Geomagnetic Storms Can Trigger Stroke

Evidence From 6 Large Population-Based Studies in Europe and Australasia

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Background and Purpose—Although the research linking cardiovascular disorders to geomagnetic activity is accumulating, robust evidence for the impact of geomagnetic activity on stroke occurrence is limited and controversial.

Methods—We used a time-stratified case-crossover study design to analyze individual participant and daily geomagnetic activity (as measured by Ap Index) data from several large population-based stroke incidence studies (with information on 11 453 patients with stroke collected during 16 031 764 person-years of observation) in New Zealand, Australia, United Kingdom, France, and Sweden conducted between 1981 and 2004. Hazard ratios and corresponding 95% confidence intervals (CIs) were calculated.

Results—Overall, geomagnetic storms (Ap Index 60+) were associated with 19% increase in the risk of stroke occurrence (95% CI, 11%–27%). The triggering effect of geomagnetic storms was most evident across the combined group of all strokes in those aged <65 years, increasing stroke risk by >50%: moderate geomagnetic storms (60–99 Ap Index) were associated with a 27% (95% CI, 8%–48%) increased risk of stroke occurrence, strong geomagnetic storms (100–149 Ap Index) with a 52% (95% CI, 19%–92%) increased risk, and severe/extreme geomagnetic storms (Ap Index 150+) with a 52% (95% CI, 19%–94%) increased risk (test for trend, $P<2\times10^{-16}$).

Conclusions—Geomagnetic storms are associated with increased risk of stroke and should be considered along with other established risk factors. Our findings provide a framework to advance stroke prevention through future investigation of the contribution of geomagnetic factors to the risk of stroke occurrence and pathogenesis. **(*Stroke*. 2014;45:1639-1645.)**

Key Words: environment ■ stroke

Although research linking cardiovascular disorders to geomagnetic activity during the past 40 years is accumulating,[1–7] robust evidence for the effect of geomagnetic activity (the earth's magnetic field) on stroke occurrence is lacking and remains a matter of controversy.[1,4,6,8] This is because most studies to date are complicated by significant methodological limitations: high likelihood of stroke misclassification and selection bias (eg, official mortality data are particularly inappropriate for studying determinants of stroke occurrence, or use of hospital-based data, including both incident and recurrent strokes in the analysis, inaccurate data on stroke onset, poor neuroimaging verification of stroke types [there are significant differences in the pathogenesis and determinants of different stroke pathological types]), arbitrary selection of a time lag between exposure and outcome (spurious associations), and small sample sizes (type I error). No reliable data exist on effects of geomagnetic activity on the risk of occurrence of different stroke pathological types in various population groups

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(eg, by age, region). Yet, these data might be important for better understanding of interrelationships between nature and human health and advancing stroke prevention.

Although accurate daily data on geomagnetic activity are readily available in most regions of the world, accurate data on stroke occurrence are only available for a limited number of regions/populations.[9] To determine associations between stroke occurrence and geomagnetic activity, it is important that stroke is seen and studied in a population context as a large proportion of the burden of care for stroke is borne outside the hospital sector.[9–11] Furthermore, studies based on official mortality data have classification bias and cannot provide reliable data on stroke onset. Stroke registers that meet criteria for an ideal population-based study[12] are regarded as the gold standard for determining stroke incidence[13] and are ideal for studying environmental triggers of stroke.[8] Yet, conducting population-based studies of stroke is challenging[9,10] and such studies are rare compared with those using mortality data, hospital-based registers, or limited to certain age groups. Another methodological challenge of studying environmental triggers of stroke is the size of the study population. As the effect of environmental factors on the risk of stroke occurrence is likely to be small (compared with biological, behavioral, and lifestyle factors), reliable determination of their effects requires a large number of incident stroke cases. However, the number of incident stroke cases in a single ideal population-based study rarely exceeds a few hundred. Pooling data from several ideal population-based stroke incidence studies containing reliable data on stroke onset and stroke pathological types offers a logical solution to the problem, but this requires sharing individual-participant data, which is not always achievable. Therefore, the pooled data used for analyses in this study provide a unique opportunity to explore environmental associations with stroke occurrence in a robust and reliable manner.

Our objective was to analyze associations between stroke occurrence in adults (age, ≥16 years) and changes in geomagnetic activity by pathological type of stroke, age groups (16–64, 65–74, ≥75 years), and level of solar activity (maxima years [greatest solar activity in the 11-year solar cycle of the Sun] and minima years [least solar activity in the 11-year solar cycle of the Sun]). This project aims to obtain robust evidence to support or refute the hypothesis that geomagnetic storms can trigger stroke onset.

Methods

Study Population

The collaboration was performed under the auspices of the International Stroke Incidence Studies Data Pooling Project[14] using individual-participant population-based stroke data in people aged ≥16 years obtained from observations that met criteria for ideal population-based stroke incidence studies[11] undertaken in Auckland, New Zealand (1981–1982, 1991–1992, and 2002–2003); Melbourne, Australia (1996–1999); Perth, Australia (1989–1990 and 1995–1997); Oxfordshire, United Kingdom (2002–2005); Dijon, France (1994–2004); and Northern Sweden (1985–2004). Details of stroke case ascertainment in these centers have been reported elsewhere.[15–21] In brief, multiple overlapping sources, including hospitals within and outside the study areas, local community services, general practitioners, residential care facilities, and national mortality and hospital morbidity data, were checked prospectively to identify all new stroke cases (including cases of suspected stroke and transient ischemic attack) that occurred in adults (≥16 years) who were residents of the study region of each of the participating centers. In each of the centers, the local Ethics Committee approved the study, and written informed consent was obtained from all patients or from a next of kin when patients were dead or severely disabled. We followed Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines.[22]

Diagnostic Criteria and Units of Measurement

Stroke was defined by standard World Health Organization clinical criteria[23] and categorized into 3 pathological types (ischemic stroke, intracerebral hemorrhage, subarachnoid hemorrhage, total strokes, including stroke of undetermined pathological type) according to neuroimaging (computed tomography/MRI/autopsy) findings. Cases without neuroimaging or pathological autopsy confirmation of stroke type were classified as stroke of undetermined type. Only first-ever-in-a-lifetime stroke cases (incident strokes) were analyzed in this report. Planetary geomagnetic activity, as measured by daily averaged Ap indices, was evaluated as effects of geomagnetic storms categorized by the level of storm severity into 3 groups: moderate (60–99 Ap Index), strong (100–149 Ap Index), and severe/extreme (150+ Ap index).[24] Geomagnetic activity was obtained from the World Data Center for Geomagnetism, Kyoto, and National Oceanic and Atmospheric Administration Space Environment Center, Boulder, CO, for the same study periods as for the stroke occurrence.

