Contributions of mean and shape of blood pressure distribution to global trends and variations in raised blood pressure

NCD Risk Factor Collaboration (NCD-RisC)

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Abstract

Both shifts in the entire distribution of blood pressure and changes in its high-blood-pressure tail could change the prevalence of raised blood pressure. We pooled 981 population-based studies with 11.6 million participants, and used a generalised linear mixed model, to examine the contributions of the two drivers to worldwide trends in prevalence from 1985-1994 to 2005-2016. In 2005-2016, at the same level of population mean SBP and DBP, men and women in south Asia would have the highest prevalence of raised blood pressure, and those in the high-income Asia Pacific region would have the lowest. In most region-sex-age groups where the prevalence of raised blood pressure declined, one half or more of the decline was due to the decline in mean blood pressure. Where prevalence of raised blood pressure increased, the change was entirely driven by increasing mean blood pressure, offset partly by the change in the prevalence-mean association.

Introduction

Raised blood pressure, commonly defined as systolic blood pressure (SBP) ≥140 mmHg or diastolic blood pressure (DBP) ≥90 mmHg, is used to identify high-risk individuals (1-3). Globally, one in four men and one in five women, totalling 1.13 billion adults, had raised blood pressure in 2015 (4). One of the global non-communicable disease (NCD) targets adopted by the World Health Assembly in 2013 is to lower the prevalence of raised blood pressure by 25% compared to its 2010 level by 2025 (5).

The prevalence of raised blood pressure varies substantially across and within regions and countries, with age-standardised adult prevalence in 2015 ranging from 20% in the high-income Asia Pacific region to 33% in central and eastern Europe for men, and from 11% in the high-income Asia Pacific region to 28% in sub-Saharan Africa for women (4). Prevalence has declined substantially in high-income regions for decades and is also declining in some middle-income regions; it has been stable or has increased in other low- and middle-income regions (4).

Blood pressure is a multifaceted trait, affected by genes, foetal and early childhood nutrition and growth (6), adiposity (7, 8), diet (especially sodium and potassium intakes) (7, 9, 10), alcohol use (8, 11), smoking (12), physical activity (8, 13), air pollution (14), lead (15), noise (16), psychosocial stress (17), and the use of blood pressure lowering medicines. Changes in some of these factors, for example increase in body-mass index (BMI) and better nutrition in childhood and adolescence, can shift the entire population distribution of blood pressure, and hence change its mean as well as the prevalence of raised blood pressure. In contrast, the use of antihypertensive medicines and lifestyle change to reduce blood pressure in those with elevated levels would reduce the prevalence of raised blood pressure by acting on the high-blood-pressure tail of the distribution, and hence change the shape of the distribution with a relatively small impact on its mean. An important question that can inform strategies for meeting the global target and reducing the burden of raised blood pressure, is to what extent regional differences and changes over time in the prevalence of raised blood pressure are driven by variations in the mean SBP and DBP versus by the shape of the distribution. We used a database of population-based studies with global coverage conducted over three decades to investigate contributions of population mean and high-blood-pressure individuals to worldwide trends and variations in raised blood pressure.

Results

We used data from 981 population-based studies with 11,618,576 participants (Supplementary Table 1), of whom 10,630,495 were aged 20-79 years and satisfied the above inclusion criteria. 380 studies were from the high-income western region, 101 each from central and eastern Europe and east and southeast Asia, 98 from central Asia, Middle East and north Africa, 80 from sub-Saharan Africa, 76 each from high-income Asia Pacific and Latin America and the Caribbean, 36 from south Asia and 33 from Oceania. The individual-level data were summarised into 7,600 age-sex specific pairs of mean and prevalence of raised blood pressure.

The coefficients of the regression models are listed in Supplementary Tables 2 and 3. Together, mean SBP and DBP, decade, age group and region explained most of the variation in the prevalence of raised blood pressure, evidenced by the high pseudo-R^2 statistics of 0.952 for women and 0.932 for men.

The prevalence of raised blood pressure decreased substantially from 1985-1994 to 2005-2016 in the two high-income regions and central and eastern Europe in both men and women across all ages (Figure 2) (4). It also decreased in Latin America and the Caribbean, and central Asia, Middle East and north Africa, and marginally in men in sub-Saharan Africa. Over the same period, mean SBP and mean DBP decreased in these regions and sexes, except in men in sub-Saharan Africa, whose mean SBP and DBP increased, and in men in central Asia, Middle East and north Africa, whose mean SBP and DBP were unchanged. In 2005-

2016, the age-standardised prevalence of raised blood pressure in people aged 20-49 years ranged from 4% (95% credible interval: 3%-6%) in the high-income Asia Pacific to 16% (13%-19%) in sub-Saharan Africa in women, and from 14% (11%-17%) in the high-income Asia Pacific to 25% (21%-30%) in central and eastern Europe in men. In those aged 50-79 years, the range was from 31% (26%-36%) in high-income Asia Pacific to 56% (52%-61%) in sub-Saharan Africa in women, and from 40% (36%-43%) in the high-income western region to 57% (51%-63%) in central and eastern Europe in men.

Although in 2005-2016 the ranking of regions in terms of prevalence of raised blood pressure was largely the same as that of the mean, especially for women, inter-region differences in prevalence were not entirely due to those of mean blood pressure. Rather, some regions had an excess prevalence compared to what would be expected based on their mean, and others a lower prevalence compared to what would be expected based on their mean. At the same level of population mean SBP and DBP as that of the world as a whole, men and women in south Asia would have the highest prevalence of raised blood pressure, about 2-4 percentage points higher than the world average in different age and sex groups (Figure 3). Next highest would be in central Asia, Middle East and north Africa, followed by that in Latin America and the Caribbean. In contrast, at the same level of population mean SBP and DBP as that of the world as a whole, high-income Asia Pacific would have the lowest prevalence, followed by central and eastern Europe, with prevalence about 2-4 percentage points lower than the world average across different age and sex groups. The ordering of regions in terms of excess prevalence was similar between men and women.

In most regions, sex and age groups that experienced a decline in the prevalence of raised blood pressure, the decline in mean blood pressure was the main driver of the decline in prevalence (Figure 4). The main exceptions to this distributional shift were men in sub-Saharan Africa and in central Asia, Middle East and north Africa whose mean blood pressure increased or remained unchanged while prevalence declined slightly. Further, in men in Latin America and the Caribbean, change in prevalence-mean association contributed marginally more to prevalence decline than did the decline in mean blood pressure. Elsewhere, the decline in mean blood pressure accounted for about one half or more of the decline in the prevalence of raised blood pressure, with a larger contribution where mean blood pressure declined more, typically in high-income regions. Change in the prevalence-mean association, which represents change in the high-blood-pressure tail of the distribution, was responsible for the majority of the remainder of change in prevalence, and for its entirety among men in sub-Saharan Africa and in central Asia, Middle East and north Africa. The contribution of change in prevalence-mean association was larger in those aged 50-79 years than in those aged 20-49 years in most regions, especially for women.

The prevalence of raised blood pressure increased among men and women in Oceania and south Asia, and among women in sub-Saharan Africa and men in east and southeast Asia. The increase was driven entirely by rise in mean blood pressure, offset partly by the change in the prevalence-mean association. Prevalence of raised blood pressure remained largely unchanged among women in east and southeast Asia, due to opposing effects of increasing mean and the decrease brought by the changes in prevalence-mean association.

Discussion

We found that the trends and geographical variations in the prevalence of raised blood pressure are largely driven by shifts in the distribution of blood pressure in whole populations, rather than by the shape of the distribution. There was nonetheless contribution from having fewer high-blood-pressure individuals at the same level of population mean SBP and DBP, generally towards lowering the prevalence of raised blood pressure over time, especially in older age groups.

Rose and Day (18) and Laaser *et al* (19) used data from the Intersalt Study and from population-based studies in Germany, respectively, and found a strong association between prevalence of raised blood pressure and its mean, as we did, but neither analysis had sufficient data to quantify how the association varied in relation to age, time period or region as was done here. An analysis of data from the multi-country MONICA Project (20) found that the upper percentiles of blood pressure distribution changed as much as its mean in some communities, and by a larger amount in others. The authors concluded that the decline in blood pressure is mostly a population phenomenon but there was no detailed quantification of the contribution, especially in relation to age, time period or region as was done here with substantially more data. Downward shifts in the whole blood pressure distribution over time have also been reported in a few high-income countries (21-28), with some studies also finding a larger decline in the upper tail than in the mean of the blood pressure distribution which is consistent with our results.

The strengths of our study include presenting the first global analysis of how much population mean and high-blood-pressure individuals have contributed to worldwide trends and variations in raised blood pressure, using a large global database with data from different regions and over time, and using methods that allowed the prevalence-mean association to vary by sex, age group, time period and region. Despite using the most comprehensive global collection of population-based studies to date, some regions had limited data, especially early in our analysis period. Further, there have been changes over time in devices used for measuring blood pressure in health surveys, with standard mercury sphygmomanometers replaced by random-zero sphygmomanometers and more recently digital oscillometric devices. These changes are unlikely to have affected our regional comparisons, and would only affect prevalence-mean association over time if they had differential effects at high versus low blood pressure.

Although we found that changes in the prevalence of raised blood pressure have been mostly due to whole-distribution shifts, the behavioural, nutritional and environmental drivers of this shift remain uncertain. In high-income countries, the decline in blood pressure has occurred despite the rise in BMI (29), which is an established risk factor for high blood pressure, but how the concurrent and at times larger rise in BMI in low- and middle-income countries may be affecting blood pressure is unclear. Salt intake has declined in China (30) and possibly in some high-income countries (31-33), but has not changed in other countries where blood pressure has declined (34-38). Similarly, prevalence of smoking has declined in most high-income countries and in some middle-income countries but remains high or is increasing in other low- and middle-income regions (39). Other potential population-wide drivers of the decline in mean blood pressure which tend to improve with social and economic development include year-round availability of fruits and vegetables, which might increase the amount and regularity of their consumption (40); central heating at home and work which would lower winter blood pressure (41-43); and improvements in early childhood and adolescent nutrition, as seen in greater height in successive birth cohorts when they reach adulthood (44). A role for such distal determinants with life-course impacts is strengthened by the fact that blood pressure is also decreasing in adolescents in high-income countries and possibly some middle-income countries (45-49).

While these determinants act to lower mean blood pressure, better developed health systems are more effective in identifying and treating high-blood-pressure individuals, which would change the tail of the distribution without a major impact on its mean. The role of treatment in reducing the prevalence of high blood pressure has become increasingly important as clinical guidelines have lowered the threshold for diagnosing and treating hypertension, e.g., from having a SBP of 160 mmHg or DBP of 95 mmHg in the 1970s (50) to a SBP of 140 mmHg or DBP of 90 mmHg now (3, 51). Over time, a larger share of people with raised blood pressure are treated in high-income countries (21, 52-59), and in some middle-income countries (60-65). Further, there has been improvements in effectiveness of treatment over time, leading to better control of those with hypertension. It may also be the case that changes in some risk factors, e.g., lower salt intake, have larger benefits for people whose blood pressure is high compared to those with low blood pressure (9), hence changing the high-blood-pressure tail of the distribution as well as its mean.

Our results demonstrate that changes in blood pressure both at the population and individual level have contributed to lowering raised blood pressure. What factors have spurred the former over the past few decades, however, remain largely unclear, and may be related to societal changes in nutrition, housing, and health systems arising from social and economic development and technological progress. They also demonstrate the need for data that go beyond identifying the causes of low or high blood pressure, but also help measure how these factors change over time in worldwide populations. Learning about these factors would inform programmes that can help reverse the rise in the prevalence of raised blood pressure or accelerate its decline in low- and middle-income nations, where prevalence remains the highest, more effectively.

Methods

Study design

We first used population-based data to estimate the association between the prevalence of raised blood pressure, defined as SBP ≥140 mmHg or DBP ≥90 mmHg, and population mean SBP and DBP among men and women aged 20 to 79 years in nine regions of the world from 1985 to 2016. Our statistical model, described below, allowed the prevalence of raised blood pressure *at any level of mean SBP and DBP* to differ by age group, region and time period. We then used the fitted association to estimate the contributions of changes in the population mean blood pressure versus in the shape of its distribution (represented by how the prevalence-mean association varied over region and time) to the changes in the prevalence of raised blood pressure in different regions.

Data sources

We used data from NCD Risk Factor Collaboration (NCD-RisC) database, which contains studies that had measured blood pressure in representative samples of the national populations, or of one or more subnational regions and communities. Our methods for identifying and accessing data sources, and the inclusion and exclusion criteria, are described in a recent publication on blood pressure trends (4). Here, we analysed data collected from 1985 to 2016 on men and women aged 20-79 years, in 10-year age groups from 20-29 years to 70-79 years. We excluded data points which did not cover complete ten-year age groups, e.g. those in people aged 25-29 years or 60-64 years, to avoid bias in the estimated associations.

Statistical methods

We calculated mean SBP, mean DBP and prevalence of raised blood pressure by sex and 10-year age group in each study, taking into account complex survey design and survey sample weights, where relevant. We excluded age-sex groups with <25 participants, because their means and prevalence have larger uncertainty. We then estimated the relationship between the prevalence of raised blood pressure and mean, using a generalised linear mixed model, shown in the equation (where ε is the error term), separately by sex. We used a probit specification because it provided a better fit to the data than a simple linear or logit model. The model included age group (10-year age groups from 20-29 to 70-79) and the decade when the data were collected (1985-1994, 1995-2004 or 2005-2016). We also included interactions between age group and mean blood pressure, between decade and mean blood pressure, and among these three terms, which allowed the prevalence-mean association to vary by age group and over time. We included regional random intercepts to account for the differences in prevalence at any level of mean SBP and DBP by region. The regions, used in previous analyses of cardiometabolic risk factors (4, 44, 66), were: central and eastern Europe; central Asia, Middle East and north Africa; east and southeast Asia; high-income Asia Pacific; high-income western countries; Latin America and the Caribbean; Oceania; south Asia; and sub-Saharan Africa. Countries in each region are listed in Supplementary Table 4. The models were fitted using a probit link function in statistical software R. Goodness of fit of the models was assessed by McFadden's pseudo-R^2, which represents the proportional reduction in error variance, and is defined as one minus the ratio of the log-likelihood of the model and that of the null model (i.e. an intercept-only model) (67).

