Impacts of changes in North Atlantic atmospheric circulation on particulate matter and human health in Europe

Francesco S. R. Pausata,[1] Luca Pozzoli,[2] Rita Van Dingenen,[1] Elisabetta Vignati,[1] Fabrizia Cavalli,[1] and Frank J. Dentener[1]

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[1] In this study we use a global climate model to assess particulate matter (PM) variability induced by the North Atlantic Oscillation (NAO) in Europe during winter and the potential impact on human health of a future shift in the NAO mean state. Our study shows that extreme NAO phases in the 1990s modulated most of the interannual variability of winter PM concentrations in several European countries. Increased PM concentrations as a result of a positive shift in the mean winter NAO of one standard deviation would lead to about 5500 additional premature deaths in Mediterranean countries, compared to the simulated average PM health impact for the year 2000. In central-northern Europe, instead, higher wind speed and increased PM removal by precipitation lead to negative PM concentration anomalies with associated health benefits. We suggest that the NAO index is a useful indicator for the role of interannual atmospheric variability on large-scale pollution-health impacts. **Citation:** Pausata, F. S. R., L. Pozzoli, R. V. Dingenen, E. Vignati, F. Cavalli, and F. J. Dentener (2013), Impacts of changes in North Atlantic atmospheric circulation on particulate matter and human health in Europe, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50720.

1. Introduction

[2] High concentrations of airborne particulate matter (PM) can have severe impacts on human health [*Lave and Seskin*, 1970; *Nel*, 2005; *Shindell et al.*, 2012]. PM is a general term used for a mixture of solid and liquid aerosol particles of different size and chemical composition and is commonly classified as $PM_{2.5}$ and PM_{10}, i.e., the fraction of the total PM with an aerodynamic diameter less than 2.5 and 10 μm, respectively. PM can either be directly emitted as primary particles or forms in the atmosphere from gas precursors and results from both natural and anthropogenic sources.

[3] In the 1990s, air quality standards have been introduced in many countries, including the member states of the European Union [e.g., *EEA*, 1997] to regulate concentrations of hazardous air pollutants. Current EU legislation sets an annual limit value of 40 $\mu g/m^3$ for PM_{10} and 25 $\mu g/m^3$ for $PM_{2.5}$ to be reached by 2015 (Air quality directive 2008/50/EC). Several health effects have been attributed to PM, for long-term as well as short-term exposure [*WHO*, 2013]. Long-term exposure to $PM_{2.5}$ has been documented to be a cause of both cardiovascular mortality and morbidity as well as atherosclerosis, adverse birth outcomes and childhood respiratory disease. PM mass comprises other fractions (e.g., $PM_{2.5–10}$, PM_{10}) with varying types and degrees of health effects suggesting a role for both the chemical composition (e.g., transition metals and combustion derived primary and secondary organics) and physical properties (size, particle number, and surface area) as shown in the *WHO* [2013]. In Europe, in 2000, the maximum life expectancy loss caused by PM exposure was estimated to be 9 months, and as high as 12–36 months in the Po valley (Italy), Benelux and Silesia [*Amann et al.*, 2004].

[4] In recent years, the EU limit values for PM have continued to be widely exceeded throughout Europe and despite a general decrease in primary PM and PM-precursor emissions in the last decade [e.g., *Tørseth et al.*, 2012], no correspondingly downward trend in PM concentrations in urban areas has been observed [*EEA*, 2011]. On the other hand, recent studies [*Barmpadimos et al.*, 2011; *Cusak et al.*, 2012; *Barmpadimos et al.*, 2012] show that in the last decade, some European background/rural stations show downward trend linked not only to pollution abatement strategies but also to particular meteorological conditions.

[5] Other studies have shown that local-to-regional scale pollutant concentrations can be influenced by large-scale atmospheric circulation patterns, such as the North Atlantic Oscillation-NAO [e.g., *Eckhardt et al.*, 2003; *Christoudias et al.*, 2012; *Pausata et al.*, 2012]. *Pausata et al.* [2012] showed that in some regions a significant fraction of interannual tropospheric ozone anomalies are related to the NAO. The NAO commonly refers to swings in the atmospheric pressure difference between the subpolar and the subtropical North Atlantic, affecting climate variability of the neighboring continents, especially in winter [*Hurrell*, 1995]. The NAO-Index (NAOI) is traditionally defined as the difference in the normalized sea level pressure anomalies between either Lisbon, Portugal, or Ponte Delgada, Azores, and Stykkisholmur/Reykjavik, Iceland [*Hurrell*, 1995]. The NAOI is positive when the pressure contrast between the two centers of action strengthens, leading to a northward shift of the storm track (i.e., higher-than-average West-East transport) and more stable conditions over southern Europe. The NAOI is negative when the pressure contrast weakens and more storms enter the Mediterranean basin.

