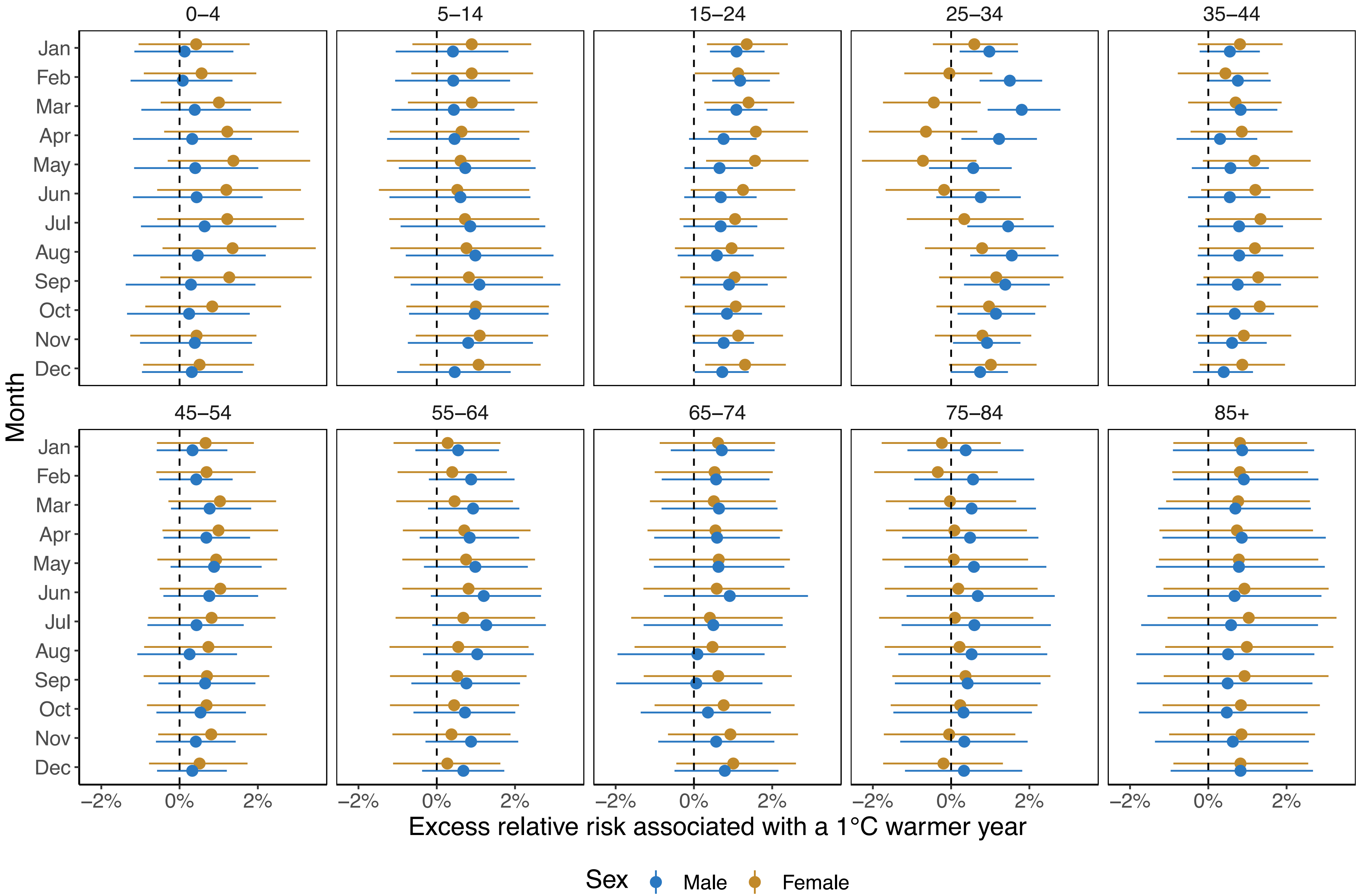

Figure 40. Excess relative risk in assault death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

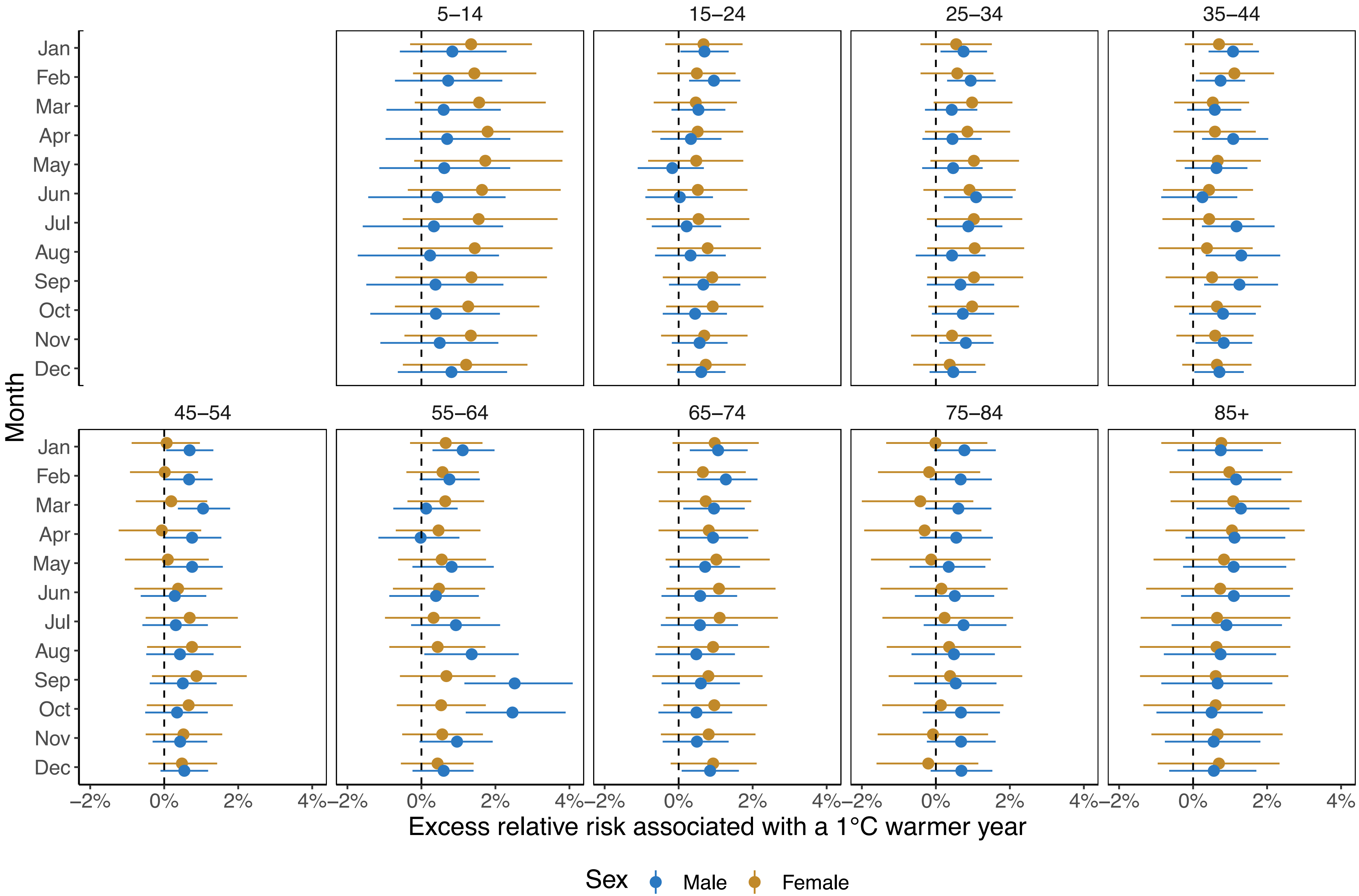

Figure 41. Excess relative risk in suicide death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

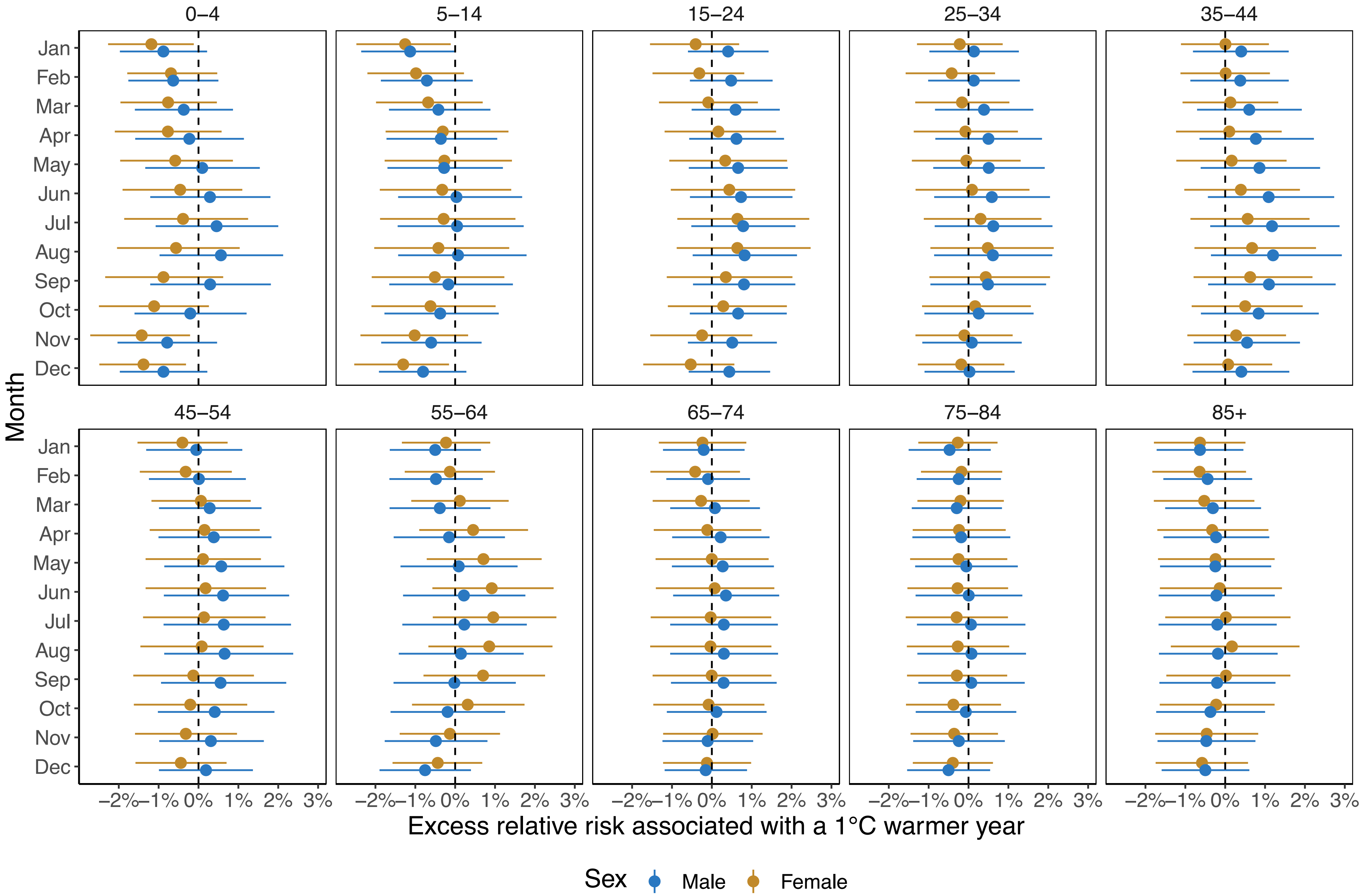

Figure 42. Excess relative risk in other unintentional injury death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

6.5.4 Percentage change of injury deaths

Proportionally, deaths from drownings are predicted to increase more than those of other injury types, by as much 8.3% (7.3%, 9.3%) in men aged 15-24 years (Figure 43); the smallest proportional increase was that of assault and suicide (less than 2% in all age and sex groups). There was a larger percent increase in transport deaths for males than for females, especially in young and middle-ages (e.g., 1.25% (0.90%, 1.60%) for 25-34 year old men versus 0.23% (0.28%, 0.76%) for women of the same age) (Figure 43).

I also found some variation in association between proportional change in deaths for all ages combined and anomalous temperature across months for drownings, with excess risk from drownings exhibiting a distinct peak in summer months (Figure 44). In contrast, I found less variation in proportional change in deaths in the other four types of injuries, with transport, assault and suicide positively associated to a similar degree across all months, with falls consistently negatively associated apart from for females in late summer months (Figure 44).

