HHS Public Access

Author manuscript

Sci Total Environ. Author manuscript; available in PMC 2023 September 10.

Published in final edited form as:

Sci Total Environ. 2022 September 10; 838(Pt 3): 156434. doi:10.1016/j.scitotenv.2022.156434.

Solar and geomagnetic activity reduces pulmonary function and enhances particulate pollution effects

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Abstract

Background: Increased solar and geomagnetic activity (SGA) may alter sympathetic nervous system activity, reduce antioxidant activity, and modulate physiochemical processes that contribute to atmospheric aerosols, all which may reduce pulmonary function.

Objectives: Investigate associations between forced expiratory volume at 1 s (FEV_1) and forced vital capacity (FVC) with SGA, and assess whether SGA enhances adverse effects of particulate pollution, black carbon (BC) and particulate matter ≤2.5 μm in diameter ($PM_{2.5}$). Methods: We conducted a repeated measures analysis in 726 Normative Aging Study participants (Boston, Massachusetts, USA) between 2000 and 2017, using interplanetary magnetic field (IMF), planetary K index (Kp), and sunspot number (SSN) as SGA measures. Linear mixed effects models were used to assess exposure moving averages up to 28 days for both SGA and pollution.

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CRediT authorship contribution statement

KA was involved in conceptualization, developing methodology and conducted the formal analysis, visualization and wrote the original draft. CLZV, EG and PK were involved in conceptualization, developing methodology and supervision. VW provided data curation and software related assistance. All authors edited and approved the final version of the manuscript.

Ethics committee approval

The study obtained informed consent from the participants and approval from the Institutional Review Boards of Harvard T.H. Chan School of Public Health and VA Boston Healthcare System.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

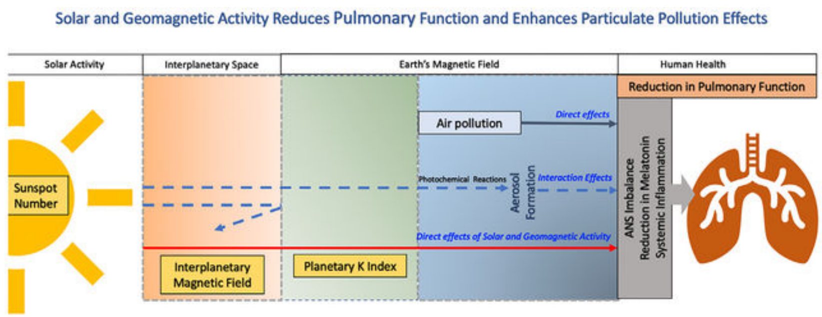
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156434.

Results: Increases in IMF, Kp Index and SSN from the day of the pulmonary function test averaged through day 28 of were associated with a significant decrement in FEV_1 and FVC, after adjusting for potential confounders. There were greater effects for longer moving averages and enhanced effects of $PM_{2.5}$ and BC on FEV_1 and FVC with increased SGA. For example, for each inter-quartile increase (4.55 μg/m3) in average $PM_{2.5}$ 28 days before testing, low IMF (10th percentile: 3.2 nT) was associated with a −21.4 ml (95 % CI: −60.8, 18.1) and −7.1 ml (95 % CI: −37.7, 23·4) decrease in FVC and FEV_1, respectively; high IMF (90th percentile: 9.0 nT) was associated with a −120.7 ml (95 % CI:-166.5, −74.9) and −78.6 ml (95 % CI: −114.3, −42·8) decrease in FVC and FEV_1, respectively.

Discussion: Increased periods of solar and geomagnetic activity may directly contribute to impaired pulmonary function and also enhance effects of $PM_{2.5}$ and BC. Since exposure to solar activity is ubiquitous, stricter measures in reducing air pollution exposures are warranted, particularly in elderly populations.

GRAPHICAL ABSTRACT



Keywords

Solar radiation; Air pollution; Pulmonary function; Geomagnetic disturbance; Solar activity; Lung outcomes; Particulate matter

1. Introduction

The Sun emits electromagnetic radiation that varies over 11-year solar cycles (Hathaway, 2015). Within each solar cycle, periods of high solar activity are characterized by an increased solar flares and corona mass ejections, which release high-energy material into the space, triggering disturbances in the Earth's magnetic field. Solar activity and geomagnetic disturbances (GMD) have been linked to direct and indirect effects on atmospheric aerosols and human health (J.-L. Chen and Zhao, 2014), including increased risk of cardiovascular mortality (Zilli Vieira et al., 2019), stroke risk (Feigin et al., 2014), higher blood pressure, reduced heart rate variability (Cornélissen et al., 2010; Dimitrova et al., 2009; Wang et al., 2021), lower peripheral white blood cell counts (Tracy et al., 2022), and mental health (Davis and Lowell, 2004). However, to date, no study has investigated the association between solar activity and pulmonary function in observational settings, despite a plausible biological link.

Solar and Geomagnetic Activity (SGA) has been associated with disruption of 24-h circadian rhythm (Riganello et al., 2019), autonomic nervous system imbalance (McCraty et al., 2017), and reduced secretion of melatonin (Burch et al., 1999). Disruption of 24-h circadian rhythm results in higher immune and inflammatory responses, which appears to promote the development and exacerbation of pulmonary diseases (Aquino-Santos et al., 2020; Sundar et al., 2015). Reduced secretion of melatonin, a free-radical scavenger, is associated with greater measures of oxidative stress, which has been implicated as a cause of cell damage and inflammation in the lungs(Bargagli et al., 2009). Similarly, particulate air pollution appears to also promote oxidative stress and inflammation that has the potential to promote lung diseases and reduce lung function (Gangwar et al., 2020; Lodovici and Bigagli, 2011). Moreover, a recent study found a significant association between solar activity and increased ambient ultrafine particle concentrations, suggesting a direct link between solar activity and higher levels of ambient air pollution (Zilli Vieira and Koutrakis, 2021). Therefore, due to joint effects related to inflammation, oxidative stress, and modulation of the physiochemical properties of atmospheric aerosols, we hypothesize interactions between periods of increased solar activity and air pollution is associated with heightened adverse pulmonary effect.

