Distant Green Thunderstorms—Fraser's Theory Revisited

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(Manuscript received 25 June 1999, in final form 28 December 1999)

ABSTRACT

The theoretical development presented by Fraser can produce a spectrum of light that would be perceived as a faint green. The theory assumed a perfectly black background thunderstorm. Severe thunderstorms are certainly not black when observed from a distance of 30–40 km. Thus it is useful to compare the theory with some observed examples of severe thunderstorms that should have been green by the Fraser theory but were not. Therefore, some elementary modifications of the Fraser model such as using a nonblack background are suggested. The use of a nonblack cloud background tends to shift the resulting dominant wavelengths away from the green portion of the spectrum, suggesting a better match with observations.

1. Introduction

Although green thunderstorms have been a topic of occasional interest for years (Donaldson et al. 1965; Fankhauser et al. 1983; Bohren and Fraser 1993; Gallagher et al. 1996), until now little or no research has been conducted on this problem. Most references to green thunderstorms are offered as notes in discussions of other topics or are offered as anecdotal evidence supporting a connection with a certain type of meteorological phenomenon. Other green colors, such as the corona (Minnaert 1954; Lynch and Livingston 1995) or the green flash (Minnaert 1954; Meinel and Meinel 1983), are often observed in the atmosphere but are not included here because they are phenomena not closely associated with thunderstorms.

According to Fraser's (Fraser 1978; Bohren and Fraser 1993) theory of distant green thunderstorms, green light does not emanate from the thunderstorm itself. Rather, the storm provides a dark backdrop against which green airlight is seen. During the day, a black object at a distance will not appear black. Light scattered by the intervening air will cause the object to appear brighter than it actually is. If this airlight is assumed to be sunlight scattered by molecules and particles that are small in comparison with the wavelength of the light, the color of the scattered light will be dominated by various shades of blue. This effect is often seen in the mountainous regions of the country where distant peaks appear bluish in comparison with the closer mountains. If the source of light is predominantly red, such as light from the setting sun, the airlight can be perceived as various shades of green.

However, recent observations of green thunderstorms (Gallagher et al. 1996; Gallagher 1997) indicate that the green light associated with severe thunderstorms in the Great Plains originates from the thunderstorm itself and is not created by the airlight processes described by Fraser (1978). In this paper, another look at Fraser's hypothesis is taken and some additional criteria are included to determine why this hypothesis, though not incapable of producing green light in the sky under certain circumstances, might not be the favored mechanism for creating the green light often observed in Great Plains thunderstorms.

2. Theoretical development

Fraser's theory suggests a two-component process that leads to the occurrence of green light from a thunderstorm. First, light from the sun is attenuated and reddened by atmospheric molecular scattering (e.g., Middleton 1952; van de Hulst 1957; McCartney 1976; Liou 1980; Bohren 1995). Much of this scattered light is lost to space, but a small amount is scattered into the eyes of the observer. Second, this scattered light is further attenuated along the path between the observer and the scattering media. Fraser (1978) and Bohren and Fraser (1993) provide a simplified mathematical sketch of this process. The key terms in the resulting equation are those that represent the optical depths of the media though which the light passes. An increment of optical depth is defined as the extinction coefficient multiplied by a unit distance along the line of sight. There are two

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different optical depths to evaluate. The first is the optical depth of the path between the sun and the earth's surface. Because there is little bulk matter in space to attenuate the radiation, we consider only the atmospheric optical depth. This depth is approximated as

$$\tau_{\lambda_s} = (s_\lambda \beta_1 + s'_\lambda \beta_2)h, \tag{1}$$

where s_λ [see Eq. (3)] is the scattering coefficient in a nonabsorbing atmosphere (m^{-1}), β_1 is the atmospheric air mass (Kasten and Young 1989), s'_λ is the absorption coefficient (m^{-1}) for ozone (Burrows et al. 1999), β_2 is the ozone air mass (Kondratyev 1969), and h is the scale height of the atmosphere (~8000 m). At larger solar zenith angles, the light must traverse more of the atmosphere, thereby increasing the optical depth. The air mass values account for this effect as well as the effects of normal refraction.