[6] Appreciating NAO's modulation of surface PM concentrations in Europe helps to understand the magnitude

Additional supporting information may be found in the online version of this article.

[1]Institute for Environment and Sustainability, European Commission, Joint Research Centre, Ispra (VA), Italy.

[2]Eurasia Institute of Earth Sciences, Istanbul Technical University Istanbul, Turkey.

Corresponding author: F. S. R. Pausata, Institute for Environment and Sustainability, European Commission, Joint Research Centre, Ispra (VA), Italy. (francesco.pausata@jrc.ec.europa.eu)

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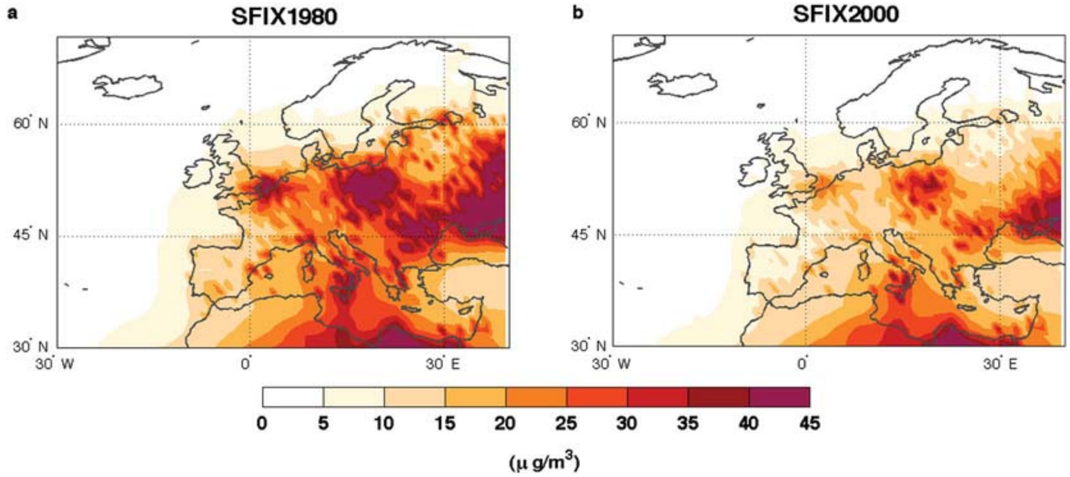

Figure 1. $PM_{2.5}^{pop}$ annual mean climatology (1980–2005) for SFIX1980 (a) and SFIX2000 (b) simulations.

of the large-scale atmospheric circulation interannual variability in driving European PM trends and their consequent effects on human health. On one hand, the relationship between NAO and PM can identify in advance those regions more likely to be exposed to pollution episodes, taking advantage of the large progress made in forecasting the NAO phases up to intraseasonal (3 to 6 weeks) time scales [*Johansson*, 2007]. On the other hand, climate model predictions [*Fyfe et al.*, 1999; *Shindell et al.*, 1999; *Kuzmina et al.*, 2005; *Stephenson et al.*, 2006] have shown a future positive shift in the winter NAO mean state with consequent impacts on air pollution levels and hence, human health. A quantitative relationship between NAO and PM concentrations provides an easily understandable method to analyze the potential impacts of climate change on air quality, which is rooted in current knowledge of the relationship between NAO and PM levels. To address these issues, we use a coupled atmosphere-chemistry climate model for the period 1980–2005 to analyze the influence of the NAO on interannual variability of surface $PM_{2.5}$ concentrations and then evaluate the potential consequences for human health of a future winter NAO shift under climate change conditions.

2. Methodology

[7] We performed two model simulations with a global fully coupled atmosphere-chemistry climate model (ECHAM5-HAMMOZ) for the period 1980–2005, with the meteorology forced to reanalysis data (see supporting information). To assess the interaction of large-scale atmospheric variability with anthropogenic emissions, we performed two model simulations, one in which the anthropogenic emissions were kept constant at the year 1980 (SFIX1980) and one with constant emissions at the year 2000 (SFIX2000). In both simulations the natural and wildfire emissions change subject to meteorological variability.