The adverse effects of short- and long-term exposure to particle matter ≤10 and ≤2.5 μm (PM_{10} and $PM_{2.5}$, respectively) and black carbon (BC) on pulmonary function has been well documented (C.-H. Chen et al., 2019; Int Panis et al., 2017; Rice et al., 2013). However, there is a paucity of epidemiological evidence on the influence of solar activity and GMD. Our objective was to investigate the association of pulmonary function [forced expiratory volume at 1 s – (FEV_1) and forced vital capacity (FVC), and FEV_1/FVC] with SGA, and to test whether SGA enhances the adverse effects of particulate air pollution on the outcome of interest.

2. Methodology

2.1. Study population

The study population comprised of elderly male residents of the greater Boston, MA, enrolled in the Normative Aging Study (NAS) cohort established by the U.S. Veterans Administration in 1963 who were free of major illness during enrolment (Bell et al., 1972). We restricted our analysis to visits between 2000 and 2017 for participants due to limitations in availability of exposure data. Participants with C-reactive protein serum levels higher than 10 mg/L (suggesting acute illness) were excluded to arrive at 726 individuals with 2075 observations. Upon every study visit, the participants were administered detailed questionnaires and underwent clinical examinations including pulmonary function tests. Spirometry testing was conducted based on ATS guidelines (Miller et al., 2005). Information on pulmonary disorders, medication use, smoking status, and other personal characteristics were collected at each visit using standardized questionnaires (Sparrow et al., 1987). The study obtained informed consent from the participants and approval from the Institutional Review Boards of Harvard T.H. Chan School of Public Health and VA Boston Healthcare System.

2.2. Exposure assessment

2.2.1. Air pollution—We obtained data on daily $PM_{2.5}$ in μg/m^3 and BC in μg/m^3 measured at a Boston Harvard supersite, located at the roof of the Harvard Medical School's Countway Library of Medicine. Particulate air pollution exposure was assessed using a Harvard Impactor to collect $PM_{2.5}$ samples and an aethalometer (Magee Scientific Company, model AE-16, Berkeley, CA) to measure hourly BC concentrations averaged to provide daily values.

2.2.2. Solar and geomagnetic activity parameters—Interplanetary Magnetic Field (IMF), sunspot number (SSN), and Planetary K (K_p) Index are indicators of SGA. Intense solar activity causes release of high-energy material entering the interplanetary space by the solar winds. This component of the Sun's magnetic field entering the interplanetary space is called IMF (Hathaway, 2015). Although the Earth is protected by its own magnetic field, during periods of high solar activity, part of the energy carried by solar wind and solar particles infiltrate the magneto-sphere causing GMD (Yermolaev and Yermolaev, 2010). The K_p Index characterizes the magnitude of fluctuations in the disturbances in the Earth's magnetic field attributable to solar activity (https://spaceweatherlive.com/en/help/the-kp-index.html). An increase in solar activity is also associated with an increase in sunspot numbers, the dark areas on the sun characterized by a strong magnetic field (Solanki, 2003). Intense solar activity periods are characterized by increases in all parameters included in our study. The data were downloaded from the OMNI data set of the NASA Goddard Space Flight Centre's Space Physics website (https://omniweb.gsfc.nasa.gov/form/dx1.html).

2.3. Statistical analysis

We used linear mixed effects models with a random intercept for each participant to account for heterogeneity among subjects and correlation between repeated measurements taken on the same subject. The models took the form:

$$Y_{ij} = \beta_0 + \beta_1 E_{ij} + \beta_2 C_{1ij} + \ldots\ldots + \beta_k C_{nij} \varepsilon_{ij} + u_i$$

where Y_{ij} is the lung function measurement in subject i at visit j, β_0 is the intercept, β_1 is the effect of the exposure variable on lung function measurement, and E_{ij} is the exposure concentration for the subject i in the day-of and days prior to the visit j. The covariates for subject i at visit j are denoted by C_{1ij} to C_{nij}, ε_{ij} was the within-participant error and u_i represents a subject-specific random intercept.

Firstly, we estimated the effect of the exposure on the day of testing (day 0) through 28 day moving averages for both air pollutant and solar activity parameters on FEV_1 and FVC. Exposure windows/moving averages were calculated as average cumulative exposure (through day 28) starting prior to the day of outcome measurement (day 1). We tested for effect modification with multiplicative interaction terms between air pollution and SGA for each moving average calculated over the same time periods.

We then calculated the effect of these interactions at high (90th percentile) and low (10th percentile) levels of the overall distribution of SGA at each visit for the entire follow up period.

All models were adjusted for a priori determined confounders and covariates based on known associations that included age (yr), height (inches), body mass index (kg/m^2), sine and cosine terms based on the pulmonary function test date [sin(2**π***(day of year)/365) and cos(2**π***(day of year)/365)] adjusting for long-term seasonal trends, day of the week, race category (white or non-white), physician diagnosed asthma (yes/no), chronic bronchitis or emphysema (yes/no), history of chronic heart disease (yes/no), history of stroke (yes/no), smoking status (never, current, former), cumulative smoking in pack-years (number), two or more drinks per day (yes/no), use of corticosteroids (yes/no), use of beta blockers (yes/no) (Lepeule et al., 2014). The FEV_1/FVC models were not adjusted for height. We also adjusted for ambient temperature (°C) and relative humidity (%) on the day of pulmonary function testing using data obtained from Boston Logan Airport (https://www.ncei.noaa.gov/). Solar parameters were treated as continuous variables and effect estimates for the above-mentioned period were expressed as the change in FEV_1 and FVC (in ml) or change in FEV_1/FVC (in %) for interquartile range (IQR) increment for each moving average. All statistical analyses were performed using software R Version 3.6.3.

3. Results

Table 1 shows the baseline and longitudinal characteristics of the study population. There were 726 individuals with 2075 observations between 2000 and 2017. Participants were male, mostly white (98 %) with a mean age of 73 years, and mean BMI of 28.1 kg/m^2 at baseline of the present study. In the year 2000, <5 % of subjects were current smokers, but most were former smokers (64·5 %). At study entry the mean FEV_1 and FVC were 2.51 L and 3.35 L and respectively and mean percent predicted FEV_1, FVC at baseline were 92.7 % and 94.3 % respectively. The FEV_1/FVC at baseline was 75 %.

