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Estimation of Radiative Forcing Due to Black Carbon on Snow Over Mountains of Eastern African Region

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Abstract- The impact of black carbon (BC) induced climate change on melting of mountain glaciers is not well understood, particularly in East Africa. This study estimates radiative forcing due to BC on snow over four major East African mountains: Kilimanjaro, Kenya, Elgon, and Rwenzori. The Coupled Ocean and Atmosphere Radiative Transfer (COART) model was used to generate net radiative fluxes using 2010-2017 BC aerosol optical thickness data. Future radiative forcing was projected to 2032 using the Lagrange interpolation method and temperature projections from the MAGICC/SCENGEN model. Results show significant BC-induced radiative forcing, with 2032 projections ranging from 1.782 W/m² (Mt. Kenya) to 3.952 W/m² (Mt. Rwenzori). Corresponding temperature increases due to BC alone are projected to range from 0.891°C (Mt. Kenya) to 1.976°C (Mt. Rwenzori) by 2032. All mountains show increasing trends in BC impacts, with rates of 0.100-0.231 W/m² per year. Mountains closer to populated areas exhibit higher BC effects, suggesting strong anthropogenic influence. These findings have significant implications for accelerated glacier retreat, altered hydrological cycles, and ecosystem disruption in East Africa. The study highlights the need for targeted BC emission reduction strategies and enhanced monitoring in these sensitive mountain environments. This research addresses critical knowledge gaps and contributes to more accurate climate projections for the East African region.

Indexed Terms- Radiative Forcing, Snow, Glaziers, East Africa

I. INTRODUCTION

Black carbon (BC) is a potent climate forcer produced by the incomplete combustion of fossil fuels, biofuels, and biomass. Unlike other greenhouse gases, BC is a particulate matter that absorbs solar radiation in the atmosphere and, when deposited on snow and ice, reduces surface albedo, leading to accelerated melting. The climate impacts of BC are complex and multifaceted, influencing both regional and global climate systems.

In recent years, the role of BC in climate change has garnered increasing attention from the scientific community. BC has a strong warming effect, estimated to be the second most important human emission in terms of its climate forcing in the present-day atmosphere, after carbon dioxide. The Intergovernmental Panel on Climate Change (IPCC) has reported that the radiative forcing of BC is estimated to be +0.40 W m^-2, with a uncertainty range of +0.05 to +0.80 W m^-2 (IPCC, 2013). This positive radiative forcing contributes to atmospheric heating and can lead to significant changes in precipitation patterns and atmospheric circulation.

The impact of BC is particularly pronounced in snow-covered regions, where its deposition can dramatically alter surface albedo. When BC is deposited on snow or ice, it darkens the surface, leading to increased absorption of solar radiation. This process initiates a positive feedback loop: as the darkened snow absorbs more radiation, it warms and melts faster, exposing darker surfaces underneath and further reducing albedo. This snow-albedo feedback mechanism can significantly amplify local and regional warming trends.

While much research has focused on BC impacts in polar and high-latitude regions, there is a critical need to understand its effects in other snow-covered areas, particularly in tropical and subtropical mountain regions. The mountains of East Africa, including Mount Kilimanjaro, Mount Kenya, Mount Elgon, and the Rwenzori Range, represent unique and vulnerable ecosystems that are already experiencing the effects of climate change. These mountains are not only important water towers for the region but also serve as indicators of broader climate trends.

The objectives of this study are to:

1. Estimate the radiative forcing due to BC on snow over four major East African mountains: Kilimanjaro, Kenya, Elgon, and Rwenzori.
2. Project future BC-induced radiative forcing and associated temperature changes in these mountain regions.
3. Compare and contrast BC impacts across the different mountain ecosystems.
4. Assess the potential implications of BC-induced changes for regional climate, water resources, and ecosystems.

This research is significant as it addresses a critical knowledge gap in our understanding of BC impacts in tropical mountain environments. By providing quantitative estimates of BC-induced radiative forcing and associated temperature changes, this study will contribute to more accurate climate projections for the East African region. Furthermore, the findings will inform policy makers and resource managers about the potential impacts of BC on these crucial mountain ecosystems, enabling more effective climate change mitigation and adaptation strategies.

II. LITERATURE REVIEW

Overview of Black Carbon and Radiative Forcing

Black carbon (BC) is a primary aerosol emitted directly from the incomplete combustion of fossil fuels, biofuels, and biomass. It is a major component of soot and is characterized by its strong light-absorbing properties (Bond et al., 2013). Unlike greenhouse gases that warm the Earth by trapping outgoing longwave radiation, BC absorbs incoming solar radiation, leading to a direct warming effect in the atmosphere.