The second optical depth is that from the observer to the storm. It is defined as

$$\tau'_\lambda = d s_\lambda, \tag{2}$$

where d is the distance to the storm. Formulations by many authors (e.g., Kondratyev 1969; Fraser 1978; Liou 1980) result in a similar expression for the scattering coefficient s_λ in a molecular atmosphere. Given the number density of molecules at the earth's surface at standard temperature and pressure we can write the scattering coefficient as

$$s_\lambda \simeq \frac{1.4224 \times 10^{-30} \quad \mathrm{m}^3}{\lambda^4}, \tag{3}$$

where the wavelength λ is expressed in meters.

The equation for the radiance is derived (see, e.g., Fraser 1978; Liou 1980) from the following relationship:

$$dI_\lambda(p, \mathbf{s}) = -s_\lambda\, ds\, I_\lambda(p, \mathbf{s}) + s_\lambda\, ds\, J_\lambda(p, \mathbf{s}), \tag{4}$$

where the term on the left-hand side represents the change in radiance along the path **s**. The first term on the right-hand side is the loss of light due to extinction, and the second term is the addition of light due to sources. By writing the equation in terms of optical depth and differentiating with respect to optical depth, one can solve for the radiance at location p along path **s**. If it is assumed that the background is completely black and there are no inhomogeneities along the path, one can write the radiance as

$$I_\lambda(p, \mathbf{s}) = J_\lambda(p', \mathbf{s})[1 - \exp(-\tau'_\lambda)]. \tag{5}$$

Here J_λ is the airlight source term. If it is assumed that the source of airlight is light scattered by small molecules in the atmosphere, one can write

$$J_\lambda(p, \mathbf{s}) = \frac{\delta\omega_s}{4\pi}\left(\frac{3}{4}\right)(1 + \cos^2\phi) I_{\lambda_s} \exp(-\tau_{\lambda_s}), \tag{6}$$

where $\delta\omega_s$ is the solid angle subtended by the solar disk, and $(\frac{3}{4})(1 + \cos^2\phi)$ is the scattering phase function. Last, the equation that is used to calculate the total observed radiance along a path between the observer and the black cloud can be written as

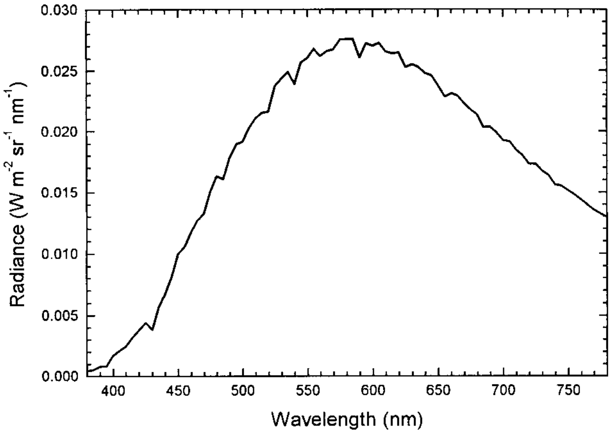

FIG.1. Computed spectrum of light using the Fraser theory with a solar zenith angle of 85° and a distance to the storm of 35 km.

$$I_\lambda(p, \mathbf{s}) = \frac{I_{\lambda_s} 3\delta\omega_s}{16\pi}(1 + \cos^2\phi) \exp[(s_\lambda\beta_1 + s'_\lambda\beta_2)h] \times [1 - \exp(s_\lambda d)]. \tag{7}$$

The first exponential term represents the selective attenuation (scattering and ozone absorption in the Chappuis bands) of sunlight along a path between the sun and the observer's line of sight to the storm. The second exponential term (in brackets) represents the airlight contribution of the sunlight scattered into the observer's line along a path between the observer and the storm.

3. Evaluation of the Fraser theory

Given the simplifications and assumptions made in the previous section, the Fraser theory tentatively explains the occurrence of a special type of green thunderstorm. Bohren and Fraser (1993) show that, by using the two exponential attenuation functions in Eq. (7), it is possible to compute a spectrum that, to a normal observer, would appear green. To expand on Fraser's work, this paper uses a realistic (Neckel and Labs 1984) solar spectrum (I_{λ_s}) in the calculations.

