Annual Variation of Global Air Pollution: Initial Aerosol Effect or Climate Interaction?

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The aerosol at the previous time (initial aerosol) and climate conditions control the next step annual variation of global air pollution through the complex aerosol-climate interaction. However, the individual influences remain unclear, leaving a great gap for understanding the mechanism of air pollution evolution and supporting the environment management. We estimate the annual variation using statistical methods and satellite observations at global scale from 2001 to 2016. Results show that significant variation of annual aerosol occurs over 13.6% of land areas, in which a perturbation of aerosol may cause 0.58 ± 0.45 times change in the next phase. Initial aerosol and climate influences contribute 48.4–51.6% of the total variation, respectively. Specifically, the influences of precipitation, air temperature and surface temperature represent 0.1, 18.3 and 33.2% of the total variation. Physically, the observed variation is strongly correlated with fine mode aerosols, radiative scattering and warm/hot summers in temperate and cold zones. The environmental management therefore should implement cause-oriented strategies for emission control or climatic adaption.

Keywords: aerosol variation, natural evolution, climate change, contribution analysis, satellite

INTRODUCTION

Aerosol variation in response to a perturbation is one of the key issues in studies on global climate and environmental changes (Carslaw et al., 2010; Andread and Rosenfeld, 2008; Gettelman et al., 2016; Rosenfeld et al., 2014). Essentially, the variation comes from the aerosol at the previous time step (initial aerosol) and the corresponding climate influence. The initial aerosol provides the sources of air pollution evolution, while the climate conditions act as drivers of the evolution. Furthermore, the two influencing factors show complex interaction. Specifically, the initial aerosols affect the climate (particularly the temperature) through direct (Bellouin et al., 2005), indirect (Twomey, 1977; Garrett and Zhao, 2006) and semidirect (Allen and Sherwood, 2010) aerosol radiative forcing, which subsequently exerts a significant feedback effects on the aerosol evolution in the next phase (Shindell et al., 2009; Feng and Zou, 2019a). It is necessary to clarify the mechanism of aerosol variation for climate predictions and environmental management (Scott et al., 2017). However, the current results are still controversial, and the contributions of initial aerosol and climate condition remain unclear (Bonan and Doney, 2018; Carslaw et al., 2013). Although numerous models have been used to evaluate the impacts and responses of aerosols by comparing scenario predictions with and without the potential driving factors, unavoidable uncertainties originate from the initial conditions, model
errors, and prediction scenarios (Bonan and Doney, 2018). Considering these uncertainties, researchers have suggested that direct observations, particularly satellite remote sensing observations, are needed to accurately capture aerosol impacts and forcing (Seinfeld et al., 2016).

Here, we estimate the driving factors of aerosol variation using statistical methods based on satellite observations. Methodologically, the aerosol variation was first identified as the initial aerosol, climate condition and their interactions. A stepwise multiple linear regression (MLR) model was then adopted to estimate the sign and magnitude of the contributions of the different components. The methods and corresponding datasets are described in Section 2. The results and discussion are presented in Section 3. The conclusions are provided in Section 4. The results of this study will help clarify the mechanism of global aerosol change, which will support relative climate adaption and environmental management.

**MATERIALS AND METHODS**

**Theory and Method**

As described above, the aerosol variation originates from initial aerosol and climate condition with their complex interactions. The interactions are shown in Figure 1. Specifically, aerosols affect the climate (particularly temperature and precipitation) through direct, indirect and semidirect radiative forcing, which in turn influences the aerosol change. Therefore, two main loops of “initial aerosol perturbation → temperature response → aerosol change” (ATA) and “initial aerosol perturbation → precipitation response → aerosol change” (APA) can be identified. Because aerosol forcing exerts influences on both air temperature (Ta) and land surface temperature (Ts) (Feng and Zou, 2019b; Feng et al., 2019a), the ATA loop can be further divided into the interactions between aerosol and Ta (ATaA) and between aerosol and Ts (ATsA).

A stepwise MLR model is then used to assess the contributions of the initial aerosol and climate condition, which had been proven to be an effective and reliable way to capture the driving factors in the previous studies (Li et al., 2019; Feng and Zou, 2020). Mathematically, it firstly calculates correlation coefficient matrix and F-test statistics between aerosol evolution and each factor of initial aerosol and climate condition. Certain factors could enter the MLR model and act as the independent variables under significant F-test statistics ($p < 0.05$). Otherwise, the factors should be excluded from the model. Specifically, the influences of initial aerosol and climate are firstly identified by whether the variables enter the MLR model, while the sign and magnitude are estimated by measuring the response of aerosol change to the initial perturbation. Mathematically, the aerosol at next phase ($A_{t+1}$) is a function of the initial aerosol ($A_t$), precipitation ($P_t$), temperature ($T_t$), and their interactions, which can be written as:

$$A_{t+1} = f(A_t, T_t, P_t, I(A_t, T_t, P_t))$$  \hspace{1cm} (1)$$

where $A_t$, $T_t$, and $P_t$ are the aerosols, temperature and precipitation at time $t$, respectively, and $I(A_t, T_t, P_t)$ is their interaction. Our previous studies demonstrated that aerosol affects both $T_A$ and $T_s$, which should be considered in this study (Feng and Zou, 2019b; Feng et al., 2019a). In this study, we carry out the research at annual scale to capture the general characteristics of aerosol variation. Therefore, the time step of $t$ refers to the year.

