Estimating the direct radiative forcing of wildfire smoke using aerosol optical properties measured during FIREX-AQ.

Adam T. Ahern1,2, Nicholas L. Wagner3,4,5, Charles A. Brock1, Meng Lu6, Richard H. Moore6, Elizabeth B. Wiggins6, Edward Winstead7, Claire E. Robinson8, Daniel M. Murphy1

1) NASA-NOAA Chemical Sciences Laboratory (CSL), 325 Broadway, Boulder, Colorado 80305
2) Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, Colorado 80309
3) University of Alberta, Dept. Of Chemistry, Edmonton, Canada T6G 2P3
4) NASA Langley Research Center, Hampton, Virginia 23666

Before we start, here's what you need to know:
- Global warming is caused by the imbalance of energy being absorbed by and emitted from Earth.
- Greenhouse gases contribute to warming by causing more energy to be absorbed by the atmosphere.
- Particles in the atmosphere, like smoke, can reflect energy back into space before it can be absorbed.
- This is called the direct radiative effect, and it can mask global warming caused by greenhouse gases.
- The contribution of smoke particles to the direct radiative effect is uncertain in part because of their complicated optical properties.
- In this work, we measured what direction smoke particles scattered light and compared it to what direction is typically assumed by models. Then we calculated what effect this would have on the direct radiative effect.

When sunlight hits particles in the atmosphere, the light scatters in many directions.

Three ways to determine g:
1) Calculate using Mie theory (requires assumptions about particle shape, particle size distribution, and refractive index.)
   BUT smoke composition varies with source and time.
2) Measure it directly using the NOA LiNeph Nephelometer.
   Precise measurements with a relative standard deviation of 3% but only at two wavelengths.
3) Measure it directly using the NOAA Laser Imaging Nephelometer.
   Precise measurements with a relative standard deviation of 3% but only at two wavelengths.

When sunlight hits particles in the atmosphere, the light scatters in many directions.
If it scatters upwards, away from Earth, this causes global cooling. If it scatters downwards, then there is no cooling effect.
Climate models use the asymmetry parameter, g, to describe which direction scattered light will go.

\[ g = \frac{1}{2} \int_0^\infty \cos(\theta) \cdot P(\theta) \cdot \sin(\theta) \, d\theta \]

Where \( \theta \) is the scattering angle and \( P(\theta) \) is the probability that light will scatter in that direction.
\[ g = 1 \rightarrow \text{all scattered light continues forward (towards earth, depending on solar angle)} \]
\[ g = 0 \rightarrow \text{scattered light is evenly split between forward and backward} \]

Aerosol Microphysical and Optical Measurements during FIREX-AQ:
- FIREX-AQ was an airborne mission to study wildfire smoke in the western USA in the summer of 2019.
- The NASA DC-8 airborne laboratory (top right) was equipped with instruments to measure aerosol optical and microphysical properties.
- 12 wildfires in the western US were sampled in a pseudo Lagrangian pattern (middle right shows flight tracks.)
- Bottom right plot shows the time series where the aircraft transits the plume very close to the fire, then travels downwind for subsequent transects, resulting sets of measurements with smoke roughly the same age.

1) Calculating the phase function from Mie theory:
- An example of the size distributions measured is shown in the top right. The number size distribution is dominated by the fine mode.
- The lognormal mode size grows and the distribution narrows with age.
- The equation shown here calculates the aerosol radiative forcing efficiency (\( g_{\text{eff}} \)) caused by smoke. This is a scalar that can be used in a radiative transfer model to simulate the effect of wildfires on global and regional climate and atmospheric stability.

\[ g = \frac{1}{2} \int_0^\infty \cos(\theta) \cdot P(\theta) \cdot \sin(\theta) \, d\theta \]

2) Inferring g from backscatter measurements:
- Hemispheric backscatter (b) is the ratio of all backwards scattered light to total light, routinely measured globally by the Hemispheric backscatter (b).
- The contribution of smoke particles to the direct radiative effect is uncertain in part because of their complicated optical properties.
- We used Mie theory to calculate g at five wavelengths based on the size distribution measured by the optical particle counter.
- The bottom panel of figure shows g calculated using the mean refractive index from AERONET retrievals, where the refractive index is found to be 1.5 + 0.02i for all wavelengths (Dubovik et al., 2002).
- However, more recent in situ studies have found higher and wavelength dependent refractive indices (Espiau et al., 2015, Wermack et al., 2021 ).
- Bottom panel shows g calculated with the higher refractive indices from Espiau et al.
- For comparison, the top panel shows the results using a refractive index from previous in situ measurements of the phase function.

3) Measuring g directly with the LiNeph:
- The NOA LiNeph Nephelometer (LiNeph) directly measures the intensity and direction of scattered light by aerosol particles.
- From this measurement, we can directly calculate both the asymmetry parameter, g, and the hemispheric backscatter, b.
- The Henyey-Greenstein approximation works well for scattering of 405 nm light, deviating on average by 1%.
- For 560 nm, the predicted from the Henyey-Greenstein approximation results in an average 14% overestimation compared to the measurements.
- This is consistent with theoretical studies that show that for particle size distributions dominated by small particles, the Henyey-Greenstein phase function tends to overpredict g (Marshall et al., 1995).

Measured g shows more backscatter than RI values from remote retrievals would predict:
- We used Mie theory to calculate g at five wavelengths based on the size distribution measured by the optical particle counter.
- g values from remote retrievals would predict a higher g, but only at two wavelengths.
- This higher assumed refractive index also affects the interpretation of the size distribution measurements, shifting the volume mode of the size distribution 20% smaller.

The equation shown here calculates the aerosol radiative forcing efficiency (\( g_{\text{eff}} \)) caused by smoke. This is a scalar that can be used in a radiative transfer model to simulate the effect of wildfires on global and regional climate and atmospheric stability.

The equation is:
\[ g_{\text{eff}} = \frac{1}{2} \int_0^\infty \cos(\theta) \cdot P(\theta) \cdot \sin(\theta) \, d\theta \]

For this work, we will integrate across the solar spectrum, shown to the left. A reference case is evaluated using Mie theory and a commonly assumed refractive index to calculate g (grey line) and SSA as a function of wavelength. Then, a linear empirical adjustment is made to get the Mie-calculated g to match the measured g (black line).

Conclusions and future directions:
- For there to be agreement between the modelled and measured g, one must use a higher refractive index than the remote-retrieval literature for both the particle size measurements and the Mie calculations.
- Direct measurements of the asymmetry parameter show models may be underestimating the cooling effect of smoke by 20%.
- We will use the GRASP retrieval algorithm to find the optimal solution for the refractive index of the smoke.

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References: