Implementation of the SBDART model for the estimation of the aerosol radiative forcing

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This study aims to estimate the aerosol radiative forcing (ARF) in the Aburrá Valley using the SBDART model. Given the global temperature rise of 1.1℃ since the 19th century, potentially mitigated to some extent by atmospheric aerosols, understanding their impact is crucial for accurate climate predictions and effective policy implementation. The project followed a cascade methodology, including a comprehensive literature review, installation and setup of the SBDART program, an in-depth study of the physico-mathematical model, implementation and adaptation of the model to local conditions, and a comparative analysis of results. Simulations revealed a high correlation between aerosol optical depth (AOD) and ARF, with a determination coefficient of 0.99, underscoring the importance of aerosols in climate regulation. Future work will focus on further characterizing aerosols using Mie theory and detailed atmospheric composition analysis. This project supports the goals of Medellín's Climate Action Plan 2020-2050 by providing essential data for climate predictions and environmental policy decisions [1], [6].

Aerosol Radiative Forcing (ARF) | Aerosol Optical Depht (AOD) | Single Scattering Albedo (SSA) | Asymmetry Factor (g)

1. Introduction

The global temperature has increased by 1.1°C since the 19th century, a rise potentially mitigated to some extent by atmospheric aerosols. Understanding the impact of aerosols is crucial for accurate climate predictions and the implementation of effective policy measures. Aerosols can influence the Earth's radiative balance by scattering and absorbing solar radiation, thereby affecting the climate both directly and indirectly [6].

The Aburrá Valley, located in Colombia, is a region with unique geographical and atmospheric conditions. Estimating the aerosol radiative forcing (ARF) in this area is essential for understanding local climate dynamics and supporting the goals of Medellín's Climate Action Plan 2020-2050. The SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) model provides a robust framework for simulating atmospheric radiative transfer and assessing the radiative impacts of aerosols [1].

This study aims to estimate the ARF in the Aburrá Valley using the SBDART model. The project follows a cascade methodology, encompassing a comprehensive literature review, installation and setup of the SBDART program, a detailed study of the physico-mathematical model, and adaptation of the model to local conditions. Through simulations, the project examines the correlation between aerosol optical depth (AOD) and ARF, providing insights into the role of aerosols in regional climate regulation.

The findings from this study highlight the high correlation between AOD and ARF, with a determination coefficient of 0.99, emphasizing the significant influence of aerosols on the local climate. Future work will involve further characterization of aerosols using Mie theory and detailed atmospheric composition analysis, contributing to more accurate climate predictions and effective environmental policy decisions. This research supports the development of strategies to manage and mitigate the impacts of climate change in the Aburrá Valley.

Significance Statement

Global temperatures have risen by 1.1℃ since the 19th century, potentially reaching 1.6℃ without the mitigating effects of atmospheric aerosols. Estimating the radiative forcing of aerosols in the Aburrá Valley is essential for climate predictions and implementing Medellín's Climate Action Plan 2020-2050. Understanding aerosols' impact allows policymakers to make informed decisions to address climate challenges [15], [6].

EAFIT University´s research programs, 4DAir-MOLIS and 4DAir-MISDAM, aim to measure atmospheric components, predict climate dynamics, and estimate urban pollution's health impacts. These programs focus on calculating radiative transfer, crucial for air governance and climate change management. The success of this project relies on understanding the SBDART model and aerosols' properties.

A physics engineer is ideal for this task, equipped to analyze models, handle scientific programming, and adapt the model to the Aburrá Valley's needs, playing a vital role in the project's success.

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2. Methodology

This project implemented a cascade methodology encompassing the following phases:

A. Literature Review. The objective of this phase was to understand radiative forcing and identify the main elements in the SBDART model. A comprehensive review of existing literature was conducted to gather necessary background information and to ensure a solid theoretical foundation for the project.

B. SBDART Program Installation. In this phase, the software requirements necessary for the operation of the SBDART model were established. The SBDART program was set up and initiated using open-source software, ensuring that all necessary components were correctly installed and configured.

C. Detailed Study of the SBDART physico-mathematical Model and Program Operation. This phase involved an in-depth examination of each variable in the physico-mathematical model of SBDART. Input and output variables of the code were determined.

