Original Article

Seasonal variation in blood pressure and its relationship with outdoor temperature in 10 diverse regions of China: the China Kadoorie Biobank

Sarah Lewington[a], Liming Li[b,c,d,*], Paul Sherliker[a], Yu Guo[c,d], Iona Millwood[a], Zheng Bian[c,d], Gary Whitlock[a], Ling Yang[a], Rory Collins[a], Junshi Chen[c], Xianping Wu[e], Shaojie Wang[f], Yihe Hu[g], Li Jiang[h], Liqiu Yang[i], Ben Lacey[a], Richard Peto[a], Zhengming Chen[a]

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Objectives: Mean blood pressure varies moderately with outdoor air temperature in many western populations. Substantial uncertainty exists, however, about the strength of the relationship in other populations and its relevance to age, adiposity, medical treatment, climate and housing conditions.

Methods: To investigate the relationship of blood pressure with season and outdoor temperature, we analysed cross-sectional data from the China Kadoorie Biobank study of 506 673 adults aged 30–79 years recruited from 10 diverse urban and rural regions in China. Analyses related mean blood pressure – overall and in various subgroups – to mean local outdoor temperature.

Results: The mean difference in SBP between summer (June–August) and winter (December–February) was 10 mmHg overall, and was more extreme, on average, in rural than in urban areas (12 vs. 8 mmHg; *P* for interaction <0.0001). Above 5°C, SBP was strongly inversely associated with outdoor temperature in all 10 areas studied, with 5.7 (SE 0.04) mmHg higher SBP per 10°C lower outdoor temperature. The association was stronger in older people and in those with lower BMI. At lower temperatures, there was no evidence of an association among participants who reported having central heating in their homes.

Conclusion: Blood pressure was strongly inversely associated with outdoor temperature in Chinese adults across a range of climatic conditions, although access to home central heating appeared to remove much of the association during the winter months. Seasonal variation in blood pressure should be considered in the clinical management of hypertension.

Keywords: blood pressure determination, China, cross-sectional studies, epidemiology, lifestyle, prospective studies

INTRODUCTION

Raised blood pressure is a leading cause of disease, disability and premature death in China [1], chiefly because of its effects on stroke [2], but its determinants in China and some other developing countries are still poorly understood [3]. In western countries, average SBP among adults is generally higher in winter than in summer, and this variation is considered to be largely mediated through outdoor air temperature [4–7]. Despite this, substantial uncertainty remains about the strength of the association in different parts of the world (especially in low-income and middle-income countries) and whether the association is modified by other climatic conditions (such as humidity), housing conditions (such as central heating), other known determinants of blood pressure (such as age, alcohol drinking and adiposity) or anti-hypertensive treatment.

Although regional and seasonal variations in outdoor temperature are unusually large in China (http://2011.cma.gov.cn/en/forecasts/), their relationship with blood pressure in the country has never been examined properly in a large-scale study. We report a large cross-sectional study of the relationships between measured clinic blood pressure, season and outdoor temperature in over 500 000 men and women aged 30–79 years who were recruited from 10 geographically diverse areas of China over a 4-year period.

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[a]Clinical Trial Service Unit and Epidemiological Studies Unit (CTSU), University of Oxford, UK, [b]School of Public Health, Peking University, [c]Chinese Center for Disease Control and Prevention, [d]Chinese Academy of Medical Sciences, Beijing, [e]Sichuan Center for Disease Control, Chengdu, Sichuan, [f]Qingdao Center for Disease Control, Qingdao, [g]Suzhou Center for Disease Control, Suzhou, Jiangsu, [h]Huixian Center for Disease Control, Huixian, Hennan and [i]Nangang Center for Disease Control, Haerbin, Heilongjiang, China

Correspondence to Sarah Lewington, China Kadoorie Biobank International Co-ordinating Centre, Clinical Trial Service Unit and Epidemiological Studies Unit (CTSU), Richard Doll Building, Old Road Campus, University of Oxford, Oxford OX3 7LF, UK. Tel: +44 1865 743824; fax: +44 1865 743985; e-mail: sarah.lewington@ctsu.ox.ac.uk

*Chinese correspondence to LiMing Li, China Kadoorie Biobank National Co-ordinating Centre, 9 Dong Dan San Tiao, Dong Cheng District, CAMS, Beijing 100730 China, e-mail: lmlee@vip.163.com.

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METHODS

Baseline survey

Detailed information about the study design and procedures has been reported previously [3,8]. In brief, the baseline survey took place from June 2004 to July 2008 in 10 (five urban and five rural) geographically defined areas of China (eFig. 1, http://links.lww.com/HJH/A178). In each study area, temporary assessment clinics were set up within the local residential centre (village or street committee), and all men and women aged 35–74 years who were permanent residents and had no major disability were identified through official residential records and invited to participate. (A small number of volunteers who were slightly outside the defined age range were also enrolled during the survey.) All the study clinics were provided with electric heaters to keep the rooms warm during winter, with the exception of two areas: Harbin in the far northeast because it had central heating in all clinics and Haikou in the most southern region of China because it did not need heating.