Statistical Analysis

We applied a time-stratified case-crossover design to determine associations of daily stroke occurrence with geomagnetic activity (Figure 1). This study design method,[25] in which cases serve as their own controls at different time points before the event, is commonly used for evaluation of short-term exposures on the risk of acute events,[25] including stroke. Because geomagnetic activity has been suggested to influence global meteorologic factors,[26] these analyses were adjusted for weather parameters (daily mean ambient temperature [°C], atmospheric pressure [kPa], and relative humidity [%]; associations between weather parameters and stroke will be reported in a separate article).

For each analysis, an individual study participant would contribute data relating to geomagnetic storm severity on the event day and 8 referent days. These referents were selected as part of a time-stratified sampling technique where a time frame of 7 days was selected to control for day-of-the-week effects. These referent days were selected depending on the event day specific for each individual, hence ensuring that the estimates would not be biased by a referent time sampling frame.[27] Each event day was matched to 8 referent days at 7, 14, 21,

Figure 1. Schematic diagram of case-crossover techniques. The design focused on the point in time when the event occurred. Thus, the covariate levels at the time of stroke occurrence (event day) were compared with levels obtained in a period chosen before and after (bidirectional) the stroke onset (referent days). Each case day was matched to 8 referent (REF) days (7, 14, 21, and 28 days before and after stroke event). The times are denoted as t_0=event day (day that stroke occurred), t_{-7}=7 days before the stroke day, and t_{+21}=21 days after the stroke event day.

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and 28 days using a bidirectional sampling frame, before and after the event day (Figure 1). The referent days were selected to represent the usual exposure levels in the source population that produce the stroke. The bidirectional referent time frame allowed for individual adjustment for seasonality, longer term trends, and days of the week by avoiding bias because of time trends in the exposure.[28] Although a case-crossover design might present a loss of statistical power compared with other commonly used statistical methods (eg, time series analysis),[29] it allows controlling for confounding factors associated with individual subject characteristics, as well as seasonality and long-term trends. Analyses were conducted using a conditional logistic regression model via Cox proportional hazard models.[30]

Additional stratified analyses by stroke subgroup according to individual factors (age group and study city) were performed to identify individuals susceptible to the effects of geomagnetic activity. Secondary analyses (not shown) using a unidirectional approach (7, 14, 21, and 28 days) before (lag) stroke to investigate associations with meteorologic parameters found results consistent with the bidirectional approach presented here. Hazard ratios for associations of daily stroke occurrence with geomagnetic storms with corresponding 95% confidence intervals (CIs) were calculated. Population-attributable hazard fraction[31] was used to assess proportion of population hazard of stroke occurrence attributable to the exposure to the environmental factors.[31–34] This formula corresponds[32] to the traditional population-attributable risk formula.[35,36] The analysis was done in R (R Foundation for Statistical Computing).[37] All raw data from each study city were harmonized and pooled for analyses. Meta-analyses using a fixed-effect model were conducted by combining the study-specific results and to test for heterogeneity for each stroke pathological type. The standard Cochran test for heterogeneity and I^2 were computed. Values of I^2 range between 0% and 100% and describe the percentage of variability across study (city) findings that are because of heterogeneity rather than chance alone.[38]

Results

Overall Characteristic of the Study Population

There were 11 453 incident stroke cases (16 031 764 person-years of observation) registered in the 6 study centers during the past 23 years (1981–2004; Table 1). In 8581 (75%) of these, the diagnosis of the type of stroke was confirmed by neuroimaging within 2 weeks after stroke occurrence. The mean age at incident stroke was 70 years (SD, 12) and did not vary much between the participating centers, except Sweden where no patients with stroke >75 years of age were registered. Women constituted about half of strokes. Because the access to neuroimaging studies was limited in the 80s and early 90s, the proportional frequency of stroke of undetermined pathological type was relatively high (25.1%). History of hypertension and smoking were the most frequent risk factors in the study population across all centers. Geomagnetic activity, as measured by the Ap level, varied moderately between different study years and was lowest during the solar minima years in between 1996 and 1998 (Table I in the online-only Data Supplement).

Effects of Geomagnetic Activity

Changes in geomagnetic activity were significantly associated with the risk of stroke (Table 2; Tables II and III in the online-only Data Supplement; Figures I and II in the online-only Data Supplement; Figures 2 and 3). There was a significant direct relationship between the risk of stroke and