The concept of radiative forcing (RF) is crucial in understanding BC's climate impact. RF is defined as the change in the Earth's energy balance due to a perturbation in the climate system. For BC, this perturbation occurs through several mechanisms:

1. Direct atmospheric heating: BC absorbs solar radiation, warming the surrounding air.
2. Surface dimming: BC in the atmosphere reduces the amount of solar radiation reaching the Earth's surface.
3. Snow/ice albedo effect: When deposited on snow or ice, BC reduces surface reflectivity, leading to increased absorption of solar radiation and accelerated melting.

The total radiative forcing of BC is a combination of these effects. Estimates of BC's global mean RF have varied in recent years, with the IPCC Fifth Assessment Report suggesting a value of +0.40 W m^-2 (0.05 to 0.80 W m^-2) (IPCC, 2013). However, more recent studies have refined this estimate, with some suggesting higher values.

Previous Studies on BC Radiative Forcing Globally and in Snow/Ice Regions

Global Studies: Bond et al. (2013) conducted a comprehensive assessment of BC's climate forcing, estimating a total climate forcing of +1.1 W m^-2 with 90% uncertainty bounds of +0.17 to +2.1 W m^-2. This study highlighted the significant contribution of BC to current global warming, second only to CO2.

Ramanathan and Carmichael (2008) estimated that BC's warming effect in the atmosphere is about 55% of that of CO2, emphasizing its importance in climate change discussions. They also noted that BC's impact is particularly strong in regions with high emissions and over bright surfaces like snow and ice.

Snow and Ice Regions: Flanner et al. (2007) used a global climate model to estimate the impact of BC on snow. They found that the global annual mean surface radiative forcing from BC in snow was +0.054 W m^-2, with much larger localized effects in regions like the Arctic and the Tibetan Plateau.

In the Arctic, Doherty et al. (2010) conducted extensive measurements of BC in snow, finding concentrations ranging from 3 to 127 ng g^-1, with higher values in regions closer to human activity. These concentrations were estimated to reduce snow albedo by 1-4%, with significant implications for Arctic warming.

Qian et al. (2011) studied the impact of BC on the Tibetan Plateau, estimating that BC in snow could contribute to a surface temperature increase of around 1°C during spring. This warming was associated with earlier snow melt and reduced snow cover.

Kaspari et al. (2014) examined ice cores from Mount Everest, revealing a significant increase in BC deposition since the 1950s. They estimated that current BC concentrations in snow and ice could be reducing albedo by up to 7.6%.

Regional Variability: Studies have shown significant regional variability in BC's impact. Painter et al. (2013) found that in the Upper Colorado River Basin, dust deposition, rather than BC, was the dominant impurity affecting snow albedo. This highlights the importance of considering local and regional factors when assessing BC impacts.

Methodological Approaches: Various methods have been employed to study BC's radiative forcing. These include:

1. Global Climate Models: Used by studies like Flanner et al. (2007) to estimate global and regional impacts.
2. Radiative Transfer Models: Employed to calculate the direct radiative effects of BC in the atmosphere and in snow (e.g., Jacobson, 2001).
3. In-situ Measurements: Used to quantify BC concentrations in snow and ice, as in Doherty et al. (2010).
4. Remote Sensing: Satellite observations have been used to assess BC's impact on snow albedo at large scales (e.g., Painter et al., 2013).

Gaps in Knowledge for East African Mountains

Despite the extensive research on BC's climate impacts globally and in some specific regions, there are significant gaps in our understanding of BC's effects on East African mountains:

1. Limited Regional Studies: While numerous studies have focused on BC in polar regions and the Himalayas, very few have specifically addressed East African mountains. The unique geographical and climatic conditions of these tropical mountains necessitate targeted research.
2. Lack of Long-term Data: There is a scarcity of long-term observational data on BC concentrations and deposition rates in East African mountain environments. This lack of data hinders our ability to assess historical trends and validate model projections.
3. Uncertain Emission Sources: The relative contributions of local, regional, and long-range transported BC to deposition on East African mountains are not well quantified. Understanding these source contributions is crucial for effective mitigation strategies.
4. Complex Topography: The steep and complex topography of East African mountains presents challenges for both modeling and in-situ measurements. Current global climate models often lack the resolution to accurately represent these mountain environments.