Figure 1 shows a computed spectrum, using Eq. (7), of the resulting radiation using sunlight as a source. The computed spectrum, using a realistic sunlight source, shows more detail than the calculations shown by Bohren and Fraser (1993) while maintaining the basic shape predicted by the ideal curves. The peak wavelength of the computed spectrum shown in Fig. 1 is 550 nm, a wavelength typically associated with the color yellowish green. All references to the maxima (either local or for the entire spectrum) are chosen with respect to wavelength. Standard texts on colorimetry (e.g., Wyszecki and Stiles 1982; Nassau 1983) typically show the special

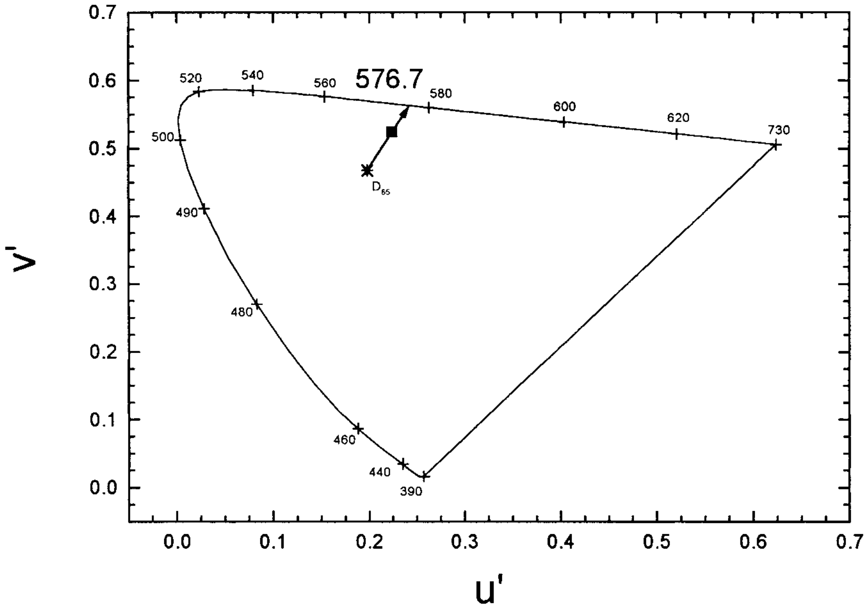

FIG. 2. CIE 1976 UCS chromaticity diagram of the spectrum in Fig. 1. The dominant wavelength is 576.7 nm, and the excitation purity is 53.2%. The spectrum is represented by the ■ symbol, and the D_{65} achromatic point is represented by the * symbol.

response of the human eye as a function of wavelength. That practice shall be followed here. Figure 2 shows the computed spectrum of Fig. 1 plotted on a Commission Internationale de l'Eclairage (CIE) 1976 chromaticity diagram. The CIE diagram represents a color space in which an individual spectrum is represented by a pair of chromaticity coordinates (u', v'). The coordinates are arrived at by integrating over wavelength the spectral power of the incident radiation multiplied by three previously defined color-matching functions (Wyszecki and Stiles 1982). Any source of visible light is perceived by a human observer to be equivalent to a mixture of white light and light of a single wavelength. This single wavelength is called the dominant wavelength. The relative amount of the single-wavelength light in the mixture is called the purity. I have chosen to use the CIE standard illuminant D_{65} for the white-light (achromatic) source needed to compute the dominant wavelength and purity. Here D_{65} represents an approximation to the mixture of direct solar radiation and diffuse skylight that illuminates surfaces near the ground. It is the primary CIE standard daylight illuminant and is represented by *. Obviously, if one were to select a different standard for a white light (e.g., CIE Standard Illuminant A), the dominant wavelength and purity would change. However, to facilitate comparisons or to determine sensitivities to changes, a standard must be chosen for the purposes of computing the colorimetric quantities. In this case, D_{65} is the best CIE standard that represents the perceived color ''white'' from daylight.

