The Impact of Aerosols on the Color and Brightness of the Sun and Sky

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1. INTRODUCTION

Long before the climatic impact of aerosols was recognized, their impact on the appearance of the sky was considered obvious (Minnaert, 1954). The sky is deepest blue when air is clean and dry, but it always whitens toward the horizon when the sun is high in the sky and reddens at the horizon during twilight. Hazy skies are typically brighter, particularly near the sun, but less blue, and may even take on pastel or earth tones. At twilight, aerosol laden skies can exhibit rich red colors near the horizon, and volcanic aerosol particles may even turn the twilight sky crimson far above the horizon.

Sky colors result from a combination of factors including the solar spectrum and zenith angle, the scattering properties of air molecules and aerosol particles, and the optical thickness of the path of light through the atmosphere. Air molecules scatter light with an efficiency proportional to λ^{-4} because they are much smaller than the wavelength, λ, of visible light, as was first shown by Rayleigh (1871).

Rayleigh scattering produces blue skies so long as the optical thickness of the light path through the atmosphere is small. At twilight, the optical path is so long and the source of light is so distant that the sky turns red near the horizon.

Aerosol particles have such highly irregular and variable shapes, size distributions, number densities and chemical compositions (i. e., indices of refraction) that there is no accurate quantitative theory for the light they scatter. Some insight about light scattering by aerosol particles is provided by Mie theory for spheres of various sizes and indices of refraction. The theory confirms that because aerosol particles are similar in size or larger than visible light waves, they scatter light less selectively by wavelength and by smaller angles than air molecules do. This is what whitens and brightens hazy skies, particularly near the sun.

Given the enormous complexity and variability of aerosol particles and their scattering properties, there is an allure to simple models of sky color and brightness that capture the main aspects of scattering behavior. **SKYCOLOR** is such a model. It is available at www.sci.ccny.cuny.edu/~stan (then click on Atmospheric Optics). In §2, SKYCOLOR is briefly described and in §3 it is applied to situations that indicate how sky color and brightness provide information about the aerosol and ozone content of the atmosphere. This shows its relevance to climate problems.

2. SKYCOLOR: THE MODEL

SKYCOLOR is a simplified model of sky color and brightness in the vertical plane including the sun and the observer (Gedzelman, 2005). Model skylight consists of sunbeams that are scattered toward the observer, but depleted by scattering and absorption in the Chappuis bands of ozone. SKYCOLOR includes the Earth's curvature, atmospheric refraction, cloud shadows and solar eclipses. Scattering is given a wavelength (λ) dependence described below. Multiple scattering is calculated directly in clouds but is parameterized in clear air by decreasing the scattering rates of sunlight and of skylight in the Earth's shadow by 30%.

A simple approximation to Mie scattering can be given in terms of the wavelength dependence of scattering efficiency, $\lambda^{-\alpha}$, where α is the Ångstrom exponent, and the angular scattering phase function, $P(\psi)$. The Ångstrom exponent varies with particle size. It ranges from $\alpha = 4$ for Rayleigh scattering by air molecules to $\alpha \approx -1$ for volcanic aerosols. Negative values of α indicate particles that scatter long waves more efficiently than short waves. They are not common and only occur in a narrow size range with radius $r \approx 0.4$ μm. Aerosols producing typical hazy skies are smaller ($r \approx 0.15$ μm), and have $\alpha \approx 1$. Large aerosol particles (e. g., from dust storms) scatter all waves with comparable efficiency, and have $\alpha \approx 0$.

The angular scattering phase function, $P(\psi)$, is also highly size dependent. A heuristic formula that approximates the gross features of the Mie

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scattering phase function with a major forward and minor backward peak is

$$P(\psi)=\frac{2(1+a^2)}{1+e^{-a\pi}}\left[(1-e^{-\frac{a\pi}{2}})e^{-a\psi}+e^{-\frac{a\pi}{2}}e^{-a(\pi-\psi)}\right] \quad (1)$$

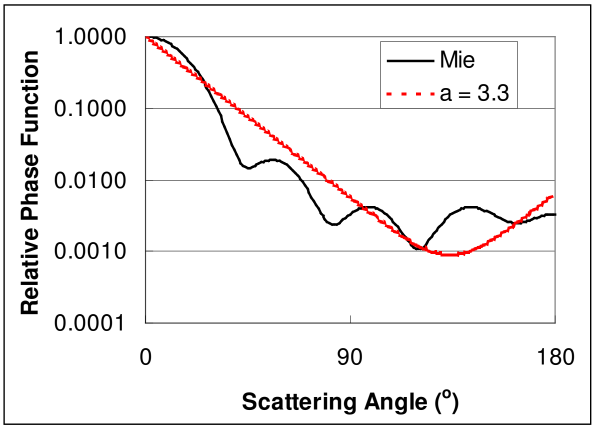

Fig. 1. Comparison of angular scattering phase function using a = 3.3 (red dots) in Eq. 1 with Mie solution for spheres of r = 0.4 µm, at λ = 0.5 µm and index of refraction, n = 4/3.

For typical haze conditions, *a* = 1.5. Fig. 1 compares the results of Eq. 1 for volcanic aerosols with r = 0.4 µm, a = 3.3. with the Mie solution for spheres with refractive index, n = 4/3.

3. SIMULATIONS

SKYCOLOR is designed to show the changes of sky color as the sun sets. A representative example of the output is shown in Fig. 2.