The MLR model was used to execute the function, as this model has been widely used to capture the aerosol influences and drivers in previous studies (Li et al., 2019; Feng and Zou, 2020). The interaction terms (for example, the interaction of the $ith$ and $jth$ parameters, $x_i x_j$) are up to second-order terms. Therefore, $A_{t+1}$ can be written as follows:

$$A_{t+1} = \beta_1 A_t + \beta_2 P_t + \beta_3 T_A + \beta_4 T_s + \beta_5 A_t T_A + \beta_6 A_t T_s + \beta_7 P_t T_A + \beta_8 P_t T_s + \beta_9 T_A T_s$$  \hspace{1cm} (2)$$

where the series of $\beta$ terms are the corresponding coefficients of the normalized $A_t$, $T_A$, $T_s$, $P_t$ and their interactions. The stepwise method was used to select the entered variables, which further identified the variation coefficient ($\lambda$) by measuring the response of aerosols at time $t+1$ ($A_{t+1}$) to the perturbation of the initial aerosols $A_t$:

$$\lambda = \frac{\partial A_{t+1}}{\partial A_t} = \beta_A + \beta_{AP} P_t + \beta_{AT_A} T_A + \beta_{AT_s} T_s$$  \hspace{1cm} (3)$$

where $\beta_A$ refers to the impact of the initial aerosol, while $\beta_{AP} P_t$, $\beta_{AT_A} T_A$ and $\beta_{AT_s} T_s$ are the climate interactive influences.
Through this way, the contributions of initial aerosol and climatic combined influences can be isolated. Meanwhile, individual influence of each climatic variables can also be captured through the corresponding items of Eq. 3.

The stepwise method allows limited variables to enter the MLR model. Therefore, the patterns of variables and the corresponding coefficients may vary at the pixel scale over land. The contribution of each component is calculated by taking the area coverage into consideration:

$$C_i = \frac{\lambda_i \cdot S_i}{\sum \lambda_i \cdot S_i}$$

where $\lambda_i$ and $S_i$ are the variation and area of component, respectively.

**Data Sources and Preprocessing**

To carry out the investigation, global aerosol and climate data sets are used. Aerosol optical depth (AOD), which is obtained from the Clouds and the Earth’s Radiant Energy System (CERES) (https://ceres.larc.nasa.gov/), is adopted to present the aerosol amount, with average relative error of 10% over land (Kato et al., 2018). The data is from an aerosol transport model MATCH, that assimilates the NASA-GSFC MODIS MOD04-L2/MYD04_L2 products. The precipitation data are obtained from the Global Precipitation Climatology Centre (GPCC) Full Data Monthly Product Version 2018 (ftp://ftp-anon.dwd.de/pub/data/gpcc/html/downloadgate.html). The data are based on 67,200 ground site measurements and are interpolated across the global land surface at a spatial resolution of 0.5° from 1891 to 2016. Ta data are obtained from the Global Historical Climatology Network version two and the Climate Anomaly Monitoring System (GHCN_CAMS) Gridded 2 m Temperature (Land) https://www.esrl.noaa.gov/psd/data/gridded/data.ghcncams.html) from 1948 to 2019 at a spatial resolution of 0.5°. The Ts data are obtained from the CERES_SYN1deg_Ed4A dataset (https://ceres.larc.nasa.gov/) with a spatial resolution of 1 × 1 at a monthly scale. All the datasets are resampled to a spatial resolution of 1° at an annual scale from 2001 to 2016.

**RESULTS AND DISCUSSIONS**

Using the MLR model, the variation is first identified by examining the variables entering the model. We first execute the model at global scale, while no variables enter the model (Supplementary Table S1). Results suggests that it is difficult to
build a universal model between aerosol and its driving factors at a large scale. In contrast, various variables and their interactions enter the model in only some parts of the global grid cell (Figure 2). Therefore, significant aerosol variation is more likely to be observed at the regional scale. Specifically, the variables of initial aerosol, precipitation, Ta and Ts that entered the model cover 6.6%, 4.3%, 3.0% and 4.9% of the land, respectively, indicating the relatively primary influence of initial aerosol. Furthermore, the patterns of the coefficients are spatially inconsistent, suggesting the heterogeneity of the forcing due to the nonlinear relationship with aerosol (Feichter et al., 2004).