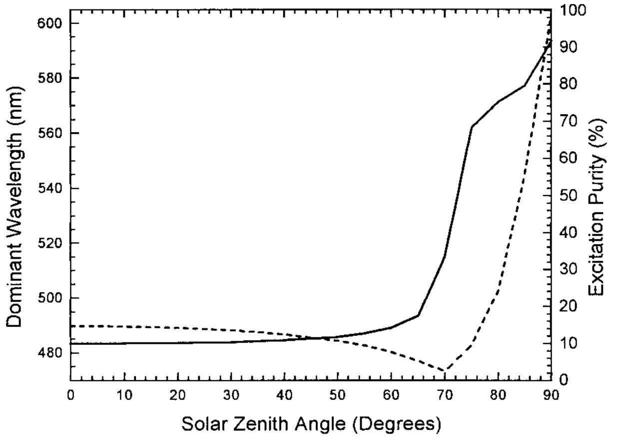

FIG. 3. The variation in the dominant wavelength (solid) and excitation purity (dashed) with solar zenith angle for a distance to the storm of 45 km using the Fraser theory. A black cloud background is assumed.

Fraser's calculations were shown at only one solar zenith angle and one distance to a storm. To evaluate the theory further, I included various solar zenith angles and distances to the storm. Figure 3, not shown by Fraser, indicates how the purity and dominant wavelength change with solar zenith angle for a constant distance (45 km) to the storm. For small zenith angles, the light received by the observer is blue, indicating that the sunlight has not been sufficiently reddened by the atmosphere to create any color other than blue when the light is scattered by the atmospheric molecules. The purity and dominant wavelength vary slightly for zenith angles less than about 65°. As the zenith angle approaches 70°, the purity decreases to a minimum and

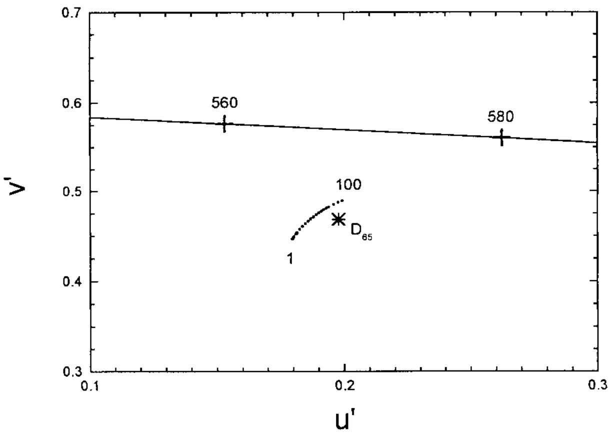

FIG. 4. CIE 1976 UCS chromaticity diagram showing the variation of chromaticity with distance to the storm for a solar zenith angle of 70° using the Fraser theory. A black cloud background is assumed. The numbers indicated next to the plotted points represent distance to the storm in kilometers.

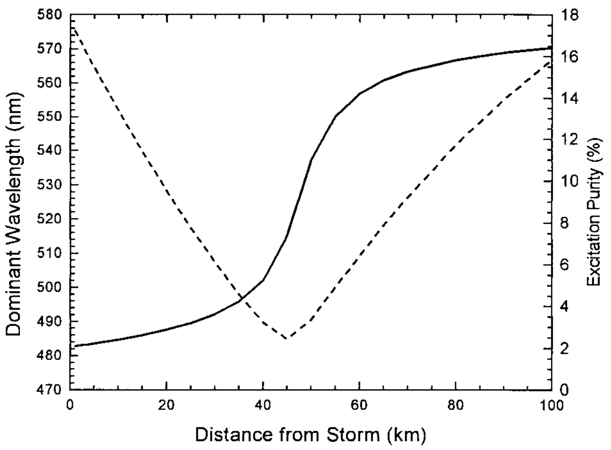

FIG. 5. The variation in the dominant wavelength (solid) and excitation purity (dashed) with distance to the storm for a solar zenith angle of 70° using the Fraser theory. A black cloud background is assumed.

the dominant wavelength increases rapidly toward the red part of the spectrum. If green is assumed to be represented by a wavelength band centered near 515 nm, then this figure indicates that a spectrum with dominant wavelengths in the green region is also associated with very low (almost zero) purity. This result suggests that if a green sky were to occur as a result of the process described by the Fraser theory, the purity would likely be so low that a person with normal vision might not be able to discern a color. As the solar zenith angle increases beyond 80°, the optical thickness increases such that the sunlight is too red for the formation of any color other than red light to be seen by the observer.

