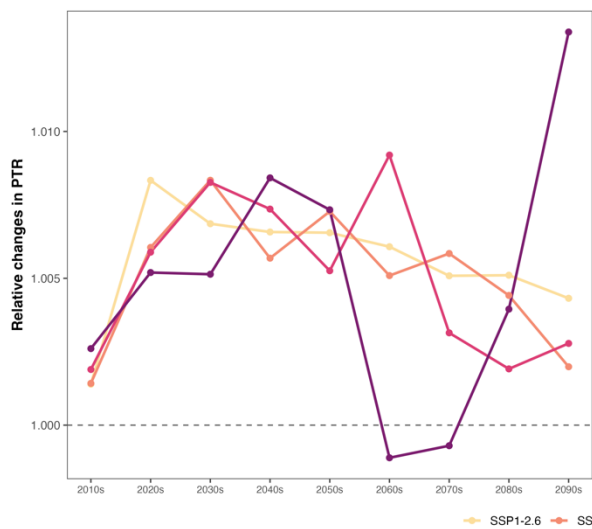
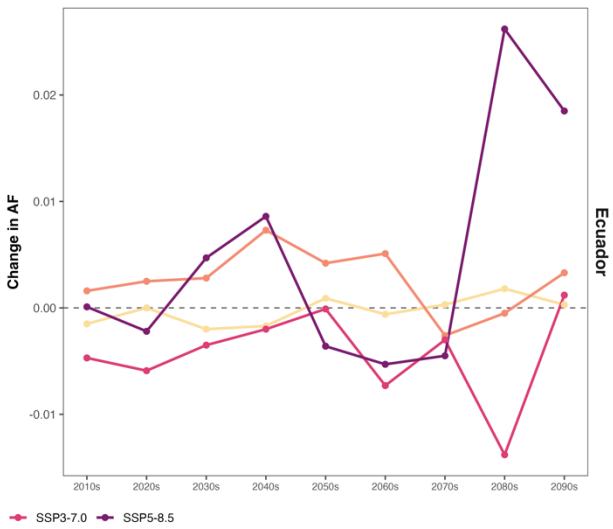
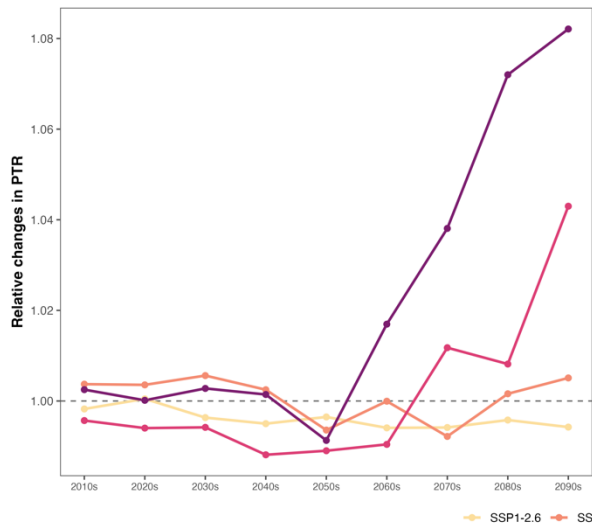
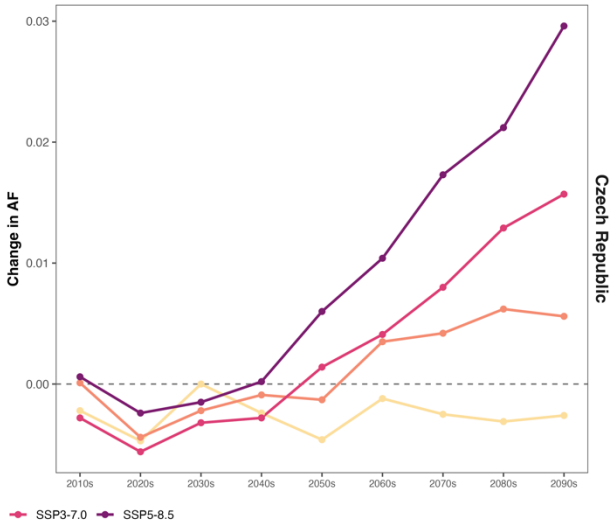
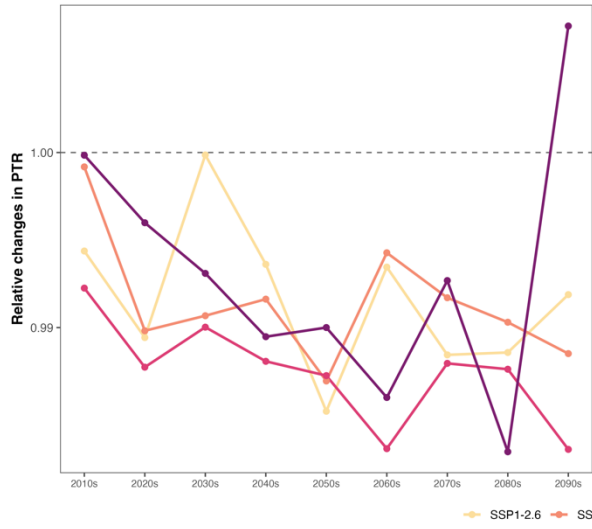
SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5