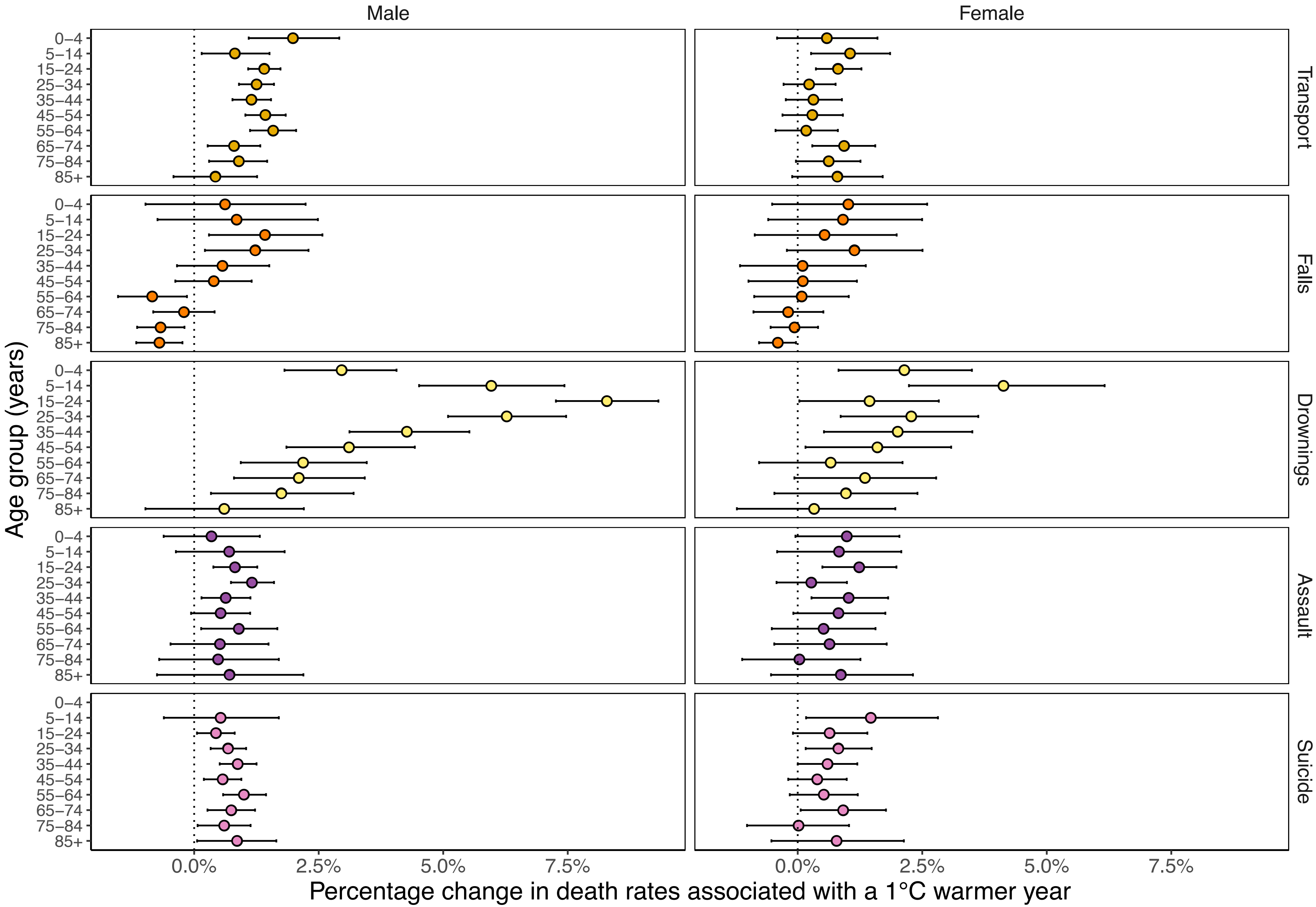

Figure 43. Percent change in death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by type of injury, sex and age group summarised across months.

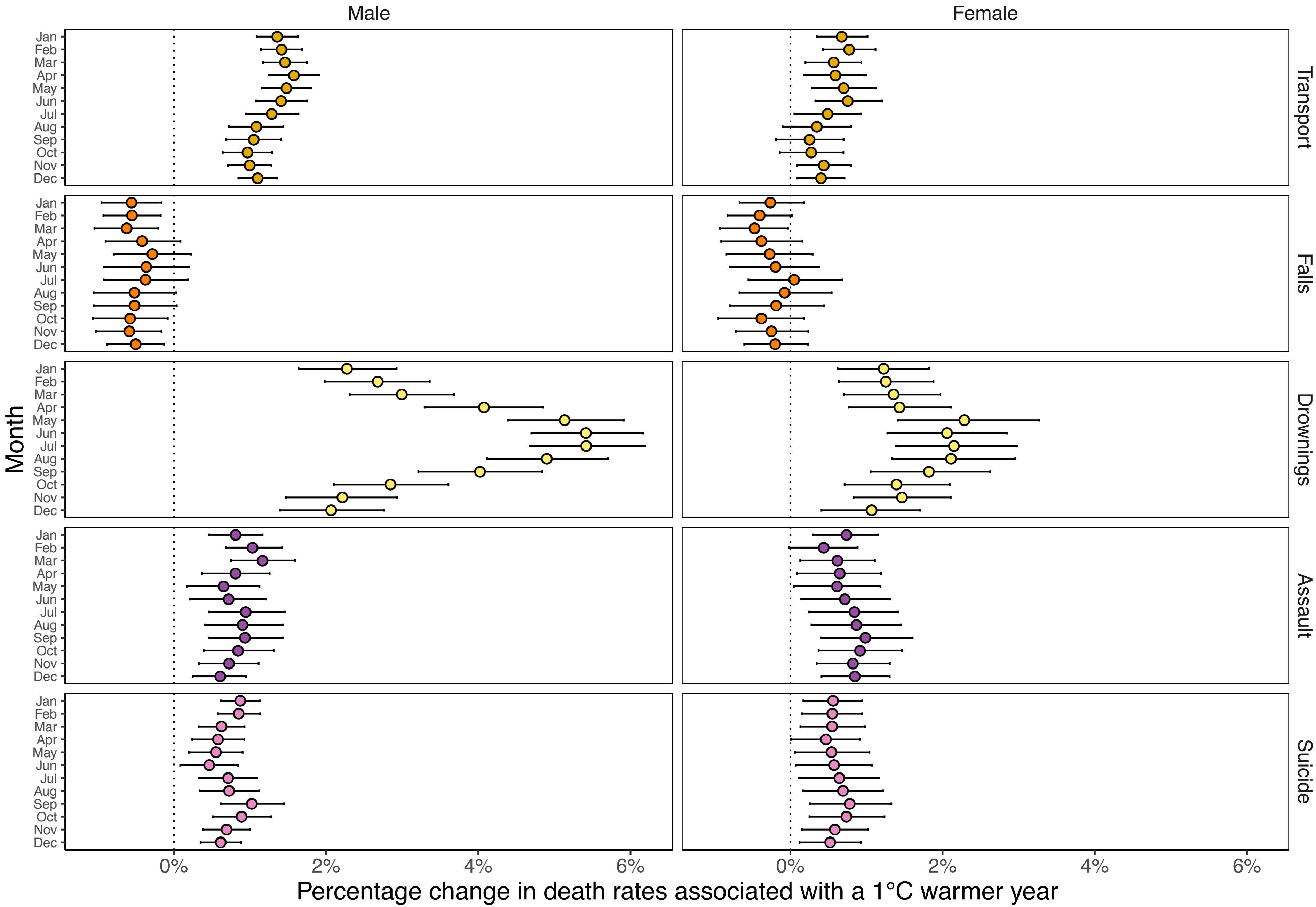

Figure 44. Percent change in death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by type of injury, sex and month summarised across ages.

6.5.5 Change in injury deaths

I estimated that there would be 941 (831, 1,053) excess injury deaths, equivalent to 0.5% of all injury deaths in 2016, in a year in which each month in each state were +1°C above its long-term norm (Figure 45). Deaths from drowning, transport, assault and suicide would be predicted to increase, partly offset by a decline in deaths from falls in middle and older ages and in winter months (Figure 45). Most excess deaths would be from transport injuries (448) followed by suicide (315). 87% of the excess deaths would occur in males and 13% in females. 80% of all male excess deaths would occur in those aged 15-64 years, who have higher rates of deaths from transport injuries. In those aged 85 years and older, there would be an estimated decline in injury deaths, because deaths from falls are expected to decline in a warmer year.

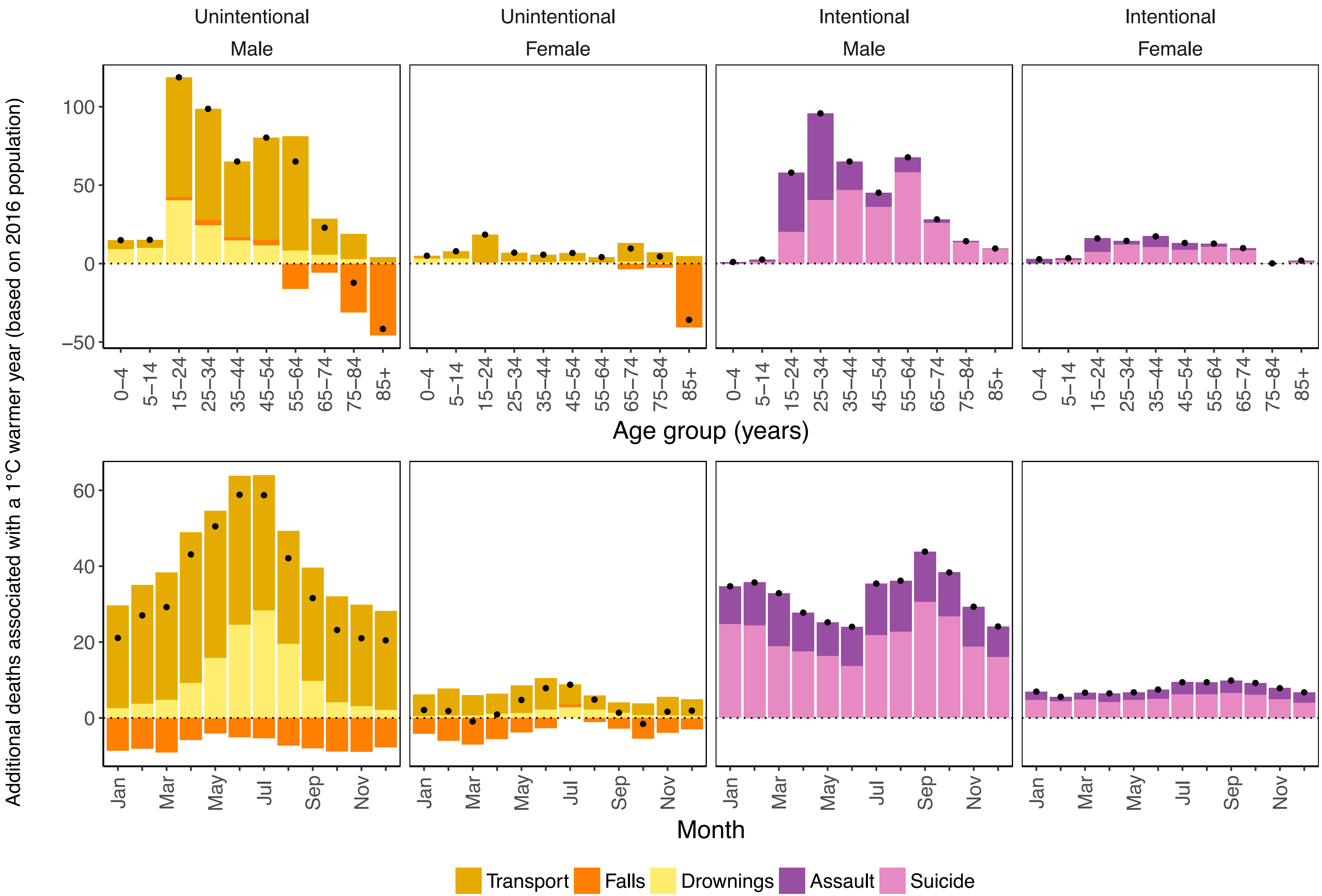

Figure 45. Additional annual injury deaths for the 2016 US population in year in which each month was +1°C warmer compared with 1980-2009 norm temperatures. The top row shows breakdown by type of injury, sex and age group. The bottom row shows the break down by type of injury, sex and month. Black dots represent net changes in deaths for each set of bars.

6.6 Discussion

While there are no previous studies of how temperature deviations from long-term norm in each month are associated with injury mortality, my results are broadly in agreement with those that have analysed associations with absolute temperature and for specific injury types. A study of suicide in US counties over 37 years (1968-2004) estimated that 1°C higher monthly temperature would lead to a 0.7% rise in suicides,[108] compared to my findings of 0.44-1% in males and 0.39-1.47% in females in different ages. In a study of six French heatwaves during 1971-2003, mortality from unintentional injuries rose by up to 4% during a heatwave period compared to a non-heatwave baseline.[133] A study of daily mortality from all injuries in Estonia found a 1.24% increase in mortality when daily maximum temperature went from the 75th to 99th percentile of long-term distribution.[132]

That anomalously warm temperature influences deaths from drowning, although not previously quantified, is highly plausible because swimming is likely to be more common when monthly temperature is higher. The higher relative and absolute impacts on men compared with women may reflect differences in behaviour. For example, over half of swimming deaths for males occur in natural water, compared to about quarter for females (1999-2010),[251] which may lead to a larger rise in the former in warmer weather. Similarly, the decline in deaths from falls, which are mostly in older ages, may be because falls in older people are more likely to be due to slipping on ice than in younger ages.[252–254]

The pathways from anomalous temperature to transport injury are more varied. Firstly, driving performance deteriorates at higher temperatures.[255–258] Further, alcohol consumption increases during warm temperature anomalies,[259] potentially also explaining why teenagers, who are more likely than other age groups to crash while intoxicated,[260] experience a larger proportional rise in deaths from transport than older ages when temperatures are anomalously warm. Lastly, warmer temperatures generally increase road traffic in North America;[261–264] With more people generally outdoors in warmer weather,[265] this could lead to more fatal collisions.

Pathways linking anomalously high temperatures and deaths from assault and suicide are less established. One hypothesis is that, similar to transport, more time spent outdoors in anomalously warm temperatures leads to an increased number of face-to-face interactions, and hence arguments, confrontations, and ultimately assaults.[266,267] These effects could be compounded by the greater anger levels linked to higher temperatures.[268,269] Regarding suicide, higher temperature has been hypothesised as associated with higher levels of distress in younger people.[270] Nonetheless, links between temperature and mental health requires further investigation,[271] including whether the relationship varies by sex and age group, as indicated by my results.

The major strength of my study is that I have comprehensively modelled the association of temperature anomaly with injury by type of injury, month, sex and age group. My measure of temperature anomaly internalises long-term historical experience of each state, and is closer to what climate change may bring about than solely examining daily episodes, or average temperature to which people have adapted. To utilise this metric, I integrated two large disparate national datasets on mortality (United States VR data) and meteorology (ERA-Interim), described in Chapter 3, and developed a bespoke Bayesian spatio-temporal model, described in Chapter 5. A limitation of my study is that, like all observation studies, I cannot rule out confounding of results due to other factors, although it is unlikely that such factors will have the same anomalies as temperature, even if their average space and time patterns are the same.

My work highlights how deaths from injuries are not only currently susceptible to temperature anomalies but could also be modified by rising temperatures resulting from climate change, unless countered by social and health system interventions that mitigate these impacts. Though absolute impacts on mortality are modest, some groups, especially men in young to middle-ages, will experience larger impacts. Therefore, a combination of public health interventions that broadly target injuries in these groups – for example targeted messaging for younger males on the risks of transport injury and drowning – and those that trigger in relation to forecasted high temperature periods – for example more targeted blood alcohol level checks – should be a public health priority.

6.7 Summary

Using the mortality and temperature datasets I developed in Chapter 3 and the Bayesian spatio-temporal model I described in Chapter 5, I estimated how anomalous temperatures affect injury deaths in the United States. I calculated that a 1°C anomalously warm year would result in a net increase in injury deaths. The large majority of these additional injury deaths would occur in males of adolescent to middle ages. Four of the five injury groups (transport, drownings, assault and suicide) contribute to the increase in injury deaths under anomalously warm temperatures, with a decline in deaths from falls in older ages.

