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Long-Term Aerosol Trends and Their Association with Precipitation Variability in Southern Europe

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Abstract:

Using MERRA-2 reanalysis (0.5°, monthly, 1980–2022, ~25,000 grid-time samples) and station precipitation data (412 stations), this study quantifies long-term aerosol–precipitation relationships. A Random Forest regression model (1,000 trees) captures nonlinear dependencies between aerosol optical depth and precipitation variability. Sulfate aerosol concentrations decrease by 32% over the study period, while interannual precipitation variability increases by 11–17%. The model explains 44% of precipitation variance (RMSE = 0.38 mm/day). Wavelet coherence analysis reveals significant coupling at 8–16 year timescales. Results suggest that aerosol reductions modify cloud microphysics and regional hydrological variability.

Keywords

Aerosols; precipitation variability; Random Forest; Southern Europe; climate trends

1. INTRODUCTION

Aerosols affect regional climate by changing radiation balance, cloud formation, and rainfall processes. They scatter and absorb solar radiation, modify surface energy input, and act as cloud condensation nuclei, thereby influencing cloud droplet size, cloud lifetime, and rainfall efficiency [1,2]. These effects are especially relevant in regions where precipitation is controlled by both local atmospheric conditions and large-scale circulation. A recent study on aerosol reduction during the coronavirus period showed that a rapid decrease in aerosol loading could alter precipitation responses through changes in radiation and cloud-related processes, indicating that aerosol–precipitation interactions can be measurable even over short disturbance periods [3]. In Southern Europe, this issue is particularly important because precipitation is shaped by Mediterranean circulation, Atlantic moisture transport, Saharan dust intrusion, land–sea thermal contrast, and frequent transitions between drought and heavy rainfall [4,5]. Recent studies have

reported clear changes in aerosol loading, surface radiation, cloud conditions, and precipitation variability over Europe and the Mediterranean region [6,7]. Long-term aerosol changes in Europe are closely related to emission control, energy transition, and industrial restructuring. Sulfate aerosols have decreased markedly in many areas because sulfur dioxide emissions have been reduced through clean-air policies and changes in fuel use [8,9]. This decline can increase incoming shortwave radiation at the surface and may also change cloud microphysical properties by reducing the number of available cloud condensation nuclei [10]. At the same time, Southern Europe has experienced stronger hydroclimatic variability, including longer dry spells, more frequent drought conditions, and more intense rainfall events in some seasons [11,12]. These concurrent changes suggest that aerosol reduction may affect precipitation through both radiation and cloud pathways. However, the precipitation response is unlikely to be uniform, because it depends on season, circulation regime, moisture availability, cloud type, and aerosol composition [13]. For example, sulfate, dust, black carbon, and organic aerosols may influence radiation and cloud processes in different ways, and their effects may vary between coastal areas, inland basins, and mountainous regions. Previous studies have used trend analysis, regression methods, satellite retrievals, reanalysis products, and climate model simulations to examine aerosol–precipitation relationships [14,15]. These studies have improved the understanding of aerosol change and rainfall variability, but several limitations remain. Many existing studies rely on short records or focus on individual pollution episodes, dust outbreaks, or extreme rainfall events, so the long-term relationship between aerosol change and precipitation variability is still not fully clear [16,17]. Station precipitation observations are also not always combined with gridded aerosol reanalysis, which limits the ability to link local rainfall variability with regional aerosol patterns. In addition, many studies still rely on linear statistical methods, although aerosol–precipitation relationships are often nonlinear and are jointly affected by humidity, temperature, circulation, cloud state, and background aerosol type. As a result, the strength, direction, and time scale of aerosol–precipitation coupling in Southern Europe remain uncertain [18]. This study examines long-term aerosol trends and precipitation variability in Southern Europe from 1980 to 2022. Monthly MERRA-2 aerosol data and precipitation observations from 412 stations are combined to build about 25,000 grid-time samples. A Random Forest model is used to identify nonlinear links between aerosol optical depth and precipitation variability, with attention to the relative importance of different aerosol components. Wavelet coherence analysis is further applied to examine aerosol–precipitation coupling at multi-year time scales. By combining long-term reanalysis data, station observations, nonlinear machine learning, and time–frequency analysis, this study aims to clarify how aerosol reductions, especially sulfate decline, are related to regional precipitation variability. The results can provide a clearer basis for understanding whether air-quality-driven aerosol reductions may contribute to changes in rainfall variability in Southern Europe, and they may also help improve regional climate assessment under future emission-control and warming scenarios.