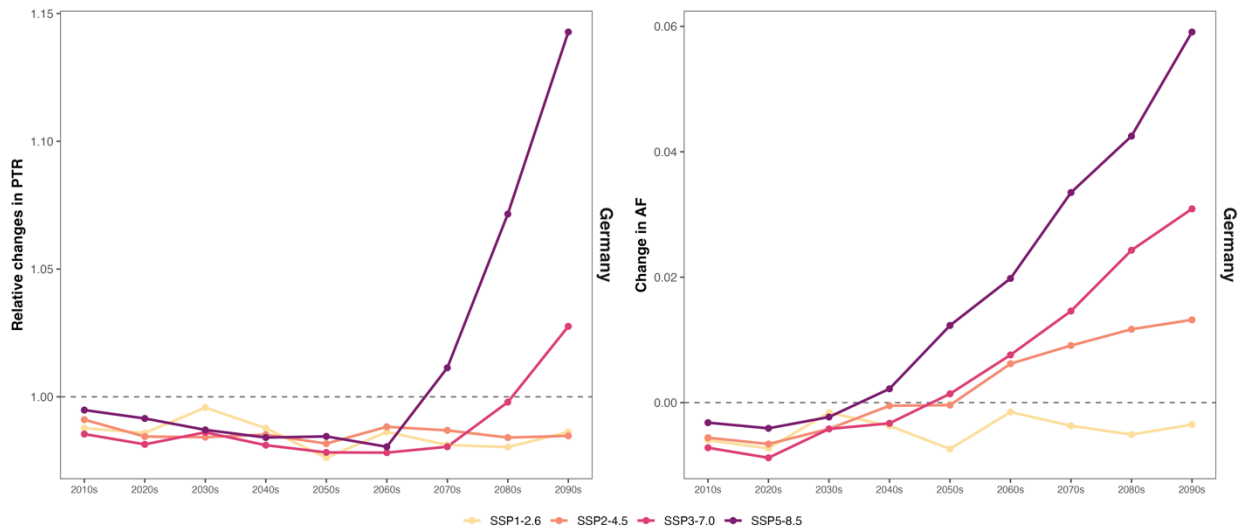
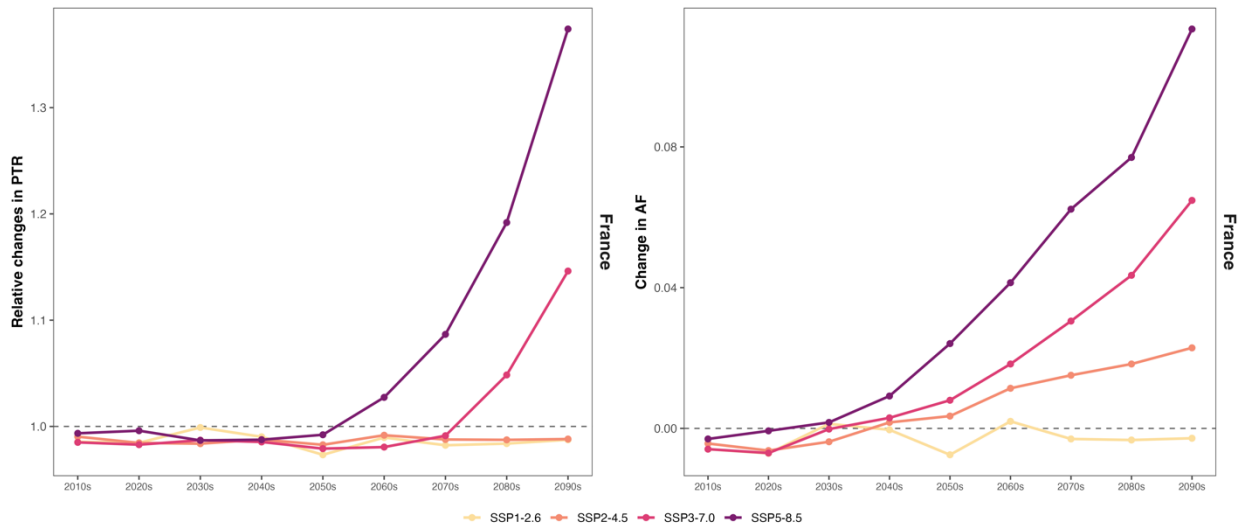
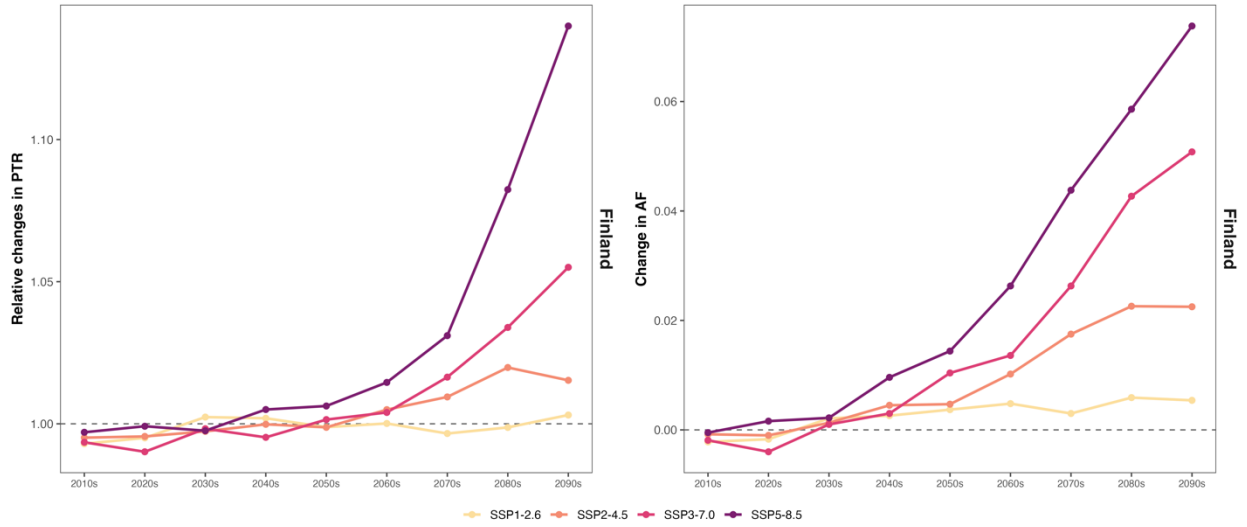