Mean SGA and air pollutant exposures on the day of pulmonary function testing over the study visits (2000–2017) are summarized in Table 2. Across the study period, the mean (±SD) IMF, K_p Index and SSN were 5.80 (±2.6) nT, 18.6 (±11.6), 83.8 (±74.5), respectively. Average $PM_{2.5}$ and BC were 9.3 (±6.4) and 0.75 (±0.40) μg/m^3, respectively, across the study period. The mean values of ambient temperature and relative humidity were 13.3 (±8.7)°C and 68.1 (±17.3) %, respectively.

The spearman correlation coefficient among the three SGA parameters ranged between 0.31 and 0.69 (Table 3) SGA and the air pollutants were not meaningfully correlated. The correlations between IMF and Kp Index with $PM_{2.5}$ and BC were between 0.09 and 0.13, and were slightly greater for SSN with $PM_{2.5}$ and BC (Table 3).The variations in solar and geomagnetic activity over the study period are shown in Fig. 1. The figure illustrates daily variation of the parameters on the day of pulmonary function testing, as well as their magnitude over the solar cycle. The study captured two solar maximum and one solar minimum.

3.1. Solar and geomagnetic activity and pulmonary function

In our primary models, we found negative associations between 0 to 28 day moving average of all SGA parameters and FVC, FEV_1 and positive associations with FEV_1/FVC, after adjusting for potential confounders. Other than the association between K_p index and FEV_1, the effects were significant, with a greater decrement in FVC (Table S2 and Fig. 2) and FEV_1 (Table S1 and Fig. 2) with longer moving averages. For an increase in inter-quartile range of SSN, K_p index, and IMF, for a 28 day moving average (the longest moving average assessed), the decrease in FVC was −173.7 ml (95 % CI: −204.9, −142.6), −26.8 ml (95 % CI: −48, −5.7), and −90.3 ml (95 % CI: −119.5, −61), respectively, and decrease in FEV_1 was −116.1 ml (95 % CI: −142.1, −91), −5.2 ml (95 % CI: −21.7, 11.4), and −46.3 ml (95 % CI:−69.8, −22.8). We also observed that an increase in SGA was associated with a slight increase in FEV_1/FVC ratio (Table S3, Fig. 3). For an increase in interquartile range of SSN, K_p index, and IMF, for a 28 day moving average, the increase in FEV_1/FVC was 0.4 % (95 % CI: −0.1, 0.8), 0.3 % (95 % CI:0,0.6), and 0.4 % (95 % CI: 0,0.8), respectively.

3.2. Effects of solar and geomagnetic activity on association of particulate air pollution with pulmonary function

As noted by other investigators in other cohorts (Chen et al., 2019; Int Panis et al., 2017; Rice et al., 2013), we found significant negative associations between $PM_{2.5}$ and BC with of FEV_1 and FVC (Supplementary Material Table S4), with a greater effect on FVC. We noted associations with moving averages through day 28 of $PM_{2.5}$ and BC, with greater adverse effects for longer moving averages. We did not find consistent significant associations between air pollutants and FEV_1/FVC (Table S4). We observed significant modification of the effects of particulate pollution on FVC and FEV_1 for all SGA parameters across different moving averages, except for the combination of BC and SSN (Supplementary Material Table S5–10). We observed that the interaction between particulate pollution and SGA was associated with a significantly greater decrease in FVC and FEV_1 at higher levels of SGA (Figs. 4 and 5).

The magnitude of effect modification is shown as the difference in effect estimates between the 10th and 90th percentile values of SGA parameters (green and orange bars in the figure). We noted significantly greater decrements in FVC and FEV_1 during periods of increased activity (90th percentile), while smaller decrements that were not statistically significant were observed during periods of decreased activity (10th percentile). The effect estimates tended to be associated with larger decrements in pulmonary function with an increase in cumulative exposure. An IQR (4.55 μg/m^3) increase in average exposure 28 days prior to examination to $PM_{2.5}$ during low IMF (10th percentile: 3.2 nT) over the same time period was associated with a −21.4 ml (95 % CI: −60.8, 18.1) and −7.1 ml (95 % CI:−37.7, 23·4) decrease in FVC and FEV_1, respectively, whereas an equivalent increase in $PM_{2.5}$ during high IMF (90th percentile: 9.0 nT) was significantly ($p < 0{\cdot}001$) associated with a −120.7 ml (95 % CI:−166.5, −74.9) and −78.6 ml (95 % CI: −114.3, −42·8) decrease in FVC and FEV_1. K_p Index and SSN also appeared to modify effects of air pollution exposure on FVC and FEV_1, although with overlapping confidence intervals for effects at the 10th and 90th percentiles of BC and $PM_{2.5}$. The directions of the interactions between $PM_{2.5}$ and BC with SGA on FEV_1/FVC were inconsistent and nearly all were not significant (Table S12, S13).

4. Discussion

We found a significant decrease in pulmonary function associated with solar and geomagnetic activity with greater decrements for longer moving averages. All the three SGA parameters studied were associated with lower pulmonary function and a greater FEV_1/FVC. The greater effect on FVC compared to FEV_1 is consistent with a restrictive ventilatory defect attributable to SGA. Our study also explored interactions between SGA parameters and particulate air pollution to assess the concomitant impact of both exposures. We noted a greater impact of $PM_{2.5}$ and BC on a reduction in FVC and FEV_1 (but not FEV_1/FVC) during the periods of increased SGA, suggesting that solar and geomagnetic activity modifies the association of $PM_{2.5}$ and BC on FVC and FEV_1. The magnitude of effect modification and of the temporality of interactions with $PM_{2.5}$ and BC varied based on SGA parameter, but the overall direction of the effect was similar for all interactions. As with other studies of the association between particulate pollution and pulmonary function, we also found an association between exposure and a reduction in FVC and $FEV_{1.}$. Our findings are consistent with other cohorts (Rice et al., 2015; Rice et al., 2013), where associations between particulate pollution and FEV_1/FVC have been weak or inconsistent.