[8] The coarse T42 ($\sim 2.8° \times 2.8°$) model resolution used cannot capture PM concentration gradients between urban settlements and the regional background that may occur at subgrid scales. However, since a large part of air pollution health-related impacts occurs in urban areas, we rescaled the modeled coarse resolution $PM_{2.5}$ concentrations to a more realistic population-exposed concentration $PM_{2.5}^{pop}$, making use of high-resolution population data (7.5' × 7.5') to calculate an exposure enhancement factor. We only applied the population exposure scaling factor to the $PM_{2.5}$ components that have a predominantly anthropogenic signature—namely sulfate, black, and organic carbon (see supporting information). The population statistics are from the year 2000 following the UN population database (http://esa.un.org/unpd/wpp/Excel-Data/population.htm). The PM of natural origin (sea salt and mineral dust) have not been modified, as no urban enhancement induced by local sources can be expected. The scaled $PM_{2.5}^{pop}$ gives more realistic spatial PM concentration distributions [see also *Rao et al.*, 2012; *Brauer et al.*, 2012] with only 15% of the analyzed monitoring stations having differences greater than 50% compared to the model (Figures S2, S3, and Table S1, supporting information).

[9] Our analysis of model data is restricted to the Atlantic sector (20°N–90°N, 90°W–40°E) and the results are based on monthly anomalies from the climatological mean seasonal cycle. Standard Empirical Orthogonal Function (EOF)/Principal Component (PC) analysis has been used to calculate the leading mode of monthly sea level pressure variability in the North Atlantic, as a proxy for the NAO [*Hurrell*, 1995] and the temporal variability, as an approximation for NAOI (see supporting information). Instead of the canonical NAOI, the PC time series have been used to represent the NAO variability, since it has been shown that PC1 is better able to capture the relationship between atmospheric circulation and air pollutants [*Pausata et al.*, 2012]. Hereafter, we refer to the NAO as the first EOF (EOF1) and to NAOI as the leading PC (PC1). All correlations discussed in this study are significant at 90% confidence interval.

3. Result

[10] We focus our analysis over Europe and neighboring countries. First, we discuss the simulated $PM_{2.5}^{pop}$ anomalies associated with the NAO (section 3.1). Then, we address the potential impact of a future shift in the mean winter NAO state on mean $PM_{2.5}^{pop}$ concentrations and hence, change in annual premature deaths from cardio-pulmonary and lung cancer diseases (section 3.2).