Table 1. Overall Characteristics of the Study Populations by Study Center

	Auckland*	Melbourne	Perth†	Oxfordshire	Dijon	Northern Sweden‡	Total
Time period covered	1981–2003	1996–1998	1989–1997	2002–2005	1994–2004	1985–2004	1981–2005
No. of patients with stroke	2805	1316	766	543	1756	4267	11 453
Person-years	4 448 508	737 396	697 687	304 396	1 369 297	8 474 480	16 031 764
Age, y, mean (SD)	71 (15)	75 (14)	74 (14)	75 (12)	73 (14)	67 (7)	70 (12)
Age groups, y							
15–65, n (%)	804 (28.7%)	247 (18.8%)	161 (21.0%)	100 (18.4%)	449 (22.2%)	1214 (28.5%)	2975 (25.4%)
65–74, n (%)	684 (24.4%)	298 (22.6%)	170 (22.2%)	138 (25.4%)	432 (21.4%)	3044 (71.4%)	4768 (40.7%)
≥75, n (%)	1317 (47.0%)	771 (58.6%)	435 (56.8%)	305 (56.2%)	1142 (56.5%)	Not registered	3977 (33.9%)
Women, %	1499 (53.4%)	731 (55.6%)	377 (49.2%)	282 (51.9%)	1075 (53.1%)	1608 (37.7%)	5572 (47.5%)
Stroke pathological type							
Ischemic stroke, n (%)	1195 (42.6%)	921 (70.0%)	301 (39.3%)	469 (86.4%)	1488 (84.7%)	2541 (59.6%)	6915 (60.4%)
Intracerebral hemorrhage, n (%)	234 (8.3%)	191 (14.5%)	87 (11.4%)	48 (8.8%)	194 (11.1%)	433 (10.2%)	1187 (10.4%)
Subarachnoid hemorrhage, n (%)	179 (6.4%)	68 (5.2%)	35 (4.6%)	26 (4.8%)	45 (2.6%)	126 (3.0%)	479 (4.2%)
Undetermined stroke type, n (%)	1197 (42.7%)	136 (10.3%)	343 (44.8%)	…	29 (1.7%)	1167 (27.3%)	2872 (25.1%)
History of hypertension, n (%)	1248 (45.5%)	703 (54.4%)	459 (61.4%)	318 (59.1%)	1223 (60.5%)	2291 (59.2%)	6242 (55.7%)
History of heart disease, n (%)	672 (24.0%)	246 (18.7%)	470 (72.3%)	111 (20.4%)	424 (26.8%)	Not reported	1923 (17.2%)
Current smoker, n (%)	992 (37.9%)	402 (36.0%)	285 (43.6%)	218 (41.0%)	Not reported	356 (23.8%)	2253 (35.1%)
Former smoker, n (%)	577 (22.0)	188 (16.8%)	23 (3.5%)	86 (16.1%)	533 (35.5%)	612 (40.9%)	2019 (25.5%)
Mean [range], daily AP average	18.02 [1–197]	10.13 [0–144]	15.70 [1–164]	17.14 [1–204]	13.78 [0–204]	15.14 [0–246]	15.26 [0–246]
Mean [range], max 3-h AP	35.41 [3–300]	20.93 [2–236]	33.11 [3–400]	34.04 [3–400]	27.68 [0–400]	30.34 [2–400]	30.58 [0–400]
Mean [range], min 3-h AP	7.10 [0–111]	3.59 [0–94]	5.89 [0–94]	6.82 [0–80]	5.43 [0–94]	5.92 [0–111]	5.99 [0–111]

Levels of geomagnetic activity (as measured by Ap Index). The daily AP average is the mean level of 3-hourly geomagnetic activity.

*Includes 3 studies performed in 1981 to 1982, 1991 to 1992, and 2002 to 2003.

†Includes 2 studies: 1 performed in 1989 to 1990 and another in 1996 to 1997.

‡No strokes were recorded in people aged ≥75 years.

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geomagnetic storms, which were classified by the level of storm severity (Table 2). After adjusting for weather parameters, geomagnetic storms (Ap Index 60+) were associated with 19% increase in the risk of stroke occurrence (95% CI, 11%–27%), and the effect was more pronounced in people aged <65 years compared with older people. Although moderate geomagnetic storms were associated with a 15% increased risk of stroke occurrence (95% CI, 6%–25%), strong geomagnetic storms were associated with a 36% increased risk of stroke occurrence (95% CI, 19%–56%). The rarer severe/extreme geomagnetic storms were associated with a 13% (95% CI, −1% to 29%) increased risk of stroke occurrence (test for trend, χ^2=933.59; *df*=8; $P<2\times10^{-16}$). There was evidence of a weak trend across the combined group of all strokes in those aged <65 years: moderate geomagnetic storm was associated with a 27% (95% CI, 8%–48%) increased risk of stroke occurrence, strong geomagnetic storms with a 52% (95% CI, 19%–92%) increased risk, and severe/extreme geomagnetic storms with a 52% (95% CI, 19%–94%) increased risk (Table 2; Figure I in the online-only Data Supplement; 16–64 years test for trend, χ^2=247.05; *df*=7; $P<2\times10^{-16}$). The triggering effects of increased geomagnetic activity on the risk of stroke occurrence were consistent across all study populations and age groups (Figure 2) and stroke pathological types (Figure I in the online-only Data Supplement), apart from a peak in stroke risk among those aged >75 years during strong geomagnetic storms. Statistical heterogeneity between study cities was low, I^2=0% (Figure 3; Figure II in the online-only Data Supplement). Geomagnetic storms (Ap Index 60+; 7-day lag) accounted for 2.64% (95% CI, −0.92% to 6.20%) of the population-attributable hazard fraction for all strokes.

Additional analyses not adjusting for weather parameters produced similar results. Overall, geomagnetic storms (Ap Index 60+) were associated with 12% increase in the risk of stroke occurrence, with moderate geomagnetic storms showing a 7% increased risk of stroke occurrence, strong geomagnetic storms were associated with a 41% increased risk of stroke occurrence, and severe/extreme geomagnetic storms with a 6% increased risk of stroke occurrence (test for trend, χ^2=23.04; *df*=3; $P=3.96\times10^{-5}$; Table II in the online-only Data Supplement).

Discussion

To the best of our knowledge, this study is the largest to date, a sufficiently statistically powered, individual-participant population-based stroke incidence study of the effects of geomagnetic activity on the risk of first-ever stroke and major pathological stroke types across different populations and age groups. Although subject to ecological fallacy,[39] our study is one of the first to provide robust evidence on a population level for the triggering effect of geomagnetic storms on stroke occurrence.

We showed that although geomagnetic storms can account for only 2.64% of all strokes on a population level, exposure to geomagnetic storms (with Ap Index >60) on an individual level increases the relative risk of stroke by 19% across all ages (95% CI, 11%–27%) and by 37% (95% CI, 21%–54%) across those aged <65 years, a risk comparable with the effect of some major well-established modifiable stroke risk factors, such as postmenopause hormone therapy.[40] As each patient with stroke in our case-crossover study served as their own control, effectively meaning that stroke cases were matched to controls in terms of known and unknown risk factors except the exposure of interest (geomagnetic storms), our data provided evidence that the observed association of geomagnetic storms with stroke occurrence is independent of other known and unknown cardiovascular risk factors. Moreover, the triggering effects of increased geomagnetic activity on the risk of

Table 2. Hazard Ratios and 95% Confidence Intervals for Associations Between Stroke Occurrence and Geomagnetic Storm Severity Adjusted for Weather Parameters (Daily Mean Ambient Temperature [°C], Atmospheric Pressure [kPa], and Relative Humidity [%])