At the baseline survey, detailed socio-demographic, lifestyle and medical data were collected using an interviewer-administered laptop-based questionnaire. A range of physical measurements were done, including height, weight and blood pressure, and a blood sample was collected for storage and future analyses. Blood pressure was measured twice using a UA-779 digital monitor after participants had remained at rest in a seated position for at least 5 min. If the difference between the two measurements was more than 10 mmHg for SBP, a third measurement was made and the last two measurements were recorded. The mean of the two recorded values was used for analysis. The procedure for blood pressure measurement was standardized across the 10 study areas, and all measurements were made by trained study personnel, generally within 20 min of entering the clinic. The digital monitor has been tested according to ANSI/AAMI SP-10 1987 (http://www.aandd.jp/products/manual/medical/ua-779.pdf), and all devices were regularly maintained and calibrated to ensure consistency of measurements.

Ethics approval was obtained from the Ethics Review Committee of the Chinese Center for Disease Control and Prevention, Beijing, China, and the Oxford Tropical Research Ethics Committee, University of Oxford, Oxford, UK. All study participants provided written informed consent.

Meteorological data

Daily meteorological measurements for the years 2004–2008 were obtained from the local offices of the China Meteorological Administration (http://2011.cma.gov.cn/en/forecasts/). For urban areas, the local meteorological offices were located in the same city as the study site, whereas for rural areas, they were in the same county as the study site (the distances between the meteorological offices and the study sites was generally within 15 km). Of the 512 891 people recruited, 99% (506 673 participants) had corresponding data on mean outdoor temperature (the average of four measurements taken at 0200, 0800, 1400, 2000 h) on the day of their baseline survey, 78% of whom also had data on mean outdoor relative humidity (no data were available for two areas). Mean monthly, summer (June, July, August) and winter (December, January, February) outdoor temperatures were calculated as the average of the recorded mean outdoor temperatures for all the participants who were surveyed during that month or season.

Statistical methods

The mean SBP and DBP – adjusted to the mean age and the distributions of sex and area within the whole study population – were calculated for each calendar month of the 4-year study recruitment period (January and February have been combined to allow for the very limited recruitment over the Chinese New Year) and plotted against the mean number of days from the first day of recruitment. Adjusted mean values were calculated using the method of least squares. For subgroup analyses, participants were grouped by month of recruitment (regardless of the year) and adjusted mean blood pressure was plotted against the mean day of the year for each month. Subgroups studied were study area, sex, age, BMI, use of antihypertensive treatment, type of home heating used and, for men only, current alcohol drinking status and current smoking status (there were too few female drinkers and smokers for reliable analyses). To obtain the estimated change in blood pressure per 10°C lower outdoor temperature, a multiple linear regression analysis was done of individual SBP on individual outdoor temperature adjusted for age, sex and area; observations below 5°C were omitted from the regression because they showed a different pattern to those above 5°C (see Results section).

In addition, adjusted means of SBP were calculated for participants grouped by deciles of both outdoor humidity and temperature (i.e. 100 groups). To investigate whether humidity was a modifier of the association between outdoor temperature and SBP, adjusted mean SBP in each group was plotted against the mean outdoor temperature with symbols indicating the deciles of humidity. Conversely, to investigate whether outdoor temperature was a modifier of the association between humidity and SBP, adjusted mean SBP in each group was plotted against the mean relative humidity with symbols indicating the deciles of outdoor temperature.

All analyses were performed using SAS version 9.2 (SAS Institute Inc., Cary, North Carolina, USA).

RESULTS

The main characteristics of the study participants are given in Table 1. Overall, the mean (SD) age at the baseline survey was 52 (11) years and 41% of participants were men, with mean age ranging from 49 to 53 years and percentage men from 36 to 44% across the 10 study areas. Both SBP and DBP were slightly lower in urban than in rural areas (129/77 vs. 133/78 mmHg), but the proportion reported receiving antihypertensive treatment was higher in urban areas (15 vs. 11%). The mean (SD) BMI was 24.3 (3.4) kg/m^2 in urban areas compared with 23.2 (3.3) kg/m^2 in rural areas. The prevalence of regular alcohol drinking in men was higher in urban than in rural areas (38 vs. 29%), whereas the opposite was true for current smoking (55 vs. 66%). The prevalences were much lower in women – about 2% overall for both

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TABLE 1. Characteristics of study participants, by area