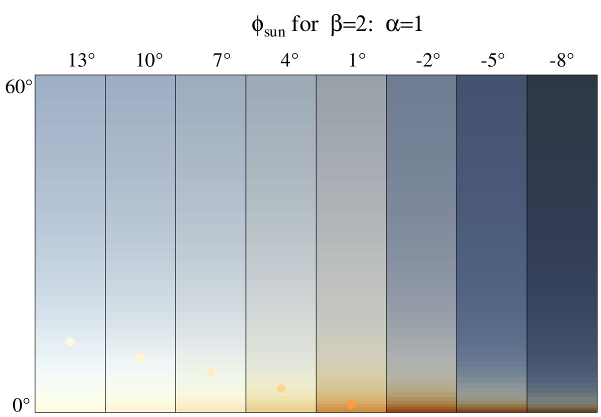

Fig. 2. SKYCOLOR generated view of the sun and sky up to 60º above the horizon for a range of solar elevation angles from 13º to -8º in an atmosphere with α=1, β=2.

Fig. 2 shows that sky color and brightness vary widely with the sun's height in the sky. In Fig 2, atmospheric turbidity, $\beta = 2$ Turbidity is defined as the ratio of optical thickness of the atmosphere to that of a molecular atmosphere.

Sky color and brightness vary widely with turbidity and with the size of aerosol particles. Fig. 3 shows that aerosols greatly increase sky brightness at almost all viewer angles and especially near the sun when β = 2 compared to the molecular atmosphere (β = 1). The amplification of forward scattering is also greater for large aerosols (α = 0). However, because aerosols scatter most light by relatively small angles, the horizon sky opposite the sun is brighter for the molecular atmosphere than when aerosols are present.

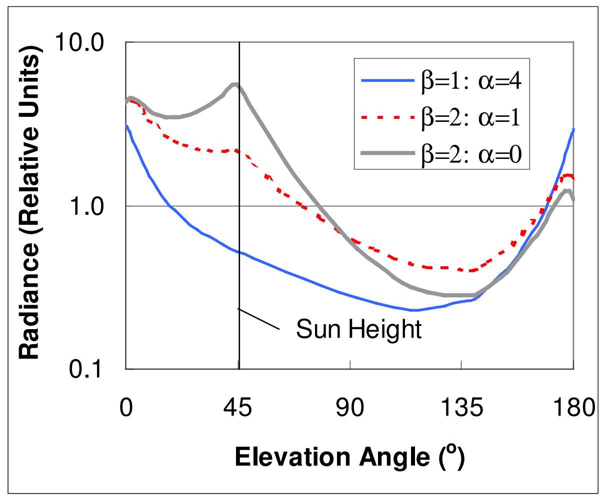

Fig. 3. Sky brightness as a function of elevation angle when β=2 for small (α=1) and large (α=0) aerosols compared to that of a molecular atmosphere.

Fig. 4 shows the impact of aerosol particles on sky color at the zenith for the conditions of Fig. 3. The molecular atmosphere has by far the deepest blue color with a color purity of 40%. The two skies with b = 2 have a similar washed out appearance at the zenith.

Fig 5. shows that absorption by the Chappuis bands of ozone ($\lambda \approx 0.6$ µm) is largely responsible for the blue color of the sky when the sun is at the horizon. The spectrum of skylight at the zenith is much bluer for a molecular atmosphere than a turbid atmosphere (α=1: β=2), but in this case, the ozone content (expressed in Dobson Units, D) has even greater impact on deepening the blue.

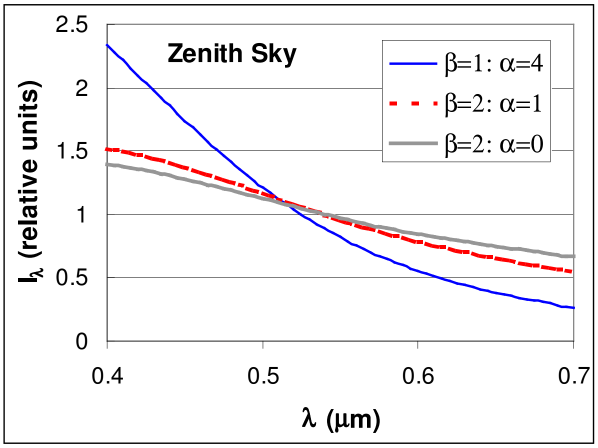

Fig. 4. Spectra of skylight at the zenith when the sun's elevation angle = 45º for the same cases as in Fig. 3. Molecular atmosphere is much deeper blue than the atmospheres with turbidity, β = 2.

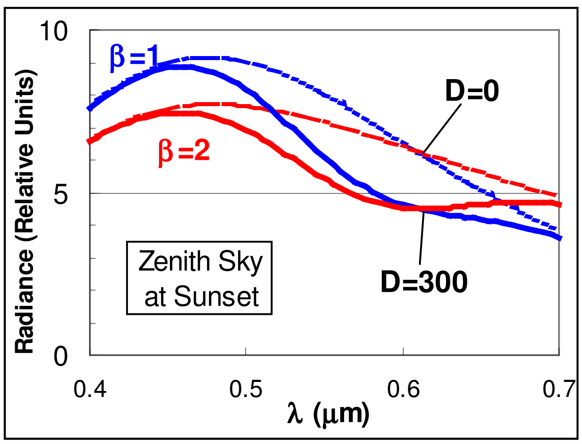

Fig. 5. Sunset spectra of skylight at the zenith for the molecular atmosphere and a turbid atmosphere (α=1: β=2) for both with (D=300) and without (D=0) ozone.

ACKNOWLEDGEMENTS

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