One of the challenges faced by the researchers examining the influence of solar activity on human health has been establishing plausible biological mechanisms to explain the associations. Evidence suggests association of SGA with disruption of 24-h circadian rhythm (Riganello et al., 2019) and autonomic nervous system imbalance (McCraty et al., 2017). Solar radiation regulates the circadian rhythm through suprachiasmatic nucleus (SCN) located in the hypothalamus (central clock) (Reppert and Weaver, 2001). Studies suggest disruption of circadian rhythm and dysregulation of autonomic nervous system could result in higher immune and inflammatory responses, as well as cell damage, which may be finally leading to impairment of lung function and development of lung diseases (Aquino-Santos et al., 2020; Benedusi et al., 2021; Comas et al., 2017; Sundar et al., 2015). Reduced secretion of melatonin, a hormone secreted by pineal gland that regulates the sleep wake cycle and circadian rhythm, has also been linked to solar activity (Burch et al., 1999). Melatonin has shown ability to scavenge free radicals which protects against the effects of harmful radiations (Goswami and Haldar, 2015). Reduced melatonin may increase the oxidative stress increasing pulmonary inflammation and damaged lung cells (Bargagli et al., 2009).

Mechanistic studies explaining the association between particulate air pollution and reduced pulmonary function suggest that exposure can promote small airway remodelling, pulmonary inflammation, cellular changes in immune function, ANS imbalance (Gangwar et al., 2020; Lodovici and Bigagli, 2011; Thurston et al., 2020). These mechanisms suggest that it is biologically plausible that particulate air pollution might be synergistically contributing towards decreased lung function during periods of increased solar activity. Melatonin has been known to mitigate the pathophysiologic responses to air pollution(Carvalho-Sousa et al., 2020; He, 2020; He et al., 2018, 2021); however, it is possible that a reduction in melatonin linked to solar activity can leave individuals more susceptible to the effects of air pollution. Increased ROS generation due to either of the exposures might eventually exacerbates the body’s response to the other. Although the correlation between solar activity with $PM_{2.5}$ and BC was weak in this study, solar activity also interacts chemically with environmental factors such as air pollution in the atmosphere, which leads to formation of secondary pollutants and aerosols. Discrepancies in the electrical gradient in the atmosphere during periods of intense solar activity can ionize air pollutants and alter the physical and chemical properties (e.g., nature, composition, and toxicity) (Madronich and Flocke, 1999; Mironova et al., 2011; Rycroft et al., 2000). Solar activity has been known to enhance ultrafine particles (Zilli Vieira and Koutrakis, 2021). Therefore, the results corroborate our research hypothesis, which suggests a mechanistic overlap in biology and atmospheric chemistry in the reduction of pulmonary function linked to interactions between solar activity and air pollution.

To the best of our knowledge, this is the first study to investigate the association of pulmonary function with SGA and its interaction with air pollution. We were unable to capture more than one solar cycle due to constraints in availability of data, a more robust association would be possible by considering two solar cycles (22 years). We did not account for exposures other than the measured outdoor exposures (e.g., indoor, and occupational exposures, indoor radiation could not be included). Our study was conducted in a well characterized cohort based in and around Boston with low air pollution levels and relatively high solar radiations (due to high latitude). Association was observed after controlling for a comprehensive list of potential confounders; however, residual confounding remains possible. The NAS population is homogenous composed of healthier elderly white men; therefore, results of the study may not be generalizable to other populations.

These findings suggest that natural phenomena related to solar activity and GMD influence pulmonary function. Our exposure model indicates that these effects may be particularly detrimental during periods of high air pollution. This observation suggests that efforts to mitigate particulate pollution exposures may have more impact when solar disturbances are highest. Our findings also have important public health implications particularly in vulnerable populations such as the elderly since SGA exposures cannot be avoided and exposure to ambient pollution is common (Bentayeb et al., 2012; Simoni et al., 2015).Accounting for SGA in air pollution studies can also help better analyse and understand environmental factors that contribute to impaired lung function.

5. Conclusion

This study demonstrates periods of intense solar activity and geomagnetic disturbances impair lung function. Ambient air pollution and solar radiation might be synergistically contributing towards decreased lung function through biological pathways including increased systemic inflammation, autonomic nervous system imbalance, and reduced melatonin secretion. The chemical pathways of interaction include increased aerosol formation and alteration of the chemical composition of pollutants in the atmosphere. Further studies are required to extend the results across various regions and populations consisting of women, other age groups, race, co-morbidities, varied air pollution levels, geospatial and temporal scales to strengthen the understanding of such interactions in the atmosphere and its underlying biological mechanism. Future research may be able to identify local variations of solar radiation spectra which can have different impacts on human health, including respiratory diseases.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgement

The VA Normative Aging Study is supported by the Cooperative Studies Program/Epidemiology Research and Information Center of the U.S. Department of Veterans Affairs and is a component of the Massachusetts Veterans Epidemiology Research and Information Center (MAVERIC), Boston, Massachusetts. This publication was made possible by U.S. EPA grant RD-835872. Its contents are solely the responsibility of the grantee and do not necessarily represent the official views of the U.S. EPA. Further, US EPA does not endorse the purchase of any commercial products or services mentioned in the publication. This study was also supported by NIH National Institute of Environmental Health Sciences R21 ES029637 and by resources and the use of facilities at the Veterans Affairs Boston Healthcare System. The views expressed in this article are those of the authors and do not reflect the position or policy of the Department of Veterans Affairs or the United States government.

Data sharing

Individual participant data and data dictionary will not be available for sharing.

Abbreviations:

SD	Standard Deviation
BMI	Body Mass Index
$PM_{2.5}$	Particulate Matter with aerodynamic diameter <2.5 µm
BC	Black Carbon
FEV_1	Forced Expiratory Volume at 1 s
FVC	Forced Vital Capacity
K_p Index	Planetary K Index
IMF	Interplanetary Magnetic Field
SSN	Sunspot Number
SGA	Solar and Geomagnetic Activity
GMD	Geomagnetic Disturbance
IQR	Interquartile Range
CI	Confidence Intervals
NAS	Normative Aging Study
ROS	Reactive Oxidative Species
ANS	Autonomic Nervous System

CRY	Cryptochrome

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HIGHLIGHTS

- First study to analyse the impact of solar and geomagnetic activity (SGA) on lungs.
- Intense SGA may contribute to impaired pulmonary function.
- Higher SGA promotes adverse effects of particulate pollution on pulmonary function.
- Air pollution mitigation may be more impactful when SGA is high.