Environmental Factor	Age Group, y	Ischemic Stroke (n=6915)	Intracerebral Hemorrhage (n=1187)	Subarachnoid Hemorrhage (n=479)	All Strokes Combined (n=11 453)
Moderate geomagnetic activity	16–64	1.20 (0.97–1.47)	1.19 (0.76–1.86)	1.65 (1.00–2.70)	1.27 (1.08–1.48)
	64–75	1.13 (0.95–1.34)	0.90 (0.59–1.37)	1.63 (0.51–5.18)	1.18 (1.04–1.34)
	≥75	0.86 (0.71–1.05)	0.57 (0.31–1.05)	0.77 (0.10–5.92)	1.03 (0.89–1.20)
	Total	1.02 (0.92–1.14)	0.90 (0.68–1.17)	1.61 (1.04–2.51)	1.15 (1.06–1.25)
Strong geomagnetic activity	16–64	1.40 (0.95–2.07)	1.55 (0.82–2.93)	1.39 (0.83–2.35)	1.52 (1.19–1.92)
	64–75	1.03 (0.76–1.39)	1.25 (0.40–3.90)	0.80 (0.20–3.31)	1.03 (0.82–1.29)
	≥75	1.35 (0.94–1.93)	1.08 (0.34–3.39)	Model did not converge	1.92 (1.53–2.40)
	Total	1.22 (1.00–1.49)	1.46 (0.89–2.39)	1.12 (0.69–1.82)	1.36 (1.19–1.56)
Severe/extreme geomagnetic activity	16–64	1.34 (0.95–1.89)	2.14 (1.05–4.36)	2.50 (1.39–4.48)	1.52 (1.19–1.94)
	64–75	1.27 (0.96–1.66)	1.30 (0.70–2.44)	0.51 (0.07–3.66)	1.15 (0.94–1.41)
	≥75	0.79 (0.56–1.12)	1.18 (0.48–2.89)	Model did not converge	1.01 (0.79–1.29)
	Total	1.10 (0.92–1.32)	1.45 (0.96–2.19)	1.84 (1.06–3.21)	1.13 (0.99–1.29)
All geomagnetic storms	16–64	1.26 (1.06–1.48)	1.40 (1.00–1.96)	1.70 (1.23–2.34)	1.37 (1.21–1.54)
	64–75	1.13 (0.99–1.30)	1.01 (0.72–1.42)	0.95 (0.41–2.19)	1.15 (1.04–1.27)
	≥75	0.91 (0.77–1.06)	0.72 (0.45–1.15)	0.24 (0.03–1.80)	1.16 (1.03–1.30)
	Total	1.07 (0.98–1.17)	1.06 (0.86–1.31)	1.44 (1.08–1.94)	1.19 (1.11–1.27)

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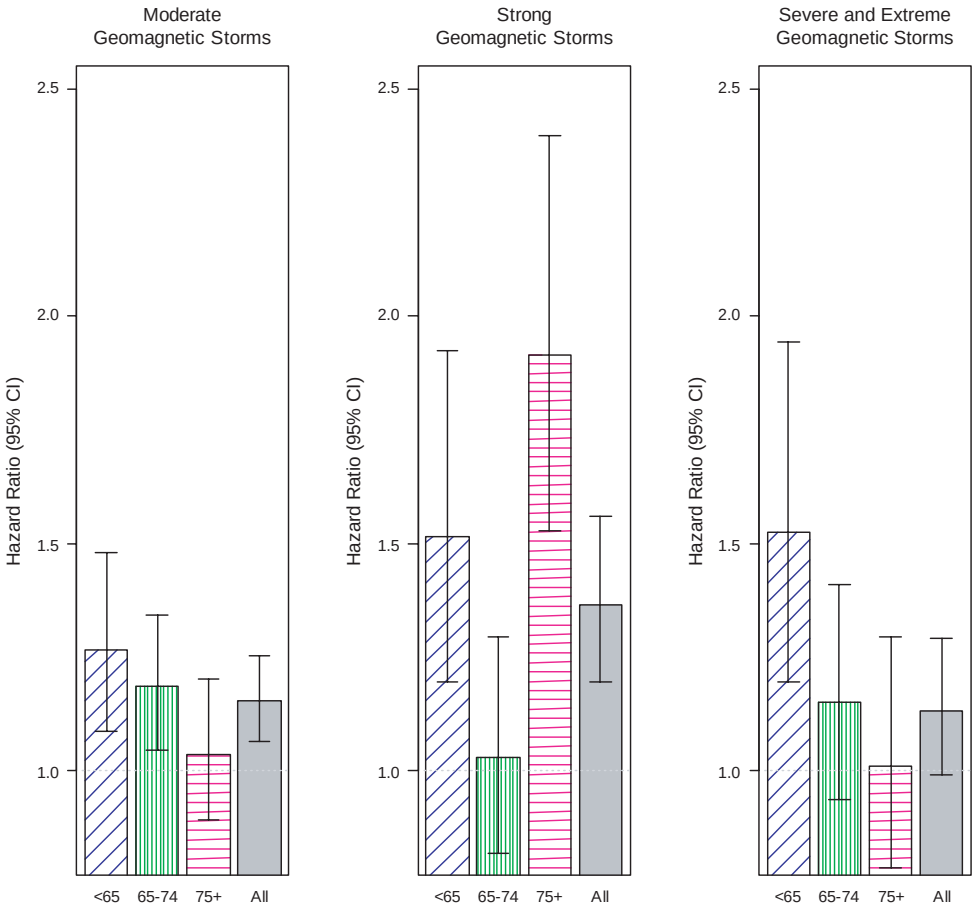

Figure 2. Bar plots of hazard ratios and 95% confidence intervals (CIs) for associations between stroke occurrence and geomagnetic storm severity (adjusted for weather parameters; daily mean ambient temperature [°C], atmospheric pressure [kPa], and relative humidity [%]) by age groups.

stroke occurrence were consistent across all study populations and age groups and stroke pathological types. The trend was observed for increased risk of stroke occurrence with increasing severity in geomagnetic storms especially during increased geomagnetic activity over solar maxima years. In contrast to other centers, an inverse association between geomagnetic activity and stroke onset was observed in Melbourne. This is possibly because of data collection for Melbourne occurring during solar minima years (1996–1998) when proportionally lower global geomagnetic activity was observed (Table III in the online-only Data Supplement). The fact that we found a significant inverse association between this low geomagnetic activity and stroke occurrence in Melbourne further supports the notion that high levels of geomagnetic activity (ie, those accompanying geomagnetic storms, predominately during solar maxima years) are important predictors of stroke. The delayed (7 days) triggering effect of exposure to geomagnetic storms on stroke occurrence of any pathological type may be associated with the suggested hazardous effects of geomagnetic activity on blood pressure,[2,7] whereas the suggested hazardous effect of geomagnetic activity on heart rate[6] and blood viscosity/coagulability[41] might be implicated in the observed associations between geomagnetic storms and the increased risk of ischemic stroke. It has been suggested that variations in geomagnetic activities may act to synchronize endogenous circannual and circadian rhythms leading to stroke.[8] Our findings on the hazardous triggering effects of increased geomagnetic activity on stroke are in line with some other observations in association with stroke and other vascular events.[1,3,5]