7 Anomalous temperature and seasonality of cardiorespiratory disease and cancer mortality

7.1 Overview

I applied the Bayesian spatio-temporal model, as described in Chapter 5, to cardiorespiratory disease and cancer mortality data in the United States, as described in Chapter 3. I estimated how anomalous temperatures, defined in Chapter 3, affect deaths from different cardiovascular diseases (ischaemic heart disease (IHD), cerebrovascular disease, other cardiovascular diseases), respiratory diseases (chronic obstructive pulmonary disease (COPD), respiratory infections, other respiratory diseases) and cancers. A total of 61 million deaths from cardiorespiratory disease and cancer deaths in the United States from 1980-2016 were used in this analysis.

In this chapter, I present results of how a 1°C anomalously warm year would change the total number of cardiorespiratory disease and cancer deaths in the United States, by sex and age group. I then present additional results of how the percentage change of cardiorespiratory disease deaths would vary spatially for a 1°C anomalously warm year.

7.2 Introduction

The relationship between daily temperature and cardiorespiratory disease deaths is well-established.[2–7,120] However, climate change is predicted to modify seasonal and monthly as well as daily patterns of temperature. This has the potential to disrupt long-term adaptation. This was one of the main motivations for building my Bayesian spatio-temporal model to associate monthly death rates with anomalous temperature, as detailed in Chapter 5. There is also limited analysis on how monthly deviations of temperature from long-term norms will impact deaths in a consistent way across different types of cardiorespiratory disease and cancer deaths for demographic subgroups of the population.

My results from Chapter 6 predicted that there would be an increase in injury deaths, concentrated in younger males, with a 1°C anomalously warm year. In contrast, some previous studies predicted a decrease in cardiorespiratory disease deaths in a warmer climate.[59,80,81,109] This would be the net effect of increases in cardiorespiratory disease deaths in the summer with larger decreases in the winter. Others argue that this may not be true due to a weakening association of excess winter mortality with temperature,[272,273] though methods in these studies have been criticised as misinterpreting excess winter mortality.[58,59] Cardiorespiratory diseases made up 40% of all deaths in the United States in 2016 and therefore remain significant to public health policy and planning. Deaths from cancers also make up a considerable proportion of deaths in the United States, with 23% of all deaths in 2016 being from cancers. Only a few studies have examined an association between temperature and deaths from cancers,[127,135,138] though slight seasonality in cancer death rates exists for older age groups, shown in Chapter 4. My aim was to evaluate how deaths from cardiorespiratory diseases and cancers may be affected by changes in temperature that could arise as a result of global climate change in the United States.

7.3 Data

Full details of the data processing choices I made can be found in Chapter 3. Here, I used VR data on all 60,967,769 cardiorespiratory disease and cancer deaths in the contiguous United States from 1980 to 2016 along with population records to calculate monthly death rates for each type of cardiorespiratory disease and cancer death, state, sex and age group combination. Of cardiorespiratory disease and cancer deaths, 41,105,009 (67.4%) were from cardiorespiratory diseases and 19,862,760 (35.6%) were from cancers. For each death, I mapped each ICD-9 and ICD-10 code to cardiorespiratory diseases and cancers (Table 11). I separated the cardiorespiratory disease deaths into three cardiovascular (IHD, cerebrovascular disease, other cardiovascular diseases) and three respiratory (COPD, respiratory infections, other respiratory diseases) diseases. Other cardiovascular diseases included rheumatic, hypertensive and inflammatory heart diseases. Other respiratory diseases included asthma and bronchiectasis. I did not further subdivide cancer deaths as death outcomes are not generally considered as sensitive to temperature changes.[127,135,138] The remainder of deaths not included in analysis in Chapters 6 and 7 were from a heterogeneous group of causes other than cancers, cardiorespiratory diseases and injuries, described in more detail in Chapter 3. The causes of death that led to deaths in this group varied by sex and age group. Therefore, I did not include them in the analysis. I obtained monthly population-weighted temperature anomalies from ERA-Interim by a process described in Chapter 3.[215]

7.4 Statistical methods

I analysed the association of monthly death rates with anomalous temperature using a Bayesian spatio-temporal model, fully described in Chapter 5 and described in brief in Section 6.4.

Chronic disease	ICD-9	ICD-10
Cardiorespiratory diseases	381-382, 390-519	H65-H66, I00-J99
Cardiovascular diseases	390-459	I00-I99
Ischaemic heart disease (IHD)	410-414	I20-I25
Cerebrovascular disease	430-438	I60-I69
Other cardiovascular diseases	390-409, 415-429, 439-459	I00-I19, I26-I59, I70-I99
Respiratory diseases	381-382, 460-519	H65-H66, J00-J99
Chronic obstructive pulmonary disease (COPD)	490-492, 495-496	J40-J44
Respiratory infections	381-382, 460-466, 480-487	H65-H66, J00-J6, J9-J18, J20-J22
Other respiratory diseases	467-479, 488-489, 493-494, 497-519	J7-J8, J19, J23-J39, J45-J99
Cancers	140-239	C00-C99, D00-D48

Table 11. Cardiorespiratory disease and cancer groups used in the analysis with ICD-9 and ICD-10 codes.

7.5 Results

7.5.1 Summary of cardiorespiratory disease and cancer deaths

From 1980 to 2016, 20,070,797 boys and men and 21,034,212 girls and women died from cardiorespiratory diseases in the contiguous United States. These deaths accounted for 46.3% and 49.9% of all male and female deaths respectively (Figure 2 in Chapter 3). 77.1% of male cardiorespiratory disease deaths and 88.7% of female cardiorespiratory disease deaths were in those aged 65 years and older (Figure 46). For females, 42.7% of cardiorespiratory disease deaths were in those aged 85 years and older (Figure 46).

IHD accounted for 45.3% of cardiorespiratory disease deaths in males and 38.7% in females (Figure 46). Men 35 years and older and women 45 years and older died from IHD more than any other cardiorespiratory disease. Below 35 years of age for men and 45 years of age for women, other cardiovascular diseases were the largest single cause of cardiorespiratory disease death in both males and females (Figure 46). As I presented in Chapter 4, there has been a persistent seasonality of mortality in cardiorespiratory disease deaths over time for most age groups in both sexes (Figure 17 and Figure 18). For each of the six types of cardiorespiratory disease death, there were more deaths in the winter than in the summer (Figure 47).

There were 10,428,202 cancer deaths for boys and men and 9,434,558 for girls and women in the contiguous United States during 1980-2016 (Figure 2 in Chapter 3). There were slightly more deaths from cancers in winter than in summer (Figure 47) as we found for those 55 years and older in Chapter 4 (Figure 15 and Figure 16).

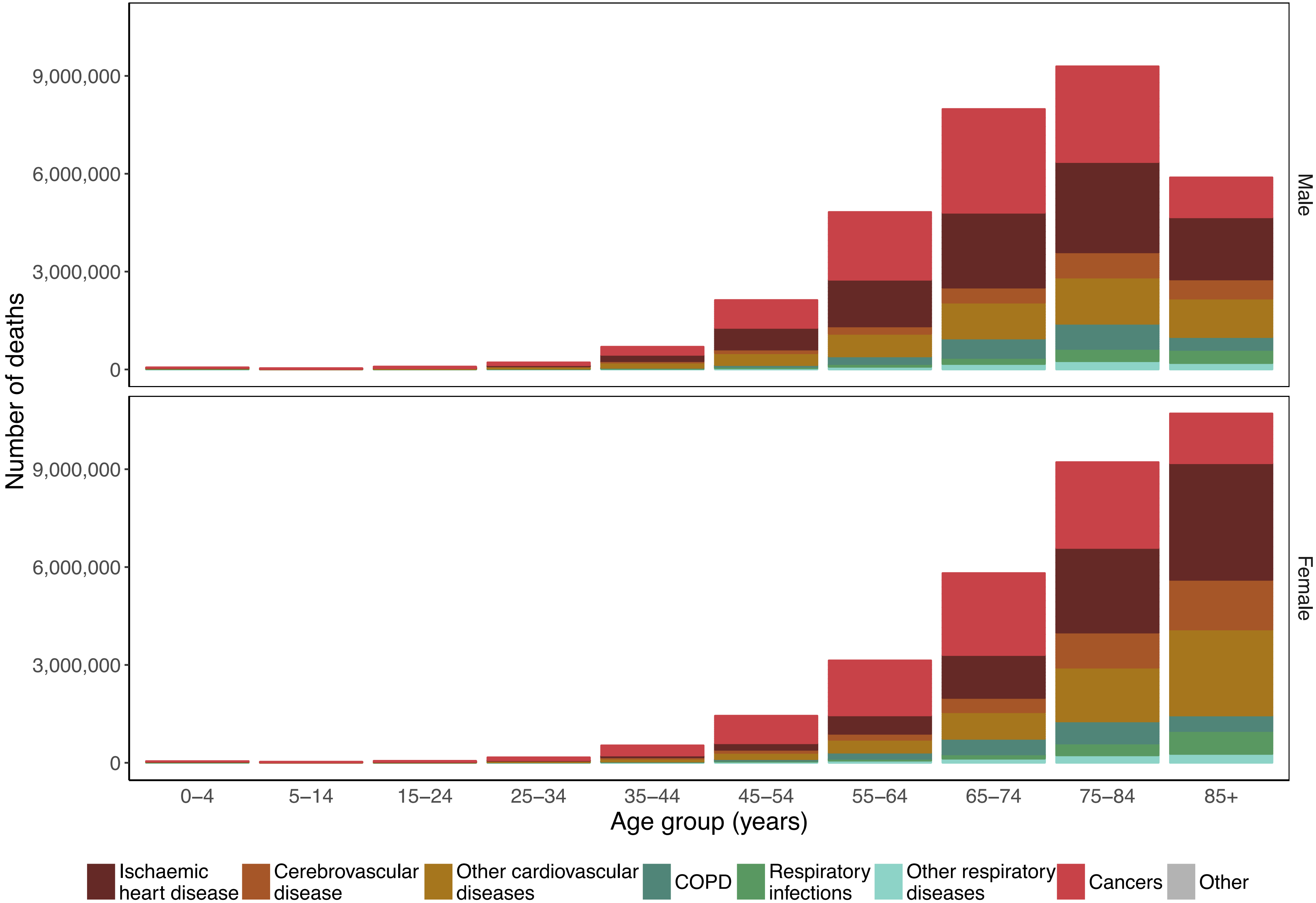

Figure 46. Number of deaths by cardiorespiratory disease and cancer, sex and age group in the contiguous United States for 1980-2016.

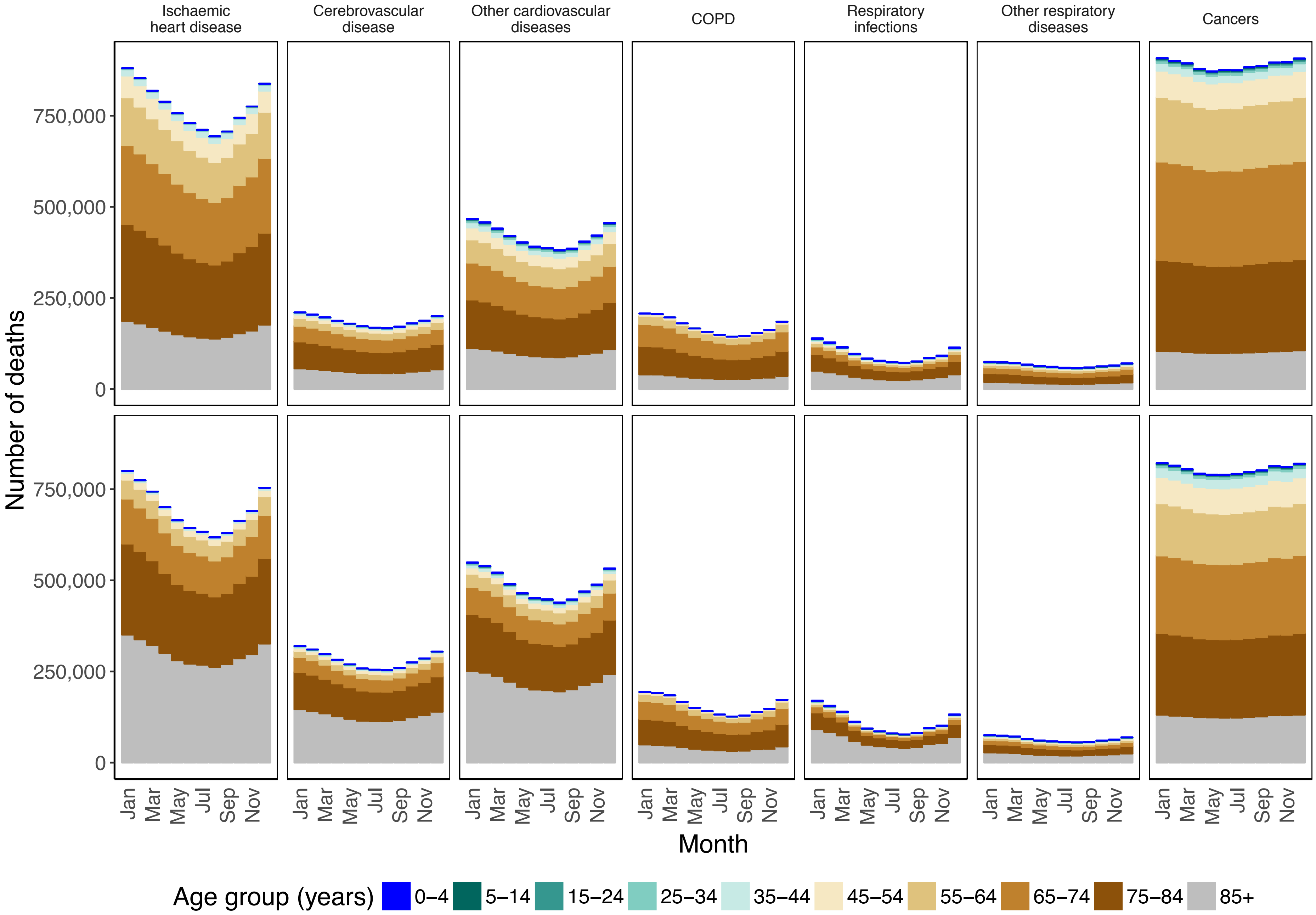

Figure 47. Number of deaths by cardiorespiratory disease and cancer, month, sex and age group in the contiguous United States for 1980-2016.