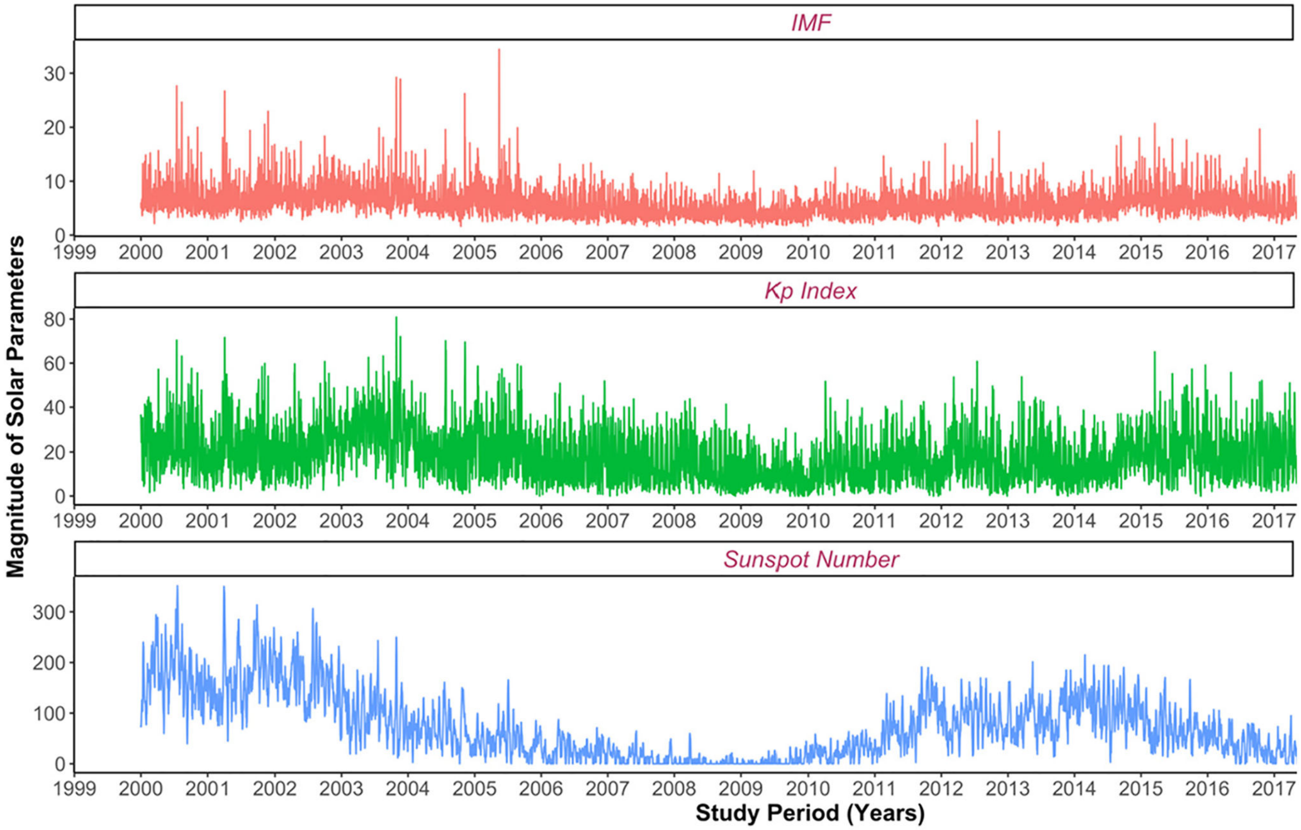

Fig. 1.

Variations of solar and geomagnetic activity parameters over the study period. Note: IMF is measured in nT (nano tesla), Kp Index is dimensionless and sunspot number is measured in number (#). Footnote: IMF (interplanetary magnetic field); K_p Index (planetary K index).