The main limitation of the study was that we were not able to get individual-participant data from ideal population-based studies in Asia, Africa, North and Latin America. Therefore, our findings need to be confirmed in other regions of the world. Second, although our study covered a period from 1981 to 2005, stroke incidence data in the participating centers were collected during relatively short periods of time and that limited our ability to study associations between stroke occurrence and geomagnetic activity during 11-year cycles of solar maxima periods. Finally, although vascular risk factors are important predictors of stroke, we did not have detailed data across all studies to enable stratified analyses investigating the associations among geomagnetic activity, vascular risk factors, and stroke onset. Nevertheless, the strength and consistency of the independent associations between geomagnetic storms and stroke occurrence, with dose–effect associations, are highly suggestive of the true triggering effect of increased geomagnetic activity and stroke occurrence.

These findings suggest that reducing the hazardous effect of geomagnetic storms (eg, via tighter control of conventional stroke risk factors during the days preceding geomagnetic

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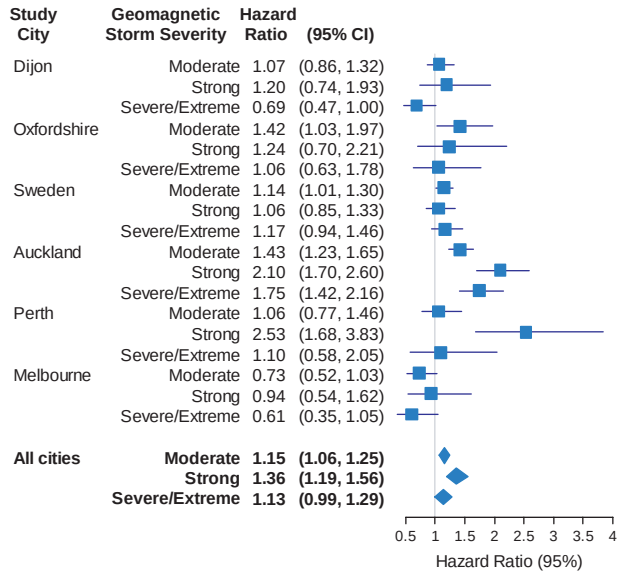

Figure 3. Forest plots of stroke occurrence by geomagnetic storm severity by study center. Hazard ratios and 95% confidence intervals (CIs). Quantifying heterogeneity: $\tau^2<0.0001$, $H=1$, and $I^2=0\%$. Overall test of heterogeneity: $Q=1.91$, $df=26$ ($P>0.10$). All models adjusted for weather parameters; daily mean ambient temperature (°C), atmospheric pressure (kPa), and relative humidity (%) for all ages and strokes combined, including strokes of undetermined pathological type. Levels of geomagnetic storm severity (as measured by Ap Index): Melbourne has geomagnetic data collected during solar minima years only and Auckland has the most data collected during high levels of geomagnetic activity.

storms, presenting geomagnetic storm warnings along with weather reports) may reduce stroke incidence on a population level. Although the effect of geomagnetic activity alone is modest, in combination with other risk factors, it could be extremely important. Of 16.9 million new strokes currently happening in the world every year,[42] almost a half million of these strokes could be attributed to geomagnetic storms. Our study suggests that geomagnetic activity should be considered along with other well-established risk factors for stroke. Our findings warrant further methodologically robust research in the area, including research into the biological mechanisms (pathogenesis) of the triggering effect of geomagnetic activity and developing new strategies to diminish the hazardous effects of geomagnetic storms on stroke occurrence.

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Disclosures

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SUPPLEMENTAL MATERIAL

Table I: Number of global Ap events defined by geomagnetic storm severity by years, study city, and solar cycle.

YEAR	Solar cycle*	Total	Moderate events (Ap = 60-100)	Strong events (Ap = 100-149)	Severe and Extreme Events (Ap ≥ 150)	City
2005	Minima	31	14	8	9	Oxfordshire
2004	Minima	25	15	4	6	Dijon, Northern Sweden, Oxfordshire
2003	Minima	64	48	8	8	Dijon, Northern Sweden, Oxfordshire, Auckland
2002	Maxima	23	12	10	1	Dijon, Northern Sweden, Oxfordshire, Auckland
2001	Maxima	26	10	11	5	Dijon, Northern Sweden
2000	Maxima	40	21	11	8	Dijon, Northern Sweden
1999	Minima	23	17	2	4	Dijon, Northern Sweden
1998	Minima	26	14	6	6	Dijon, Northern Sweden, Melbourne
1997	Minima	17	11	5	1	Dijon, Northern Sweden, Melbourne, Perth
1996	Minima	8	5	2	1	Dijon, Northern Sweden, Melbourne, Perth
1995	Minima	33	28	4	1	Dijon, Northern Sweden
1994	Minima	41	28	9	4	Dijon, Northern Sweden
1993	Minima	42	29	9	4	Northern Sweden
1992	Maxima	40	24	13	3	Northern Sweden, Auckland
1991	Maxima	75	38	22	15	Northern Sweden, Auckland
1990	Maxima	39	19	13	7	Northern Sweden, Perth
1989	Maxima	58	34	17	7	Northern Sweden, Perth
1988	Maxima	24	16	6	2	Northern Sweden
1987	Minima	16	15	1	0	Northern Sweden
1986	Minima	19	11	4	4	Northern Sweden
1985	Minima	32	22	7	3	Northern Sweden
1984	Minima	55	40	8	7	
1983	Minima	50	38	4	8	
1982	Maxima	72	47	18	7	Auckland
1981	Maxima	41	25	12	4	Auckland

*****The Ap index refers to the level of geomagnetic activity observed on earth. Geomagnetic activity is natural variations in the geomagnetic field. A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field which interacts with the Earth's magnetic field, these are prominent during the solar maxima phase of the solar cycle. The sun has a solar cycle which averages at 11 years in length and at the end of each cycle the polar magnetic field of the sun reverses. During these cycles there is either increased solar activity (solar maxima) which generally has a peak in the middle of the solar cycle (at about 5-6 years after the start of the solar maxima cycle). During solar maxima an increase in sunspots and solar storms (which include solar flares and coronal mass ejections) which emit large quantities of electromagnetic and particle radiation, that if directed towards Earth can disrupt our technology such as power grids, magnetic compasses, damage satellite microchips and disturb radio and radar. A solar minima refers to a relatively low solar activity (fewer sun spots and solar flares). This takes places 5-6 years after the peak of the solar maxima.