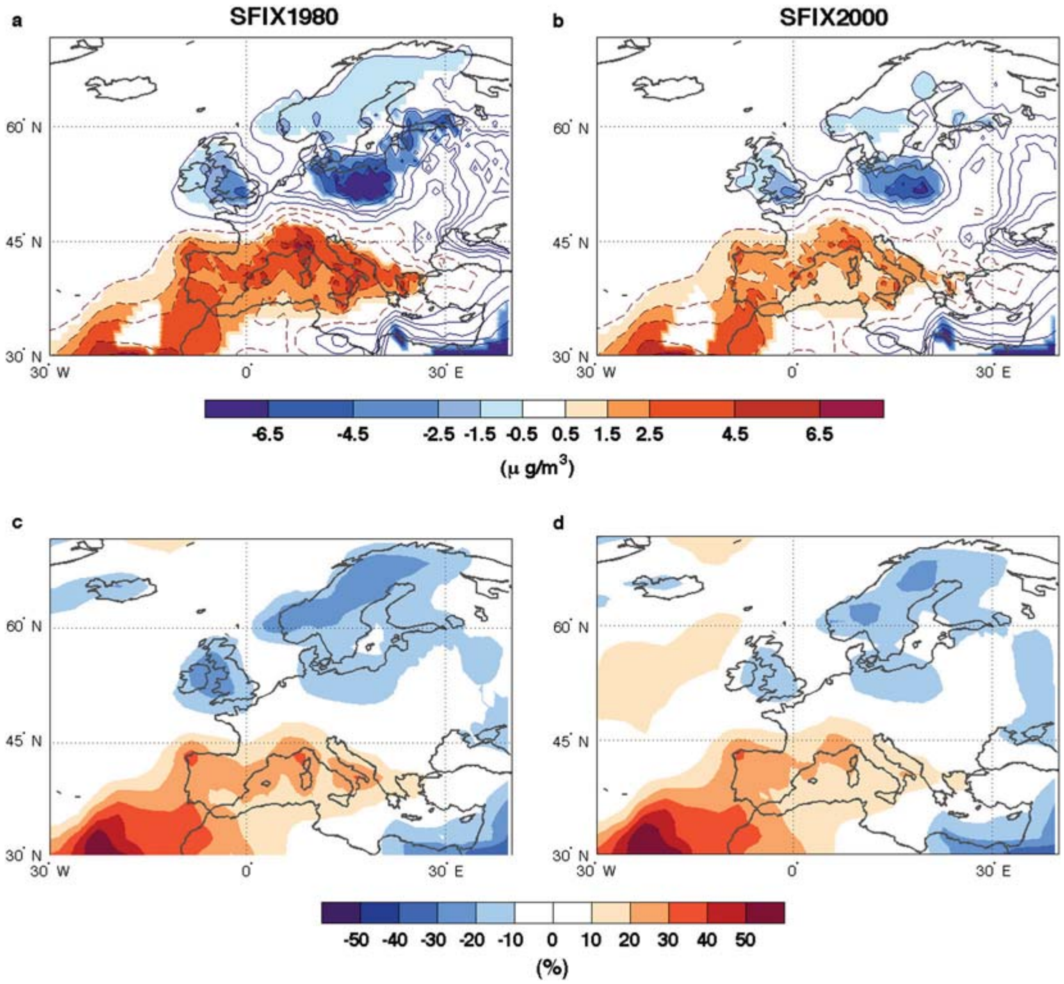

Figure 2. (a, b) $PM_{2.5}^{pop}$ anomalies in μg/m^3 and (c,d) relative difference in percentage from the DJFM climatological mean per unit of NAO standard deviation (i.e., NAOI = 1) for SFIX1980 and SFIX2000 simulations. The color shading in Figures 2a and 2ab displays $PM_{2.5}^{pop}$ significant anomalies at 90% confidence interval. The contours intervals (dashed = positive $PM_{2.5}^{pop}$ anomalies; solid = negative $PM_{2.5}^{pop}$ anomalies) follow the color bar scale. The anomalies are calculated using one-point regression analysis (see section 2).

3.1. Simulated $PM_{2.5}$ Concentrations and NAO-Driven PM Anomalies

[11] The modeled (SFIX1980) climatological annual averaged $PM_{2.5}^{pop}$ concentrations show the highest values of the order of 30–45μg/m^3 over the Black Sea, Silesia, Benelux, the Po valley, and southern Italy (Figure 1). In 2000, the model shows a decrease compared to 1980 around 25%–40% in the annual mean $PM_{2.5}$ concentrations over great part of Europe, attributable to emission reductions in the 1980s and 1990s (Figure 1). The SFIX1980 and SFIX2000 simulations show, instead, almost identical PM climatologies over northern Africa, which is reasonable given the mostly natural origin of the PM in the region.

[12] To study the degree to which surface PM anomalies are associated with the NAO, we have used a regression analysis of the model results: a regression coefficient b(i,j) is calculated at each specific latitude (i) and longitude (j) by linearly regressing the input variable of interest ($PM_{2.5}^{pop}$(t,i.j) anomalies) against the reference time series (NAOI(t)). The corresponding regression map is a composite field consisting of a linear combination of all available data, where each PM anomaly datum is weighted by the concurrent value of the NAOI time series.

$$b(i,j) = \left(\frac{1}{N}\right) \times \sum_{t=1}^{N} PM_{2.5}^{\text{anom}}(t,i,j) \times \text{NAOI}(t), \qquad (1)$$

where N is the number of time samples. The $b(i,j)$ coefficients may be viewed as the perturbations of the $PM_{2.5}^{pop}$ at the (i,j)th grid point that are observed in association with a positive perturbation in the NAOI(t) time series with an amplitude of one standard deviation (i.e., NAOI = 1) [*Lim and Wallace*, 1991]. For simplicity, we discuss only the anomalies associated with positive NAO phases; by construction, the anomaly pattern associated with the negative NAO phase differs only in sign.