$$\text{Prevalence of raised blood pressure} = \text{Probit}^{-1}\,(\beta_0 + \beta_1\, Mean_{SBP} + \beta_2\, Mean_{DBP} + \beta_3\, Age\_group + \beta_4\, Decade$$
$$+ \beta_5\, Age\_group \cdot Decade + \beta_6\, Mean_{SBP} \cdot Age\_group + \beta_7\, Mean_{DBP} \cdot Age\_group$$

$$+ \beta_8 \, Mean_{SBP} \cdot Decade + \beta_9 \, Mean_{DBP} \cdot Decade$$

$$+ \beta_{10} \, Mean_{SBP} \cdot Age\_group \cdot Decade + \beta_{11} \, Mean_{DBP} \cdot Age\_group \cdot Decade$$

$$+ Random\_intercept_{Region} + \varepsilon \,)$$

We used the fitted regression to quantify how much differences across regions and changes over time in the prevalence of raised blood pressure were driven by differences/changes in mean SBP and DBP, versus by differences/changes in the prevalence-mean association across region and over time. We first used the age-sex-specific global mean SBP and DBP in 2010 (~mid-point of 2005-2016 period) in the fitted association, and estimated the prevalence of raised blood pressure by region. The age-sex-specific mean SBP and DBP values were taken from a recent comprehensive analysis of worldwide trends in blood pressure (4). We report the differences between the predicted regional raised blood pressure prevalence and that of the world as a whole. These differences measure how much prevalence would vary across regions – due to geographical variations in the shape of blood pressure distribution – if they had the same population mean blood pressure.

We then decomposed total change in prevalence of raised blood pressure from 1985-1994 to 2005-2016 into contributions of change in mean SBP and DBP, change in the shape of prevalence-mean association, and interaction of the two. The contribution of change in mean was estimated by allowing mean SBP and DBP for each age, sex, and region to change over time, while keeping the decade variable fixed at 1985-1994. The contribution of change in association was estimated by setting mean SBP and DBP to their 1990 levels (mid-year of 1985-1994) for each age, sex, and region, and allowing the decade variable to change. The interaction of the two factors is the difference between total change in prevalence and the sum of the above two components. The three components are schematically shown in Figure 1.

All analyses were done separately for men and women. Results were calculated by 10-year age groups and then aggregated into two age bands, 20-49 years and 50-79 years, by taking weighted average of age-specific results; weights from the WHO standard population were used.

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Author contributions

M.E. designed the study and oversaw research. Members of the Country and Regional Data Group collected and reanalysed data, and checked pooled data for accuracy of information about their study and other studies in their country. B.Z. and M.D.C. led data collection. B.Z. and J.B. led the statistical analysis. B.Z. prepared results. Members of the Pooled Analysis and Writing Group collated data, checked all data sources in consultation with the Country and Regional Data Group, analysed pooled data, and prepared results. B.Z. and M.E. wrote the first draft of the report with input from other members of Pooled Analysis and Writing Group. Members of Country and Regional Data Group commented on draft report.

Competing financial interests

The authors declare no competing financial interests.