Levels of geomagnetic activity are commonly measured by Ap Index. Of all the data collected, Auckland has the most collected during solar maxima years that had high levels of geomagnetic activity including during 2003 - a solar minima year. Oxfordshire and Melbourne had data collected during solar minima years only. However, the solar minima's that Oxfordshire data was collected for had a high level of geomagnetic activity. Melbourne data was collected during times of very low geomagnetic activity. The remaining Northern hemisphere cities had more data collected during solar minima years; Dijon (8 out of the 11 years) and Northern Sweden (12 of the 20 years). Perth had data collected equally over solar maxima and solar minima years. It is important to note that four cities overlap with data collection during very low levels of geomagnetic activity (1996-1997).

Table II: Hazard ratios and 95% confidence intervals (CI) for associations between stroke occurrence and geomagnetic storm severity (unadjusted for weather parameters).

Environmental factor	Age group	Ischemic stroke (N = 6915)	Intracerebral hemorrhage (N = 1187)	Subarachnoid hemorrhage (N = 479)	All Strokes Combined* (N = 11453)
Moderate Geomagnetic Activity	16-64	1.12 (0.92-1.38)	1.08 (0.69-1.69)	1.61 (1.03-2.52)	1.21 (1.04-1.41)
	64-75	1.01 (0.86-1.20)	0.90 (0.60-1.36)	1.38 (0.43-4.39)	1.09 (0.97-1.24)
	75+	0.86 (0.72-1.03)	0.47 (0.28-0.80)	0.72 (0.17-3.01)	0.96 (0.83-1.10)
	Total	0.98 (0.88-1.09)	0.77 (0.60-1.01)	1.42 (0.96-2.12)	1.07 (0.99-1.16)
Strong Geomagnetic Activity	16-64	1.17 (0.80-1.72)	1.55 (0.82-2.92)	1.51 (0.90-2.54)	1.45 (1.14-1.83)
	64-75	1.11 (0.83-1.48)	1.37 (0.44-4.27)	0.73 (0.18-2.97)	1.06 (0.85-1.33)
	75+	1.35 (0.97-1.90)	1.30 (0.48-3.50)	0.43 (0.06-3.14)	1.87 (1.51-2.33)
	Total	1.22 (1.01-1.48)	1.44 (0.89-2.33)	1.23 (0.77-1.97)	1.41 (1.24-1.60)
Severe/Extreme Geomagnetic Activity	16-64	1.33 (0.95-1.86)	2.76 (1.42-5.40)	2.78 (1.61-4.79)	1.60 (1.27-2.02)
	64-75	1.03 (0.79-1.33)	1.30 (0.69-2.43)	0.35 (0.08-1.46)	0.98 (0.80-1.19)
	75+	0.84 (0.61-1.14)	1.04 (0.49-2.21)	Model did not converge	1.04 (0.83-1.30)
	Total	1.02 (0.86-1.21)	1.43 (0.97-2.11)	1.69 (1.04-2.76)	1.06 (0.94-1.20)
All Geomagnetic Storms	16-64	1.17 (1.00-1.38)	1.37 (0.99-1.91)	1.78 (1.31-2.42)	1.33 (1.19-1.49)
	64-75	1.03 (0.91-1.18)	1.01 (0.72-1.42)	0.67 (0.31-1.46)	1.06 (0.96-1.17)
	75+	0.91 (0.79-1.06)	0.63 (0.42-0.95)	0.78 (0.27-2.22)	1.10 (0.99-1.22)
	Total	1.02 (0.94-1.11)	0.96 (0.78-1.18)	1.42 (1.08-1.86)	1.12 (1.06-1.19)

*****All – for all strokes combined, including strokes of undetermined pathological type.

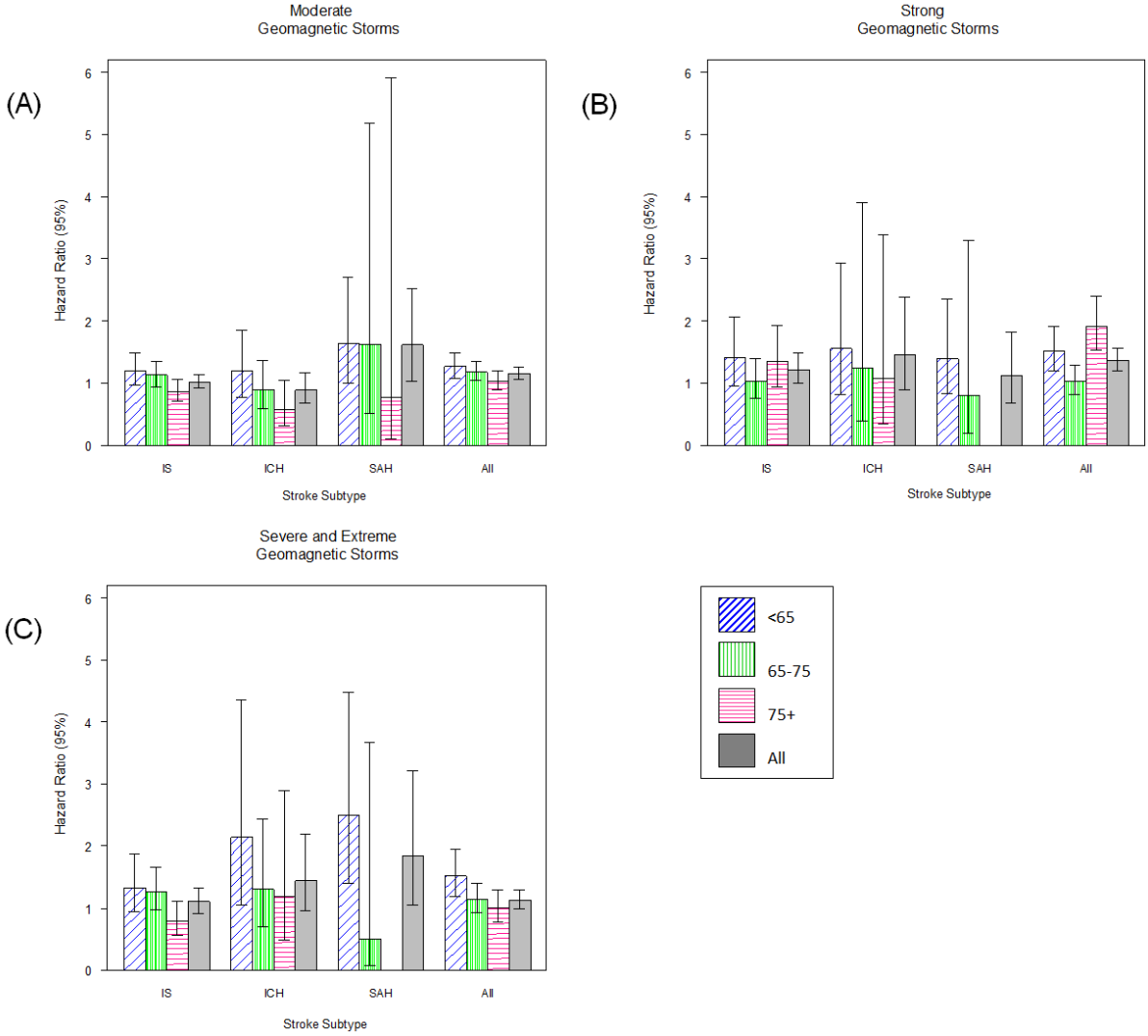
Table III: Hazard ratios and 95% confidence intervals (CI) for associations between stroke occurrence and geomagnetic storm severity by study city (adjusting for weather parameters; daily mean ambient temperature (°C), atmospheric pressure (kPa) and relative humidity (%)).