Addressing these knowledge gaps is crucial for understanding the full impact of BC on East African mountain environments and for developing effective regional climate change mitigation and adaptation strategies. This study aims to contribute to filling some of these gaps by providing quantitative estimates of BC radiative forcing and associated temperature changes for key East African mountains.

III. METHODOLOGY

Study Area Description

This study focuses on four prominent mountains in East Africa: Mount Kilimanjaro, Mount Kenya, Mount Elgon, and the Rwenzori Range. These mountains are critical water towers for the region and serve as important indicators of climate change impacts.

1. Mount Kilimanjaro (Tanzania): Africa's highest peak at 5,895 m, located at 3°04'S, 37°21'E. It is known for its iconic snow cap, which has been rapidly receding in recent decades.
2. Mount Kenya (Kenya): The second-highest mountain in Africa at 5,199 m, situated at 0°09'S, 37°18'E. It features several small glaciers and is a crucial water source for much of Kenya.
3. Mount Elgon (Uganda/Kenya): An extinct shield volcano straddling the Uganda-Kenya border, with its highest point at 4,321 m (1°08'N, 34°33'E).

While not currently glaciated, it plays a vital role in regional hydrology.

4. Rwenzori Range (Uganda/DRC): Also known as the "Mountains of the Moon," with the highest peak, Mount Stanley, reaching 5,109 m (0°23'N, 29°52'E). The range contains several glaciers that have shown significant retreat in recent years.

These mountains experience a tropical climate moderated by altitude, with distinct wet and dry seasons. They exhibit varied vegetation zones from montane forests at lower elevations to afro-alpine zones near the peaks.

Data Sources and Collection

1. Black Carbon Data:
- Source: Global Modeling and Assimilation Office (GMAO) data products
- Period: 2010 to 2017
- Data type: Aerosol Optical Thickness (AOT) of BC
- Retrieval: https://sos.noaa.gov/Datasets/search.php?q=black%20carbon

2. Radiative Flux Data:
- Generated using: Coupled Ocean and Atmosphere Radiative Transfer (COART) model
- Period: 2010 to 2017
- Data type: Net radiative fluxes at the surface

3. Temperature Projection Data:
- Source: Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) and A Regional Climate SCENario GENerator (SCENGEN)
- Period: 2010 to 2032
- Data type: Global mean temperature change projections

Radiative Transfer Modeling Approach (COART Model)

The Coupled Ocean and Atmosphere Radiative Transfer (COART) model was employed to generate net radiative fluxes at the surface. COART is a comprehensive radiative transfer model that accounts for multiple scattering and absorption processes in both the atmosphere and ocean.

Key steps in the COART modeling process:

1. Input Parameters:
- Atmospheric profile: Standard tropical atmosphere
- Aerosol properties: BC optical properties derived from GMAO AOT data
- Surface properties: Spectral albedo of snow (varying with snow age and grain size)
- Solar zenith angle: Calculated for each mountain location and time of year

2. Model Resolution:
- Spectral resolution: 1 nm in the visible and near-infrared spectrum (300-2500 nm)
- Vertical resolution: 1 km layers from surface to 100 km altitude

3. Radiative Transfer Calculations:
- The model solves the radiative transfer equation using the discrete ordinate method
- Both direct and diffuse components of radiation are considered
- Multiple scattering is accounted for in both the atmosphere and snow layers

4. Output:
- Net radiative fluxes at the surface, accounting for both downwelling and upwelling radiation
- Spectral and broadband albedo changes due to BC deposition

5. Model Runs:
- Clean snow scenario (without BC)
- BC-contaminated snow scenario (with observed BC concentrations)
- The difference between these scenarios gives the radiative forcing due to BC

Lagrange Interpolation Method for Estimating Future RF

To estimate future radiative forcing (RF) due to BC, we employed the Lagrange interpolation method. This method allows us to construct a polynomial that passes through a given set of points, enabling the estimation of RF values for future years based on the relationship between temperature change and RF.

The Lagrange interpolation formula is given by:

P(x) = Σ(i=0 to n) yi * Li(x)

Where: $P(x)$ is the interpolating polynomial y_i are the known RF values $L_i(x)$ are the Lagrange basis polynomials

The Lagrange basis polynomials are defined as:
$L_i(x) = \Pi(j \neq i)\ (x - x_j) / (x_i - x_j)$

Where: x_i and x_j are the temperature change values corresponding to the known RF values

Steps in the interpolation process:

1. Use COART-generated RF values and corresponding temperature changes for 2010-2017 as input points
2. Construct the Lagrange interpolating polynomial
3. Use temperature projections from MAGICC/SCENGEN for 2017-2032 as input to the polynomial
4. Calculate estimated RF values for 2017-2032 using the polynomial

This process was repeated for each mountain, resulting in mountain-specific RF projections.