[13] We focus our analysis only on winter months (December to March, DJFM) when the NAO dominates the atmospheric variability over Europe and PM concentrations are of most concern for public health, especially in southern Europe. In summer, significant NAO-PM correlations are found over Europe; however, the $PM_{2.5}^{pop}$ anomalies induced by the NAO are small—with local maxima reach-

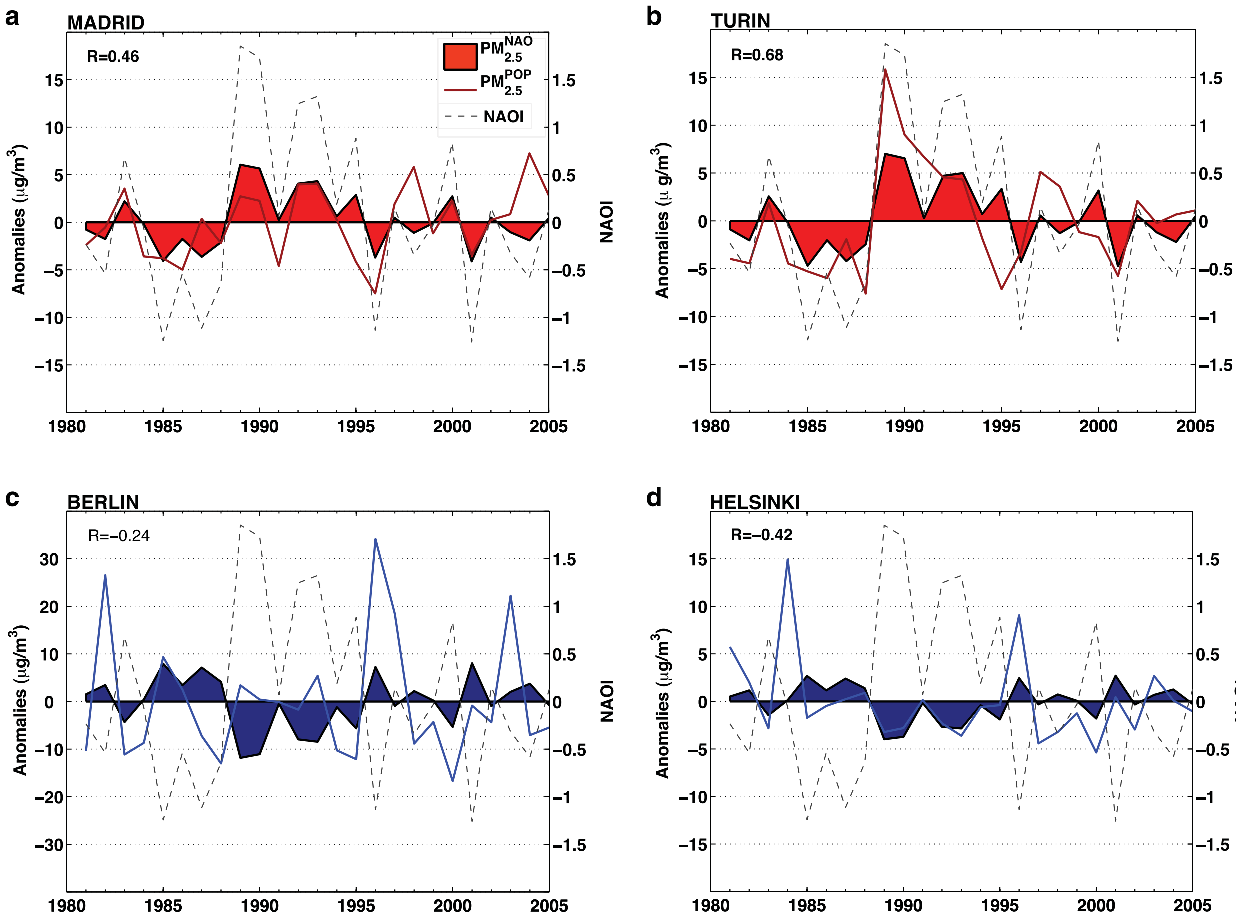

Figure 3. Modeled DJFM $PM_{2.5}^{pop}$ anomalies (SFIX2000) from the climatological (1980–2005) mean and $PM_{2.5}^{pop}$ anomalies explained by the NAO (filled area) for four selected cities. The dashed line indicates the NAOI. The number in the right corner indicates the correlation between DJFM $PM_{2.5}^{pop}$ anomalies and NAOI. In bold the significant correlation at 90% confidence interval. These four locations have been selected as representative of the regions most affected by the NAO.

ing only 1 µg/m³ (Figure S6), summer PM variability being driven more by the interaction of local emissions with small scale weather phenomena than by large-scale atmospheric variability.