The dominant wavelength also varies with distance to the storm, given a particular solar zenith angle. From the results above, a solar zenith angle of 70° was chosen because it yields a dominant wavelength in the green portion of the spectrum. Figure 4 shows a series of spectra plotted as chromaticity points on a CIE 1976 Uniform Chromaticity Scale (UCS) diagram. The solar zenith angle was kept constant at 70°, and the distance to the storm was varied from 1 to 100 km. The dominant wavelengths representing green occur at a distance to the storm between 40 and 50 km. This result also occurs at the minimum in the purity (Fig. 5) again indicating that if the green color does occur as predicted by Fraser the purity would be very low. At large distances from the storm, the dominant wavelength of the observed light is essentially that of the attenuated scattered sunlight.

4. Using a nonblack cloud

Fraser's theory assumes a perfectly black cloud as a backdrop to the airlight being viewed by the observer. Observations of severe thunderstorms show that this assumption is unrealistic. To improve upon Fraser's theory, a nonblack cloud of varying reflectance will be added to the calculation of the observed radiance. This will be called the ''gray-cloud'' approximation, given the typically gray perceived color of thunderstorm clouds. In the daytime, no real cloud is perfectly dark, so the backdrop will never be completely black and will contribute some radiation received by the observer. As an estimate of a typical thunderstorm cloud, an albedo varying from near zero to approximately 40% will be used to represent the light from the cloud. Because a true gray is a nonchromatic color, the reflectance from the cloud will be nonselective in wavelength. The cloud is still colorimetrically achromatic, but the shadowed cloud reflects much less light than a similar cloud directly illuminated by the sun and therefore is perceived as gray rather than white. Figure 6 shows the path of the illumination for the light reflected by the cloud. This path is a significant change to the geometry envisioned by Fraser (Bohren and Fraser 1993) in which he suggested that the main body of the cloud is not illuminated by the sun and is therefore black. The addition of light

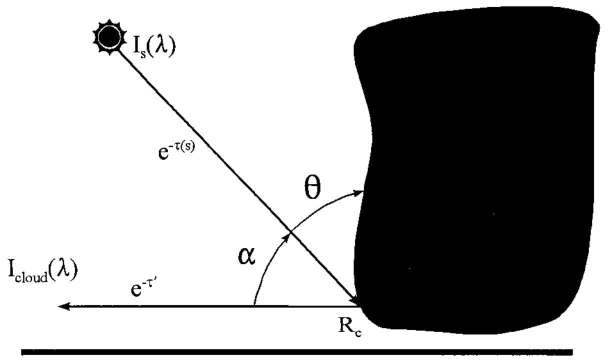

FIG. 6. Geometry of the reflected light from a distant cloud. Here θ is the solar zenith angle and α is the angle between the incident solar radiation and the normal to the cloud.

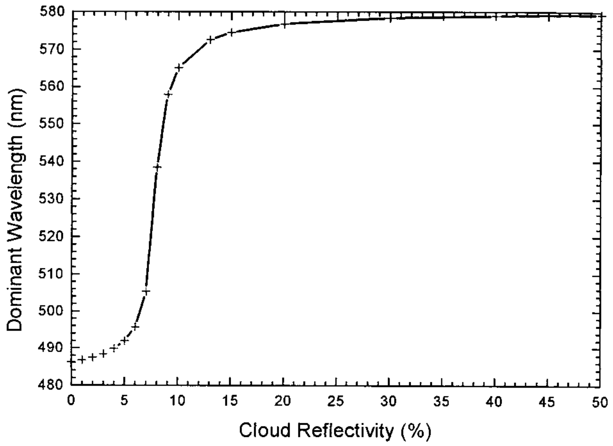

FIG. 7. The variation in dominant wavelength with changes in cloud reflectivity using the Fraser theory. The distance to the storm was fixed at 35 km, the solar zenith angle was 60°, and a molecular atmosphere is assumed for the calculations.

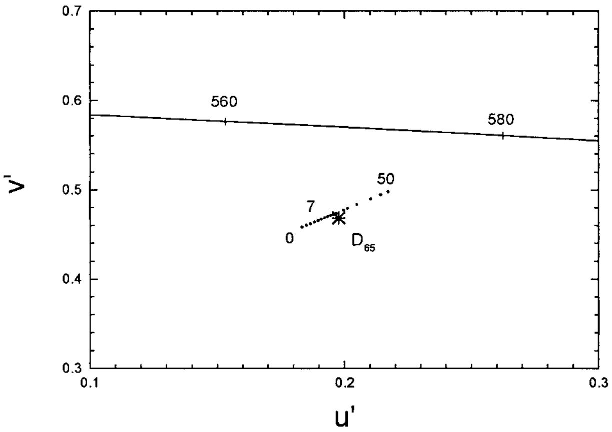

FIG. 8. CIE 1976 UCS diagram showing the variation in chromaticity with changes in cloud reflectivity using the Fraser theory. The distance to the storm was 35 km and the solar zenith angle was 60°. The numbers plotted next to the data points represent the cloud reflectivity in percent.

from the cloud should substantially affect the green-thunderstorm calculations and the perceived color of the storm.

The additional reflected radiation consists of two parts. The incident sunlight illuminating the cloud is represented, as in the previous case, by

$$I_{\lambda_{sg}} = I_{\lambda_s} \exp(-\tau_{\lambda_s}), \qquad (8)$$

Because the viewing angle of the spectrophotometer used to make the radiance measurements is 1°, one can assume that the cloud, over very small observing angles, acts as a diffuse radiator. Therefore, the radiation being scattered by the cloud to the observer through the optical depth of the atmosphere between the cloud and the observer is given by $(2/\pi)(\cos\theta)(e^{-\tau'})$. Combining these effects yields a relationship for the light from the nonblack cloud:

$$I_{\lambda_c} = \left[\frac{R \cos\alpha \exp(-\tau'_{\lambda})}{\pi}\right](I_{\lambda_s}\delta\omega) \exp(-\tau_{\lambda_s}), \qquad (9)$$

where R is the nonselective, diffuse reflectance of the cloud, and $\delta\omega_s$ is the solid angle of the solar disk. The $\cos\alpha$ term represents the angle between the normal to the cloud and the incident sunlight. The reflected light term gets added onto the previously derived equation [Eq. (7)] for I_λ, resulting in the equation for the gray-cloud approximation:

$$\begin{aligned} I_\lambda(p, \mathbf{s}) = {} & \frac{I_{\lambda_s} 3\delta\omega_s}{16\pi}(1 + \cos^2\phi) \exp[-(s_\lambda\beta_1 + s'_\lambda\beta_2)h] \\ & \times [1 - \exp(-s_\lambda d)] + I_{\lambda_s}\left(\frac{R}{\pi}\right) \\ & \times (\delta\omega_s \cos\alpha) \exp[-(s_\lambda\beta_1 + s'_\lambda\beta_2)h - s_\lambda d]. \end{aligned} \qquad (10)$$

The Fraser theory predicts dominant wavelengths in the green region under special circumstances. The calculations including a nonblack cloud show that even a small amount of reflected light from the cloud can overwhelm the light scattered by the atmosphere. The dominant wavelength of the observed radiation was computed for various values of R using a distance to the storm of 35 km and a solar zenith angle of 60°. As shown in Fig. 7, the inclusion of a reflective cloud leads to an increase in the dominant wavelength. The dominant wavelength increases slowly for reflectivities below 5%. When the reflectivity increases beyond 6%, the dominant wavelength increases rapidly. With a cloud reflectivity of 8%, the reflected light from the cloud overpowers the airlight, and the dominant wavelength approaches that of the incident solar radiation. For this particular example, there is a small range of cloud reflectance that causes the dominant wavelength to fall in the green region of the spectrum. If the reflectivities are changed by no more than 1% from the value of ''maximum green,'' the dominant wavelength shifts out of the green region of the spectrum.