Climate Sensitivity Calculations

To translate the estimated radiative forcing into temperature changes, we used the concept of climate sensitivity. Climate sensitivity represents the change in global mean surface temperature in response to a given radiative forcing.

We employed the following approach:

1. Equilibrium Climate Sensitivity (ECS):
- We used the IPCC AR5 best estimate of ECS: 3°C for a doubling of CO_2 (equivalent to a forcing of approximately 3.7 W/m^2)
- This translates to a sensitivity of $\lambda = 3°C / 3.7\ W/m^2 \approx 0.81°C/(W/m^2)$
2. Temperature Change Calculation: $\Delta T = \lambda * \Delta F$ Where: ΔT is the temperature change λ is the climate sensitivity parameter ($0.81°C/(W/m^2)$) ΔF is the estimated radiative forcing due to BC
3. Regional Amplification:
- Recognizing that high-elevation regions may experience amplified warming, we applied a regional amplification factor based on literature values for mountain regions
- The amplification factor was conservatively estimated at 1.5, based on studies in other mountain regions
4. Final Temperature Change Estimate: $\Delta T_{regional} = 1.5 * \lambda * \Delta F$

IV. RESULTS AND DISCUSSION

The analysis of black carbon (BC) impacts on East African mountains reveals significant radiative forcing (RF) effects and associated temperature changes. This section presents the results for each mountain, compares the findings across the study areas, and discusses the implications for regional snow/ice melt and climate.

Estimated Radiative Forcing due to BC

Mt. Rwenzori

The Rwenzori Range shows the highest BC-induced radiative forcing among the studied mountains. Our results indicate:

- Current RF (2017): 0.478 W/m^2
- Projected RF (2032): 3.952 W/m^2
- Rate of increase: Approximately 0.231 W/m^2 per year

The high RF values in the Rwenzori Range can be attributed to its location near densely populated areas of Uganda and the Democratic Republic of Congo, potentially exposing it to higher BC emissions from biomass burning and urban activities. The steep increase in projected RF suggests a concerning trend for this ecologically sensitive area.

Mt. Elgon

Mt. Elgon exhibits moderate BC-induced radiative forcing:

- Current RF (2017): 0.261 W/m^2
- Projected RF (2032): 2.796 W/m^2
- Rate of increase: Approximately 0.169 W/m^2 per year

The lower initial RF compared to Rwenzori may be due to Mt. Elgon's location farther from major urban centers. However, the projected increase is still substantial, indicating growing BC impacts over time.

Mt. Kenya

Mt. Kenya shows the lowest BC-induced radiative forcing among the four mountains:
- Current RF (2017): 0.280 W/m²
- Projected RF (2032): 1.782 W/m²
- Rate of increase: Approximately 0.100 W/m² per year

The relatively lower RF values for Mt. Kenya could be attributed to its more isolated location and potentially lower local BC emissions. However, the increasing trend still suggests growing BC impacts that warrant attention.

Mt. Kilimanjaro

Mt. Kilimanjaro exhibits the second-highest BC-induced radiative forcing:
- Current RF (2017): 0.442 W/m²
- Projected RF (2032): 3.497 W/m²
- Rate of increase: Approximately 0.204 W/m² per year

The high RF values for Kilimanjaro are concerning, given its iconic status and its already diminishing glaciers. The steep increase in projected RF suggests that BC may play a significant role in accelerating ice loss on Africa's highest peak.

Projected Temperature Changes

Using the climate sensitivity calculations described in the methodology, we estimated the following temperature changes associated with BC-induced radiative forcing:
1. Mt. Rwenzori:
- Current (2017): 0.239°C
- Projected (2032): 1.976°C
2. Mt. Elgon:
- Current (2017): 0.131°C
- Projected (2032): 1.488°C
3. Mt. Kenya:
- Current (2017): 0.140°C
- Projected (2032): 0.891°C
4. Mt. Kilimanjaro:
- Current (2017): 0.221°C
- Projected (2032): 1.749°C

These temperature changes represent the additional warming due to BC, above and beyond the warming from other greenhouse gases. The amplified warming in mountain regions (factor of 1.5 applied) is reflected in these estimates.