Area	Number of participants[a]	Mean (SD)				Percentage					
		Age (years)	SBP (mmHg)	DBP (mmHg)	BMI[b] (kg/m^2)	Men	Current smokers, men only[c]	Weekly drinkers, men only[c]	Treated for hypertension	With home heating	With home central heating
Harbin	57 555	53 (11)	128 (21)	78 (12)	24.6 (3.4)	40	51	49	15	100	94.4
Qingdao	35 506	50 (10)	132 (21)	79 (11)	25.7 (3.5)	44	59	48	14	98	19.5
Suzhou	53 260	52 (10)	133 (20)	79 (10)	24.0 (3.2)	42	68	41	17	20	0.3
Liuzhou	50 173	54 (10)	128 (21)	75 (11)	23.8 (3.2)	39	49	27	16	30	0.2
Haikou	29 688	53 (12)	124 (22)	74 (11)	23.3 (3.3)	36	42	16	10	0	0.0
All Urban	226 182	52 (11)	129 (21)	77 (11)	24.3 (3.4)	40	55	38	15	52	27.2
Henan	63 357	50 (10)	134 (21)	79 (11)	24.3 (3.5)	44	59	25	15	83	0.1
Gansu	50 041	49 (11)	131 (23)	78 (12)	22.7 (3.1)	39	72	8	8	99	0.6
Sichuan	49 557	51 (11)	129 (19)	77 (10)	23.3 (3.2)	38	67	49	4	28	0.3
Zhejiang	57 704	52 (10)	136 (21)	80 (11)	22.9 (3.2)	42	65	38	17	1	0.0
Hunan	59 832	52 (11)	131 (22)	76 (11)	22.4 (3.1)	44	69	24	12	99	0.2
All Rural	280 491	51 (10)	133 (21)	78 (11)	23.2 (3.3)	41	66	29	11	63	0.2
Overall	506 673	52 (11)	131 (21)	78 (11)	23.7 (3.4)	41	61	33	13	58	12.3

[a]Number with data on both SBP and mean temperature on day of screening visit.
[b]BMI was calculated as weight in kilograms divided by the square of the height in metres.
[c]Only 2% of women were current smokers and 2% weekly drinkers.

drinking and smoking. There were very large differences between the areas in the reported availability and type of heating in the home: 94% of participants in Harbin and 20% in Qingdao (both northern urban areas) reported having central heating in their homes, but less than 1% of the participants in the remaining areas, even though other forms of heating were used to a certain extent in many areas.

Figure 1 shows the mean SBP in each month of recruitment. There was an approximately sinusoidal pattern, with

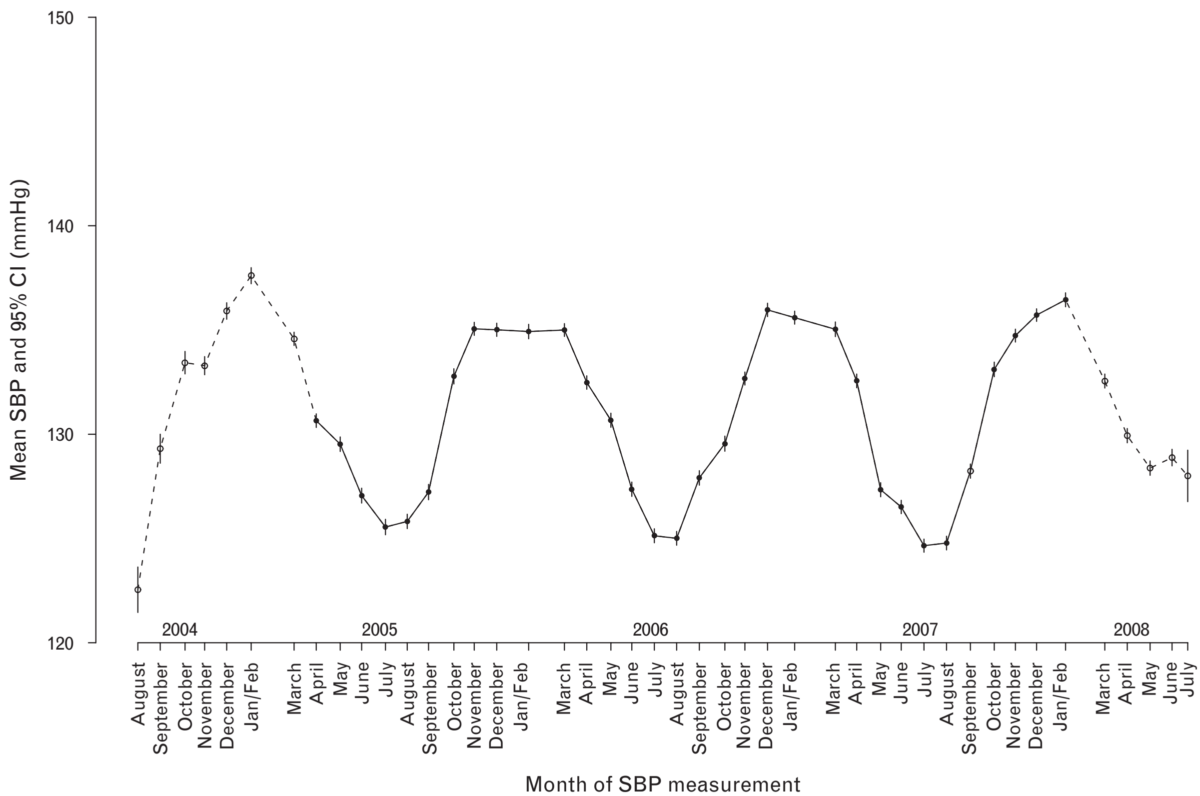

FIGURE 1 SBP by month of measurement among 506 673 men and women. Mean SBP adjusted for age, sex and area. Only includes months with more than 100 participants. The solid circles joined by a solid line indicate months when all 10 areas were actively recruiting and the open circles (joined by a dotted line at the beginning and end of the study period) indicate months when only some were active. There is an open circle for September 2007 when Haikou did not recruit due to re-organization of the survey team. The horizontal placement of each month indicates, for participants recruited in that month, the mean number of days since the first participant was recruited. Jan/Feb, January and February combined (recruitment dropped in January and February due to the Chinese New Year).