Geomagnetic Storm Classification	Age group	Study city	All Strokes Combined*
Moderate Geomagnetic Storm	16-64	Dijon	1.04 (0.64-1.69)
Strong Geomagnetic Storm			1.19 (0.38-3.73)
Severe/Extreme Geomagnetic Storm			0.81 (0.34-1.98)
Moderate Geomagnetic Storm	65-74		1.06 (0.65-1.73)
Strong Geomagnetic Storm			1.14 (0.47-2.77)
Severe/Extreme Geomagnetic Storm			1.04 (0.46-2.34)
Moderate Geomagnetic Storm	75+		1.01 (0.77-1.32)
Strong Geomagnetic Storm			2.45 (1.26-4.74)
Severe/Extreme Geomagnetic Storm			0.90 (0.55-1.48)
Moderate Geomagnetic Storm	Total		1.07 (0.87-1.33)
Strong Geomagnetic Storm			1.20 (0.74-1.94)
Severe/Extreme Geomagnetic Storm			0.69 (0.47-1.02)
Moderate Geomagnetic Storm	16-64	Oxfordshire	2.05 (0.87-4.99)
Strong Geomagnetic Storm			1.01 (0.13-7.57)
Severe/Extreme Geomagnetic Storm			Model did not converge
Moderate Geomagnetic Storm	65-74		1.50 (0.75-3.00)
Strong Geomagnetic Storm			1.33 (0.54-3.29)
Severe/Extreme Geomagnetic Storm			0.73 (0.30-1.84)
Moderate Geomagnetic Storm	75+		1.24 (0.87-1.88)
Strong Geomagnetic Storm			1.11 (0.49-2.51)
Severe/Extreme Geomagnetic Storm			1.22 (0.61-2.45)
Moderate Geomagnetic Storm	Total		1.36 (0.98-1.88)
Strong Geomagnetic Storm			1.16 (0.64-2.06)
Severe/Extreme Geomagnetic Storm			0.91 (0.53-1.55)
Moderate Geomagnetic Storm	16-64	Sweden	1.15 (0.92-1.45)
Strong Geomagnetic Storm			0.95 (0.65-1.39)
Severe/Extreme Geomagnetic Storm			1.49 (0.99-2.24)
Moderate Geomagnetic Storm	65-74		1.14 (0.98-1.33)
Strong Geomagnetic Storm			1.14 (0.86-1.51)
Severe/Extreme Geomagnetic Storm			1.08 (0.84-1.40)
Moderate Geomagnetic Storm	75+		No data
Strong Geomagnetic Storm			No data
Severe/Extreme Geomagnetic Storm			No data
Moderate Geomagnetic Storm	Total		1.11 (0.98-1.27)
Strong Geomagnetic Storm			1.02 (0.82-1.29)

Severe/Extreme Geomagnetic Storm			1.11 (0.89-1.38)
Moderate Geomagnetic Storm			1.63 (1.25-2.14)
Strong Geomagnetic Storm	16-64		2.19 (1.56-3.09)
Severe/Extreme Geomagnetic Storm			2.16 (1.52-3.07)
Moderate Geomagnetic Storm			1.65 (1.21-2.24)
Strong Geomagnetic Storm	65-74		1.83 (1.00-3.34)
Severe/Extreme Geomagnetic Storm		Auckland	1.59 (1.05-2.40)
Moderate Geomagnetic Storm			1.19 (0.96-1.48)
Strong Geomagnetic Storm	75+		1.99 (1.46-2.73)
Severe/Extreme Geomagnetic Storm			1.49 (1.05-2.11)
Moderate Geomagnetic Storm			1.37 (1.18-1.60)
Strong Geomagnetic Storm	Total		1.94 (1.56-2.41)
Severe/Extreme Geomagnetic Storm			1.61 (1.30-2.00)
Moderate Geomagnetic Storm			0.99 (0.52-1.92)
Strong Geomagnetic Storm	16-64		6.9 (2.05-23.22)
Severe/Extreme Geomagnetic Storm			0.91 (0.22-3.71)
Moderate Geomagnetic Storm			1.20 (0.66-2.20)
Strong Geomagnetic Storm	65-74		2.65 (0.83-8.52)
Severe/Extreme Geomagnetic Storm		Perth	0.68 (0.22-2.18)
Moderate Geomagnetic Storm			0.92 (0.58-1.46)
Strong Geomagnetic Storm	75+		2.16 (1.33-3.50)
Severe/Extreme Geomagnetic Storm			1.45 (0.56-3.78)
Moderate Geomagnetic Storm			1.00 (0.73-1.38)
Strong Geomagnetic Storm	Total		2.30 (1.51-3.49)
Severe/Extreme Geomagnetic Storm			0.78 (0.41-1.52)
Moderate Geomagnetic Storm			0.76 (0.36-1.62)
Strong Geomagnetic Storm	16-64		0.27 (0.04-1.91)
Severe/Extreme Geomagnetic Storm			0.54 (0.13-2.26)
Moderate Geomagnetic Storm			0.56 (0.26-1.19)
Strong Geomagnetic Storm	65-74		1.09 (0.41-2.95)
Severe/Extreme Geomagnetic Storm		Melbourne	0.74 (0.18-2.99)
Moderate Geomagnetic Storm			0.86 (0.55-1.34)
Strong Geomagnetic Storm	75+		1.36 (0.68-2.75)
Severe/Extreme Geomagnetic Storm			0.64 (0.33-1.24)
Moderate Geomagnetic Storm			0.76 (0.54-1.07)
Strong Geomagnetic Storm	Total		1.00 (0.58-1.73)
Severe/Extreme Geomagnetic Storm			0.67 (0.39-1.17)