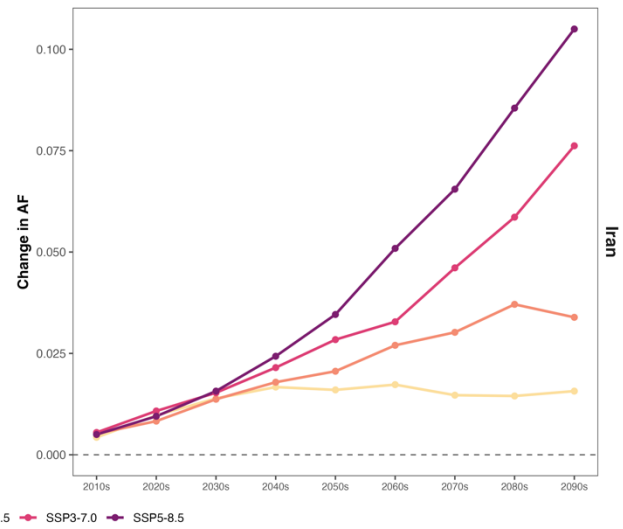
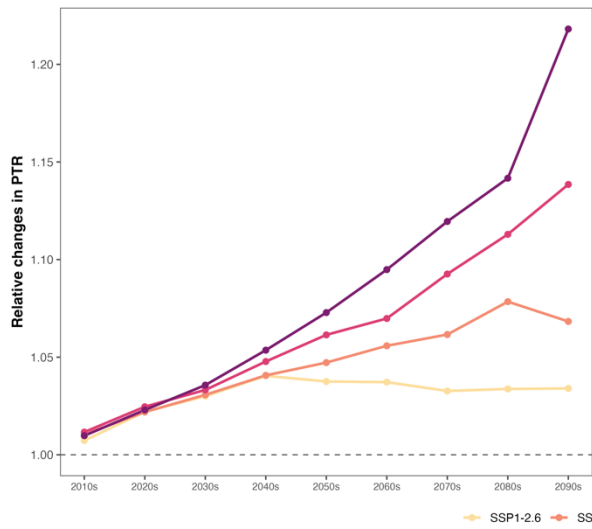
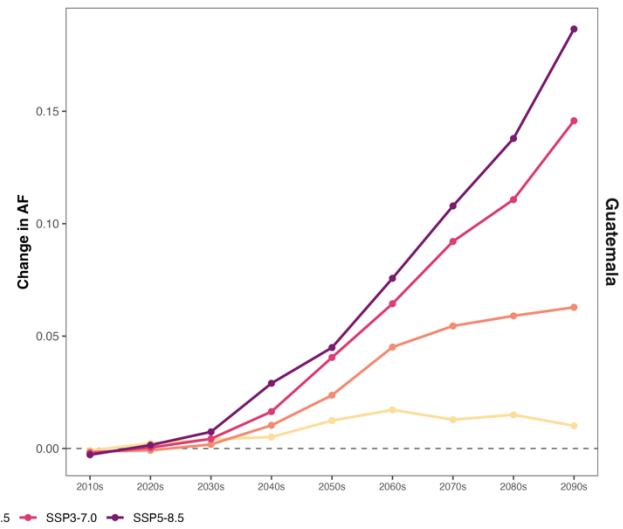
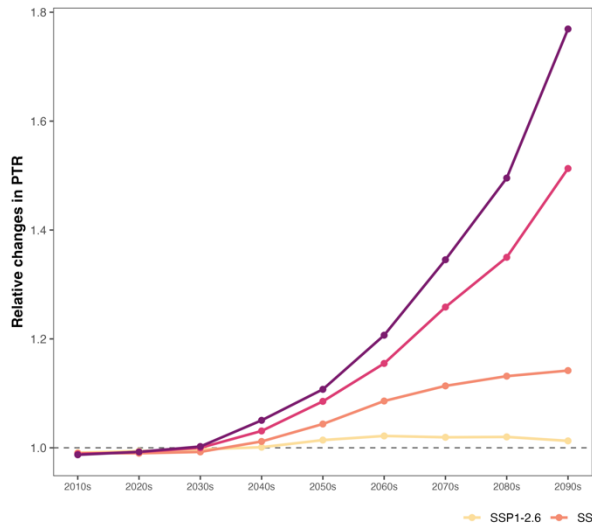
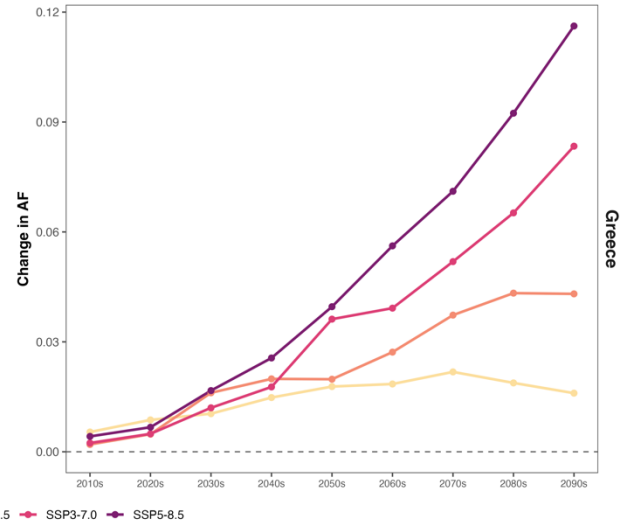
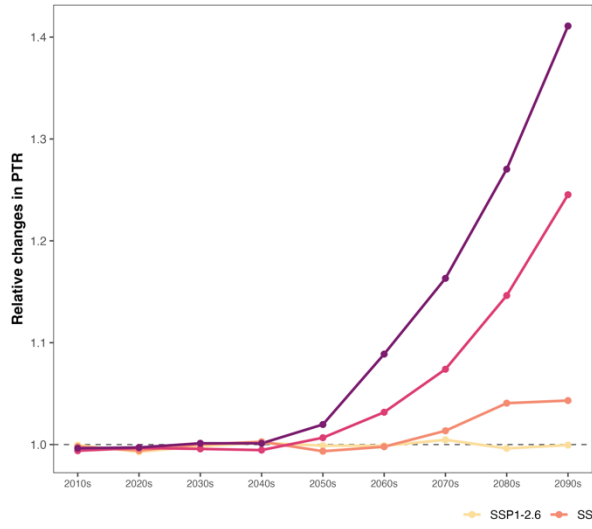
SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5

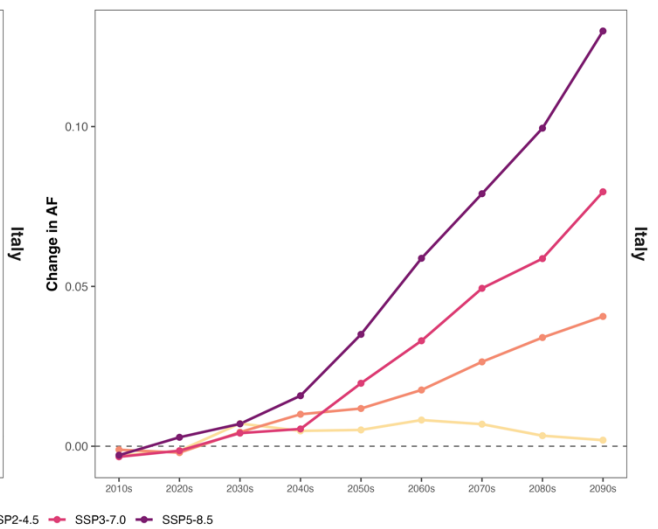
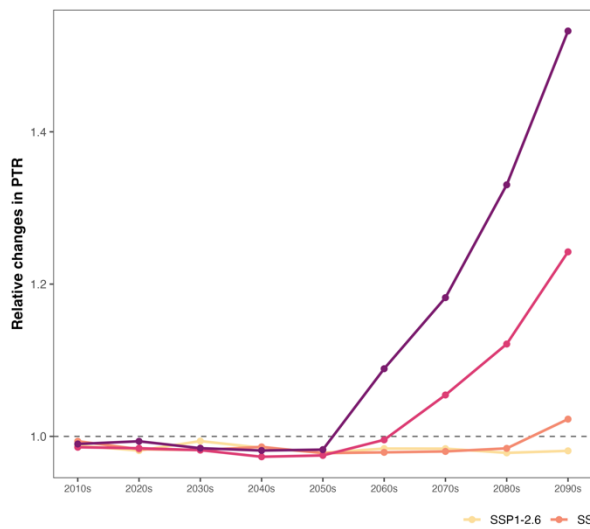
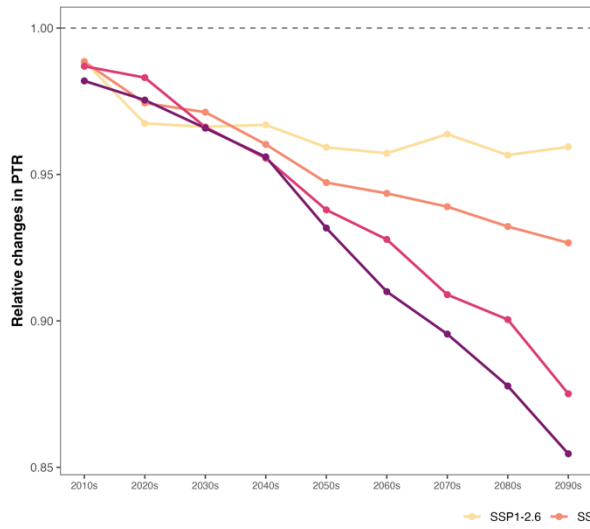
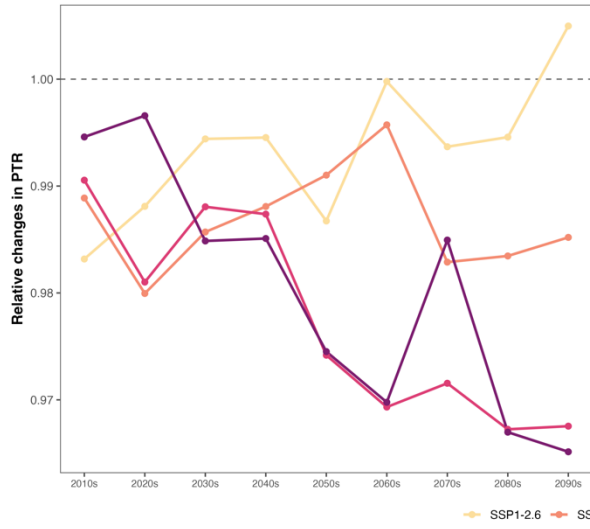