7.5.2 Trends in cardiorespiratory disease and cancer mortality

There was a decline in age-standardised death rates of four out of six types of cardiorespiratory disease (IHD, cerebrovascular disease, other cardiovascular diseases and respiratory infections) for both men and women from 1980 to 2016. IHD death rate declined more than other cardiorespiratory diseases from 1980 to 2016, by over 50% for both men and women (Figure 48). COPD death rates increased in males from the 1980s until the late 1990s, and steadily decreased since then. In contrast, COPD death rates in females have increased since the 1980s (Figure 48). Age-standardised death rates from other respiratory diseases also increased over the time period (Figure 48). There is a discontinuity in age-standardised death rates in other cardiovascular diseases due to the change from the ICD-9 to ICD-10 coding in the United States in 1999, when some deaths in this group were assigned to IHD (Figure 48). Death rates from cancers have decreased over time (Figure 48).

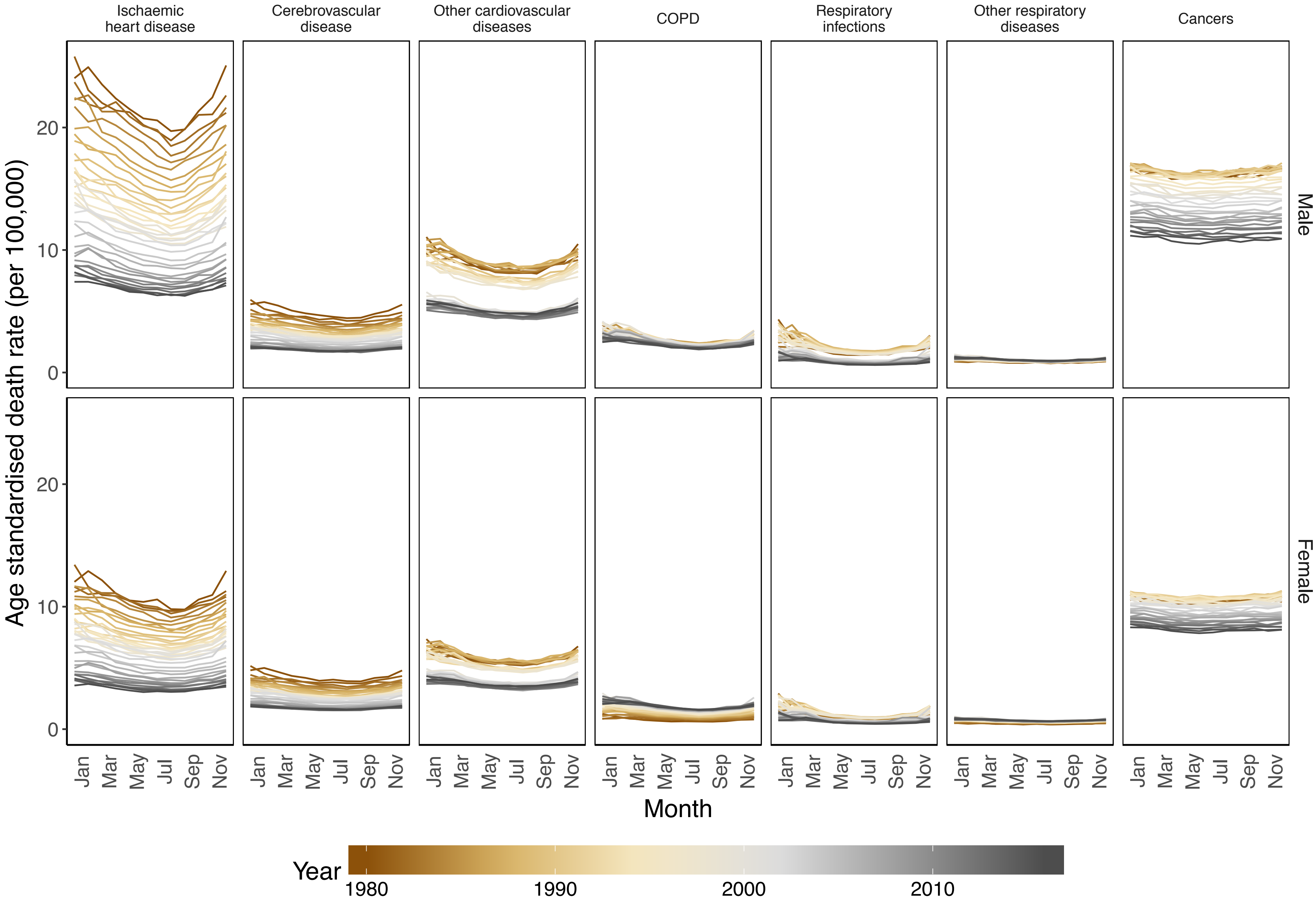

Figure 48. National age-standardised death rates from 1980 to 2016, by cardiorespiratory disease and cancer, month and sex.

7.5.3 Excess risk of cardiorespiratory disease and cancer deaths

I used the resultant risk estimates (Figure 49-Figure 55) to calculate additional deaths if each month in each state were +1°C above its long-term norm. I found no consistent association between deaths for cancers and anomalous temperature (Figure 55). I therefore did not include the results in further calculations.

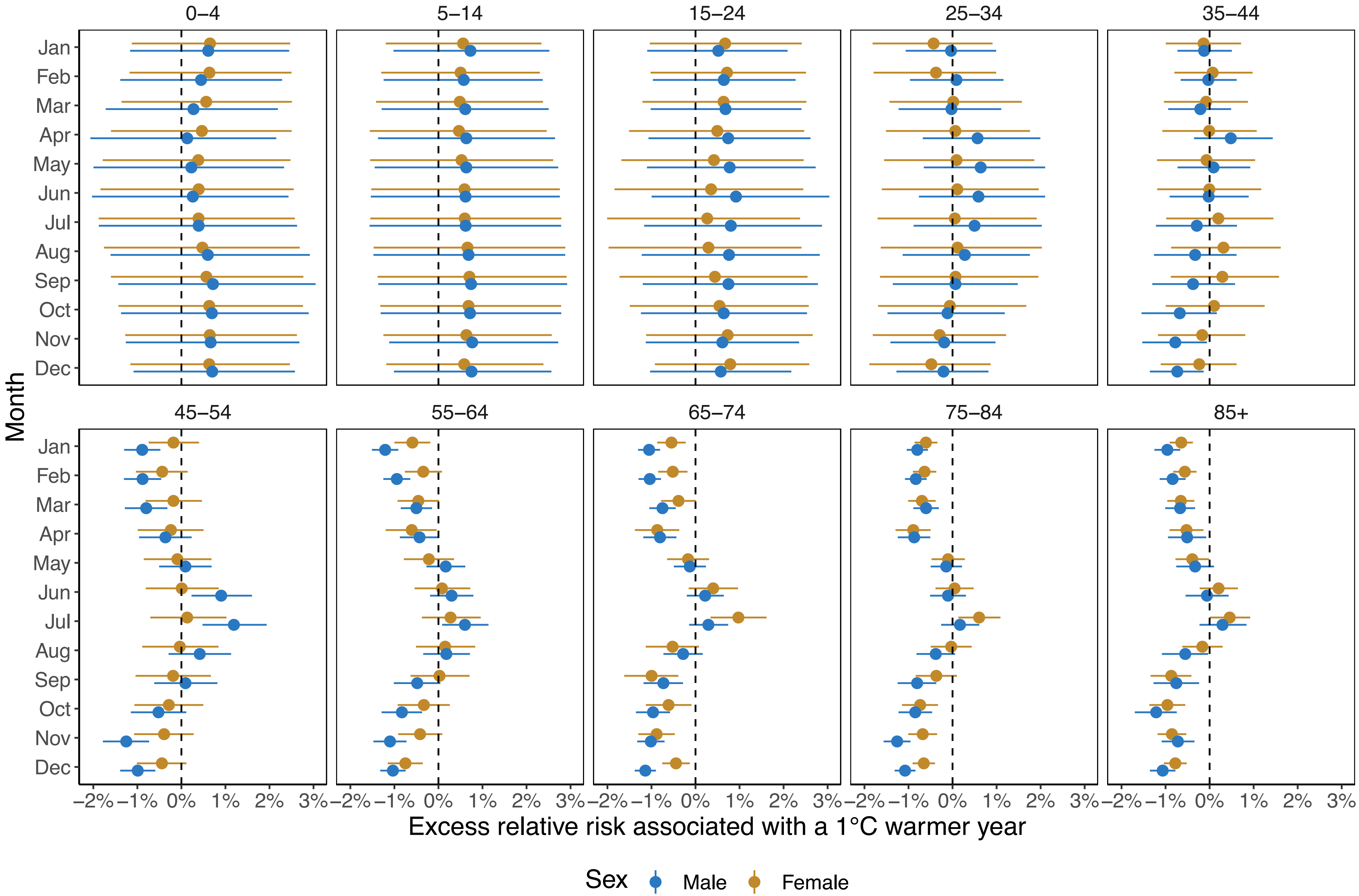

Figure 49. Excess relative risk in IHD death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

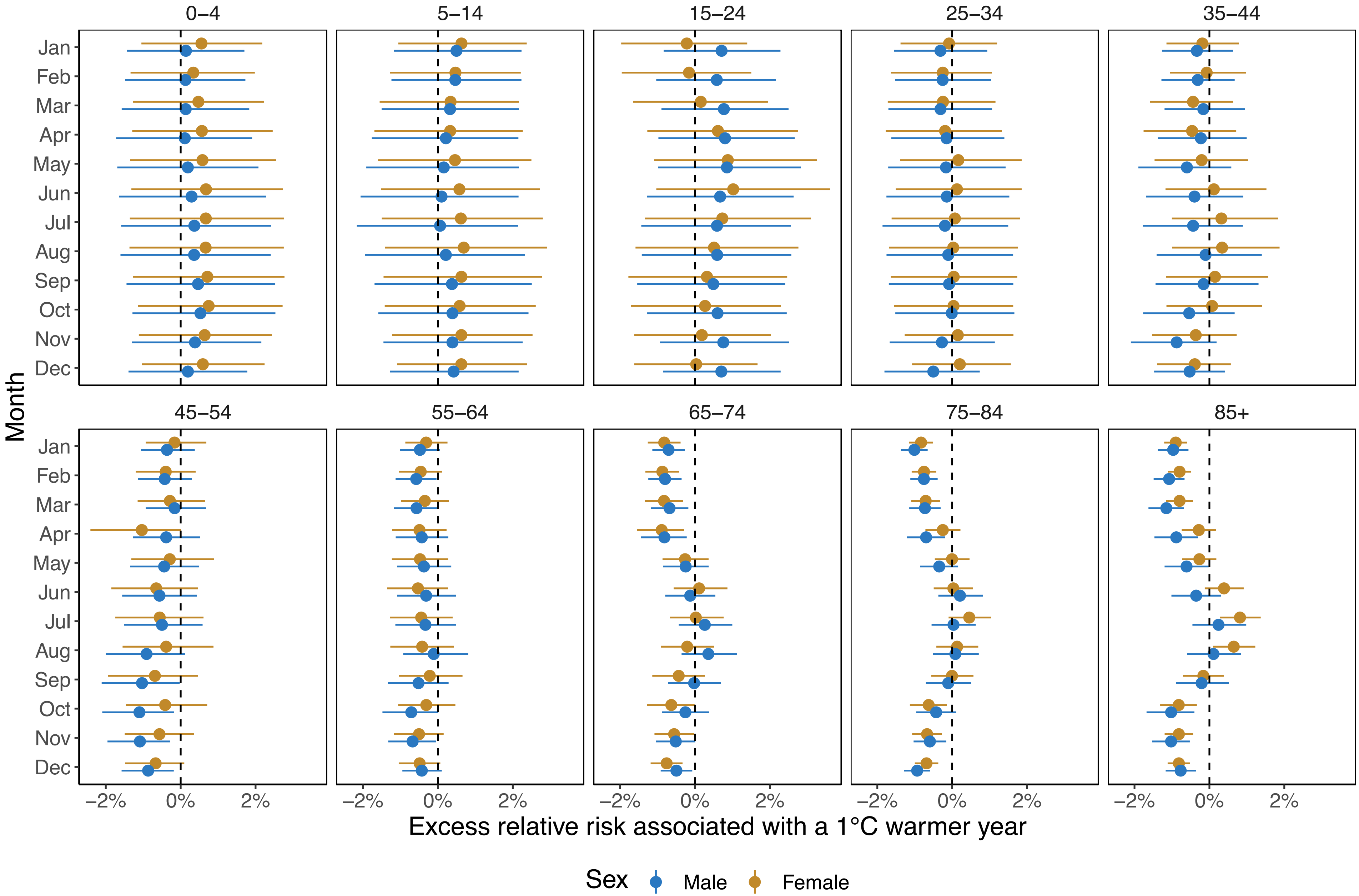

Figure 50. Excess relative risk in cerebrovascular disease death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