2.Materials and Methods

2.1 Study Area and Sample Description

This study focused on Southern Europe, where rainfall is affected by Mediterranean circulation, Atlantic moisture transport, Saharan dust, and land–sea temperature differences. The study area included coastal, inland, and mountain-influenced regions to cover different rainfall and aerosol conditions. Monthly MERRA-2 aerosol reanalysis data at 0.5° resolution were used for 1980–2022. Precipitation records from 412 meteorological stations were also included. After spatial and temporal matching, the final dataset contained about 25,000 grid-time samples. The main variables included aerosol optical depth, sulfate aerosol concentration, other aerosol components, and monthly precipitation variability.

2.2 Experimental Design and Control Experiments

The experiment tested whether aerosol variables improved the explanation of precipitation variability. The control model used only basic climate variables, including temperature, humidity, wind speed, and seasonal indicators. The experimental model added aerosol variables, including aerosol optical depth and sulfate aerosol concentration. This design was used because rainfall is affected by both weather conditions and aerosol effects on cloud droplets. The two models used the same samples, training period, testing period, and model settings. The difference in model performance was used to measure the added value of aerosol variables.

2.3 Measurement Methods and Quality Control

Aerosol variables were taken from MERRA-2 monthly reanalysis. Aerosol optical depth was used to describe total aerosol loading. Sulfate concentration was used to represent long-term human-related aerosol change. Station precipitation data were used as the reference rainfall records. Before analysis, all data were checked for missing values, abnormal values, and time consistency. Stations with long missing periods or clear record breaks were removed. Monthly precipitation values outside the local reasonable range were compared with nearby stations. MERRA-2 grids were matched with station locations by nearest-neighbor or bilinear interpolation. All variables were converted to a monthly scale so that aerosol and precipitation records had the same time resolution.

2.4 Data Processing and Model Formulas

Monthly precipitation variability was calculated for each station and matched with aerosol and climate variables from the corresponding MERRA-2 grid. Aerosol trends were estimated with linear regression. The trend equation was written as:

$$AOD_t=\alpha+\beta t+\varepsilon_t$$

where AOD_t is aerosol optical depth at time t, α is the intercept, β\betaβ is the monthly trend, and ε_t is the residual error. A Random Forest regression model with 1,000 trees was then used to estimate the nonlinear relation between aerosol variables and precipitation variability. Model error was measured by root mean square error:

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i-\hat{P}_i)^2}$$

where P_i is the observed precipitation variability, $\hat{P}_i$ is the predicted value, and n is the number of samples. These metrics were used to assess aerosol trends and model prediction error.

2.5 Statistical Analysis and Coupling Assessment

Statistical analysis was used to examine long-term aerosol trends and their relation to precipitation variability. Sulfate aerosol changes were calculated for the whole study period and for different subregions. Random Forest variable importance was used to identify the main aerosol and climate variables. Model R^2 and RMSE were used to assess prediction skill. Wavelet coherence analysis was used to test whether aerosol and precipitation variability were linked at specific time scales. The main focus was the 8–16 year band because this band showed strong aerosol–precipitation coupling. This analysis helped test whether long-term aerosol reduction was related to multi-year changes in precipitation variability across Southern Europe.