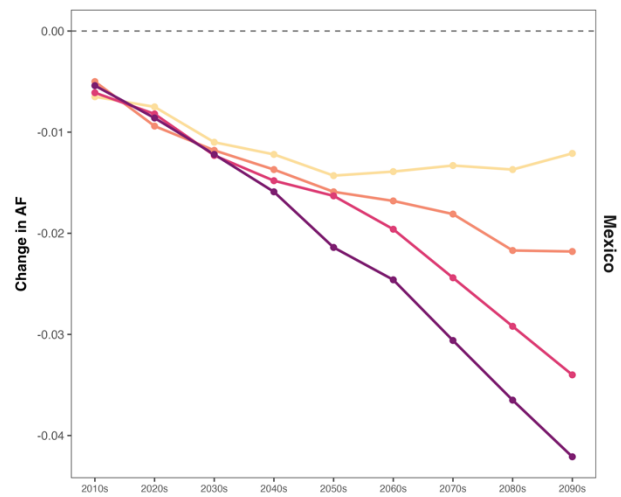
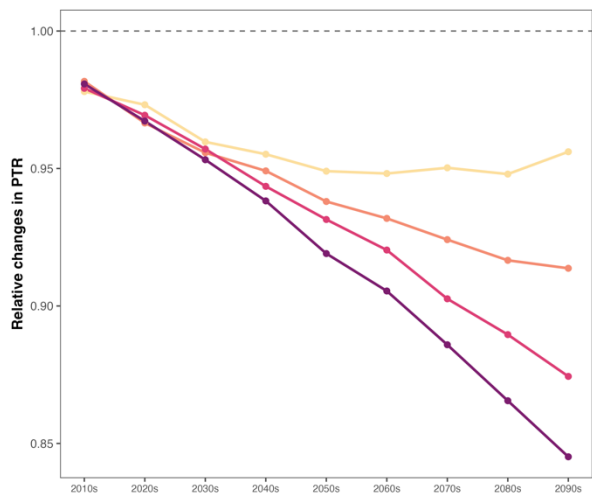
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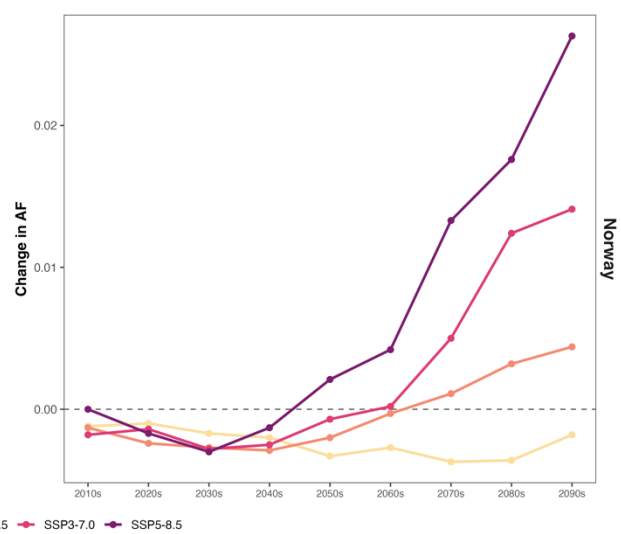
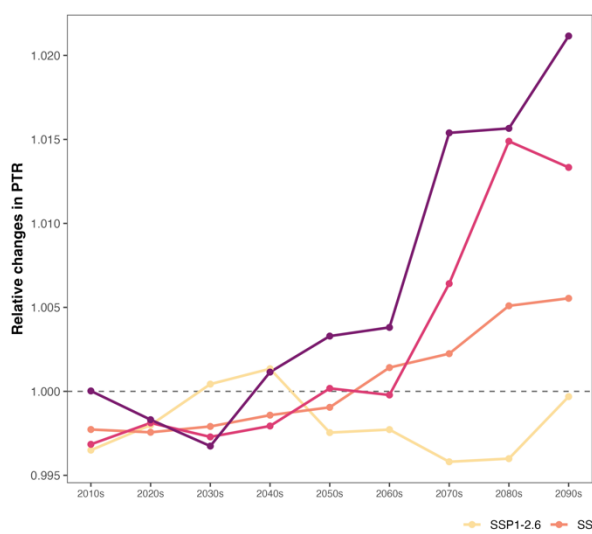
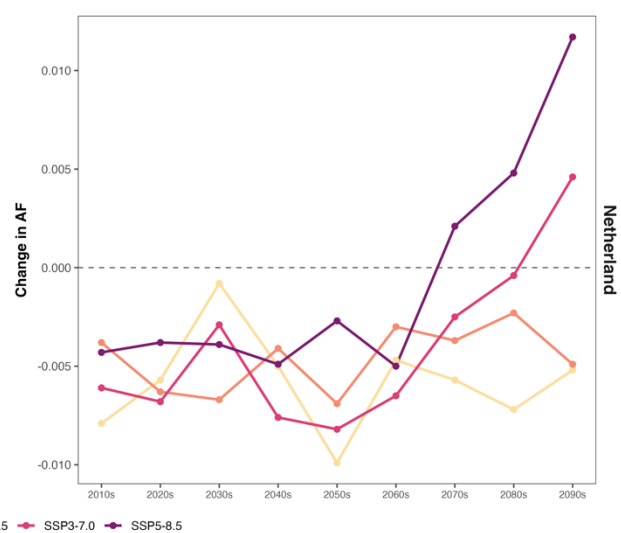
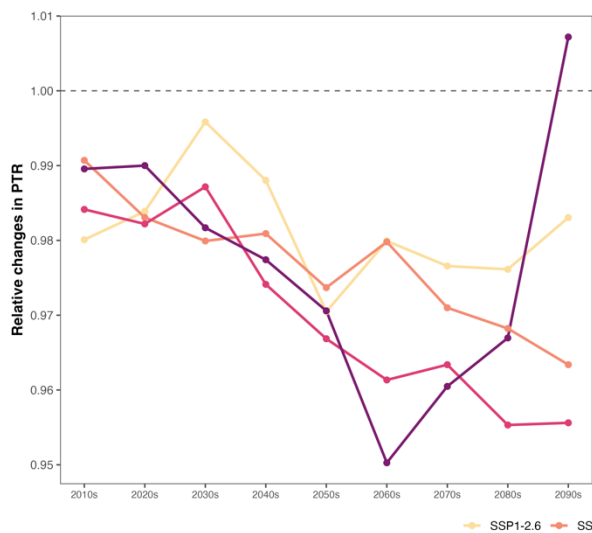
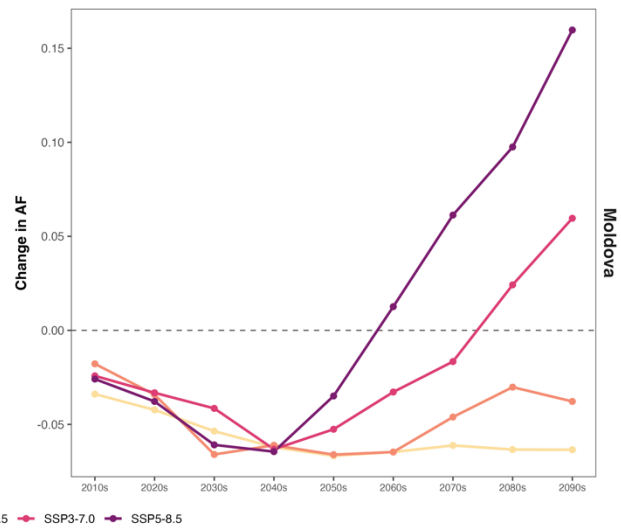
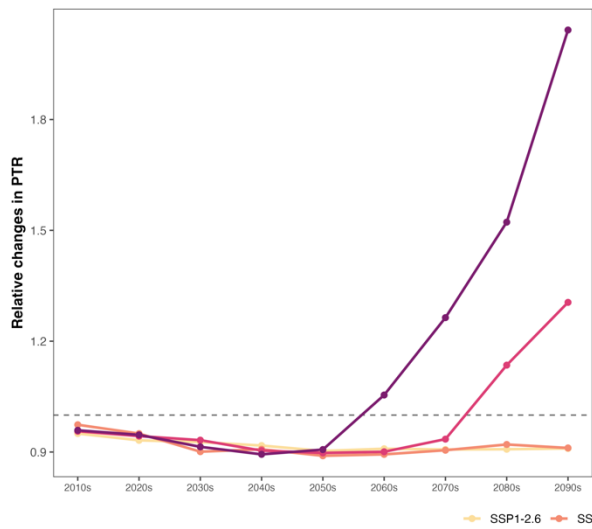