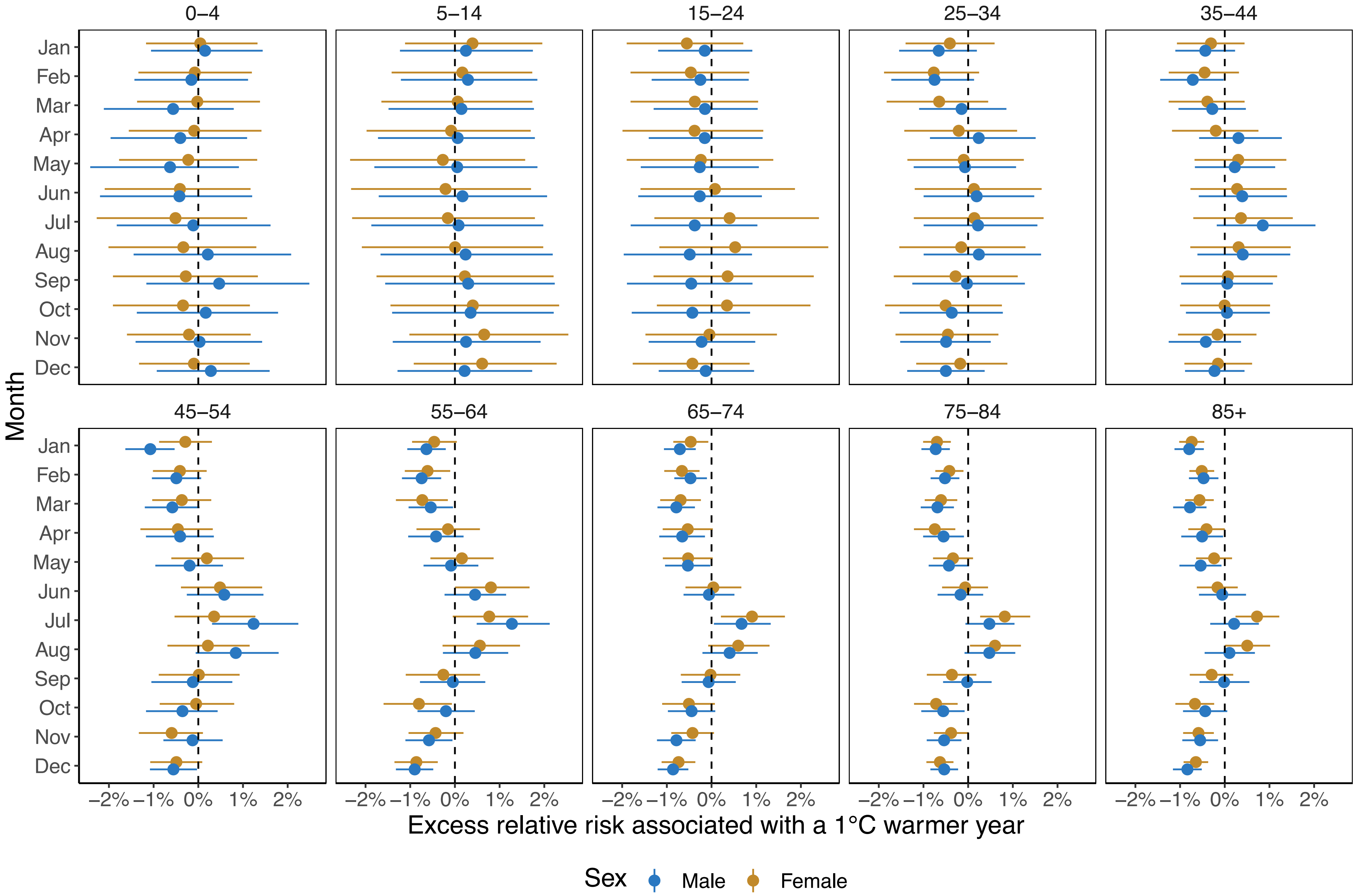

Figure 51. Excess relative risk in other cardiovascular disease death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

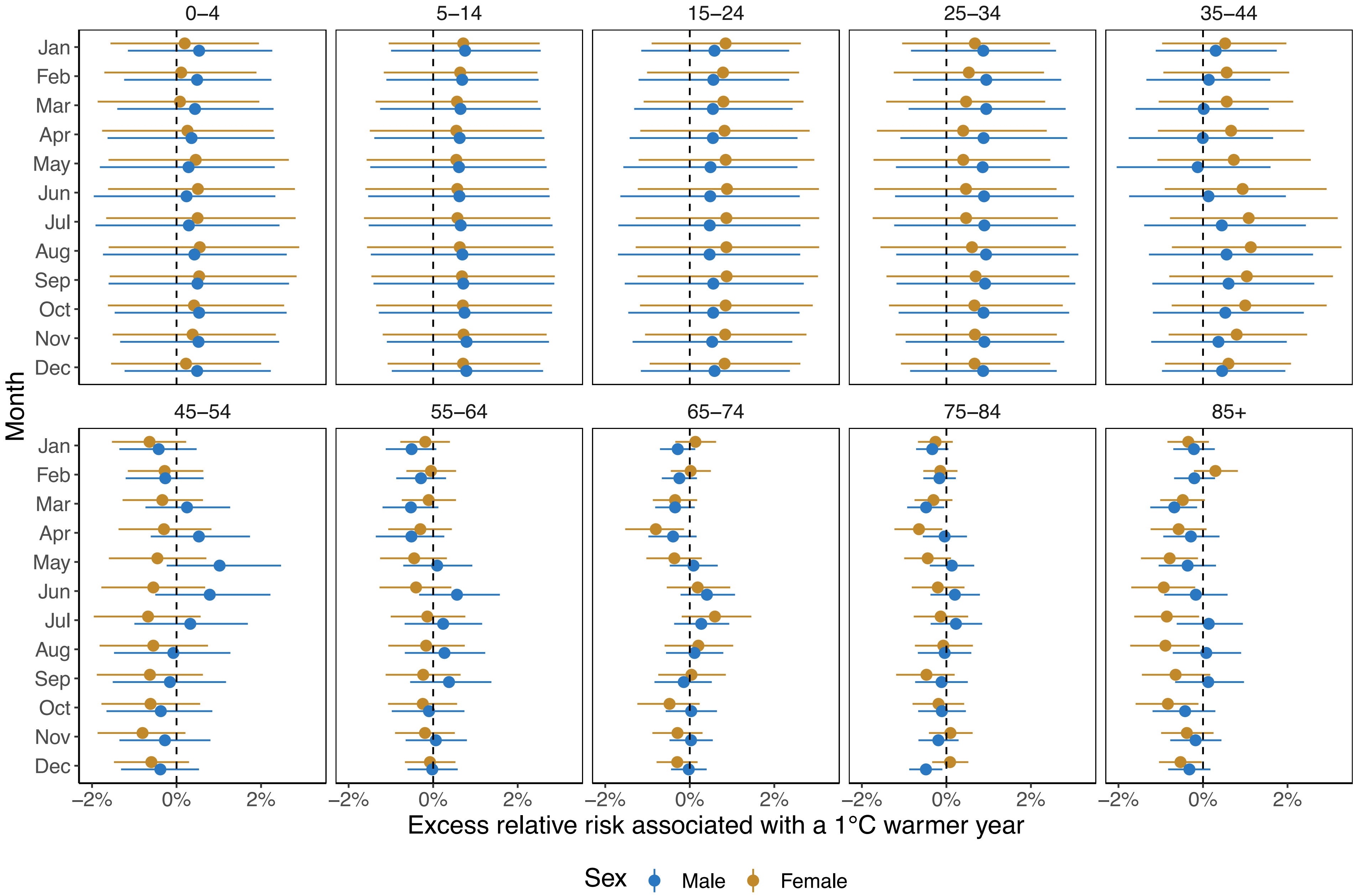

Figure 52. Excess relative risk in COPD death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

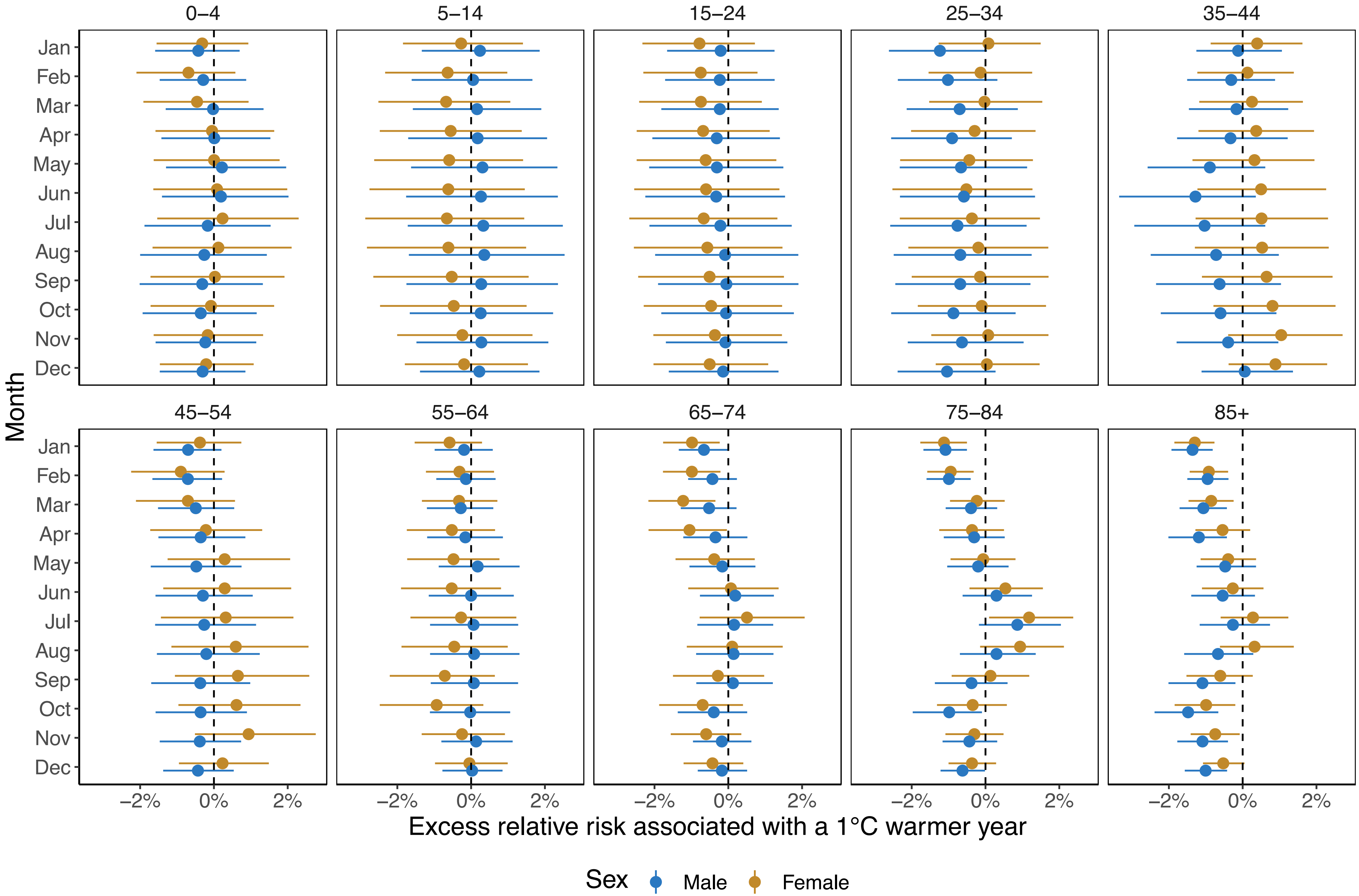

Figure 53. Excess relative risk in respiratory infection death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

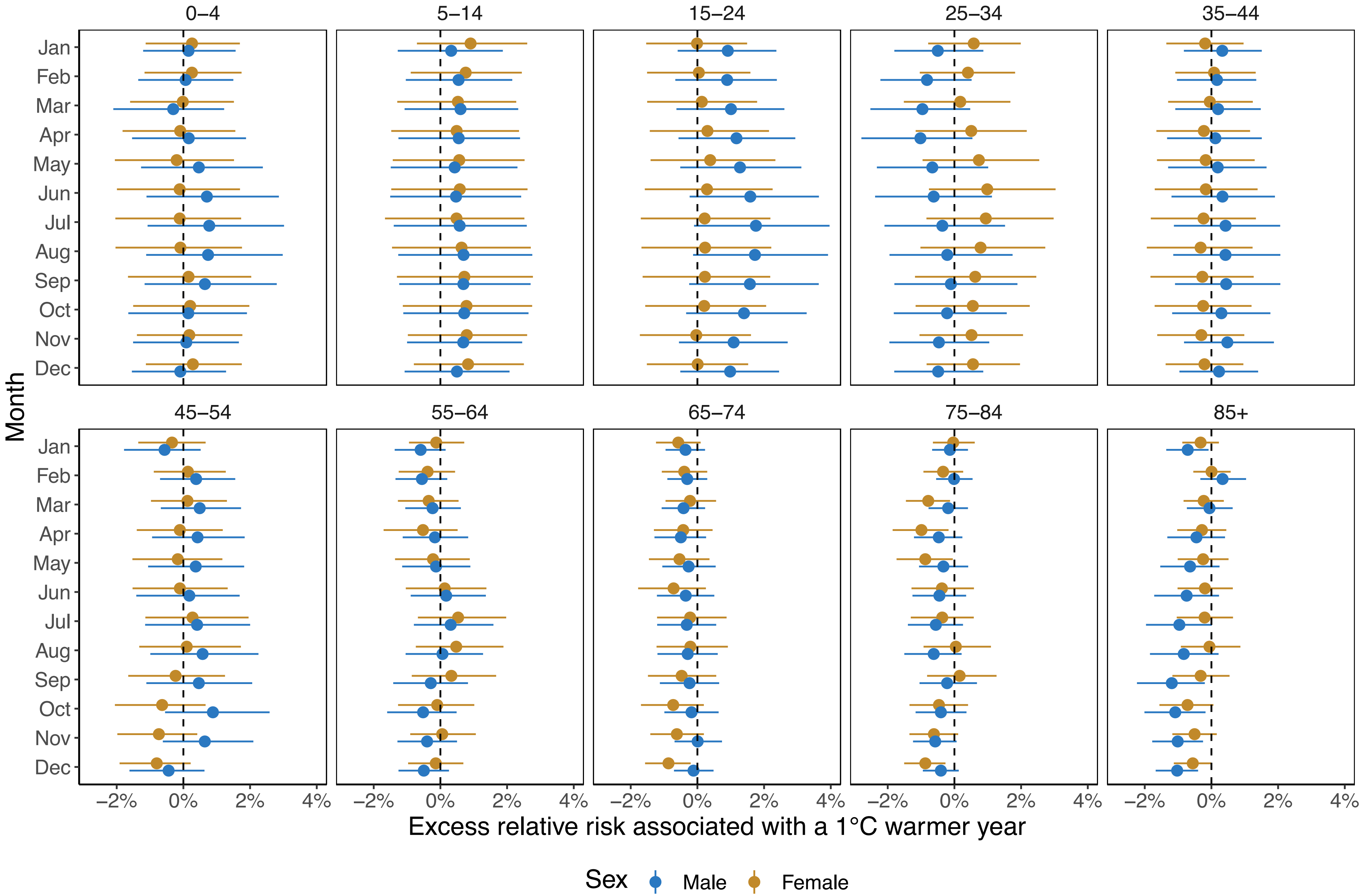

Figure 54. Excess relative risk in other respiratory disease death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