[14] In Europe, during winter, PM concentration anomalies in both simulations show dipolar peaks of 5–7 µg/m³ (Figure 2) with negative anomalies over central-northern Europe and positive anomalies over the Mediterranean basin. The dipolar PM response is primarily connected to changes in wet deposition associated with positive NAO phases: more precipitation caused by increased storminess at mid-high latitudes and drier and more stable conditions—associated with the expansion of the Azores anticyclone—over southern Europe. Anomalies over northern Africa are instead related to a modification of the wind-induced dust emissions: during positive NAO, the higher pressure over the Mediterranean Sea (Figure S4) increases the easterly flow along the southern edge of the Azores anticyclone. The strengthening of the trade winds enhances the emission and transport of dust toward the coast of western Africa and, to a lesser extent, toward south-western Europe (Figure S7). Consequently, during positive NAO dust plumes are less frequent in eastern Africa and south-eastern Europe. In our model, mineral dust emissions dominate the $PM_{2.5}$ anomalies over Northern Africa, whereas over Europe, the $PM_{2.5}$ anomaly pattern is determined by anthropogenic emissions (cf. Figure S7 with Figures S8, S9, and S10). As expected, the impact of atmospheric variability on PM concentrations is greater in SFIX1980 than SFIX2000 simulation in the areas strongly affected by anthropogenic emissions (cf. Figures 2a and 2b); whereas the relative impacts in percentages do not strongly change (cf. Figures 2c and 2d).

[15] Modeled winter $PM_{2.5}^{pop}$ anomalies in the Mediterranean region closely follow the NAO variability (Figure 3): for example, $PM_{2.5}^{pop}$ anomalies are significantly correlated with the NAOI in Madrid and Turin (R = 0.46 and R = 0.68, respectively). In northern Europe, the correlation is greatest in Scandinavia, and it is significant but lower than in southern Europe (e.g., Helsinki R = –0.42). In central Europe, the correlation is negative but not always significant (e.g., Berlin R = –0.24). For NAOI = 1, on average the NAO can account for up to 30% of the modeled $PM_{2.5}^{pop}$ variability (Figures 2 and 3), the remainder of the PM variability being determined by a combination of more local meteorological variability and emissions variability. During extreme NAO phases (e.g., 1989, 1990, 1996, 2001) $PM_{2.5}^{pop}$ variability is predominantly by the NAO in several European regions (Figure 3).

[16] Our model results are confirmed by an analysis of PM monitoring stations across Europe, where a similar dipolar correlation pattern is observed (Figure S5).