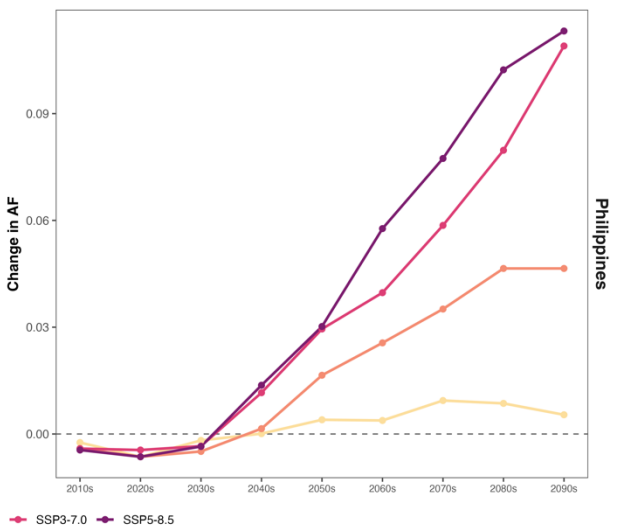
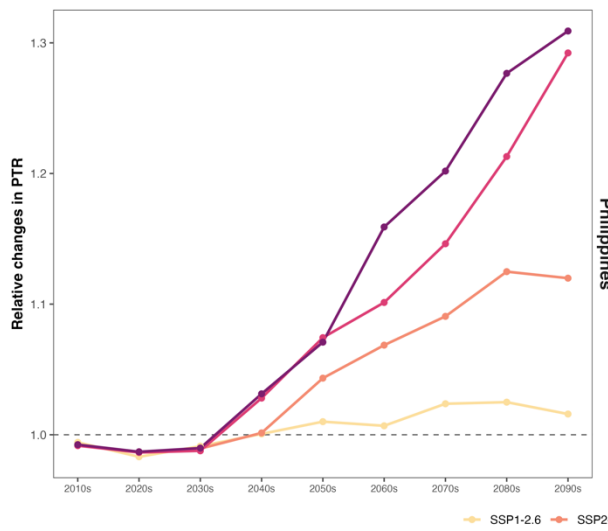
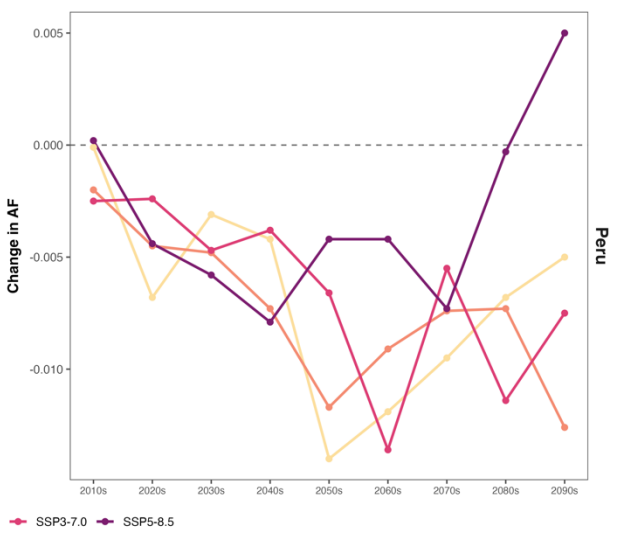
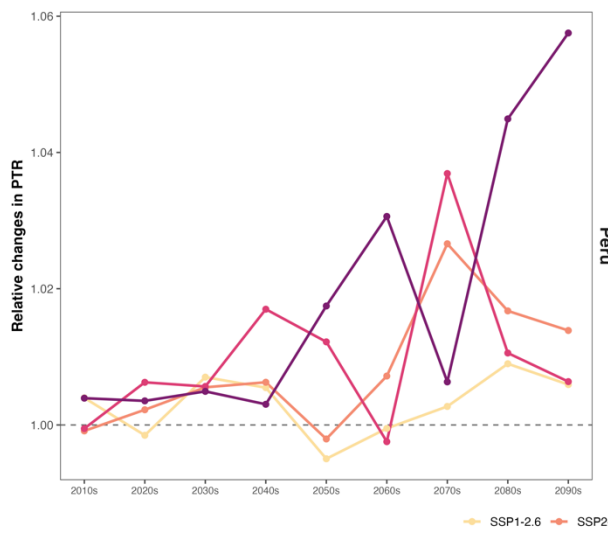
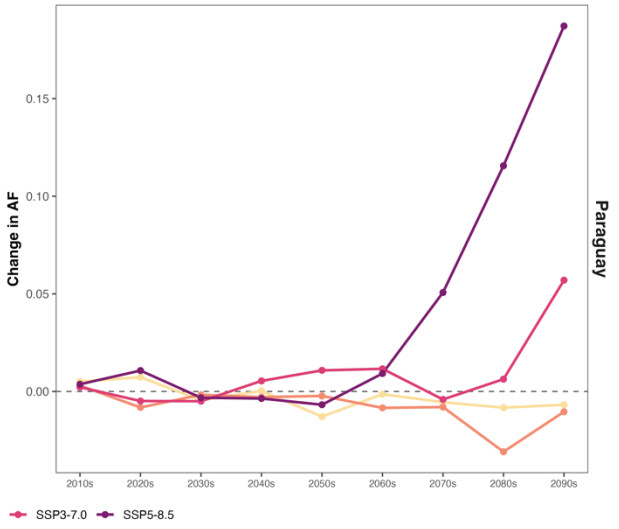
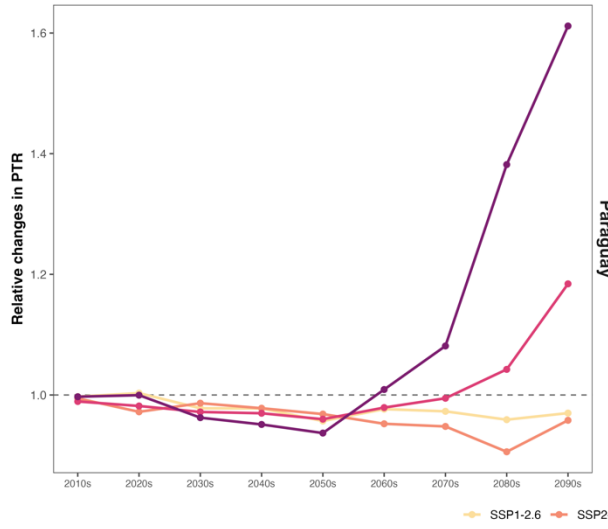