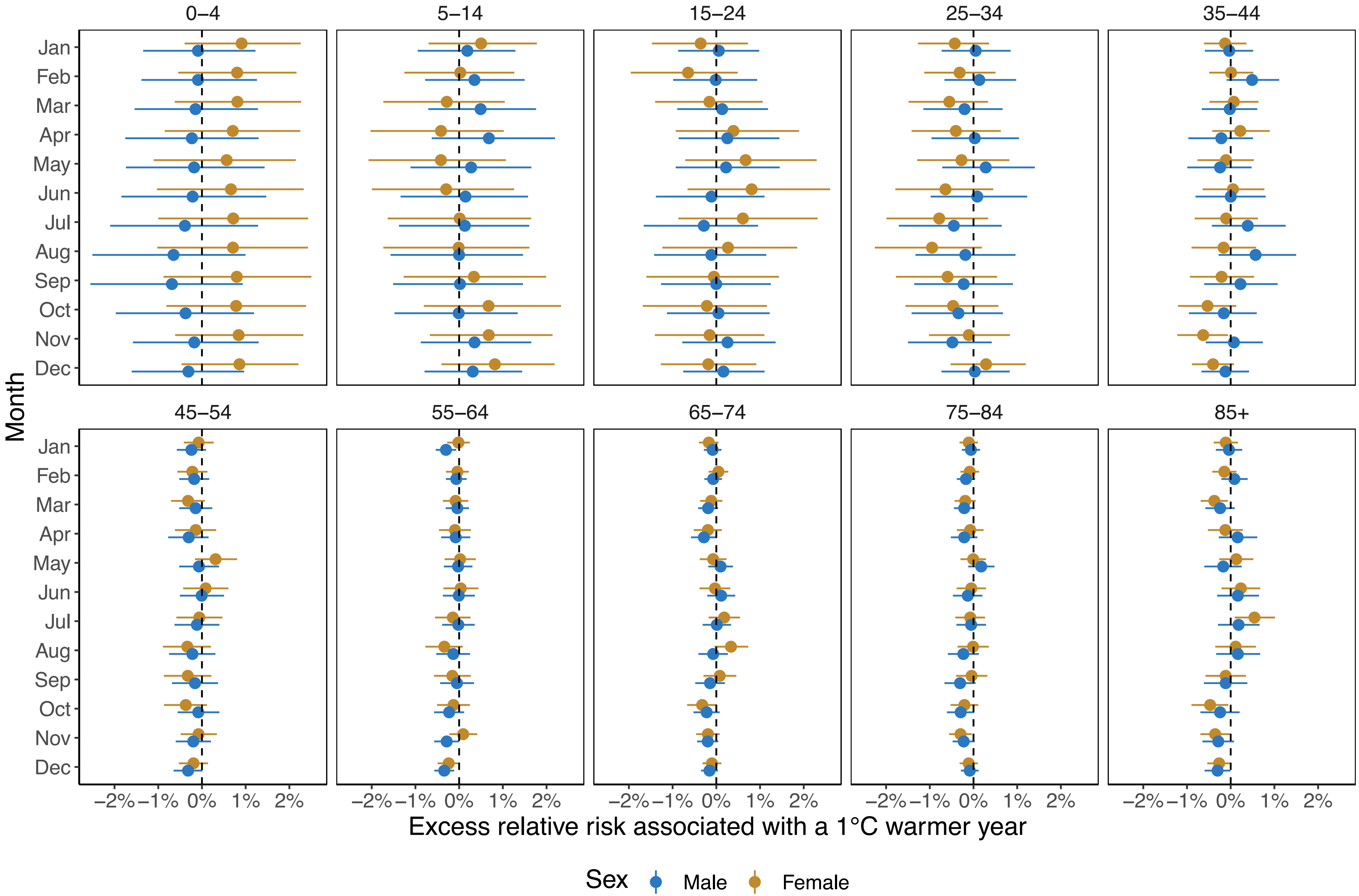

Figure 55. Excess relative risk in cancer death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by month, sex and age group.

7.5.4 Percentage change of cardiorespiratory disease deaths

Proportionally, deaths from IHD are predicted to show the most consistent decrease in older age groups (Figure 56). Proportional reductions in deaths for those 55 years and older were greater than 0.5% in males and 0.2% in females in a year in which each month in each state were +1°C above its long-term norm (Figure 56). Younger age groups generally possess a large range of uncertainty in all types of cardiorespiratory disease death due to the small numbers of deaths (Figure 56). The largest single age group decrease was that of respiratory infections in males 85 and older, (1.0% (0.7%, 1.3%)) (Figure 56). With few exceptions (e.g., those aged 15-24 years in deaths from other respiratory diseases) the scale and sign of the percent changes were similar in both males and females across ages and cardiorespiratory diseases (Figure 56).

There were variations in association between proportional change in deaths for all ages combined across months (Figure 57). The main exceptions were for COPD in females and other respiratory diseases in both sexes (Figure 57), though low absolute numbers of other respiratory disease deaths led to the large uncertainty in the estimated rate ratios (Figure 57). The largest single monthly increase was for other cardiorespiratory diseases for females in July, 0.7% (0.4%,1.0%), with the largest single decrease for IHD for males in December, 1.1% (0.9%, 1.2%) (Figure 57).

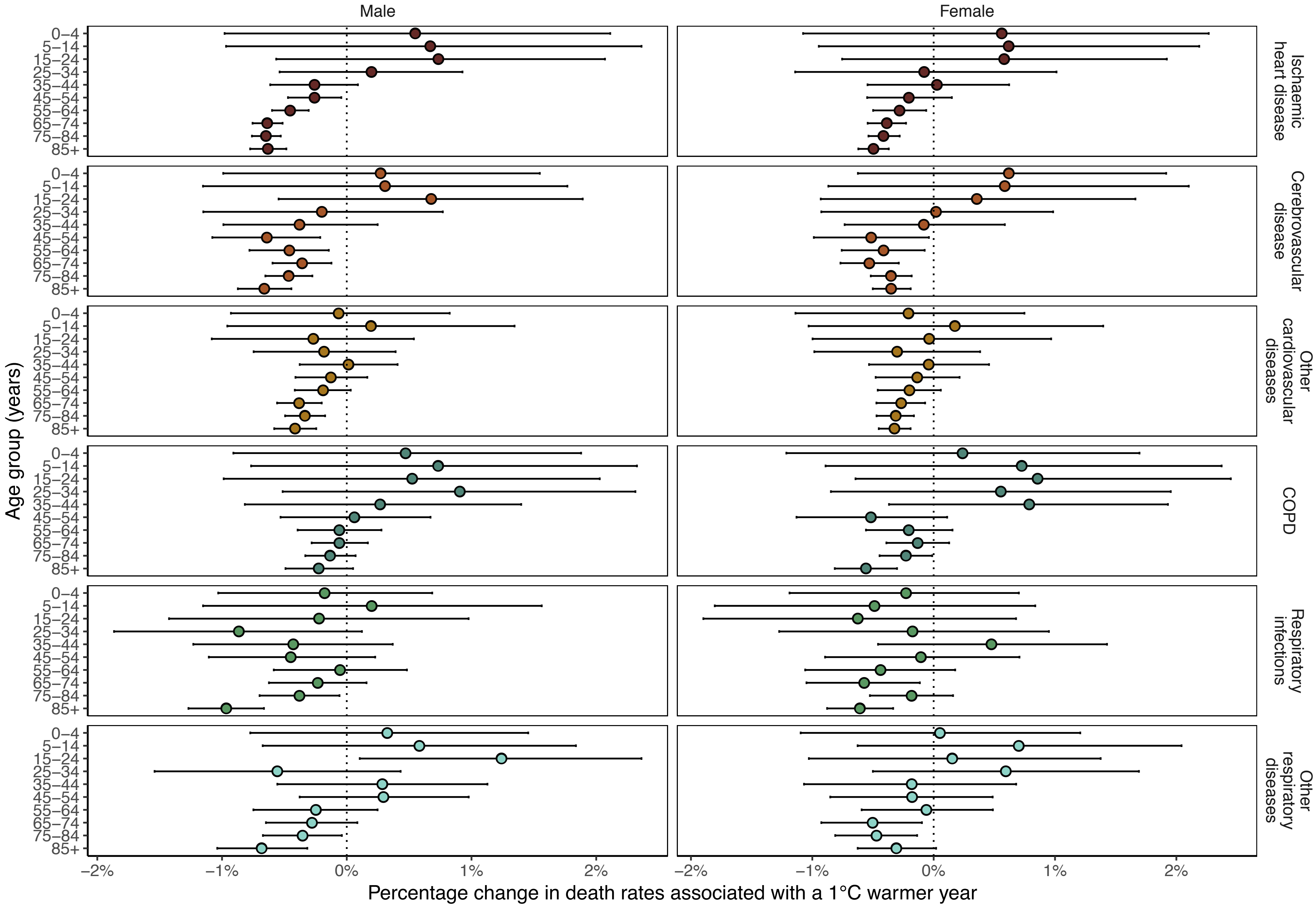

Figure 56. Percent change in death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by cardiorespiratory disease, sex and age group summarised across months.

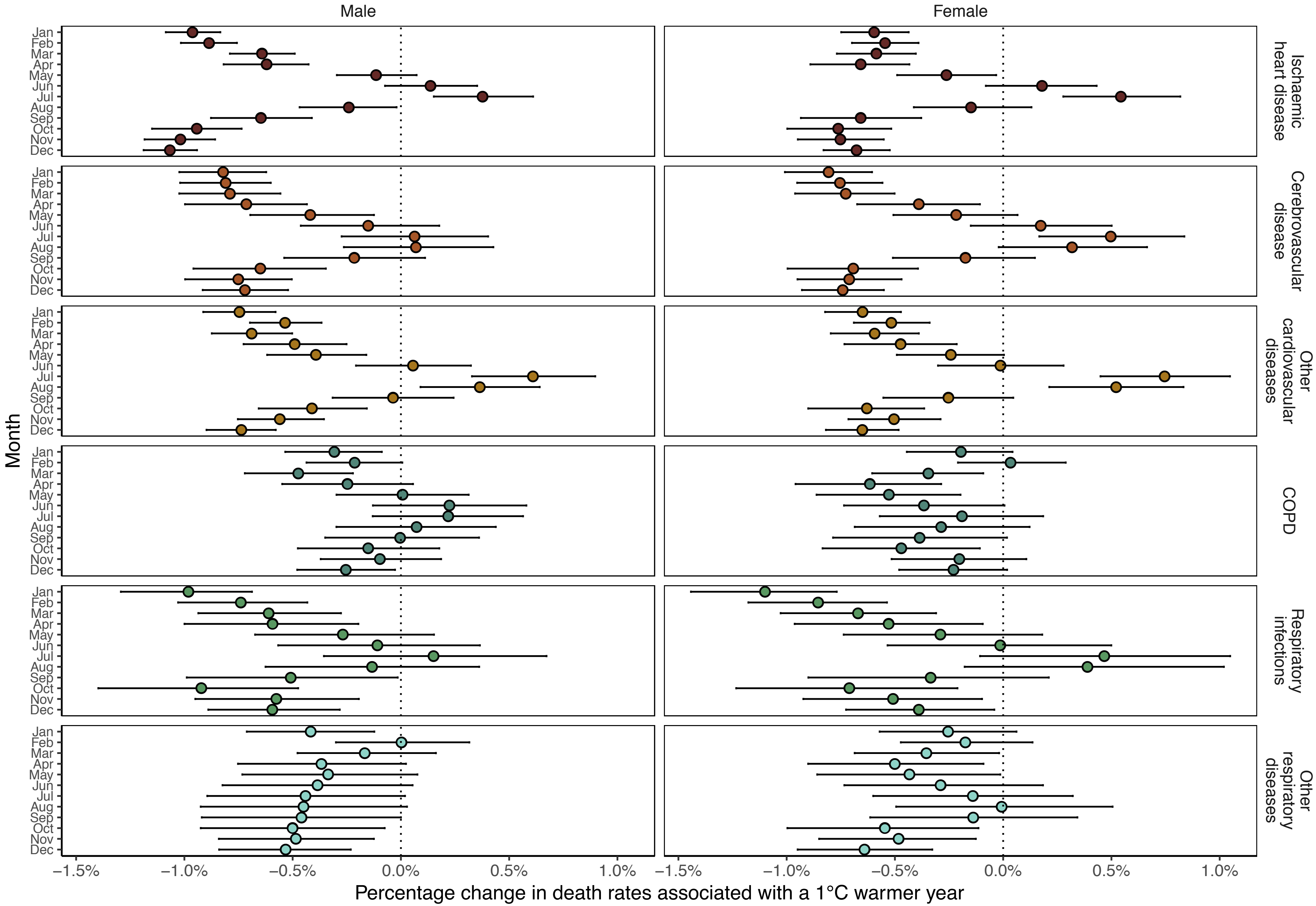

Figure 57. Percent change in death rates in year in which each month was +1°C compared with 1980-2009 norm temperatures by cardiorespiratory disease, sex and month summarised across age.

7.5.5 Change in cardiorespiratory disease deaths

I estimated that there would be 4,369 (4,024, 4,706) fewer cardiorespiratory disease deaths, equivalent to 0.4% of all cardiorespiratory disease deaths in 2016, in a year in which each month in each state were +1°C above its long-term norm (Figure 58). Deaths from all cardiovascular diseases (IHD, cerebrovascular disease and other cardiovascular diseases) and respiratory diseases (COPD, respiratory infections and other respiratory diseases) would be predicted to decrease (Figure 58). The biggest reduction of deaths would be from IHD, with 1,883 (1,706, 2,058) fewer deaths, followed by other cardiovascular diseases, with 1,039 (835, 1,243) fewer deaths. 81% of the total reduction in deaths would be from cardiovascular diseases, with the rest in respiratory diseases (Figure 58). 4,236 deaths (97%) of overall reduction would come from those aged 55 years and older. 55% of the reduction in deaths would occur in males and 45% in females (Figure 58). There would be decreases in all months across all cardiorespiratory diseases, with the exception of the summer months (June, July and August). The greatest single increase would be in July for other cardiovascular diseases for both males (76 (41, 112)) and females (103 (62, 144)). The biggest reductions would occur in the coldest months (November, December, January and February) (Figure 58).