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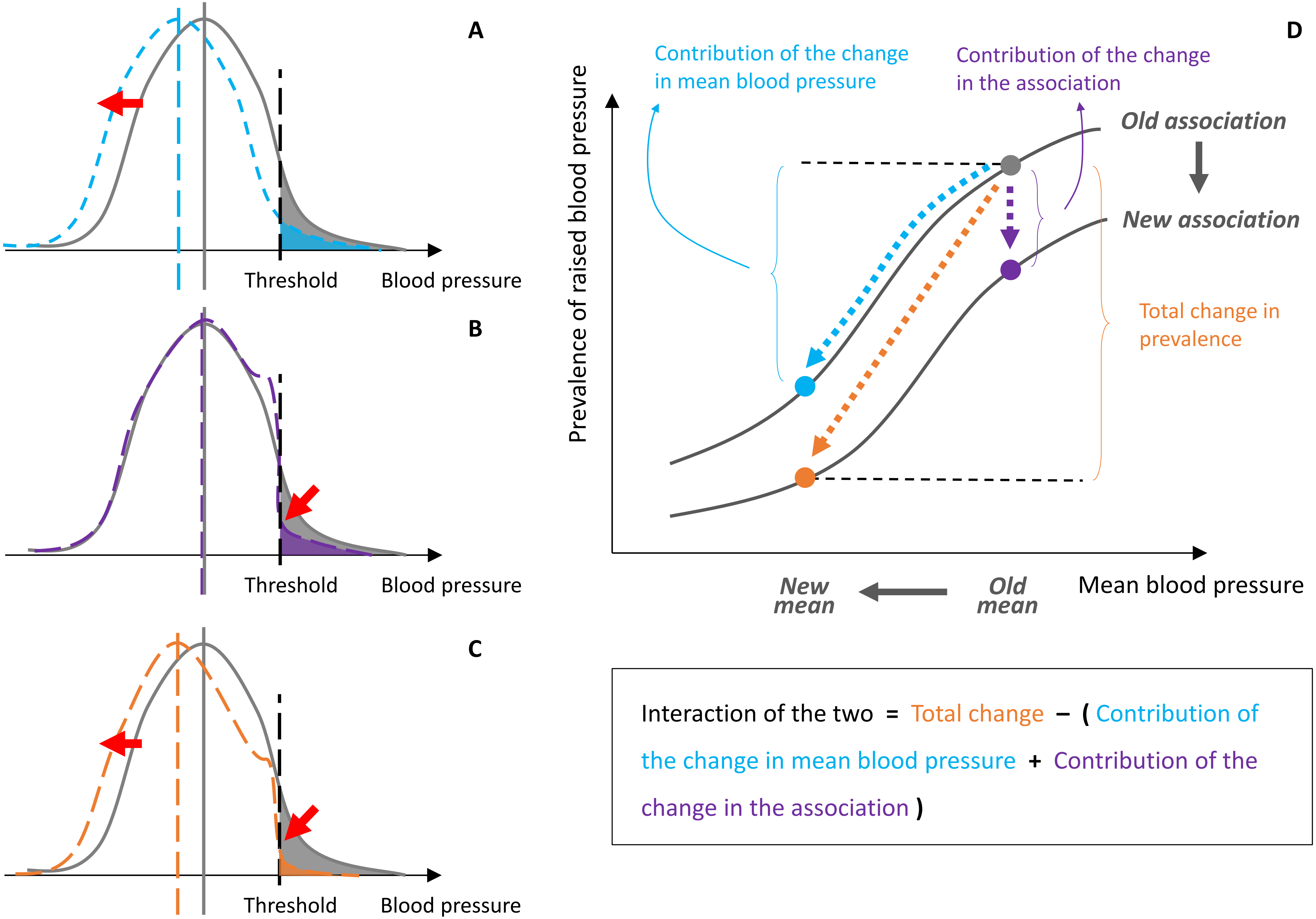
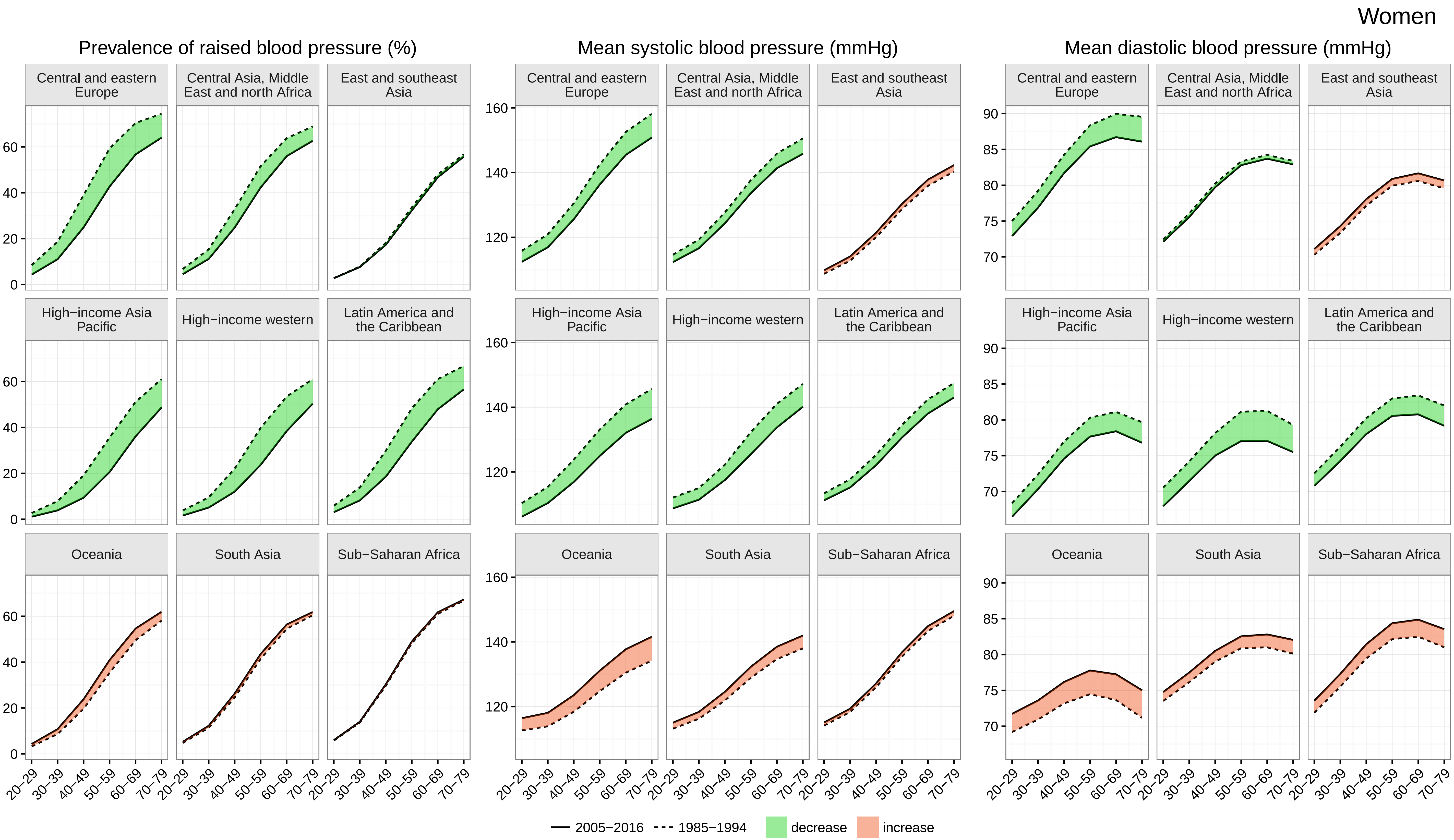


A
Threshold
Blood pressure
B
Threshold
Blood pressure
C
Threshold
Blood pressure
D
Contribution of the change in mean blood pressure
Contribution of the change in the association
Old association
New association
Total change in prevalence
Prevalence of raised blood pressure
New mean
Old mean
Mean blood pressure
Interaction of the two = Total change − (Contribution of the change in mean blood pressure + Contribution of the change in the association)

Figure 1: Schematic diagram for the contributions of change in mean blood pressure and in shape of the blood pressure distribution to the change in prevalence of raised blood pressure.