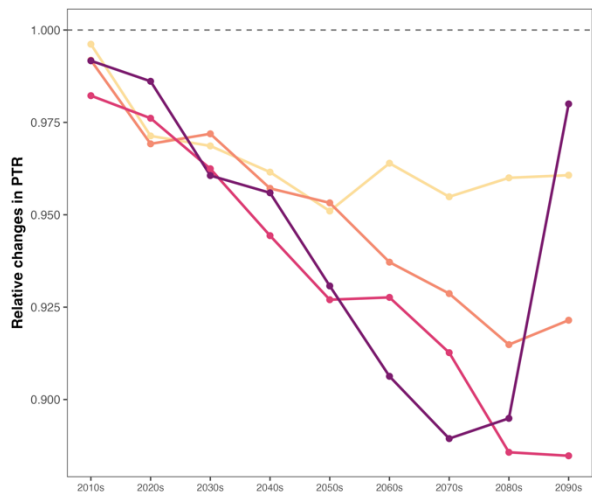




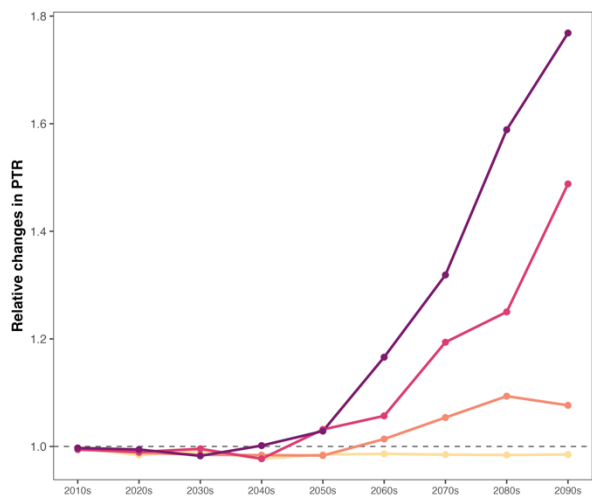




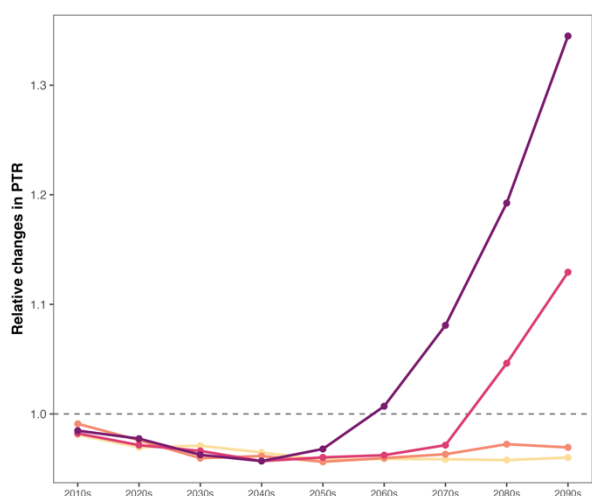
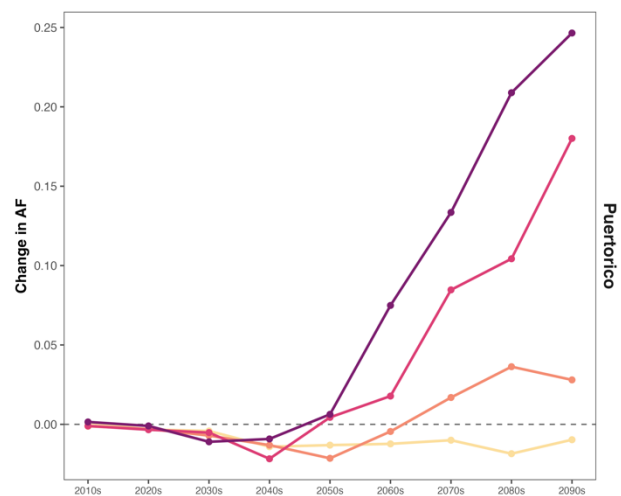




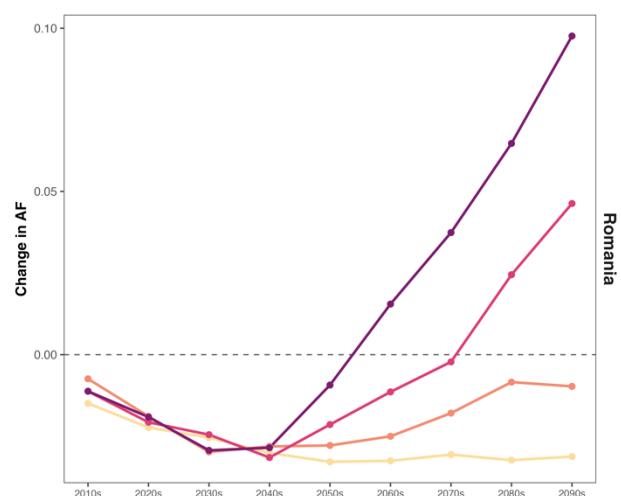
SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5