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the lowest SBP levels of about 125 mmHg during the summer months and the highest levels of about 135 mmHg during the winter months.

This seasonal variation in SBP was apparent within each of the 10 areas studied, with SBP generally rising as outdoor temperatures fell (Fig. 2). Overall, the mean difference between winter and summer was more extreme in the five rural than in the five urban areas (12 vs. 8 mmHg; P for interaction <0.0001; Table 2). Although blood pressure followed a broadly similar seasonal pattern across the 10 study areas, the differences in SBP between winter and summer ranged from 16 mmHg in Zhejiang to only 4 mmHg in Haikou (Table 2 and Fig. 2). Harbin, a city in the far northeast of China where almost all participants had proper central heating, was the most striking exception to this pattern: in that city, the mean SBP differed by only 7 mmHg even though the mean outdoor temperature was on average 36°C colder in winter than in summer (Table 2).

The seasonal variation in DBP was generally similar to SBP (eFig. 2, http://links.lww.com/HJH/A178), although with a much smaller overall mean difference of 4 mmHg between winter and summer (eTable 1 and eFig. 4, http://links.lww.com/HJH/A178). As with SBP, the mean difference appeared to be greater in rural than in urban areas (5 vs. 2 mmHg; P for interaction <0.0001), ranging from no apparent difference in Qingdao to 7 mmHg in Zhejiang (eTable 1, http://links.lww.com/HJH/A178).

When the mean SBP in each area was plotted against the mean monthly outdoor temperature in that area for each month, there was an approximately linear inverse relationship above 5°C, with a mean rise of 5.7 (SE 0.04) mmHg SBP for each 10°C lower outdoor temperature (Fig. 3 and Table 2). Despite differences in mean SBP between areas at any given outdoor temperature, the difference in SBP for a given difference in outdoor temperature above 5°C was generally similar and did not seem to be modified by latitude. Indeed, Suzhou and Zhejiang, the two closest regions (only 0.7° latitude apart), had the weakest and strongest associations with outdoor temperature, respectively.

The association between season and SBP was evident in all of the subgroups studied (Fig. 4 and eTable 2, http://links.lww.com/HJH/A178), except among participants with central heating (who were mainly in Harbin, see above), for whom mean SBP was fairly stable between October and March. The absolute difference between summer and winter increased with age up to about 70 years (from 7.8 mmHg difference at age 30–39 years to 11.2 mmHg at 60–69 years), although the percentage difference was similar in all age groups (7–8 higher in winter than in summer). By contrast, both the absolute and percentage difference increased with decreasing BMI – from 9.3 mmHg and 7%, respectively, at 30–39 kg/m^2 to 12.2 mmHg and 11%, respectively, at 15–18.4 kg/m^2. The absolute and percentage differences were slightly higher among ever smokers than never smokers ($P<0.0001$) but were not clearly different between types of drinkers ($P=0.08$). The percentage difference was unaltered by use of antihypertensive medication but, because those taking antihypertensives had higher blood pressure, the absolute difference was greater among them.

The associations of blood pressure with season and outdoor temperature were not modified by outdoor relative humidity (eFig. 5, http://links.lww.com/HJH/A178), and outdoor relative humidity was barely associated with blood pressure [0.13 (0.02) mmHg increase in SBP per 10% increase in humidity; eFig. 6, http://links.lww.com/HJH/A178].

DISCUSSION

This is by far the largest study ever conducted on the relation between clinic blood pressure, season and outdoor air temperature, involving over 500 000 men and women recruited from 10 geographically diverse regions of China over a 4-year period. The average clinic blood pressure was substantially higher in winter than in summer (SBP/DBP: 10/4 mmHg), and this pattern of seasonal variation was highly consistent over the 4-year study period. Although the overall pattern of seasonal variation was similar, there was more than a three-fold variation in the size of the SBP difference between winter and summer across the 10 study regions. In southern and central areas, there was a reasonably consistent relationship between mean SBP and outdoor temperature throughout the year, with the blood pressure and temperature curves mirroring each other. In northern urban areas, however, adjusted mean SBP varied very little with changes in outdoor temperature during the winter months, perhaps mainly because of the widespread use of central heating at home (which we documented), and possibly also because of effective heating in other environments (e.g. at work, which we did not document), both of which would have reduced the exposure to cold temperatures.

Above 5°C, each 10°C lower outdoor temperature was associated with 5.7/2.0 mmHg higher SBP/DBP in the present study – a much stronger association was seen in other large studies, which were done mostly in high-income countries: the WHO-MONICA study of 115 434 adults from 25 populations in 16 countries and the Oslo Health Study of 18 770 Norwegian adults both reported an average 2 mmHg higher SBP per 10°C lower outdoor temperature [9–12]. This study corroborates evidence from much smaller studies that the absolute size of this association increases with age (at least, in this study, up to age 70 years) [4,13]. The previous evidence on the modifying effects of BMI on the relationship between outdoor temperature and blood pressure is more uncertain, with some studies showing only a marginally larger effect among those with low BMI [4,13] but one, among elderly people, showing a much greater difference [14]. However, because these studies were small and their populations typically somewhat overweight, they had very few lean people. The present study has now provided for the first time unequivocal evidence that both the absolute and, in particular, the percentage seasonal variation were significantly greater in lean people (e.g. BMI <22.5 kg/m^2 kg/m^2) than in nonlean people.

In addition to outdoor temperature, any seasonal variation in salt intake, adiposity or physical activity could potentially also lead to changes in blood pressure. In the present study, however, there was no seasonal

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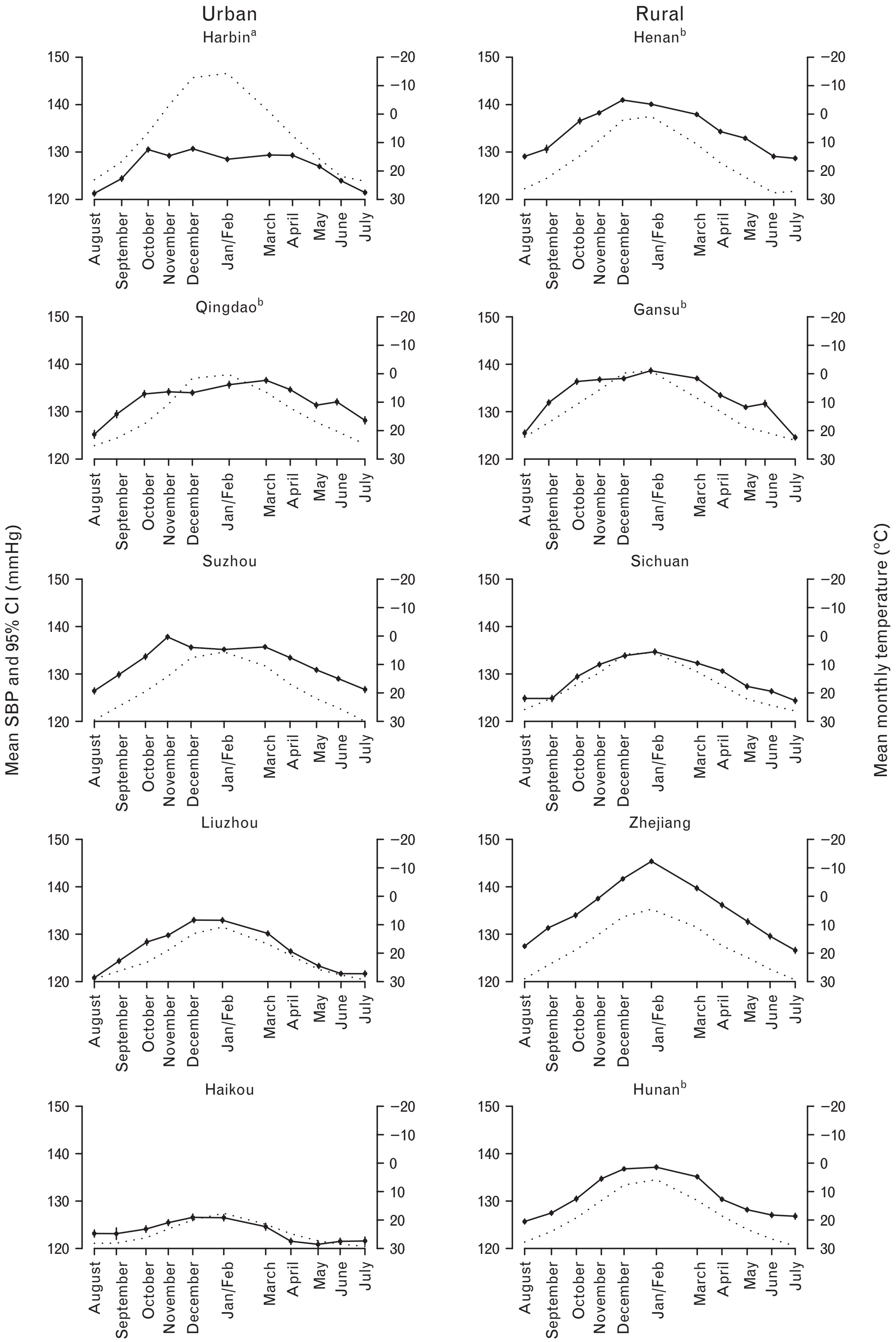

FIGURE 2 Monthly variation in SBP and outdoor temperature within each area. For both SBP and outdoor temperature, the mean monthly values are the mean for all participants whose baseline survey happened during that month (regardless of the year). SBP means adjusted for age and sex. Mean outdoor temperature is indicated by a dotted line (note the inverse scale). [a]In Harbin, 100% of participants had some form of heating in their homes; 94% had central heating. [b]Areas in which more than 80% of participants had some form of heating in their homes. Jan/Feb, January and February combined (recruitment dropped in January and February due to the Chinese New Year).

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TABLE 2. Mean outdoor temperature (°C) and SBP (mm Hg) in summer and winter, by area

Area	Latitude[a]	Summer (June, July, August) Temperature	Summer SBP[b]	Winter (December, January, February) Temperature	Winter SBP[b]	Difference (summer – winter) Temperature	Difference SBP[b]	Change (SE) in SBP per 10°C lower temperature[c] (≥5°C only)
Harbin[d]	46°N	22.8	122	−13.6	129	36.3	−7	4.8 (0.16)
Qingdao[e]	36°N	22.9	129	1.1	134	21.8	−5	4.6 (0.18)
Suzhou	31°N	27.7	127	6.5	135	21.2	−8	4.6 (0.11)
Liuzhou	24°N	28.6	121	12.0	133	16.6	−11	6.7 (0.13)
Haikou	20°N	28.6	122	18.7	126	9.9	−4	4.9 (0.25)
All Urban		26.0	124	3.5	132	22.5	−8	5.2 (0.07)
Henan[e]	35°N	27.0	129	1.5	140	25.6	−12	5.4 (0.11)
Gansu[e]	35°N	22.3	127	−0.6	137	22.9	−11	7.2 (0.17)
Sichuan	31°N	25.4	125	6.1	134	19.3	−9	5.2 (0.13)
Zhejiang	31°N	28.1	128	6.0	143	22.2	−16	7.0 (0.11)
Hunan[e]	28°N	27.8	126	6.9	137	20.9	−11	5.5 (0.11)
All Rural		26.3	127	4.0	139	22.3	−12	6.0 (0.05)
Overall		26.2	126	3.8	136	22.4	−10	5.7 (0.04)

[a]Longitude given in eTable 1, http://links.lww.com/HJH/A178.
[b]SBP adjusted for age, sex and area (where appropriate).
[c]Adjusted for age, sex and area (where appropriate).
[d]Ninety-four percent have home central heating.
[e]More than 80% have home heating.

variation in the self-reported 'usual' intake of pickled vegetables (no direct information on salt intake or excretion was available) or in measured BMI, and self-reported 'usual' physical activity levels among participants varied only slightly with season (data not shown). So, it is unlikely that the observed large seasonal variation in blood pressure in this study was importantly confounded by these factors.

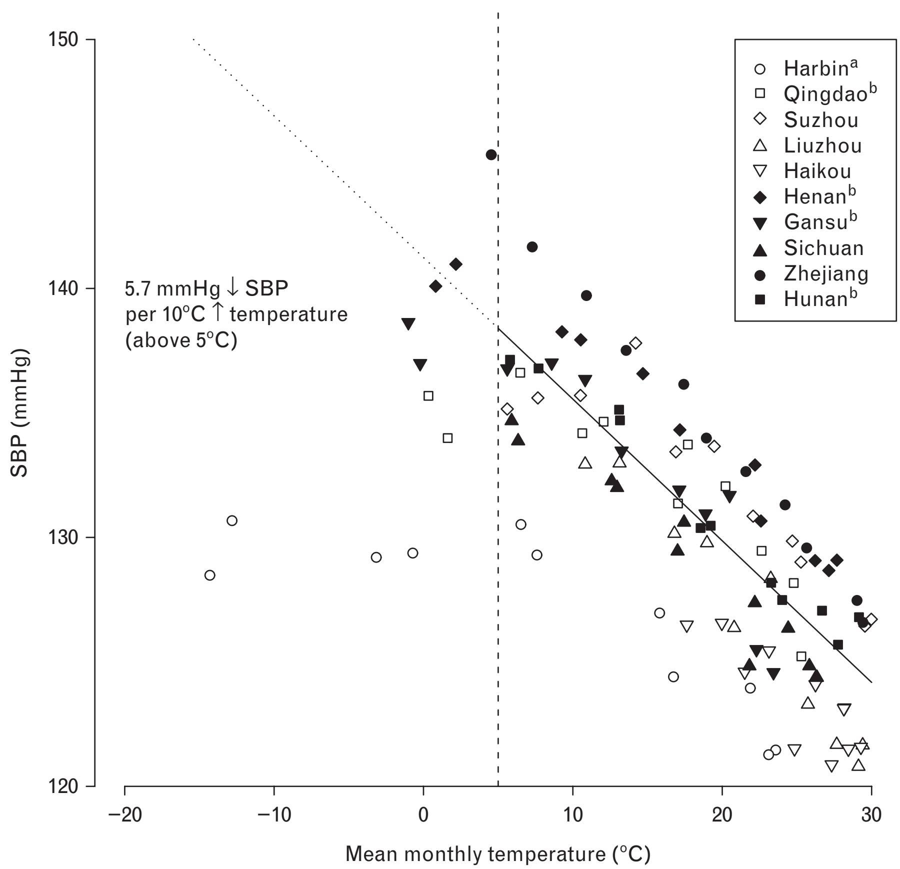

FIGURE 3 Mean SBP versus mean monthly outdoor temperature within each area. Mean SBP, but not outdoor temperature, adjusted for age and sex. Regression line is SBP versus outdoor temperature adjusted for age, sex and area, within the temperature range above 5°C. The dotted line represents the hypothetical continuation of the regression line below 5°C. [a]In Harbin, 100% of participants had some form of heating in their home; 94% had central heating. [b]Areas in which more than 80% of participants had some form of heating in their home.