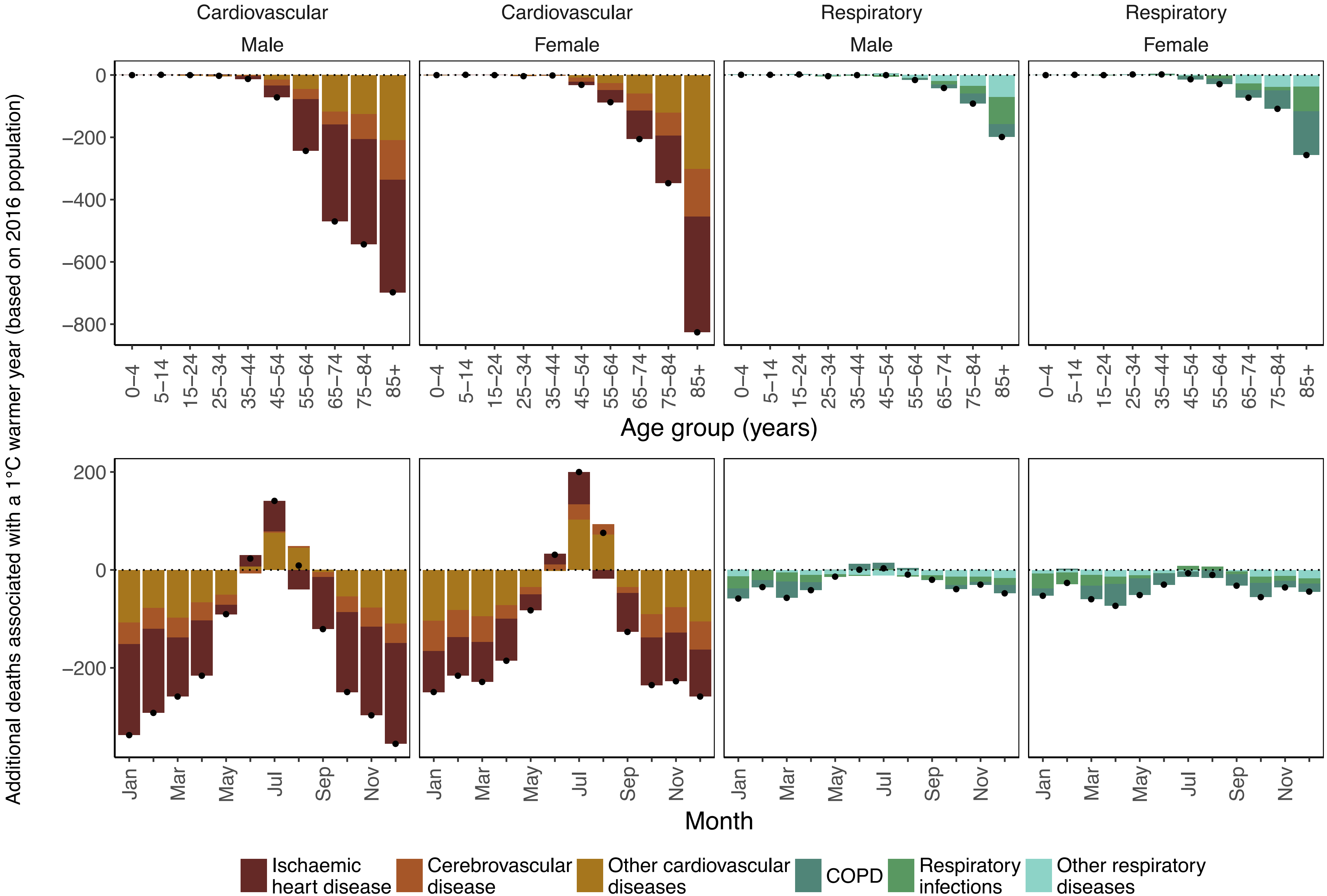

Figure 58. Additional annual cardiorespiratory disease deaths for the 2016 US population in year in which each month was +1°C compared with 1980-2009 norm temperatures. The top row shows breakdown by cardiorespiratory disease, sex and age group. The bottom row shows the break down by cardiorespiratory disease, sex and month. Black dots represent net changes in deaths for each set of bars.

7.5.6 Percentage change of sub-national cardiorespiratory disease deaths

I also ran a model where each state was given a separate temperature anomaly coefficient to examine spatial variation in percentage change in deaths if each month in each state were +1°C above its long-term norm, described by Equation 9 in Chapter 5. In this model, I used all cardiorespiratory diseases together, as models did not converge or give sensible results when breaking down deaths by type of cardiorespiratory disease in addition to state, sex and age group.

Percentage change in death rates in a year in which each month in each state were +1°C above its long-term norm varied by state and month in both males and females (Figure 59 and Figure 60), though in some months more than others. There were similar associations between males and females in the same state and month. In January, an illustrative month for the impacts of anomalous temperature in winter months, there were decreases in percentage change in death rates across the entire contiguous United States for both males and females (Figure 59 and Figure 60). These decreases ranged from 1.5% (1.2%, 1.9%) (Louisiana) to 0.2% (0.1%, 0.4%) (New Mexico) in males (Figure 59), and 1.3% (1.0%, 1.7%) (Washington) to 0.1% (0.3%, 0.5%) (Arizona) in females (Figure 60). In July, an illustrative month for the impact of anomalous temperature in summer months, there were increases in 47 out of the 49 spatial units for males (Figure 59) and all spatial units for females (Figure 60). The biggest increase in July for males was in New Mexico, at 1.1% (0.5%, 1.7%) (Figure 59) and in Utah, at 1.2% (0.6%, 1.7%) for females (Figure 60). In May and September, late spring and early autumn respectively, there were mixed positive and negative associations (Figure 59 and Figure 60). In these months, there were negative associations with anomalous temperature in coastal regions. In contrast, there were positive associations in the West North Central and Southwest regions of the United States, though it should be noted that the low population of states in this region contributed to large uncertainties in these estimates. There were similar associations in June and August across the United States in both males and females (Figure 59 and Figure 60). Overall, the Southeast region showed the greatest negative associations with anomalous temperature across all months for both sexes.

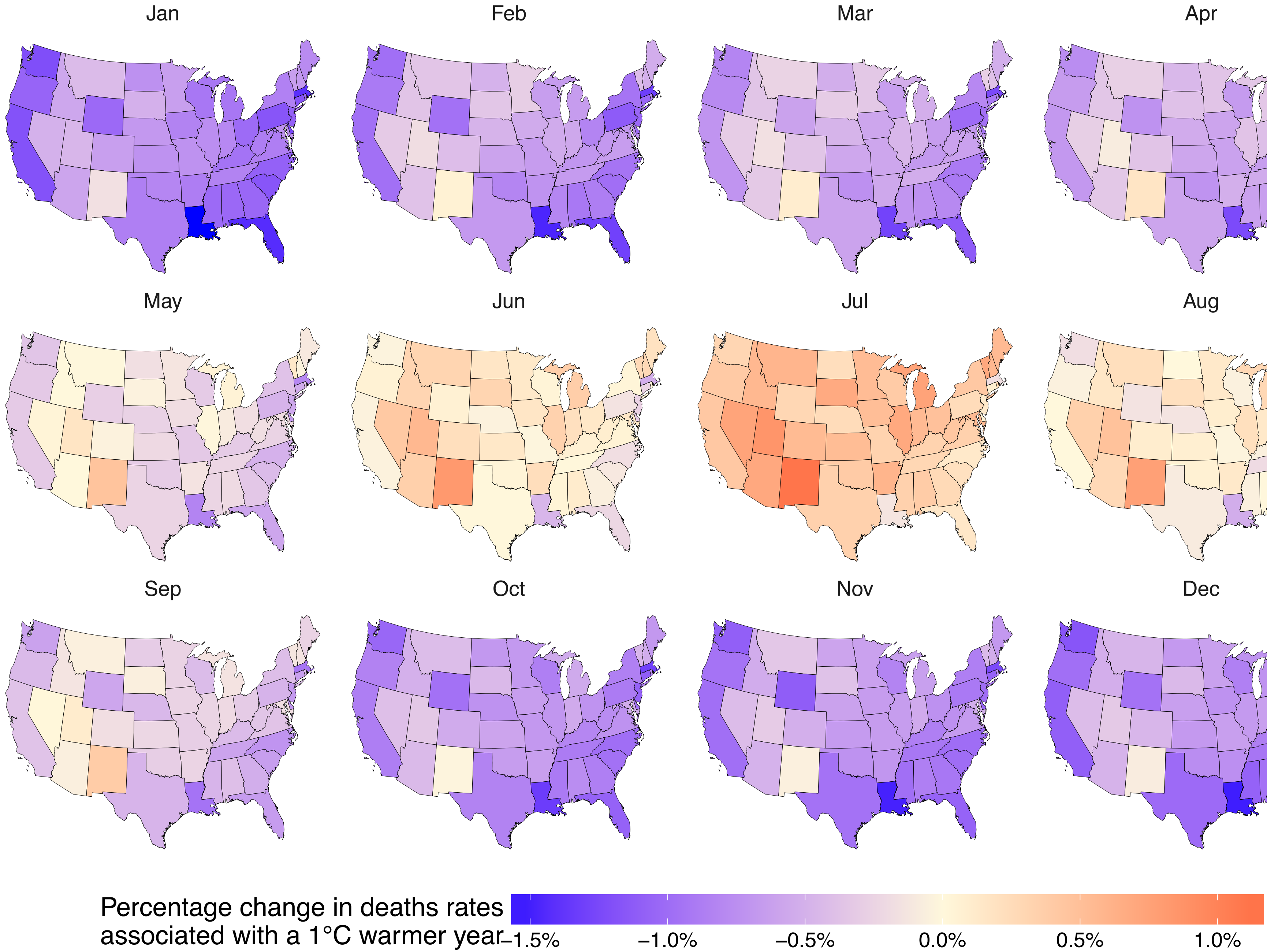

Figure 59. Percent change in cardiorespiratory disease death rates for males in year in which each month was +1°C compared with 1980-2009 norm temperatures by state and month summarised across age groups.

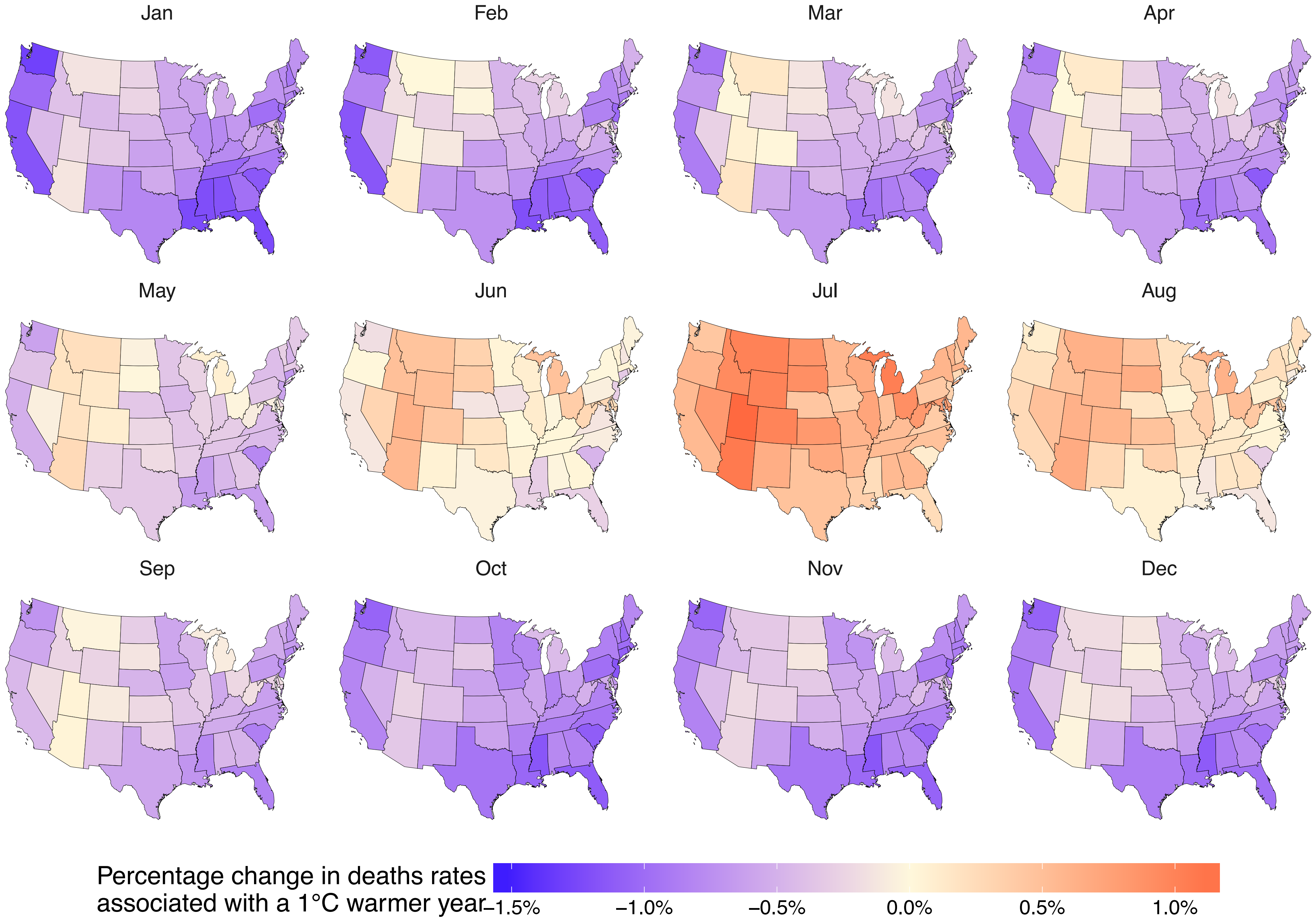

Figure 60. Percent change in cardiorespiratory disease death rates for females in year in which each month was +1°C compared with 1980-2009 norm temperatures by state and month summarised across age groups.

7.6 Discussion

My work here shows that there would be an expected net decrease from cardiorespiratory disease deaths in a year in which each month in each state were +1°C above its long-term norm (Figure 58). This reduction would be strongly concentrated in older ages, be shared almost evenly between males and females and occur in all but summer months (Figure 58).

Most previous studies have examined how deaths from all-causes[2,3,101,103,109,111–117,5,118,6,7,87,88,98–100] and cardiorespiratory disease deaths[3,5,121–127,6,7,87,88,115–117,120] are associated with daily, not monthly, temperature. Nevertheless, some limited comparisons can be made with other studies.[103,117,122] It should be noted that for summer months one study examined effect of extreme high temperatures[117] and the other the effect of a 5°C increase in temperatures.[122] A study of winter months looked at decreases below 18°C.[103]

Illustrative of summer months, there was an increase of IHD deaths in July of 0.4% (0.2%, 0.6%) for males and 0.5% (0.3%, 0.8%) in females for a 1°C anomalously warm year (Figure 57). Previous studies which studied association of IHD deaths in summer months with daily temperature found slightly higher (1.7% to 2.5%) increases of risk for all deaths from both sexes.[117,122] My cerebrovascular disease findings in July show a 0.1% (-0.3%, 0.4%) increase in males and 0.5% (0.2%, 0.8%) in females (Figure 57). Another study of daily temperature found higher risk (2.5%) than in my findings. For COPD, I found a negative association of percentage change across most months for both sexes (Figure 57). A previous study found a large daily association for summer COPD deaths (4.3%), though this was for extreme high temperatures.[117] This is in contrast to my study, which examined the association of mild deviations from long-term norm temperatures on mortality.