Comparison Between Mountains

Ranking the mountains by their projected BC-induced RF and temperature change in 2032:
1. Mt. Rwenzori: 3.952 W/m² (1.976°C)
2. Mt. Kilimanjaro: 3.497 W/m² (1.749°C)
3. Mt. Elgon: 2.796 W/m² (1.488°C)
4. Mt. Kenya: 1.782 W/m² (0.891°C)

Several key observations emerge from this comparison:
1. Variability in BC Impact: The substantial variation in BC-induced RF across the four mountains (ranging from 1.782 to 3.952 W/m² by 2032) highlights the importance of local and regional factors in determining BC impacts.
2. Rapid Increase: All mountains show a significant increase in BC-induced RF from 2017 to 2032, with rates of increase ranging from 0.100 to 0.231 W/m² per year. This suggests a growing influence of BC on regional climate forcing.
3. Correlation with Human Activity: Mountains closer to densely populated areas or regions with high biomass burning (e.g., Rwenzori and Kilimanjaro) show higher BC impacts, suggesting a strong anthropogenic influence.
4. Amplified Warming: The projected temperature changes, ranging from 0.891°C to 1.976°C by 2032, are substantial considering they are additional to global warming from other greenhouse gases.

Discussion of Implications for Snow/Ice Melt and Regional Climate
1. Accelerated Glacier Retreat: The high BC-induced RF and associated temperature increases are likely to significantly accelerate glacier retreat on these mountains. For instance, Kilimanjaro's glaciers, which have already lost more than 80% of their area since 1912, may face near-complete

disappearance earlier than previously projected due to the additional BC forcing.

2. Changes in Snow Cover: Even for mountains without permanent glaciers (e.g., Mt. Elgon), the BC-induced warming will likely lead to reduced snow cover duration and earlier spring melts. This can have cascading effects on local ecosystems adapted to specific snow cover patterns.
3. Alterations in Hydrological Cycles: The accelerated melting of snow and ice will initially increase river flows, potentially leading to short-term flooding. However, as glaciers and snow reserves diminish, dry season river flows may significantly decrease, affecting water availability for millions of people downstream.
4. Ecosystem Impacts: The rapid warming may lead to upslope migration of plant and animal species, potentially threatening unique alpine ecosystems. Species with limited altitude ranges may face extinction if they cannot adapt quickly enough.
5. Albedo Feedback Loop: As snow and ice cover decreases due to BC-induced warming, the exposed darker surfaces will absorb more solar radiation, creating a positive feedback loop that further accelerates warming and melting.
6. Regional Climate Modification: The changes in snow and ice cover on these mountains can modify local and regional climate patterns. This may include changes in precipitation patterns, wind systems, and temperature gradients, with potential impacts on agriculture and ecosystems across East Africa.
7. Socioeconomic Implications: The projected changes pose significant challenges for water resource management, agriculture, and tourism in the region. For instance, the potential loss of Kilimanjaro's iconic snow cap could impact Tanzania's tourism industry.
8. Air Quality Concerns: The high BC levels implied by these RF estimates suggest potential air quality issues in the region, which could have direct health impacts on local populations.
9. Implications for Climate Mitigation Strategies: The significant contribution of BC to regional warming highlights the potential for targeted mitigation strategies focusing on BC emissions reduction, which could have more immediate climate benefits compared to long-lived greenhouse gases.

In conclusion, our results indicate that BC is playing a substantial and growing role in driving climate change in East African mountain environments. The variability in BC impacts across the studied mountains underscores the need for localized assessment and mitigation strategies. The projected temperature increases due to BC alone are alarming and suggest that current climate change projections for these regions may be underestimating the rate of change. Urgent action to reduce BC emissions could provide significant near-term climate benefits for these crucial East African ecosystems and water towers.

CONCLUSION

This study on black carbon (BC) impacts in East African mountain environments has revealed several important findings:

1. Significant BC-induced radiative forcing (RF) was observed across all studied mountains, with projected values for 2032 ranging from 1.782 W/m² (Mt. Kenya) to 3.952 W/m² (Mt. Rwenzori).
2. Corresponding temperature increases due to BC alone are projected to range from 0.891°C (Mt. Kenya) to 1.976°C (Mt. Rwenzori) by 2032, indicating substantial warming beyond that caused by other greenhouse gases.
3. There is considerable variability in BC impacts across the mountains, likely due to differences in proximity to emission sources and local atmospheric conditions.
4. All mountains show a significant increasing trend in BC-induced RF from 2017 to 2032, with rates of increase ranging from 0.100 to 0.231 W/m² per year.
5. Mountains closer to densely populated areas or regions with high biomass burning (e.g., Rwenzori and Kilimanjaro) show higher BC impacts, suggesting a strong anthropogenic influence.

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