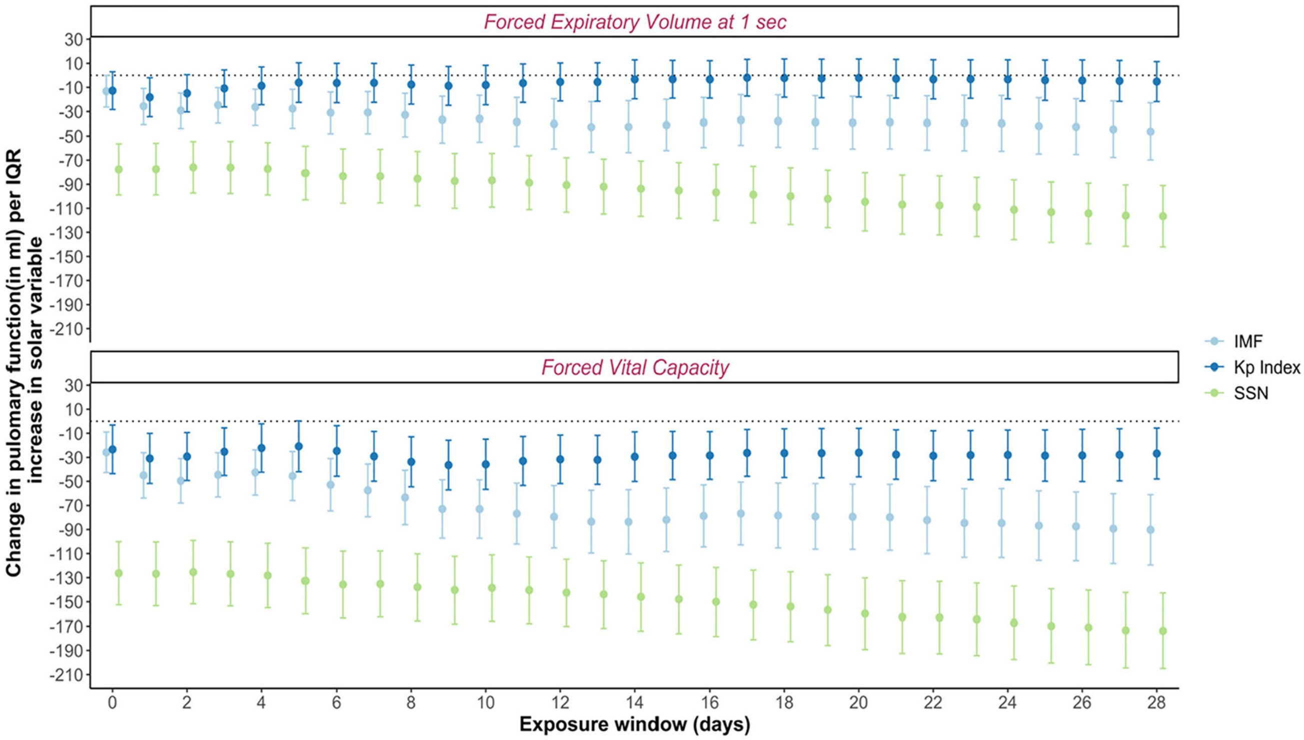

Fig. 2.

Association of exposure to solar and geomagnetic activity with forced vital capacity (FVC) and forced expiratory volume at 1 s (FEV_1). Note: Linear mixed effects models adjusted for age, height, race, selected medication, lifestyle factors (smoking, alcohol), day of the week, seasonality, and medical comorbidities, ambient temperature (°C) and relative humidity (%) on the day of pulmonary function measurement (day 0) were used to estimate the associations (n = 2075). Moving averages calculated starting on day 1 through day 28. Footnote: IMF: Interplanetary Magnetic Field; K_p: Planetary K Index; SSN: Sunspot Number. The IQRs for solar and geomagnetic activity variables are given in Supplementary Material Table S11. The figure is based on the values from Tables S1 and S2 in Supplementary material. Error bars represent the 95 % confidence intervals.

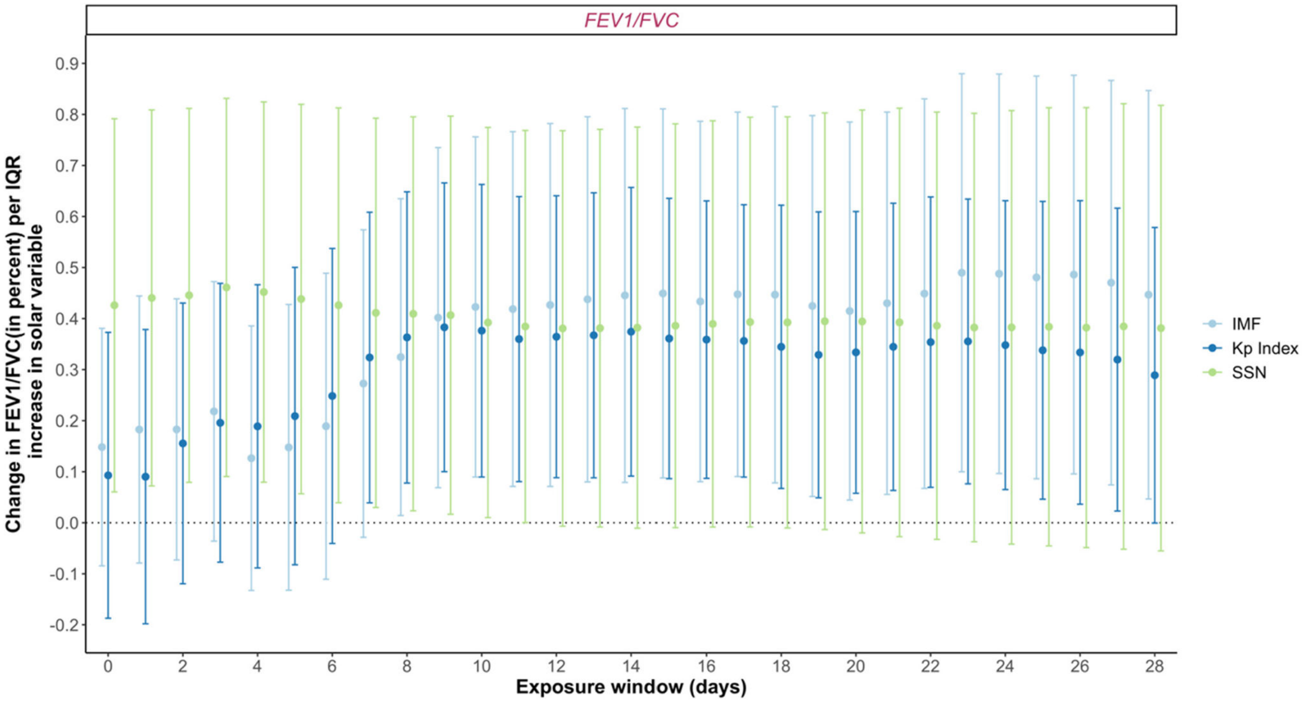

Fig. 3.

Association of exposure to solar and geomagnetic activity with FEV_1/FVC. Note: Linear mixed effects models adjusted for age, race, selected medication, lifestyle factors (smoking, alcohol), day of the week, seasonality, and medical comorbidities, ambient temperature (°C) and relative humidity (%) on the day of pulmonary function measurement (day 0) were used to estimate the associations ($n = 2075$). Moving averages calculated starting on day 1 through day 28. Footnote: IMF: Interplanetary Magnetic Field; K_p: Planetary K Index; SSN: Sunspot Number; FVC: forced vital capacity;FEV_1 forced expiratory volume at 1 s. The IQRs for solar and geomagnetic activity variables are given in Supplementary Material Table S11. The figure is based on the values from Table S3 in Supplementary material. Error bars represent the 95 % confidence intervals.