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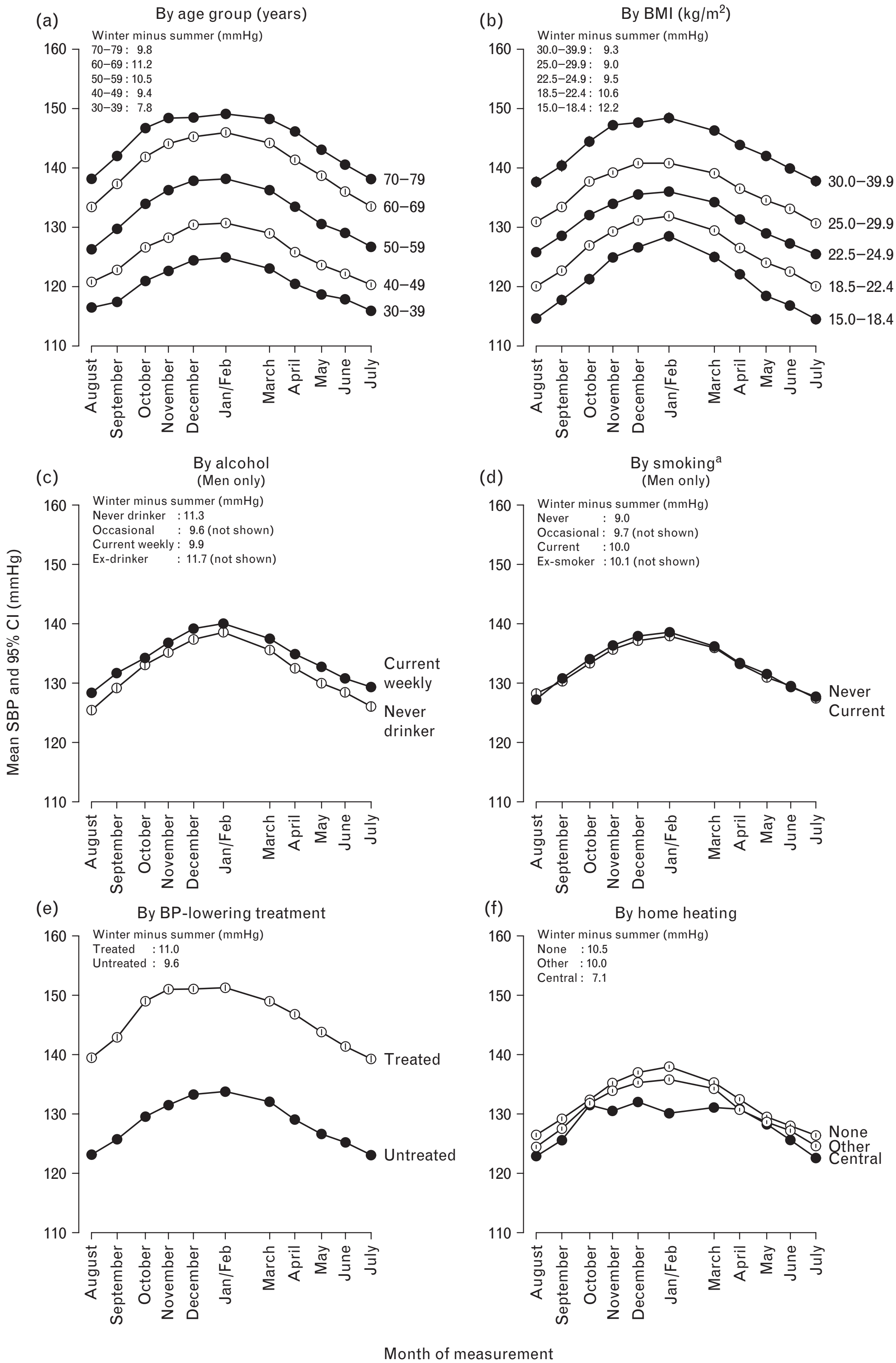

FIGURE 4 Monthly variation in SBP by various subgroups: (a) by age group (years); (b) by BMI (kg/m^2); (c) by alcohol (men only); (d) by smoking[a] (men only); (e) by blood pressure lowering treatment; and (f) by home heating. BMI was calculated as weight in kilograms divided by the square of the height in metres. Winter is December, January/February; summer is June, July, August. SBP means adjusted for age, sex and area. [a]Additionally adjusted for BMI. Jan/Feb, January and February combined (recruitment dropped in January and February due to the Chinese New Year).