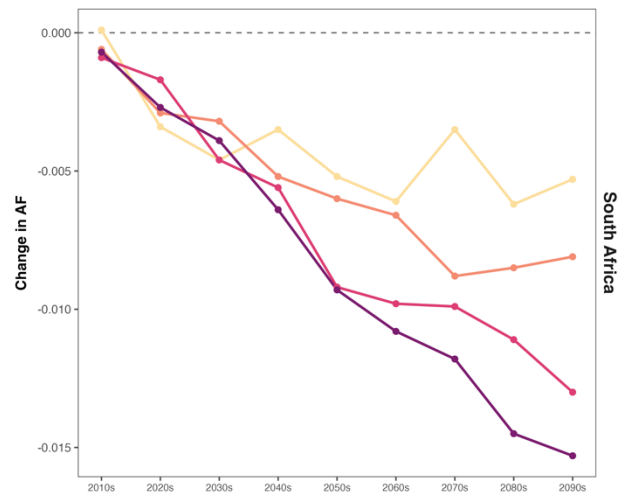


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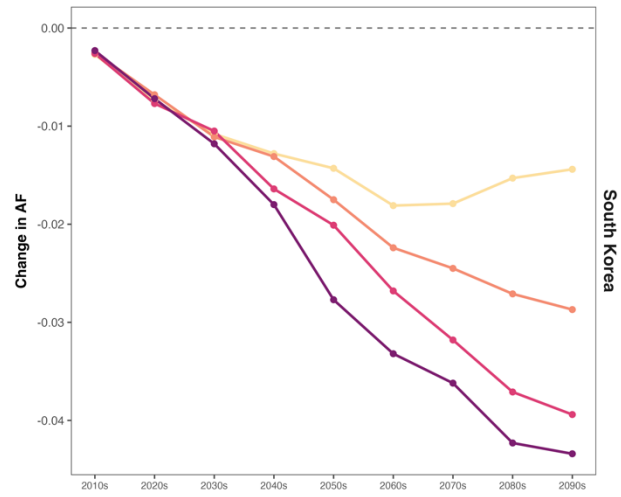
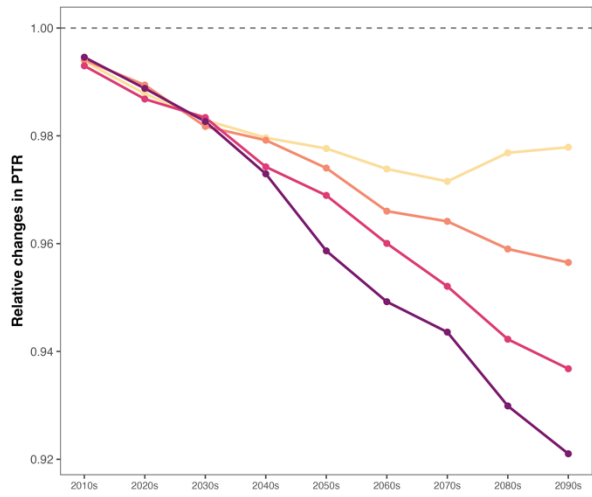


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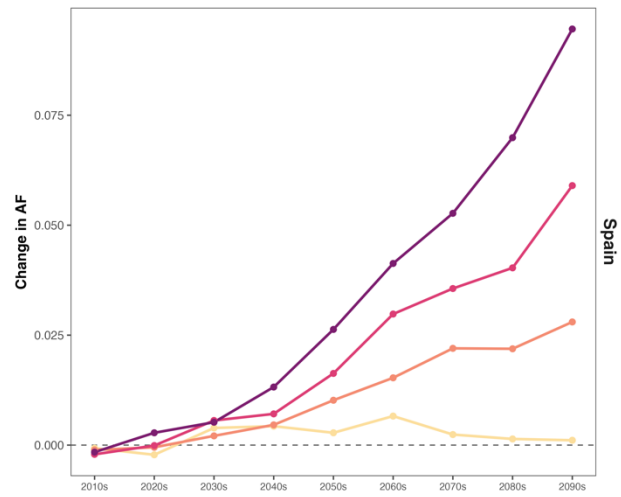
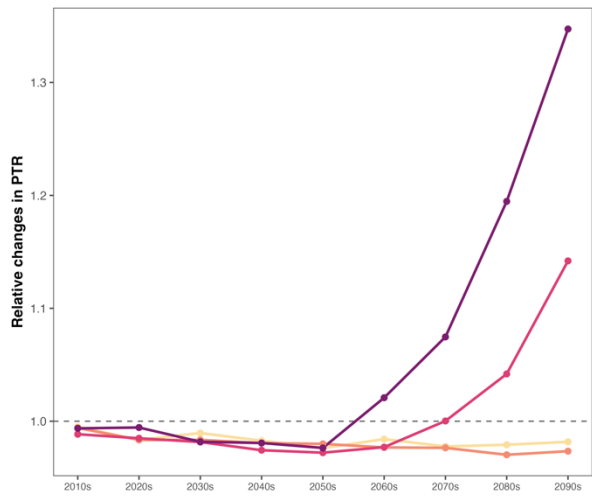