D. Model Implementation and Simulation to Obtain Radiative Forcing Results. During this phase, the code was implemented and adapted to the specific properties and variables of the local area. Simulations were performed, and the results were stored for future analysis.

E. Comparative Analysis and Sensitivity Evaluation to Different Variables. A comparative analysis of the obtained results was conducted, evaluating the sensitivity of aerosol radiative forcing with AOD.

By the reviewed phases, the project achieved a comprehensive understanding estimation of aerosol radiative forcing in the Aburrá Valley using the SBDART model.

3. Radiative Transfer Phenomenon

The notation with subscript λ indicates that the quantity is determined for a single wavelength.

Radiative transfer is the physical phenomenon of energy transmission in the form of electromagnetic waves.

The study of this phenomenon aims to explain how energy is absorbed, scattered, and emitted when it crosses a material medium.

Absorption: "The fractional energy absorbed from a pencil of radiation is proportional to the mass traversed by the radiation" [21].

This is described by:

$$\frac{dI_\lambda}{I_\lambda} = -\rho\sigma_{a\lambda}ds \qquad [1]$$

Where $\sigma_{a\lambda}$ is the absorption cross section.

Emission: The emission of a black-body is described by Planck's law, which takes the form:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{k_B\lambda T}} - 1\right)} \qquad [2]$$

For a gray-body, the form is adjusted according to Kirchhoff's law and is described by:

$$(1-\omega_\lambda)B_\lambda(T) \qquad [3]$$

Scattering: Scattering is the process of extraction and re-emission of energy by matter.

Considering that scattering and absorption are linear processes, it is possible to define the extinction cross section as:

$$k_\lambda = \sigma_{a\lambda} + \sigma_{s\lambda} \qquad [4]$$

This also allows the introduction of the single scattering albedo as:

$$\omega_\lambda = \frac{\sigma_{s\lambda}}{k_\lambda} \qquad [5]$$

Optical Depth: Optical depth (τ_λ) is a measure of the transparency of a medium to radiation at a specific wavelength. It is defined as the natural logarithm of the ratio of incident to transmitted radiant power through a material. Mathematically, it is given by:

$$\tau_\lambda = \int_0^s k_\lambda\, ds \qquad [6]$$

Given the mathematical description of these phenomena, the general form of the radiative transfer equation is described by:

$$\frac{dI_\lambda}{\rho k_\lambda ds} = -I_\lambda + (1-\omega_\lambda)B_\lambda(T) + \frac{\omega_\lambda}{4\pi}\int_{4\pi} I_\lambda(\hat{\Omega}')P_\lambda(\hat{\Omega},\hat{\Omega}')d\Omega' \qquad [7]$$

Where $P_\lambda(\hat{\Omega},\hat{\Omega}')$ is the phase function. The integral term is known as the source phase function and describes the fraction of radiation lost due to extinction from the pencil of direction $\hat{\Omega}$ out of a new pencil of radiation in direction $\hat{\Omega}'$.

A. Atmospheric Radiative Transfer. Atmospheric radiative transfer must include the atmospheric composition and the spectrum of electromagnetic waves crossing the atmosphere.

Understanding modern physics phenomena such as black-body radiation emission, gray-body radiation emission, and the interaction of light with matter through scattering and absorption is essential to accomplish the objectives of this project.

B. Aerosol Radiative Forcing. Radiative forcing is the difference between the solar energy absorbed by the Earth-atmosphere system and the energy radiated back to space. Aerosol radiative forcing is the radiative forcing specifically due to aerosols in the atmosphere.

To estimate aerosol radiative forcing, the established methodology involves taking the difference between downwelling and upwelling fluxes and the difference between the top of the atmosphere (TOA) and the bottom of the atmosphere (BOA). The radiative forcing of the actual atmosphere is compared with that of an aerosol-free atmosphere [5].

$$\Delta F = (F_{a\downarrow} - F_{a\uparrow}) - (F_{0\downarrow} - F_{0\uparrow}) \qquad [8]$$

$$\Delta F_{\mathrm{ATM}} = \Delta F_{\mathrm{TOA}} - \Delta F_{\mathrm{BOA}} \qquad [9]$$

4. SBDART model undestanding

The SBDART model is widely used in atmosphere radiative transfer contexts, the diagram flux of the program presented below 1 is necessary to understand the way it works.