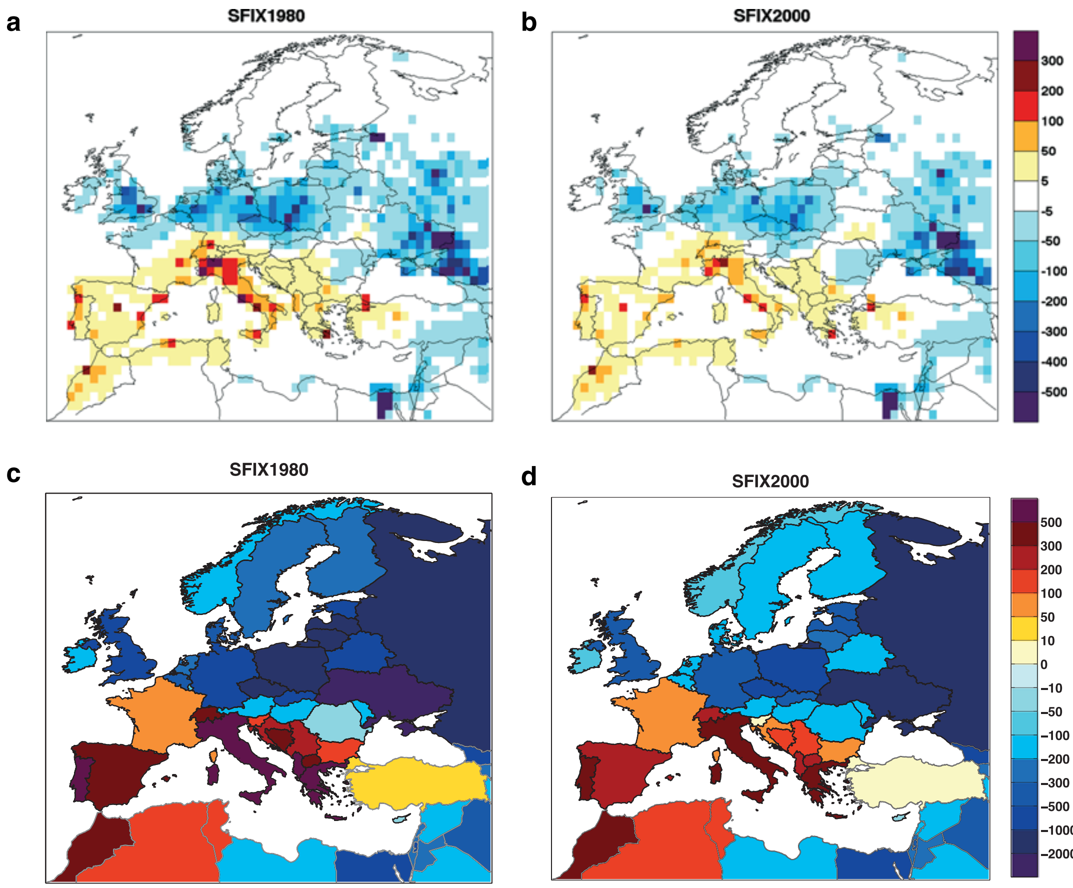

Figure 4. NAO-induced total annual mortality change (a, b) for an area of 1° × 1° and (c, d) for each country normalized to 10 million inhabitants, for (left panels) SFIX1980 and (right panels) SFIX2000 simulations.

3.2. $PM_{2.5}$ Health-Impact Changes Caused by a Future Winter NAO Shift

[17] In Europe, over 600,000 premature deaths each year from cardiopulmonary and lung cancer diseases are attributed to anthropogenic PM exposure causes [*Anenberg et al.*, 2010]. The winter NAO has shown an upward trend during winter in the 1980s and 1990s: the winter mean NAO in the period 1981–2000 was 1.2 standard deviations above the 1951–1970 winter mean (data available in www.cgd.ucar.edu/hurrell/indices.html). Climate model predictions suggest that the positive trend in winter NAO will continue in the coming decades [e.g., *Kuzmina et al.*, 2005; *Stephenson et al.*, 2006]. Future increases in the winter mean NAO state would give rise to higher PM concentra-

Table 1. NAO Impact on $PM_{2.5}$ Annual Mean and Mortalities for 10 Selected European Cities[a]

	$PM_{2.5}$ ($\mu g/m^3$) Annual Average		Anomalies ($\mu g/m^3$) Annual Departure Per NAOI = 1		Mortality Δ#Premature Deaths Per NAOI = 1	
	1980	2000	1980	2000	1980	2000
Madrid – ESP	18.6	13.4	+1.2	+0.9	+280	+180
Barcelona – ESP	33.3	22.2	+2.2	+1.1	+220	+120
Marseille – FRA	26.1	16.8	+1.8	+0.9	+71	+36
Turin – ITA	35.8	20.3	+2.6	+1.3	+230	+120
London – GBR	25.5	14.0	–2.0	–1.1	–1300	–670
Berlin – GER	45.1	24.6	–3.4	–2.1	–640	–390
Warsaw – POL	65.7	39.1	–3.9	–2.4	–360	–210
Donetsk – UKR	58.2	44.9	–4.9	–4.3	–1200	–1070
Helsinki – FIN	22.3	11.4	–1.8	–0.9	–36	–15
Moscow – RUS	53.7	25.6	–2.5	–1.2	–3400	–1700

[a]From the left to the right: annually averaged $PM_{2.5}$ concentrations ($\mu g/m^3$); $PM_{2.5}$ concentration anomalies ($\mu g/m^3$); and changes in the number of deaths for lung cancer and cardiopulmonary diseases per a winter NAOI = 1 shift for SFIX1980 and SFIX2000 simulations. The number of premature death changes have a confidence interval of ±30% based only on the effects of a given PM anomaly, without including any other uncertainties arising, e.g., from the PM-NAO relationship.

tions in some European regions, leading to an increase in premature deaths in those countries, unless compensated for by emission reductions.