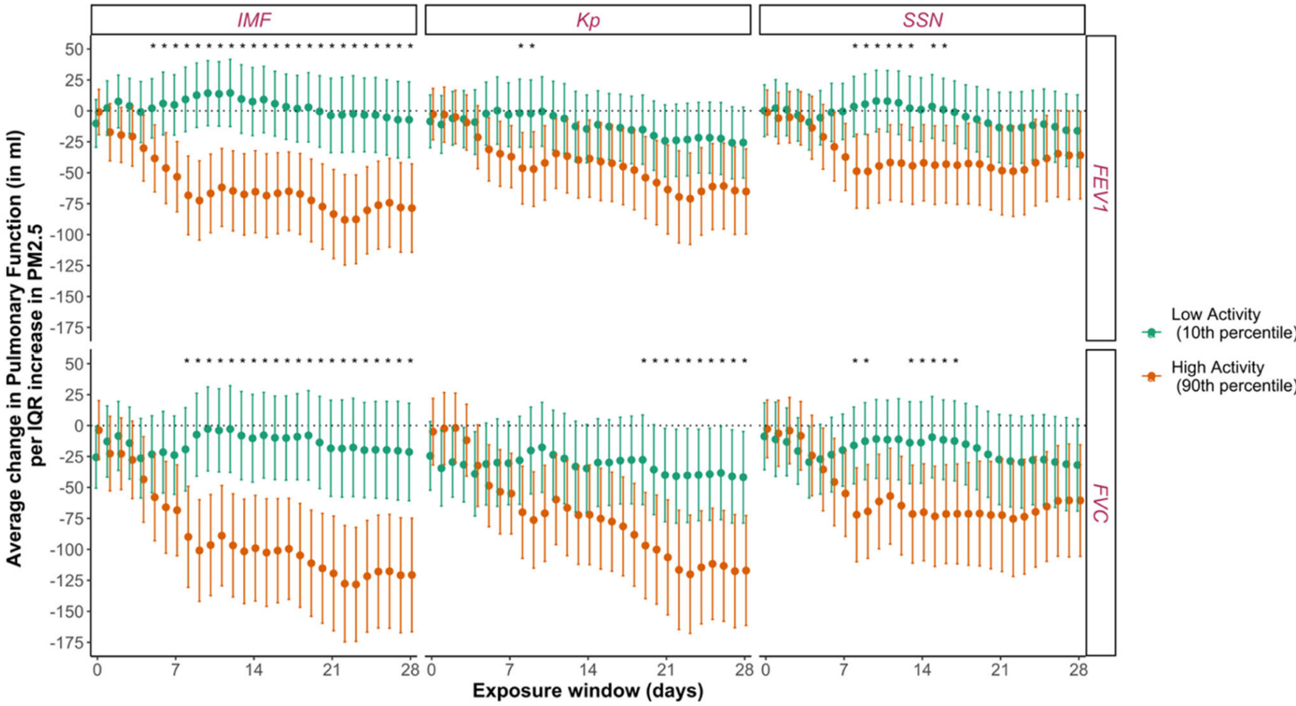

Fig. 4.

Association of exposure to $PM_{2.5}$ with forced vital capacity (FVC) and forced expiratory volume at 1 s (FEV_1) at high (90th percentile) and low (10th percentile) solar and geomagnetic activity periods. Note: Linear mixed effects models adjusted for age, height, race, selected medication, lifestyle factors (smoking, alcohol), day of the week, seasonality, and medical comorbidities, ambient temperature and relative humidity on the day of pulmonary function measurement (day 0) were used to estimate the association between exposure to $PM_{2.5}$ and pulmonary function at 10th and 90th percentile of solar and geomagnetic activity parameters (n = 2075). Moving averages calculated starting on day 1 through day 28. Error bars represent the 95 % confidence intervals. Footnote: $PM_{2.5}$ (particulate matter <2.5μm in aerodynamic diameter); IMF (interplanetary magnetic field); K_p Index (planetary K index); SSN (sunspot number). Asterisks indicate the p-value for interaction term between air pollutant and solar activity parameters with "*" for significant at <0.05 level. 90th percentile and 10th percentile for day zero of all exposure variables are given in Table 2. The IQRs for $PM_{2.5}$ are given in Supplementary Material Table S11. The figure is based on the values from Table S5, S7, and S9 in Supplementary material.