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In this study, the outdoor temperature data were the daily temperatures at the nearest meteorological office and so are not a perfect measure of the outdoor temperature to which the individual had recently been exposed. Moreover, no data were available on home, workplace or other indoor temperature nor about the time each participant spent indoors, so we can only speculate about the impact they may have had on the pattern observed. If our measured outdoor temperatures were only partially correlated with the usual temperature to which the participants were exposed during the day, then our estimate of 5.7/2.0 mmHg higher SBP/DBP per 10°C lower outdoor temperature may substantially underestimate the real association [15]. Previous research has shown that lower outdoor temperatures are associated not only with higher clinic blood pressure but also with higher mean 24-h blood pressure as well as with a larger surge in morning blood pressure [16]. Although ambulatory blood pressure monitoring could, in theory, have provided a better and fuller description of the relationship between air temperature and blood pressure than our blood pressure measurements made once during the daytime, it was logistically infeasible in a community-based study of this size.

The main mechanisms by which exposure to cold temperatures increase average blood pressure in populations probably reflect a mixture of short-term and medium-term physiological adaptations to the cold. Most notably, cold exposure commonly causes arteriolar constriction and increased peripheral resistance (via increased sympathetic nervous system activity) and it can decrease sweating and, therefore, salt loss, both of which would increase blood pressure [17,18].

Increased cardiovascular mortality during winter, particularly among the elderly, has been reported in several studies [19–21]. Raised blood pressure in winter may partly account for these findings, and the effects on mortality of a winter rise in blood pressure may be particularly pronounced in China if, as these results suggest, the seasonal rise is substantially greater in parts of this country. The continuation of long-term follow-up of participants in this and other prospective studies should allow this hypothesis to be tested.

The substantial seasonal variation in blood pressure observed in this study has implications for the clinical management of, and research into, blood pressure. Many people who would not be diagnosed as hypertensive if their blood pressure was measured only in summer might be so diagnosed if it was measured at other times of the year. For people with borderline high blood pressure, measurement in different seasons may help with the decision about whether to treat. Moreover, for people who are already on treatment, higher doses or additional drug(s) may be required in winter to achieve the same blood pressure control as at other times of the year, particularly in areas with cold winters but low availability of central heating. These results suggest that better home (and possibly other) heating should attenuate the widespread winter increase in blood pressure, potentially helping to reduce the incidence of cardiovascular events in these populations.

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Members of the China Kadoorie Biobank collaborative group: International steering committee: Liming Li, Junshi Chen, Fan Wu (ex-member), Rory Collins, Richard Peto, Zhengming Chen. Study coordinating Centres: International Co-ordinating Centre, Oxford: Zhengming Chen, Garry Lancaster, Xiaoming Yang, Alex Williams, Margaret Smith, Ling Yang, Yu-mei Chang. National Co-ordinating Centre, Beijing: Yu Guo, Guoqing Zhao, Zheng Bian, Lixue Wu, Can Hou. Regional Co-ordinating Centres: 10 areas in China: Qingdao: Qingdao Center for Disease Control: Zengchang Pang, Shaojie Wang, Yun Zhang, Kui Zhang; Licang Center for Disease Control: Silu Liu; Heilongjiang: Provincial Center for Disease Control: Zhonghou Zhao, Shumei Liu, Zhigang Pang; Nangang Center for Disease Control: Weijia Feng, Shuling Wu, Liqiu Yang, Huili Han, Hui He; Hainan: Provincial Center for Disease Control: Xianhai Pan, Shanqing Wang, Hongmei Wang; Meilan Center for Disease Control: Xinhua Hao, Chunxing Chen, Shuxiong Lin; Jiangsu: Provincial Center for Disease Control: Xiaoshu Hu, Minghao Zhou, Ming Wu; Suzhou Center for Disease Control: Yeyuan Wang, Yihe Hu, Liangcai Ma, Renxian Zhou, Guanqun Xu; Guanxi: Provincial Center for Disease Control: Baiqing Dong, Naying Chen, Ying Huang; Liuzhou Center for Disease Control: Mingqiang Li, Jinhuai Meng, Zhigao Gan, Jiujiu Xu, Yun Liu; Sichuan: Provincial Center for Disease Control: Xianping Wu, Yali Gao, Ningmei Zhang; Pengzhou Center for Disease Control: Guojin Luo, Xiangsan Que, Xiaofang Chen; Gansu: Provincial Center for Disease Control: Pengfei Ge, Jian He, Xiaolan Ren; Maiji Center for Disease Control: Hui Zhang, Enke Mao, Guanzhong Li, Zhongxiao Li, Jun He; Henan: Provincial Center for Disease Control: Guohua Liu, Baoyu Zhu,

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Gang Zhou, Shixian Feng; Huixian Center for Disease Control: Yulian Gao, Tianyou He, Li Jiang, Jianhua Qin, Huarong Sun; Zhejiang: Provincial Center for Disease Control: Liqun Liu, Min Yu, Yaping Chen; Tongxiang Center for Disease Control: Zhixiang Hu, Jianjin Hu, Yijian Qian, Zhiying Wu, Lingli Chen; Hunan: Provincial Center for Disease Control: Wen Liu, Guangchun Li, Huilin Liu; Liuyang Center for Disease Control: Xiangquan Long, Youping Xiong, Zhongwen Tan, Xuqiu Xie, Yunfang Peng.

Conflicts of interest

There are no conflicts of interest.

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