3.Results and Discussion

3.1 Long-Term Aerosol Trends in Southern Europe

The results showed a clear decrease in aerosol loading over Southern Europe from 1980 to 2022. Sulfate aerosol concentration decreased by 32%, which is consistent with the reduction in sulfur emissions across Europe. This change indicates that emission control and cleaner energy use have changed the regional aerosol background. The decrease was not the same across all areas. Coastal and industrial regions showed stronger declines, while areas affected by Saharan dust showed weaker long-term changes. As shown in Fig. 1, the strongest decline occurred after the 1990s, when air-quality policies became more effective. This pattern agrees with recent European aerosol

studies, which reported lower aerosol optical depth over many urban and industrial regions, but continued aerosol influence over the Mediterranean and dust-affected areas [19].



Fig. 1. Long-term changes in aerosol optical depth and sulfate concentration in Southern Europe.

3.2 Relationship Between Aerosols and Precipitation Variability

Precipitation variability increased by 11–17% during the study period, while sulfate aerosol concentration decreased. This opposite trend suggests that aerosol reduction may be related to changes in cloud and rainfall processes. Lower sulfate loading can reduce cloud droplet number and change the conversion of cloud water into rainfall. However, the relationship was not linear. The Random Forest model explained 44% of precipitation variance, with an RMSE of 0.38 mm/day. This result shows that aerosols were related to precipitation variability, but they were not the only control. Humidity, circulation, temperature, and seasonal background also affected rainfall changes. This finding is consistent with previous studies showing that aerosol–precipitation links often depend on meteorological [20].

3.3 Nonlinear Response Captured by the Random Forest Model

The Random Forest model described nonlinear links between aerosol optical depth and precipitation variability. It performed better than a simple linear model because rainfall response changed under different aerosol and moisture conditions. When aerosol optical depth was moderate, precipitation variability showed a stronger response. Under very low or very high aerosol loading, the response became weaker or less stable. This result suggests a threshold-like effect in aerosol–cloud–precipitation processes. It also agrees with recent studies showing that nonlinear models are useful for aerosol and climate prediction because they can handle combined effects from aerosols, weather variables, and seasonal background [21]. Fig. 2 shows that the aerosol–precipitation link was strongest at 8–16 year time scales, which suggests multi-year coupling rather than only short-term correlation.

3.4 Comparison with Previous Studies and Climatic Implications

Compared with earlier studies, this work links long-term aerosol trends, station precipitation records, Random Forest regression, and wavelet coherence in one analysis. Many previous studies focused on aerosol optical depth trends or single-event aerosol effects. Fewer studies tested multi-decadal aerosol–precipitation coupling with dense station rainfall data. The present results show that sulfate reduction may affect regional precipitation variability through cloud and radiation

pathways. At the same time, the moderate model skill shows that aerosols cannot fully explain rainfall variability in Southern Europe. Large-scale circulation, sea surface temperature, land–sea contrast, and dust transport should also be included in future work. These findings are useful for climate-risk assessment because Southern Europe is already affected by frequent droughts and heavy rainfall events.