[18] To provide insights into the health impacts of a future NAO-induced shift in $PM_{2.5}$ mean concentrations in the EU region, we have calculated changes in annual mortality (see supporting information) per unit of NAO standard deviation (i.e., NAOI = 1). To allow comparability with our earlier calculation, we used population and baseline mortality rates for the year 2000 [*WHO*, 2013]. For a given anomaly, the number of premature deaths changes shown hereafter have a confidence interval of $\pm 30\%$.

[19] Remarkable changes in mortality are found in the most populated urban areas (Figure 4a, 4b). The regions most sensitive to the NAO variability are in central-northern Europe, Russia, Ukraine, Poland, Germany, and United Kingdom with a strong reduction in annual mortalities (a decrease in premature deaths by up to 2000/10 million people, Figure 4c, 4d) and in southern Europe, Italy, Iberian peninsula, and the Balkans (an increase over 500/10 million people, Figure 4c, 4d). The integrated changes in mortality per country—normalized to a NAOI = 1 shift—range from a decrease of 25,500 premature deaths in Russia to an increase of 4700 premature deaths in Italy (Table S2).

[20] To further investigate the effects of NAO mean state shifts on pollution level on urban settlements, we have calculated the changes in annual mortality for 10 selected European cities (Table 1), located in the areas most affected by the NAO.

[21] In southern Europe, Turin and Madrid show peaks of about 120–180 and 230–280 more annual premature deaths per a NAOI = 1 shift in the SFIX2000 and SFIX1980 simulation, respectively (Table 1). On the other hand, in eastern Europe, Moscow benefits from a positive NAO shift leading to a decrease in the number of annual premature deaths between 1700 (SFIX2000) and 3350 (SFIX1980) per NAOI = 1. Other large cities, such as London, Berlin, and Donetsk, would experience a broad reduction in the number of annual deaths ranging from $\sim$400 to 1300 per NAOI = 1. For more extreme NAO shifts than NAOI = 1, the $PM_{2.5}$ anomalies would follow a linear relationship for $PM_{2.5}$ and the changes in mortality a near-linear one (following equation (1) in Supplementary). Finally, DJFM anomalies affect the annual $PM_{2.5}$ mean, consequently the likelihood of exceeding the annual limit value imposed by the European regulation will become more likely in the Mediterranean countries.

4. Discussion and Conclusions

[22] Our results have shown how decreased anthropogenic emissions (SFIX1980 versus SFIX2000) lead to a reduced influence of atmospheric circulation on $PM_{2.5}$ anomalies and hence on human health. However, reduced emissions may not immediately translate in a reduction of the $PM_{2.5}$ concentrations. From 1999 to 2009, the reported emissions of primary PM and PM precursors gases have dropped by 20%–30%, whereas among 459 monitoring stations around Europe analyzed in the *EEA* [2011] for the same period, only 42 stations showed statistically significant negative trends in PM_{10}. The reason for the absence of a broad consistent significant decline over Europe is most likely related to the impact of the interannual atmospheric variability, masking anthropogenically induced reductions in PM_{10}. Even if the impact of emission decreases cannot be statically proven in 5–10 year timescales by atmospheric variability, our model study suggests that long-term downward trends on multidecadal timescales will eventually lead to strong benefits in terms of air quality (Figures 1 and 2).

[23] Several studies have tried to quantify the influence of weather conditions on PM concentrations, using local meteorological data for each analyzed PM monitoring station [*Barmpadimos et al.*, 2011, 2012]. Our study highlights the possibility of using large-scale atmospheric indicators (NAOI/PC1) to account for interannual meteorological variability in understanding PM trends over a large spatial scale in winter. The analysis and method outlined in this study provide a consistent first-order estimation of the influence of large-scale atmospheric circulation on the interannual PM variability in winter, and on how that variability may affect PM trend estimates. The method also provides insights on PM health-impacts induced by large-scale atmospheric circulation shifts under climate change conditions.

[24] Finally, our results show that cities located in the Mediterranean area may be penalized by a NAO positive shift in a future climate, whereas central-northern and eastern Europe will benefit from such a shift. One of the areas most negatively affected by climate change is the Po-valley in Northern Italy, which is both heavily urbanized (e.g., Milan, Turin, Bologna) and also one of the largest industrialized regions in Europe. Because of its specific morphology, this area is also one of the most polluted regions in Europe, and climate change may aggravate this situation. Additional PM emission reduction measures may be necessary for those countries and cities in southern Europe, likely to experience NAO driven increases in mortality, in order to counteract these particular climate disbenefits.

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