*****All – for all strokes combined, including strokes of undetermined pathological type.

Figure I: Hazard ratios and 95% confidence interval (CI) of stroke occurrence with changes in geomagnetic activity by age groups and stroke pathological types.

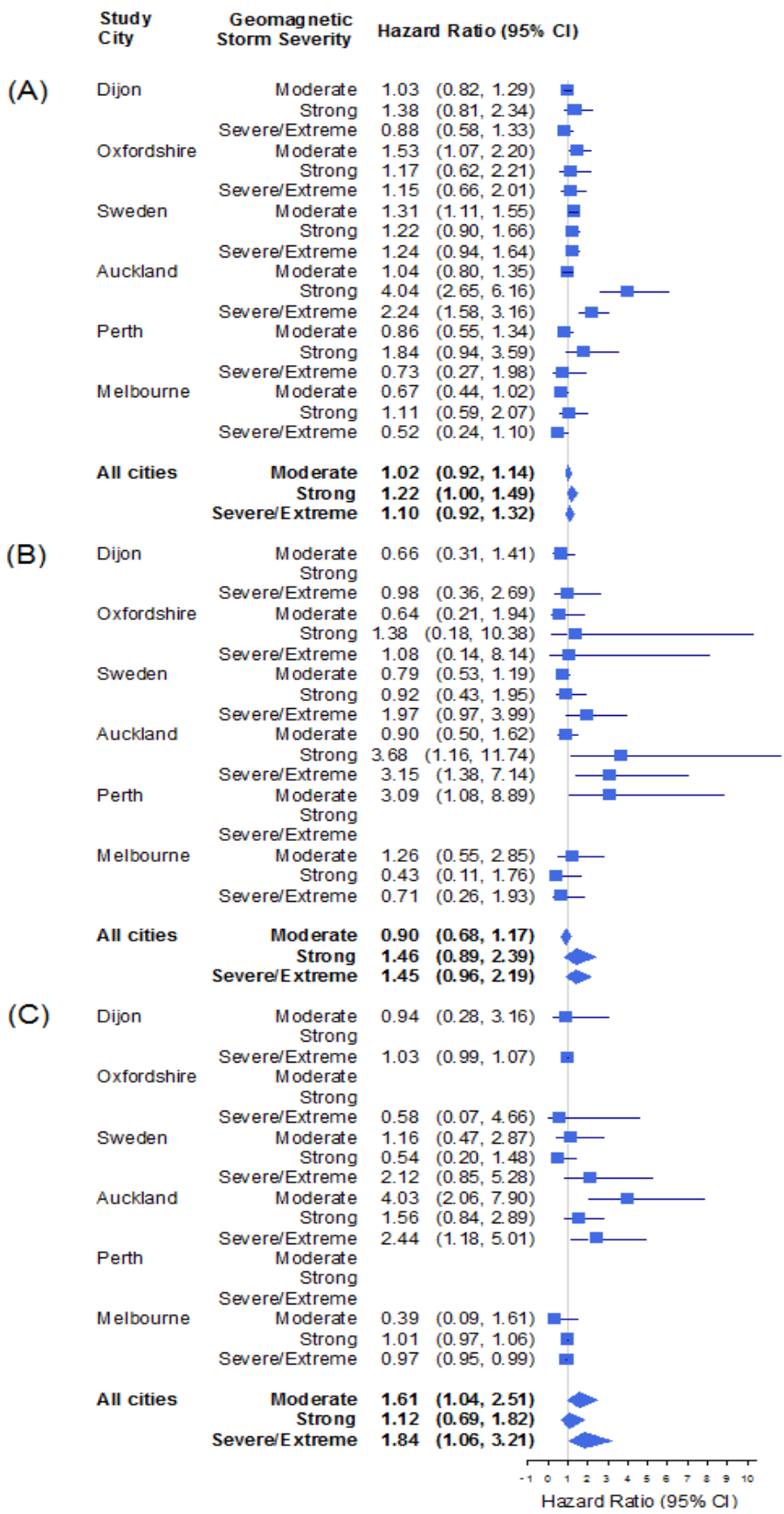


(A) Moderate geomagnetic activity; (B) Strong geomagnetic activity; (C) Severe and extreme geomagnetic activity. Levels of geomagnetic storm severity (as measured by Ap Index). IS stands for ischemic stroke, ICH – for intracerebral hemorrhage, SAH – for subarachnoid hemorrhage, All – for all strokes combined, including strokes of undetermined pathological type. All estimates are adjusted for weather parameters.

Figure II: Forest plots of hazard ratios and 95% confidence interval (CI) for associations between stroke occurrence and geomagnetic storm severity by study city (adjusted for weather parameters; daily mean ambient temperature (°C), atmospheric pressure (kPa) and relative humidity (%)).

(A) IS; Quantifying heterogeneity: $\tau^2 < 0.0001$, H = 1, $I^2 = 0\%$. Overall test of heterogeneity: Q =2.59, degrees of freedom = 26 ($p > 0.10$);

(B) ICH; Quantifying heterogeneity: $\tau^2 < 0.0001$, H = 1, $I^2 = 0\%$. Overall test of heterogeneity: Q = 2.90, degrees of freedom = 26 ($p > 0.10$);

(C) SAH: Quantifying heterogeneity: $\tau^2 < 0.0001$, H = 1, $I^2 = 0\%$. Overall test of heterogeneity: Q =3.24, degrees of freedom = 24 ($p > 0.10$)

All models adjusted for weather parameters; daily mean ambient temperature (°C), atmospheric pressure (kPa)