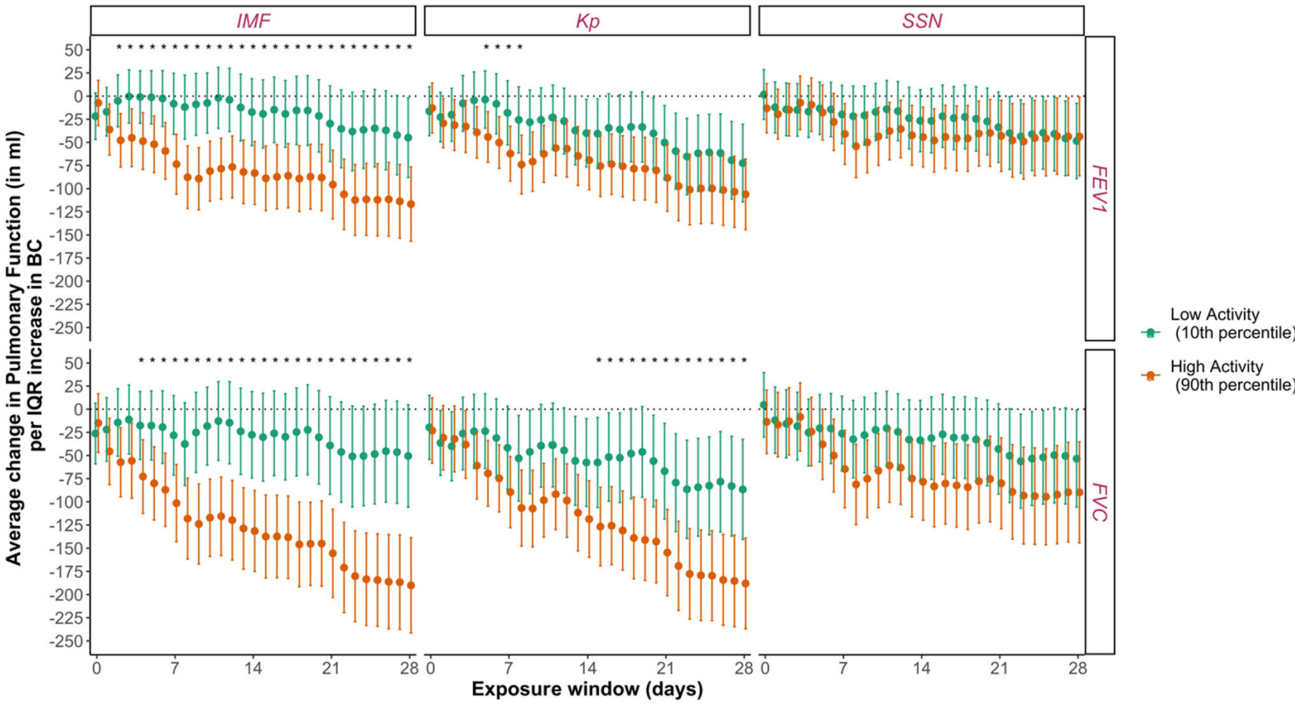

Fig. 5.

Association of exposure to black carbon (BC) with forced vital capacity (FVC) and forced expiratory volume at 1 s (FEV_1) at high (90th percentile) and low (10th percentile) solar and geomagnetic activity periods. Note: Linear mixed effects models adjusted for age, height, race, selected medication, lifestyle factors (smoking, alcohol), day of the week, seasonality, and medical comorbidities, ambient temperature and relative humidity on the day of pulmonary function measurement (day 0) were used to estimate the association between exposure to black carbon and pulmonary function at 10th and 90th percentile of solar and geomagnetic activity parameters ($n = 2075$). Moving averages calculated starting on day 1 through day 28. Error bars represent the 95 % confidence intervals. Footnote: BC (black carbon); IMF (interplanetary magnetic field); K_p Index (planetary K index); SSN (sunspot number). Asterisks indicate the p-value for interaction term between air pollutant and solar activity parameters with "*" for significant at <0.05 level. 90th percentile and 10th percentile for day zero of all exposure variables are given in Table 2. The IQRs for BC are given in Supplementary Material Table S11. The figure is based on the values from Table S6, S8, and S10 in Supplementary material.

Table 1

Descriptive characteristics of Normative Aging Study (NAS) cohort for the study period (2000–2017).

	Visit 1 (Baseline)	All visits
Total observations (n)	**726**	**2075**
Characteristics	**n (%) or Mean ± SD**	**n (%) or Mean ± SD**
Race (%White)	706 (98.1)	2012 (97.9)
Current Smoker	32 (4.4)	79 (3.8)
Former Smoker	467 (64.5)	1340 (64.7)
Never Smoker	225 (31.1)	652 (31.5)
Alcohol (>2 drinks daily)	134 (18.5)	369 (17.8)
Coronary heart disease	216 (29.8)	751 (36.2)
Stroke	52 (7.2)	171 (8.2)
Diabetes	97 (13.4)	337 (16.2)
Corticosteroids	48 (6.7)	101 (6.8)
Beta blocker	261 (35.9)	851 (41.0)
Chronic Pulmonary Diseases[a]	132 (18.3)	346 (18.7)
FVC (L)	3.35 ± 0.67	3.42 ± 0.70
%-Predicted FVC	94.29 ± 16.16	95.20 ± 15.80
FEV_1 (L)	2.51 ± 0.58	2.53 ± 0.59
%-Predicted FEV_1	92.65 ± 18.50	93.75 ± 17.88
FEV_1/FVC (%)	75.0 ± 8.00	73.0 ± 8.00
Age (y)	73.2 ± 6.90	76.7 ± 7.10
Height (in)	68.5 ± 2.70	68.3 ± 2.80
BMI (kg/m^2)	28.1 ± 4.00	27.9 ± 4.00
Cumulative smoking (pack-years)	21.0 ± 25.40	28.0 ± 22.80

SD (standard deviation); FVC (forced vital capacity); FEV_1(forced expiratory volume at 1 s); BMI (body mass index).

[a]Physician diagnosed asthma, emphysema, or chronic bronchitis.

Table 2

Solar activity and air pollution exposure on the day of clinical measurement (day zero) across the study period (2000–2017).

Exposure	Mean (SD)	IQR	10th, 90th percentile
IMF (nT)[a]	5.8 (2.6)	2.8	3.21, 8.97
K_p Index[b]	18.6 (11.6)	15.6	5.3, 35.3
Number of Sunspots (#)	83.8 (74.5)	114.6	0.0, 190.1
$PM_{2.5}$ (μg/m^3)	9.3 (6.4)	6.6	3.7, 17.6
Black Carbon (μg/m^3)	0.75 (0.40)	0.53	0.32, 1.31
Ambient Temperature (°C)	13.3 (8.7)	13.6	–
Relative Humidity (%)	68.1 (17.3)	26.7	–

SD (standard deviation); IQR (interquartile range); $PM_{2.5}$ (particulate matter <2.5μm in aerodynamic diameter); IMF (interplanetary magnetic field); K_p Index (planetary K index); SSN (sunspot number).

[a]Nanotesla (nT) – unit of measurement for magnetic field.

[b]K_p Index is Dimensionless.

Table 3

Spearman correlation coefficients of Solar and Geomagnetic Activity and Particulate Air Pollution Parameters on the day of pulmonary function measurement (n = 2075).

Exposure	$PM_{2.5}$	BC	IMF	K_p Index	SSN	Temp	RH
$PM_{2.5}$	1	–	–	–	–	–	–
BC	0.75*	1	–	–	–	–	–
IMF	013*	0.12*	1	–	–	–	–
K_p Index	012*	0.09*	0.69*	1	–	–	–
SSN	0–22*	0.26*	0.42*	0.31*	1	–	–
Temp	0.19*	0.22*	−0.07*	−0.01	−0.01	1	–
RH	−0.04	0.13*	0.2	0.01	0.11*	−0.06*	1

$PM_{2.5}$ (particulate matter <2.5 μm in aerodynamic diameter); BC (black carbon); IMF (interplanetary magnetic field); K_p Index (planetary K index); SSN (sunspot number); Temp (temperature); RH (relative humidity).

*Indicates $p < 0.05$.