Based on the coefficients of Eqs. 2, 3, the multi-year aerosol variation is subsequently estimated using the data sets of precipitation (P) and temperature (Ta and Ts) from 2001 to 2016 (see Methods). The mean value is 0.58 ± 0.45 in the regions labeled with significant variation, suggesting that the perturbation of aerosol may cause smaller change to the coming phase. Spatially, the significant variation covers 13.6% of the land area (Figure 3A). The positive variation is mainly in southeastern North America, western Europe, northern Africa and India. The negative variation occurs in only southeastern Australia due to the precipitation influence (Figure 3C). Our results detail the variation over different local sites. Several researchers have reported aerosol-climate loops at global or regional scales. Zhao et al (Zhao et al., 2006) presented a positive feedback of “more aerosol→ less precipitation→ more aerosol” over eastern central China. Yang et al (Yang et al., 2016) and Wang et al (Wang et al., 2014) reported a clear positive feedback between aerosol and downwelling solar radiation, winds and the planetary boundary layer in Beijing, while Miao et al (Miao et al., 2016) showed both positive and negative feedback between aerosols and the boundary layer. The results of this study clearly show that the estimation of variation over a large scale may conceal natural evolution at local scale. Therefore, we suggest that it should be estimated at a finer scale to capture the spatial details and support local environmental management.

To explore the driving factors and physical mechanisms, we further estimate the contributions of the initial aerosol, precipitation, air temperature and surface temperature components by considering the area weights (see Methods). The results show that variations of the four components are 0.58 ± 0.34, 0.003 ± 0.371, 0.49 ± 0.42 and 0.53 ± 0.39, contributing 48.4, 0.1, 18.3 and 33.2% of the total variation, respectively (Figure 3B-F). The initial aerosol contributes the greatest portion. The temperature in influence contributes to 51.4% of the variation, which is the most dominant impact on the climate influence when compared to the precipitation. The weak precipitation influence might be attributed to the indirect cloudy forcing that weakens the magnitude of the aerosol impacts (Supplementary Figure S1). Meanwhile, the contribution of surface temperature (Ts) is much greater than that of air

**FIGURE 3** | Spatial patterns of the global aerosol variation (A), the components of (B) initial aerosol (C) precipitation (D) air temperature and (E) surface temperature and the contribution to global variation (F). The blank regions indicate that no variables enter the stepwise MLR model.
Forcing, which tends to cool the surface and warm the top atmosphere (Feng et al., 2016). On the other hand, the greatest positive variation is mainly observed in the temperate and cold climate zones with hot or warm summers. Specifically, the influence of initial aerosol dominates the variation in a warm summer (Cfb and Dfb), while surface temperature (Ts) acts as the primary factor in a hot summer (Csa and Dfa). It is very interesting that summer climate plays a crucial role in variation, which is mainly attributed to its impact on high solar radiation and, subsequently, monsoon and aerosol transportation (Pausata et al., 2016; Lau et al., 2017).

The aerosol variation and the associated components play a significant role in global climate and environmental changes. The spatial extent of aerosol variation is consistent with the internal trend of aerosols (Supplementary Figure S3), which supports the paradigm of “Polluting in Polluted and Cleaning in Clean” (Feng et al., 2019b). Therefore, the result suggests that the recent aerosol reduction in North America and western Europe might cause substantial future decreases (Feng and Zou, 2019b), which will profoundly improve the air quality and public health. However, the net warming effects of aerosol reduction may offset the cooling effects of greenhouse gas emission restrictions, which will exert a serious burden on the global or regional eco-environment under a warming climate (Najafi et al., 2015). On the other hand, there is serious air pollution in India, which faces a risk of worsening pollution due to the great and positive aerosol variation (Guttikunda et al., 2014). Furthermore, the results of this study clearly show that the variation is affected by initial aerosol, air temperature, and surface temperature in North America and western Europe (Figure 3B, D, and E), suggesting the combined influences of aerosol-climate interactions.
interaction. In India, the variation is mainly dominated by the initial aerosol factor (Figure 3C). Thus, we suggest that India should pay close attention to the influences of aerosol emissions and aerosol-climate interactions in North America and western Europe under the changing global climate, while emission control strategies might be the main way to improve air quality in India.

CONCLUSION

Overall, we show that aerosol variation can be observed at the regional scale rather than at the global scale. Although the initial aerosol accounts for the greatest contribution to the total variation, the influences of climate conditions (precipitation (P), air and surface temperature (Ta and Ts)) are nonnegligible. Therefore, the combined influences and their interactions should be taken into consideration to fully evaluate the aerosol variation. Accurate estimations of the signs and magnitudes of variation will provide useful information for predicting climatic responses. For example, great efforts have been made to control aerosol emissions to improve global air quality in recent decades (Feng and Zou, 2019b), which is expected to substantially reduce aerosols due to positive variation. Based on the results of this study, we suggest a full investigation of climatic and environmental responses to regional variation in future studies.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

HF: Conceptualization, Methodology, Software, Writing—Original draft preparation. YD: Data curation, Visualization. BZ and CZ: Investigation, Supervision, Reviewing and Editing.

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SUPPLEMENTARY MATERIAL

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