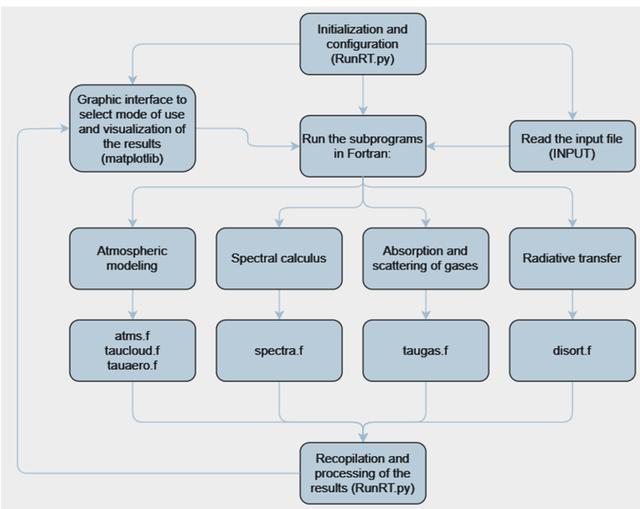

Fig. 1. SBDART flux diagram

The flux diagram presents that the program has a Python graphic interface that interacts with a Fortran90 subprograms that make strenuous calculus in order to simulate atmospheric radiative transfer. Finally, the results are displayed as graphics using the Python graphic interface.

The input file presented has different input parameters such belonging to atmospheric modeling such as concentration of gases, meteorology, cloud parameters, and optical and physical properties of aerosols. Also includes solar geometry, surface model reflectance properties, cloud parameters and some parameters of SBDART model adjustments for simulations.

5. Results and discussion

The simulations of local radiative transfer where taken by varying the aerosol AOD for different months in Medellín and this data was taken from NASA AERONET (Aerosol Robotic Network) and values were mesasured using a CIMEL CE 318 sun photometer, data is showed in Figure [16].

The selected months that presented coherent values of AOD to run the simulations were March, April, June, July and August and values of AOD are shown in the Table 1.

Month	March	April	June	July	August
AOD	0.82	0.75	0.59	0.68	0.58

Table 1. Average aerosol optical depths for different months

The results of running the model for each month extracting the data of TOA and BOA fluxes following the aerosol radiative forcing measure methodology presented was processed implementing own python codes available in Annexes section and the results are shown in Figures 2, 3, 4.

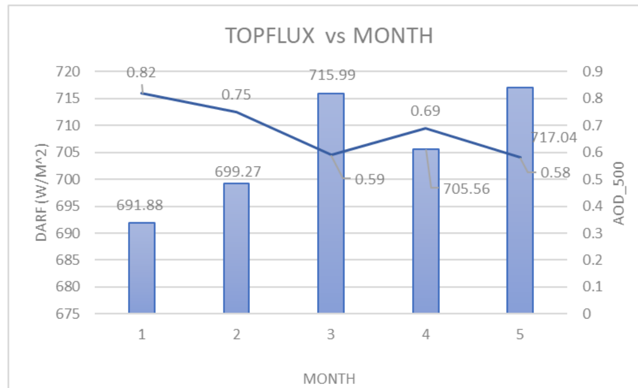

Fig. 2. TOP Flux vs Month.

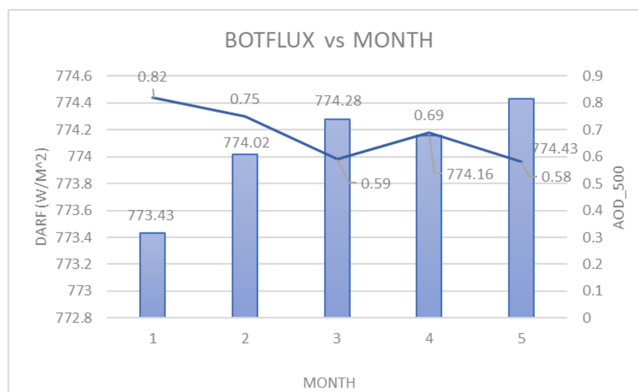

Fig. 3. BOT Flux vs Month.