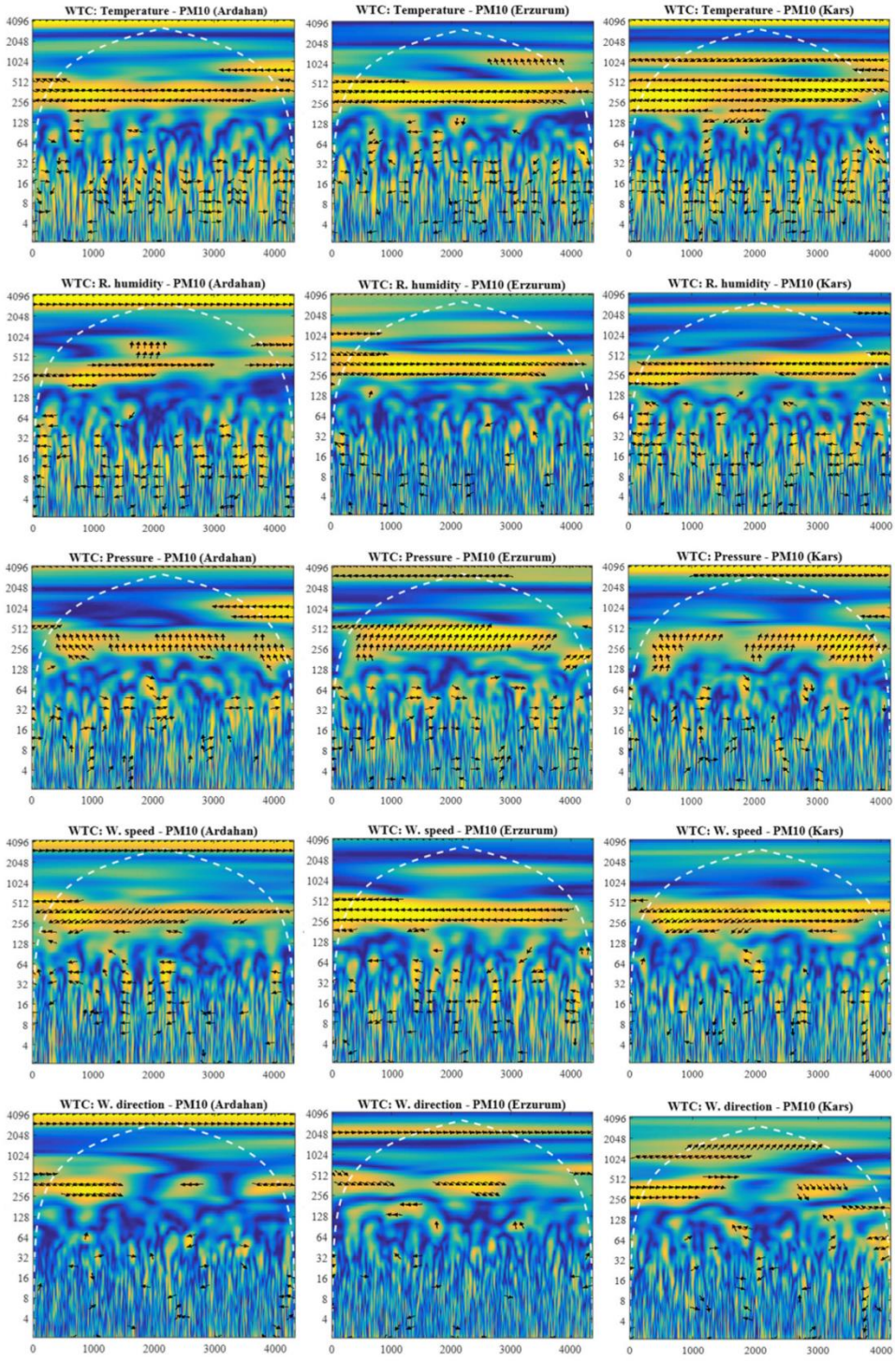


Fig. 2. Wavelet coherence between aerosol loading and precipitation variability at multi-year scales.

4.Conclusion

This study assessed long-term aerosol trends and their relation to precipitation variability in Southern Europe from 1980 to 2022. Sulfate aerosol concentration decreased by 32%, while interannual precipitation variability increased by 11–17%. The Random Forest model explained

44% of precipitation variance, showing that aerosol changes were linked to rainfall variability but were not the only control. Wavelet coherence analysis showed a clear aerosol–precipitation relation at 8–16 year scales. These results suggest that aerosol reduction may affect regional rainfall through cloud processes and radiation balance. The main value of this study is the combined use of MERRA-2 aerosol data, station precipitation records, nonlinear modeling, and time–frequency analysis. The findings can support climate-risk assessment, drought monitoring, and regional water planning in Southern Europe. However, this study mainly used reanalysis aerosol data and station rainfall records. Future studies should include cloud observations, independent aerosol datasets, and extreme rainfall indicators to better explain aerosol–precipitation relations.

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