Each S-shaped curve shows what the prevalence of raised blood pressure would be at different levels of population mean for a specific shape of population distribution. A change in mean without a change in the shape of the distribution (Panel A) would move prevalence along a curve (blue point in Panel D). A change in the shape of the distribution without a change in mean (Panel B) would vertically move prevalence from one curve to another (purple point in Panel D). The combination (Panel C) would move prevalence from one curve to another, as well as along the curve (orange point in Panel D)

The figure shows the contributions when raised blood pressure is defined based on one blood pressure (either SBP or DBP). The same concept applies when raised blood pressure is defined based on both SBP and DBP.



Women
Prevalence of raised blood pressure (%)
Mean systolic blood pressure (mmHg)
Mean diastolic blood pressure (mmHg)
Central and eastern Europe
Central Asia, Middle East and north Africa
East and southeast Asia
High−income Asia Pacific
High−income western
Latin America and the Caribbean
Oceania
South Asia
Sub−Saharan Africa
20−29
30−39
40−49
50−59
60−69
70−79
2005−2016
1985−1994
decrease
increase

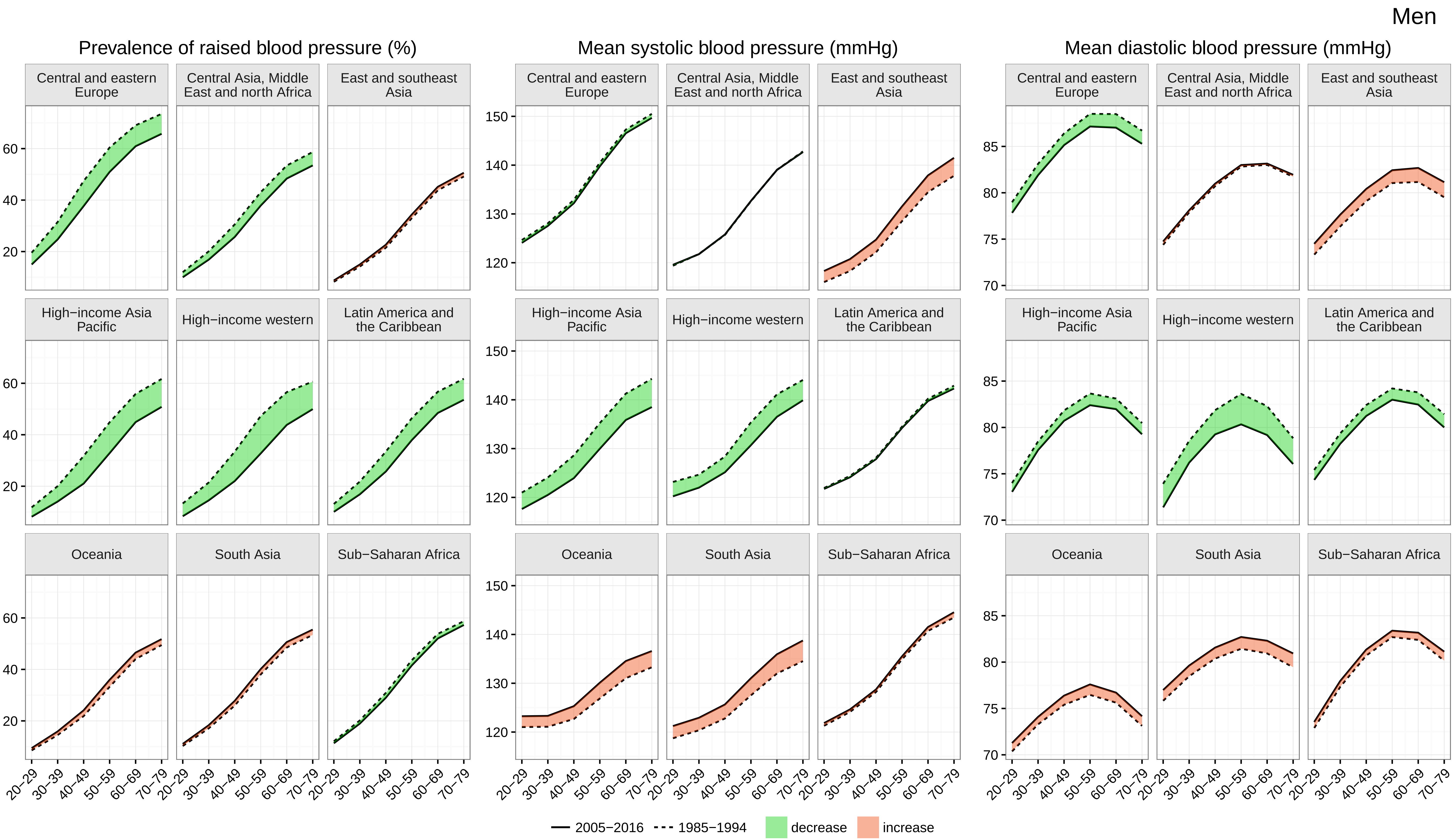

Men
Prevalence of raised blood pressure (%)
Mean systolic blood pressure (mmHg)
Mean diastolic blood pressure (mmHg)
Central and eastern Europe
Central Asia, Middle East and north Africa
East and southeast Asia
High−income Asia Pacific
High−income western
Latin America and the Caribbean
Oceania
South Asia
Sub−Saharan Africa
20−29
30−39
40−49
50−59
60−69
70−79
2005−2016
1985−1994
decrease
increase

Figure 2: Changes in prevalence of raised blood pressure, mean SBP and mean DBP from 1985-1994 to 2005-2016 by region for men and women, by age group.

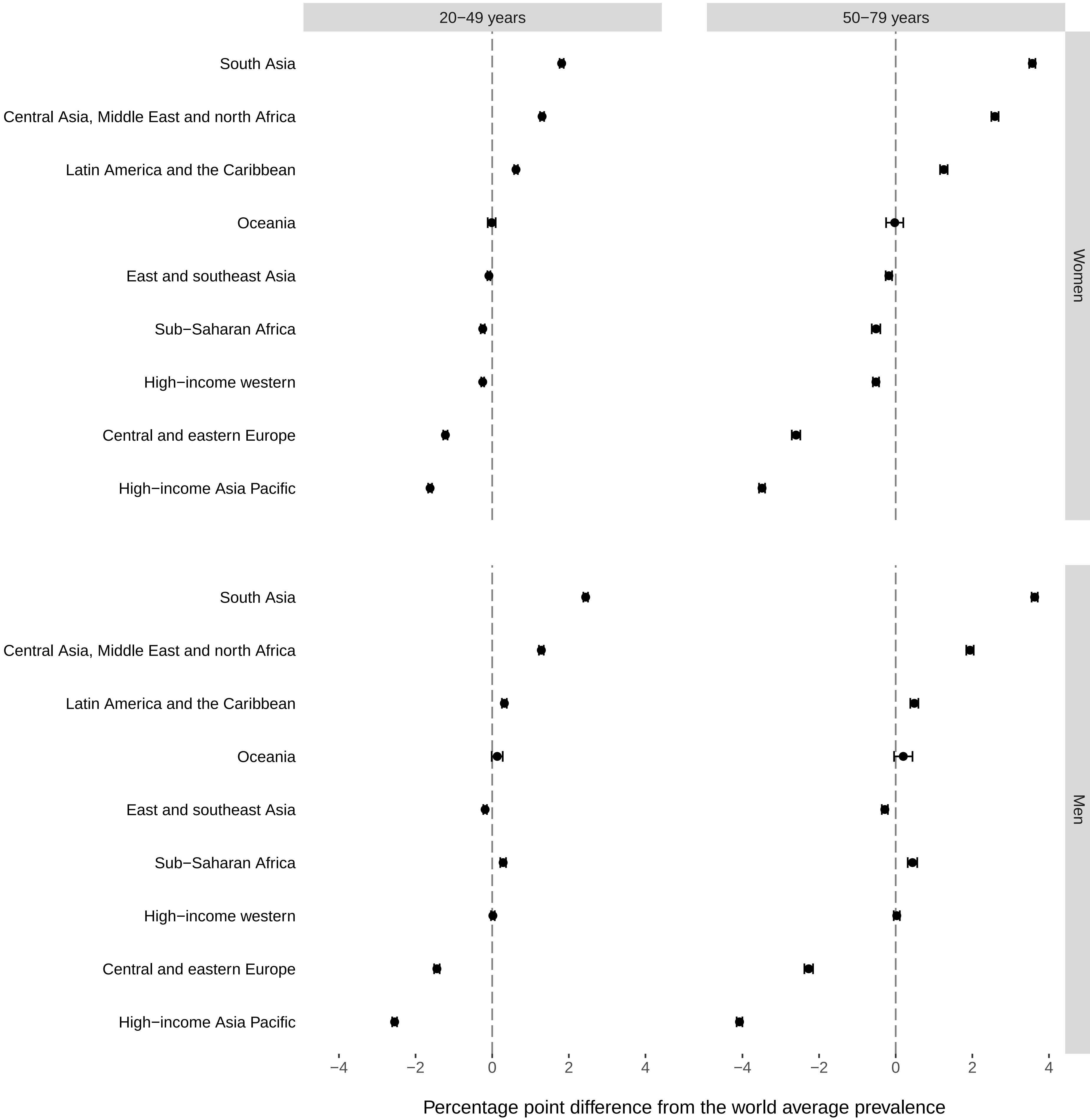
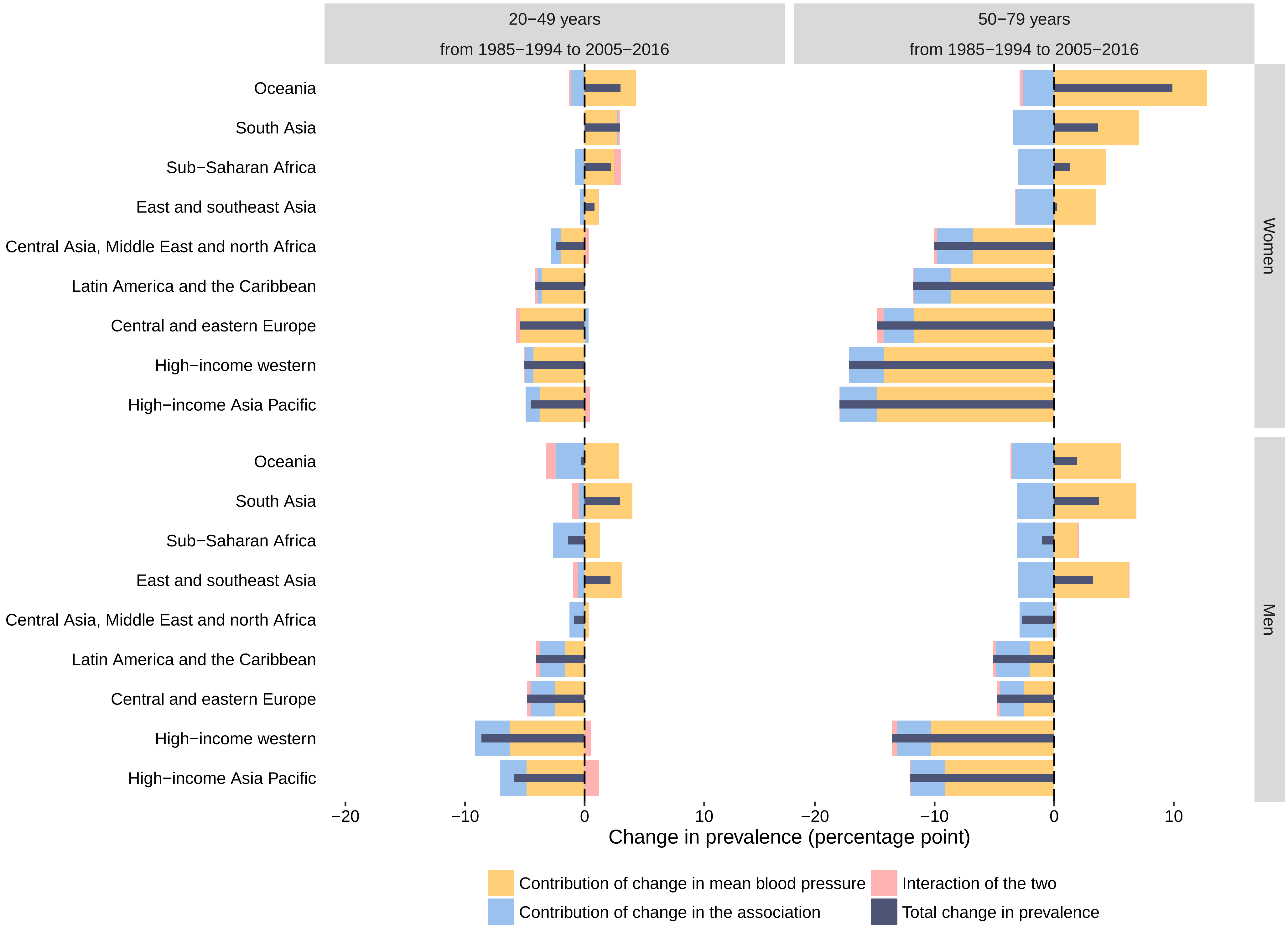

20−49 years
50−79 years
South Asia
Central Asia, Middle East and north Africa
Latin America and the Caribbean
Oceania
East and southeast Asia
Sub−Saharan Africa
High−income western
Central and eastern Europe
High−income Asia Pacific
Women
Men
−4
−2
0
2
4
Percentage point difference from the world average prevalence

Figure 3: Regional differences in prevalence of raised blood pressure among men and women aged 20-49 years and 50-79 years in 2005-2016 if every region had the same mean SBP and DBP, equal to the global age-sex-specific mean in 2010.



20−49 years
from 1985−1994 to 2005−2016
50−79 years
from 1985−1994 to 2005−2016
Oceania
South Asia
Sub−Saharan Africa
East and southeast Asia
Central Asia, Middle East and north Africa
Latin America and the Caribbean
Central and eastern Europe
High−income western
High−income Asia Pacific
Women
Men
−20
−10
0
10
Change in prevalence (percentage point)
Contribution of change in mean blood pressure
Contribution of change in the association
Interaction of the two
Total change in prevalence

Figure 4: Contributions of change in mean blood pressure, change in prevalence-mean association, and the interaction of the two, to change in prevalence of raised blood pressure since 1985-1994 by region for men and women aged 20-49 years and 50-79 years.

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