Representing winter months, my IHD findings in January show a 0.9% (0.8%, 1.1%) decrease in males and 0.6% (0.4%, 0.7%) in females for a 1°C anomalously warm year (Figure 57). This result is consistent with a previous study of cold months in Europe.[103]

There are plausible explanations for my results. Cardiovascular deaths are higher in the winter than the summer (Figure 47). This is partially explained by blood pressure being inversely associated with temperature.[129] Cold temperature in the winter therefore results in generally higher blood pressure, placing strain on the heart and damaging vessel walls.[129] The lower norm temperatures in winter months can also lead to increased blood clotting and thrombosis.[103,129] This increases the risk of IHD and cerebrovascular disease and ultimately death from these causes.[103] Warm temperatures in winter months would therefore reduce the risk of dying from these causes (Figure 58). That warmer temperatures in summer months increase risk of death in cardiovascular diseases is thought to be due to the reduction of plasma volume by release of platelets and red blood cells into the blood stream and the loss of water and salt through sweating.[131] This puts strain on the circulatory system by increasing sticking of platelets to artery walls which leads to blockages and sudden decrease in blood pressure and can lead to death.[131] Further increases away from long-term norms increase strain on the circulatory system and risk of death from cardiovascular diseases. This explains why more deaths are expected from cardiovascular diseases in anomalously warm summer months (Figure 58).

Respiratory disease deaths are also higher in winter than at other times in the year in the United States (Figure 47). Colder temperatures are associated with suppression of the immune system, which facilitates respiratory infections taking hold in humans.[103] Warmer anomalies in winter months can therefore reduce risks of respiratory infections, which explains the reduction in excess risk for older groups (Figure 53). Cold air can also cause airways to go into spasm and trigger coughing, wheezing, shortness of breath and tightness in the chest.[274] Mould spores are more common in colder air, known to cause coughing and sneezing, which exacerbate existing respiratory conditions.[275] Warmer anomalies in winter would reduce these risk factors. In contrast, warmer anomalous temperatures in summer months are associated with airway inflammation, which can lead to death from respiratory complications.[130]

I found no consistent association between deaths from cancers and a year in which each month in each state were +1°C above its long-term norm (Figure 55). This agrees with limited previous studies,[127,135,138] with the exception of an old study which advised caution in its interpretation as it did not account for geographical differences.[135] Though I found that cancer deaths were weakly seasonal in males 55 years and in females 65 years and older (Figure 15 and Figure 16 in Chapter 1), this may be for reasons other than temperature variation. I note this though I found a non-significant increase for respiratory infections in summer months and in no other respiratory disease (Figure 57).

The major strength of my anomalous temperature study is that, when combined with work in Chapter 6, I comprehensively modelled the association of temperature anomaly with a comprehensive set of causes of death, by month, sex and age group. I did this using the two large datasets I processed in Chapter 3 and the Bayesian spatio-temporal model I developed in Chapter 5. The temperature anomaly metric I also described in Chapter 3 (Figure 8) factors in long-term local experience when examining temperature-mortality association. This has enabled me to make an estimate of the change in deaths with a 1°C anomaly increase, which is within the range of anomaly size experienced by many states (Figure 9 in Chapter 3). My study design has also enabled me to show that the reduction in deaths would be greatest in older groups in the winter months, and would be almost evenly shared between males and females (Figure 58). A limitation of my study is that I cannot rule out confounding of results due to other factors that may be correlated with temperature anomalies.

My work adds to the body of evidence that suggests that a warming world will reduce winter deaths.[59,80,81,109] While increases in average temperatures would increase deaths in the summer, this would be outweighed by the reductions in winter (Figure 58). My work goes further than previous work by breaking down changes in deaths by cause of death, month, age group and sex (Figure 58). The predicted reduction of 0.4% of all cardiorespiratory disease deaths is slight and concentrated in older age groups. This demonstrates that the burden from cardiorespiratory disease deaths will remain large and a significant public health concern under climate change.

7.7 Summary

Using the mortality and temperature datasets I developed in Chapter 3 and the Bayesian spatio-temporal model I described in Chapter 5, I estimated how anomalous monthly temperatures affect cardiorespiratory disease and cancer deaths in the United States. I calculated that a 1°C anomalously warm year would result in a net decrease in cardiorespiratory disease deaths. The large majority of this reduction would be concentrated in older age groups. The reduction would be across all cardiorespiratory diseases, with the largest in ischaemic heart disease. Reductions would be shared almost evenly between males and females. Reductions would occur across the year, apart from the summer months, when deaths would increase slightly. I found no association between anomalous temperature and cancer deaths.

8 Discussion

8.1 Comparison with published literature

8.1.1 Seasonal dynamics of mortality

Prior to my work, it had been established that total mortality from the entire population in the United States are higher in the winter than in the summer.[57,60,70] This was known to be mainly due to higher winter death rates from influenza and cardiorespiratory diseases in older age groups.[71–74] Previous studies in the United States have also identified seasonality for some causes -of death.[54,57,60–62,70,224] No previous study made a consistent national and subnational analysis of seasonality in the United States by cause of death, sex, age group, over time and space, nor how it varies across climate regions. In Chapter 4 of this thesis, I used wavelet and centre of gravity analyses, which allowed me to identify seasonality of mortality and how it has changed over time. This work uncovered the distinct behaviours across causes of death, and by sex and age group.

Where studies were comparable, my results agreed with previous work. I demonstrated that the strong seasonality in older age groups of cardiorespiratory diseases and weak seasonality of cancer deaths, found in some previous studies,[60,61,70,224] have endured over the last four decades. I also extended previous work. For example, I showed that there have been variations in when injury deaths peaked and how the seasonal differences in injury deaths have changed over time in relation to age group and sex, not previously demonstrated. I also showed how changes in all-cause mortality seasonality by age group and sex can be explained by changes in particular causes of death, such as how substantial decline in seasonal mortality differences in boys under five was due to the decreasing seasonality of death from cardiorespiratory diseases in that age group.

8.1.2 Anomalous temperature and mortality

A large proportion of previous studies of the temperature-mortality relationship focused on single day or multi-day episodes and temperature.[3–7] Other studies either associated monthly or seasonal average temperatures with mortality,[108,109] or accounted for seasonal impacts by stratifying daily data by month.[81,114] Previous studies largely examined all-cause,[2,3,101,103,109,111–117,5–7,87,88,98–100] or cardiorespiratory disease deaths.[3,5,121–126,6,7,87,88,115–117,120] In the United States, studies ranged from a single spatial unit,[86,87,109,122,137,168,169] to hundreds of independently-analysed units across the country.[81,101,155,161,170,114,118,121,124,127,136,144,146] Some work used Bayesian methods to conduct meta-analyses of relative risks for temperature and mortality.[172,173]

To my knowledge, no previous study made an analysis of how temperature deviations from long-term norm in each month are associated with mortality by cause of death, sex and age group. In my work on anomalous temperature and mortality in Chapters 6 and 7, I examined deviations from long-term norms to analyse relationships using a Bayesian spatio-temporal model by cause of death, month, sex, age group and in the case of cardiorespiratory disease deaths (Chapter 7), by state.

Though previous studies did not examine anomalous temperature, some of my results can be compared with other studies of temperature. For example, my results for injury deaths, described in Chapter 6, align well with a previous study of the association between suicides and temperature in the entire contiguous United States and Mexico.[108] However, my work went further in demonstrating that while suicides are predicted to increase with rising anomalous temperature, the greatest absolute impact would be on younger men. With cardiorespiratory disease deaths, described in Chapter 7, I showed that there would be a net decrease expected with mild positive deviations from long-term norm temperatures. This would be concentrated in the oldest age groups and would be shared almost evenly between males and females. My results agreed with previous studies which predicted a decrease in absolute number of deaths for cardiorespiratory disease deaths.[59,80,81,109] My study went further by showing that this would be concentrated in older age groups, and percentage change in cardiorespiratory disease deaths would be nearly homogeneous across space in the warmest and coldest months (Chapter 7). I also showed in Chapter 7 that there was no association with cancer and anomalous temperature across any month, sex and age group combination.

8.2 Strengths and limitations

In my thesis, I processed two large datasets on death rates from VR records and monthly anomalous temperature from ERA-Interim weather reanalysis, described in Chapter 3. My work here is the first comprehensive study of the United States to use a mutually exclusive and collectively exhaustive set of causes of death for both examining dynamics of seasonality of mortality, described in Chapter 4, as well as association between anomalous temperature and mortality, described in Chapters 6 and 7.

The strengths of my dynamics of seasonality study, described in Chapter 4, were its innovative methods of characterizing seasonality of mortality dynamically over space and time, by cause of death, sex and age group and; using wavelet and centre of gravity analyses; and using ERA-Interim data to compare the association between seasonality of death rates and regional temperature.

I developed a Bayesian spatio-temporal model, described in Chapter 5, to borrow strength across spatial and temporal units. Using this model, I estimated excess risk of mortality for injuries, described in Chapter 6, and cardiorespiratory disease and cancer deaths, described in Chapter 7. I was able to go further than previous studies by examining changes in deaths due to anomalous temperature by cause of death, sex and age group.

A limitation of my results in Chapters 4 ,6 and 7 is that I did not investigate seasonality of mortality by socioeconomic characteristics which may help with understanding its determinants and planning responses. Whether temperature anomaly within a month is spread or concentrated, as described in Chapters 6 and 7, may also have different implications to health as single-day or multi-day heat and cold events are known to be a threat to human lives. However, additional extreme temperature measures, which I described in Section 5.4.11, did not add any further insight to my analysis. Like all observation studies, confounding from other factors cannot be ruled out. However, it is unlikely that such factors will have the same anomalies as temperature, even if their average space and time patterns are the same. Future climate change may also produce different types and patterns of anomalies from the ones we can study historically.

8.3 Public health and policy implications

Continued higher death counts in winter for cardiorespiratory diseases in older age groups, shown in Chapter 4, indicate that improving interventions during the winter months will remain a priority. These may include better insulation of homes, winter heat provision and influenza vaccinations. Social interventions will remain important in improving and maintaining health in older age, such as regular visits to older people or keeping them connected over the internet to other people with newer technologies. This effort is necessary irrespective of the geography and local climate in the United States, since I also showed in Chapter 4 that seasonality is present and similarly timed throughout the country. The relative difference in seasonality of mortality has decreased for children under five, which may help to demonstrate the effectiveness of efforts to reduce peaks of cardiorespiratory diseases in the winter. The continued presence of cancer death seasonality in older groups may be due to co-morbidity in winter months, causing already frail sufferers to die.

There would be increases in deaths from injuries (transport, drownings, assault, suicides) in younger males, during periods of elevated anomalous temperature, as shown in Chapter 6. My analysis demonstrated that a 1°C anomalously warm year would result in 0.5% overall increase in injury deaths, concentrated in younger men. This may have implications on interventions targeted at younger age groups during periods of elevated temperature. These could include targeted messaging for younger males on the dangers of driving and swimming triggered when higher-than-normal temperatures are forecast. The concentration of these deaths in younger age groups, particularly younger men, also means that additional injury deaths from anomalous temperatures could result in loss to the economy through loss of otherwise healthy working years. The estimated reduction in cardiorespiratory disease deaths (0.4% overall decrease in a 1°C anomalously warm year), concentrated in older age groups, demonstrate that cardiorespiratory disease deaths would remain an ongoing concern under climate change, since climate change would not reduce cardiorespiratory disease deaths by a significant amount. Policy makers should continue to aim for further reductions in such chronic diseases which, along with cancers, remain the deadliest threat to most people in the United States.

8.4 Future work

My work in this thesis is translatable to other countries with reliable vital registration data. Though many countries are still lacking appropriate high quality mortality data,[14] the analyses in Chapters 4, 6 and 7 could be replicated as data becomes available. The algorithm I developed for gridded weather data, described in Chapter 3, could be used anywhere in the world. Comparing differences between communities in different countries could serve as evidence to measure success of potential adaption measures enacted in one country but not another.

In the United States itself, other research on anomalous temperature and mortality could examine urban and rural differences. Similar work has been carried out in the United

Kingdom.[120,143] Further work could examine how socioeconomic factors explain differences by state in excess risk per 1°C temperature anomaly by state, such as in my analysis of cardiorespiratory disease deaths in Chapter 7. By combining with climate model projections of future deviations of temperature from current long-term norms, my work here could be used to help further understand the implications of climate change on mortality by cause of death, sex and age group. A recent study on all-cause mortality for several cities in the United States highlighted the differences in attributable heat mortality between meeting the Paris Agreement's temperature goals and current trajectory of about 3°C increase above preindustrial levels.[119] Further work based on my thesis could expand this tranche of work on climate change and human mortality to multiple causes of death, by sex and age group and across the entire contiguous United States, using the benefits of Bayesian spatio-temporal modelling, such as the 'borrowing of strength' across different spatial and temporal subunits.

8.5 Conclusions

Seasonality of mortality persists for deaths in older age groups in the United States, though the timing and degree to which this occurs varies by cause of death, sex and age group. Seasonal differences in deaths among children and young adults have largely disappeared. There are impacts, though slight, in how injury and cardiorespiratory disease death rates would change under anomalous temperature. Injury deaths in young men, particularly for transport, drowning, assault and suicide, are positively associated with anomalous warm temperature. In contrast, deaths from falls in older age groups were negatively associated with anomalous warm temperature. Anomalous warm temperature is also associated with decreases in cardiorespiratory disease deaths. This decrease would be concentrated in older age groups and shared almost equally between males and females. There is no association between cancer deaths and anomalous temperatures. My research shows that in the United States, continued efforts are required to further reduce peaks in mortality in older age groups through targeted interventions. Under climate change, while estimated modest increases in injury mortality in younger males is concerning, the burden of cardiorespiratory disease and cancer deaths will remain a high public health priority due to the respective small and no reduction in deaths.

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