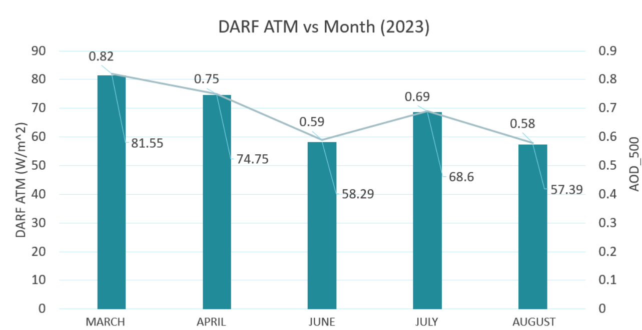

Fig. 4. Aerosol radiative forcing for different months of 2023.

From the results, a high correlation between AOD (Aerosol Optical Depth) and aerosol radiative forcing was

Month	March	April	June	July	August
TOP Flux (W/m^2)	691.88	699.27	715.99	705.56	717.04
BOA Fux (W/m^2)	773.43	774.02	774.28	774.16	774.43

Table 2. TOA and BOA net fluxes for different months.

observed, with a determination coefficient of 0.99. This indicates that higher values of AOD are associated with higher values of aerosol radiative forcing. It also clarifies that the mathematical description of AOD, which is the natural logarithm of the ratio of incident to transmitted radiant power through a material (in this case, the aerosols present in the atmosphere), accurately describes the physical behavior of the local atmosphere.

Additionally, the results indicated in the Table 2 showd that higher values of Aerosol Optical Depth (AOD) are inversely correlated with total fluxes at both the Bottom of Atmosphere (BOA) and Top of Atmosphere (TOA). This finding aligns with expectations, as solar radiation generally decreases when AOD values are higher. Moreover, at the top of the atmosphere, the net radiation flux is reduced due to aerosol backscattering [5], [2] .

6. Future work

Future work will involve the study of Mie theory to properly characterize the aerosols in the Aburrá Valley. This will include properties such as single scattering albedo (SSA), asymmetry parameter (g), Ångström exponent, extinction efficiency, and the Legendre moments of scattering phase functions to understand the aerosol spectral dependencies.

Additionally, a comprehensive characterization of the local atmosphere will be undertaken. This will include measuring the concentrations of gases such as N_2O, NO_2, CO_2, CO, NH_3, O_3, CH_4, SO_2, and HNO_3. Cloud properties such as the altitude of cloud layers, optical thickness of cloud layers, cloud droplet effective radius, liquid water path, and the phase function of clouds will also be characterized to better understand their impact on radiative forcing.

7. Acknowledgments

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Her expertise and dedication to teaching have not only enriched my understanding of the subject but have also inspired me to strive for excellence. Her patience, encouragement, and constructive feedback have been essential in shaping this work.

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8. Conclusions

- The implementation of the SBDART model for estimating aerosol radiative forcing (ARF) in the Aburrá Valley has demonstrated a high correlation between aerosol optical depth (AOD) and ARF, with a determination coefficient of 0.99. This strong correlation underscores the significant impact of aerosols on the local climate, validating the effectiveness of the SBDART model in capturing the radiative effects of aerosols.

- The detailed study and adaptation of the SBDART model to the specific conditions of the Aburrá Valley have provided critical insights into the role of aerosols in regional climate regulation. The findings support the goals of Medellín's Climate Action Plan 2020-2050, offering essential data for informed decision-making in climate policy and environmental management.

- Future research should focus on further characterizing the optical and microphysical properties of aerosols using advanced theories such as Mie theory. Additionally, comprehensive atmospheric composition analyses, including the measurement of various gas concentrations and cloud properties, will enhance the accuracy of ARF estimates and improve climate predictions. This continued effort is vital for developing effective strategies to mitigate the impacts of climate change in the Aburrá Valley.

9. Annexes

For supplementary materials such as the installation guide, user manual for the SBDART model, additional codes implemented during the project, and further literature, the author is willing to share his knowledge and additional work not presented in this article and is available at: Repository

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