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Errors in spectral fingerprints and their effects on climate fingerprinting accuracy in the solar spectrum

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ABSTRACT

Using the Earth's reflected solar spectrum for climate change fingerprinting is an emerging research area. The spectral fingerprinting approach directly retrieves the changes in climate variables from the mean spectral data averaged across large space and time scales. To investigate this fingerprinting concept, we use ten years of satellite data to simulate the monthly and annual mean reflected solar spectra and the associated spectral fingerprints for different regions over the ocean. The interannual variations in the spectral data are derived and attributed to the interannual variations in the relevant climate variables. The fingerprinting retrieved changes in climate variables are then compared with the actual underlying variable changes from the observational data to evaluate the fingerprinting retrieval accuracy. Two important errors related to the fingerprinting approach, the nonlinearity error and the averaging error in the mean fingerprints, and their impact on the retrieval accuracy, are investigated. It is found that the averaging error increases but the nonlinearity error decreases as the region size increases. The averaging error has minimal effect on the fingerprinting retrieval accuracy in small regions but has more of an impact in large regions. In comparison, the effect of nonlinearity error on the retrieval accuracy decreases as the region size increases. It is also found that the fingerprinting retrieval accuracy is more sensitive to the nonlinearity error than to the averaging error. In addition, we compare the fingerprinting accuracy between using the monthly mean data and the annual mean data. The results show that on average higher retrieval accuracy is achieved when the annual mean data are used for the fingerprinting retrieval.

1. Introduction

The Earth's radiation budget is essentially the balance between incoming radiation (the majority of which is solar) and outgoing radiation which consists of radiation energy in the reflected solar (RS) spectrum and emitted thermal infrared. An imbalance in the incoming and outgoing radiation will ultimately drive climate change. The Earth's RS spectrum is determined by the complex scattering and absorption of various atmospheric and surface components. The absorption and scattering properties are dependent upon the wavelength of the solar radiation and the type/size of the atmospheric particles. Changes in key atmospheric variables (e.g., water vapor, aerosol particles, and clouds) will lead to changes in different wavelengths of the RS radiation, generating spectral fingerprints of climate change in the RS spectrum.

In this paper, the spectral fingerprinting approach is used to attribute changes in individual climate variables (a subset of eleven relevant variables are selected) to the

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spectral change signal between the two climate states. We use space and time averaged radiative spectral variation between two climate states to infer the corresponding changes in climate variables responsible for the spectral change. This spectral climate fingerprinting technique uses the average-then-retrieval approach, providing a new method to detect climate change over the traditional retrieval-then-average approach. The major advantage of this new approach is to eliminate the instantaneous nonlinear retrieval step and thus avoid the biases/errors in individual retrieval algorithms in the traditional retrieval-then-average approach.

To date, several modeling studies on spectral climate change fingerprinting have been investigated, but they are limited to the longwave thermal spectrum [1–4]. Due to the strong multiple scattering and solar zenith impact, the RS spectrum has more complicated spectral variations in response to climate variable changes as compared to the infrared spectrum. However, the radiative response in RS spectrum provides unique information on climate change. Using ten years of satellite data for model simulation, we recently explored the feasibility of using the RS spectrum for climate change fingerprinting [5]. This pioneering study tests the concept of spectral climate fingerprinting for climate change detection and evaluates the uncertainty in RS fingerprinting retrieval in various climate regions. Comparing the fingerprinting retrieval of climate variable change to the actual underlying variable change, Jin and Sun [5] showed that the root-mean-square (RMS) differences between the two are less than twice as large as the monthly variability for all variables in all regions. Larger errors are usually observed in those variables with large nonlinear radiative response, such as the cloud optical depth and the ice particle size. The results also demonstrated the important impact of nonlinear error in fingerprints on the fingerprinting retrieval accuracy. If the nonlinearity error is taken into account in the fingerprinting process, the RMS retrieval errors are reduced to less than the monthly variability for nearly all variables.

Continuing the initial study of Jin and Sun [5], this paper analyzes various errors in the fingerprints and shows how these errors affect the fingerprinting retrieval in the RS spectrum. Particularly, we will quantify how these errors and their effects on retrieval accuracy vary with different time and space scales.

2. Data simulation and errors in fingerprints

2.1. Formulation

The interannual variation in the space and time averaged RS spectrum in a climate domain is related to the domain-averaged climate variable changes [6]. Climate change fingerprinting attributes the averaged spectral difference between two climate states to the averaged variations in climate variables. Using $\Delta X=[\Delta x_1, \ldots, \Delta x_n]$ to represent the variation between the two climate states in an ensemble of n climate variables, and $\Delta R=[\Delta R_1, \ldots, \Delta R_m]$ to represent the corresponding mean spectral difference in the m spectral channels, then ΔR and ΔX can be related through the kernel matrix $[K]_{m\times n}$ as illustrated by the following equations.

$$\Delta R = K\Delta X + E \tag{1a}$$

$$\Delta R_i = \sum_{j=1}^{n} K_{ij}\Delta x_j + E_i \tag{1b}$$

$$K_{ij} = \frac{\partial R_i}{\partial x_j}; \quad i=1,2,\cdots,m; \; j=1,2,\cdots,n \tag{1c}$$

where $E=[\Delta E_1, \ldots, \Delta E_m]$ is the error vector, representing the residuals that cannot be explained by fingerprints. The matrix K represents the spectral fingerprints of n variables associated with the spectral change. A fingerprint describes the differential response of radiation to a change in a climate variable and can be generated through radiative transfer modeling.

Based on the Eq. (1), the variation in the RS spectrum (ΔR) can be attributed to the changes in climate variables (ΔX) through the multivariate linear regression. Using the same procedure that was applied in the optimal detection [3,7], the linear fingerprinting solution (LFS) of Eq.(1) can be derived as

$$\Delta X = (K^T \varepsilon^{-1} K)^{-1} K^T \varepsilon^{-1} \Delta R \tag{2}$$

where ε is the covariance matrix of error E in Eq. (1) and $\varepsilon=EE^T$. The superscript T denotes a matrix transpose and the superscript -1 denotes a matrix inversion. To avoid the instability in matrix inversion, the ε^{-1} is Eq. (2) is actually calculated as $u^{-1}\lambda u^T$; here u and λ represent the eigenvectors and eigenvalues of ε, respectively, and only the first N ($N<m$) eigenvalues and eigenvectors are used. When all channels in the RS spectrum are equally weighted, the solution of Equation (1) reduces to

$$\Delta X = (K^T K)^{-1} K^T \Delta R \tag{3}$$

This is basically the solution of linear regression based on the ordinary least squares estimation (LSE) without error consideration.

While the trends in climate variables might be detected through reanalysis of long-term instantaneous retrieval data averaged in the climate domain, the spectral fingerprinting approach directly retrieves the changes in climate variables (ΔX) from the domain-averaged spectral data ΔR. This average-then-retrieval approach eliminates the instantaneous nonlinear retrieval step in the traditional retrieval-then-average method and provides an alternative to the reanalysis.

2.2. Model simulation

While the spectral fingerprints have to be generated from a radiative transfer model, the spectral data required to obtain the ΔR in the equations above could be either from real observations or from model simulation. In order to test the concept of climate fingerprinting using the RS spectrum and to evaluate the effect of error on the accuracy of fingerprinting retrieval, we use the same global satellite data sets to generate the spectral fingerprints and to simulate the RS spectrum in this study.