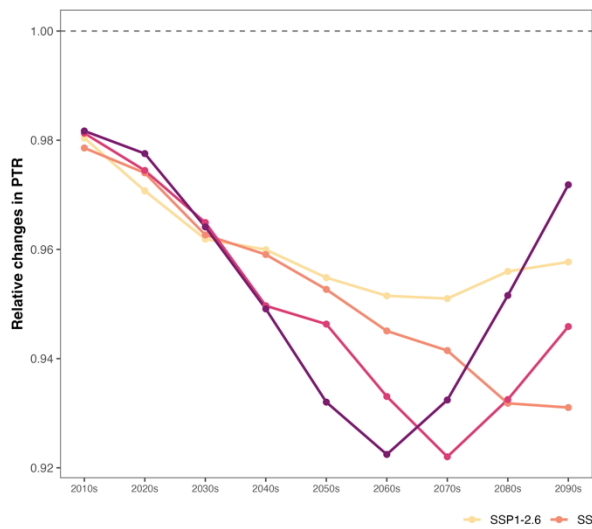
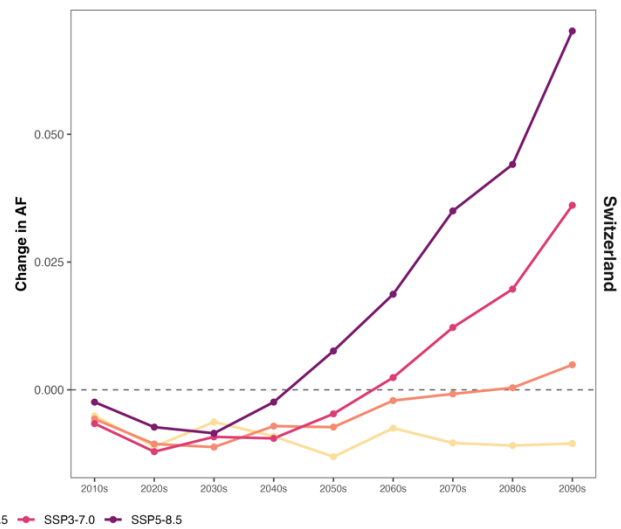
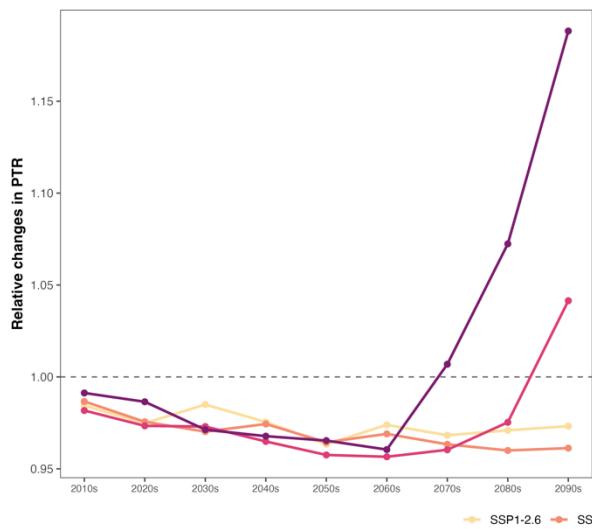
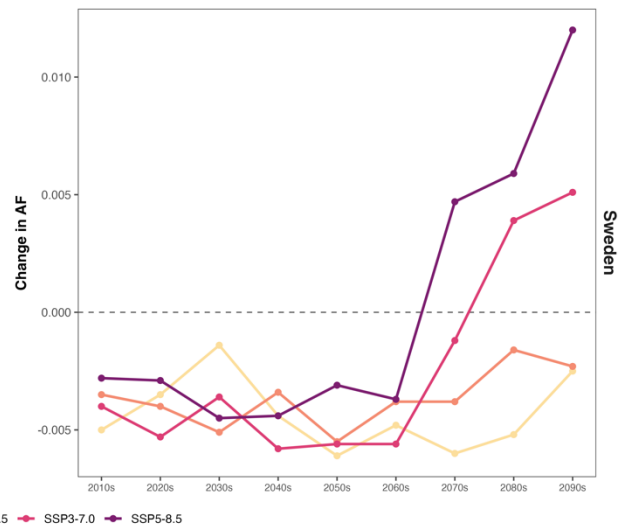
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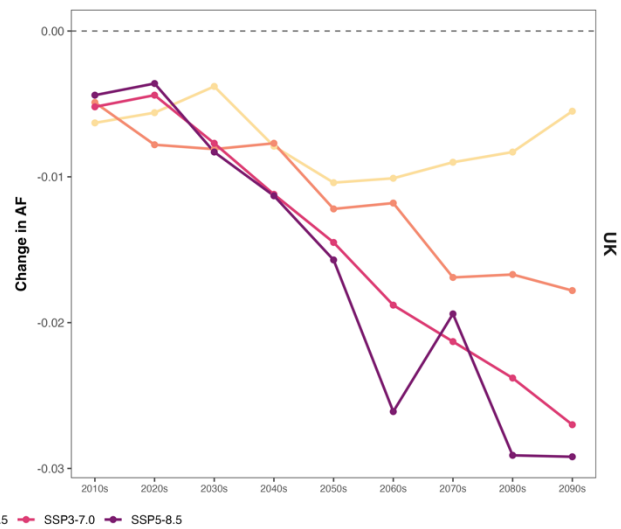
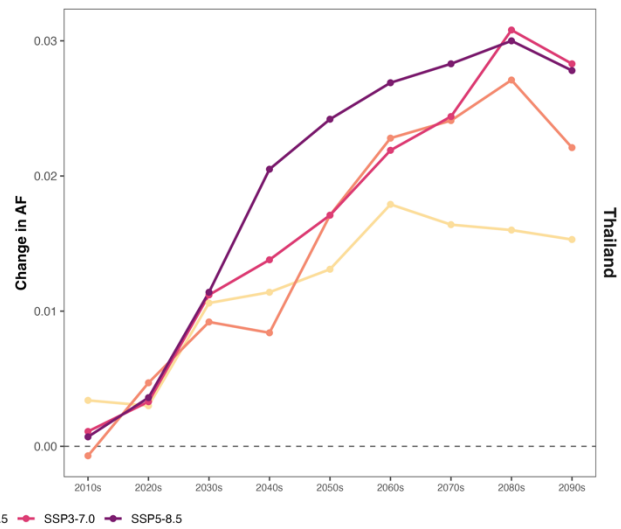
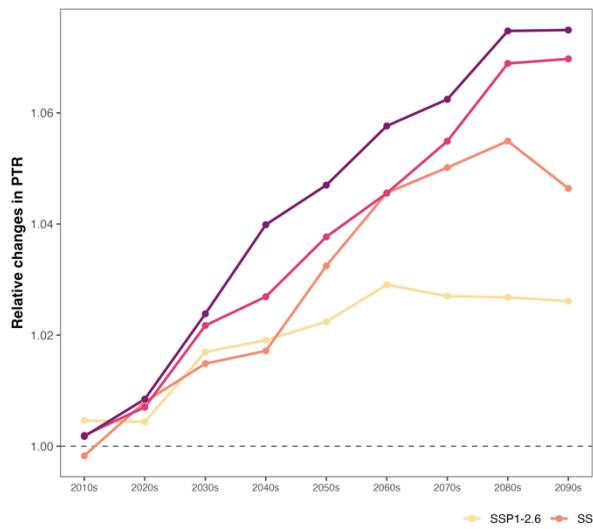


SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5



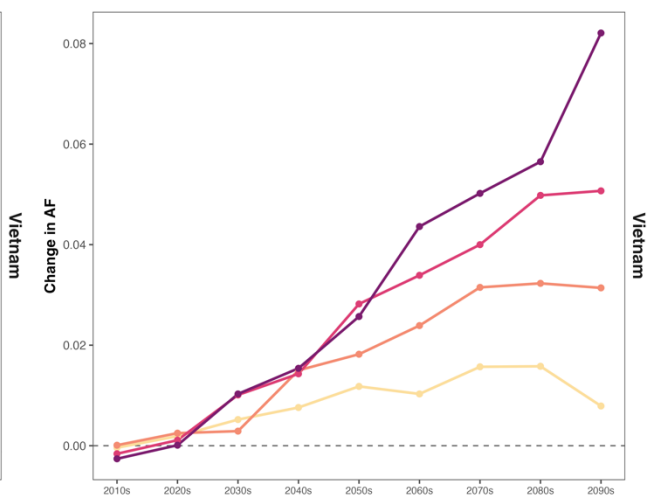
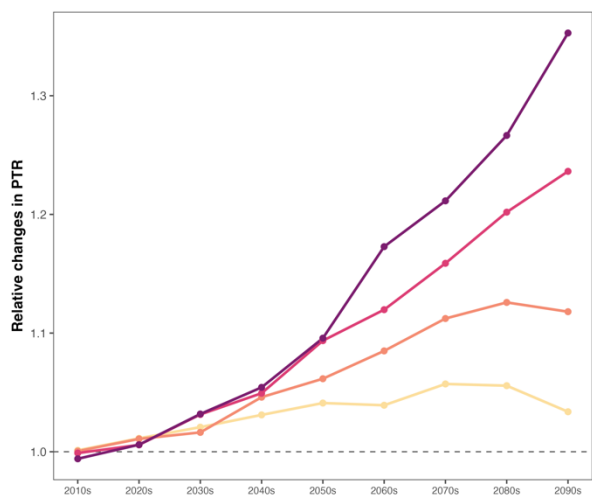
SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5







— SSP1-2.6 — SSP2-4.5 — SSP3-7.0 — SSP5-8.5



— SSP1-2.6 — SSP2-4.5 — SSP3-7.0 — SSP5-8.5