In Fig. 8, the spectral data are plotted on a CIE 1976 UCS chromaticity diagram and the reflectivities, in percent, are shown next to the plotted data. Although most of the data points are very close to the achromatic point, the spectra near 0% reflectivity would appear as a dull blue, and the spectra near 50% reflectivity would appear as a dull red. In between, where the green color is predicted, the chromaticity point of the spectrum is very close to the achromatic point and the observed light would most likely be perceived as white or gray.

5. Observations

The test of any theory is to compare the calculations with observations. Let us compare the calculated results of the Fraser theory and the gray-cloud approximation

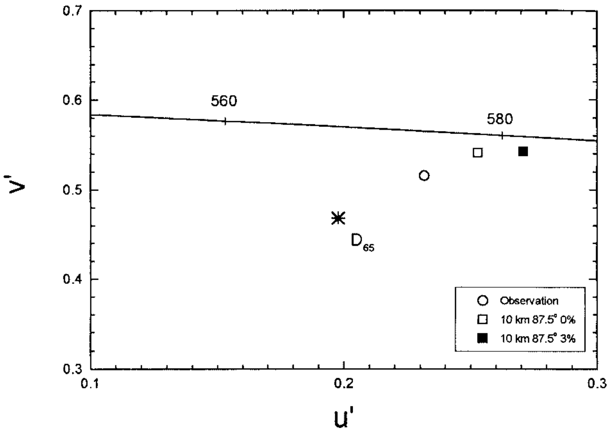

FIG. 9. CIE 1976 UCS chromaticity diagram showing an observation (○) compared with a Fraser theory calculation (□) and a 3% gray-cloud calculation (■). All calculations were performed with a solar zenith angle of 87.5°. The observation was recorded 8 km west of Walters, OK, at 0046 UTC 17 Apr 1995. The view was to the east.

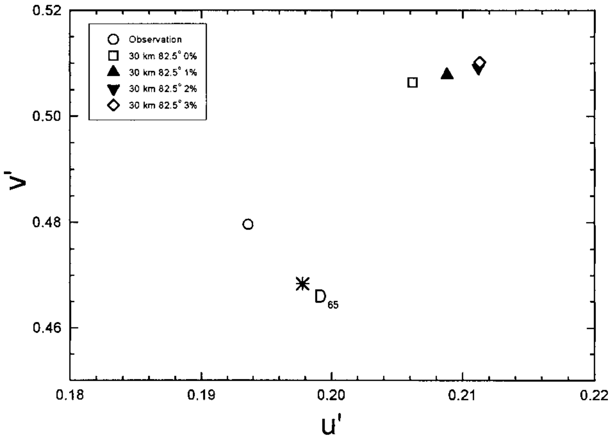

FIG. 10. CIE 1976 UCS chromaticity diagram showing the Ocala, FL, observation (○) compared with one Fraser theory calculation (□), and three gray-cloud calculations with the following reflectivities: 1% (▲), 2% (▼), and 3% (◇). All calculations were performed with a solar zenith angle of 82.5°. The observation was recorded in Ocala, FL, at 2239 UTC 24 Jul 1995. The view was to the south-southeast.

to an observation. A strong thunderstorm had moved to the east, and the skies were clearing to the west, allowing the setting sun to illuminate the atmosphere to the east, a view that most closely matches the Fraser theory configuration.

The spectral data were recorded at 0046 UTC 17 April 1995 approximately 0.6 km north of exit 14 on Interstate Highway 44 in southwestern Oklahoma. The approximate position of the storm was 10 km to the east of the observer, and the solar zenith angle was approximately 87.5°. Figure 9 shows three spectra (Fraser theory and 3% gray-cloud approximation at a distance of 10 km, and the observation) plotted on a CIE 1976 UCS chromaticity diagram. All of the dominant wavelength calculations are reasonably close to the observation, but the best one is the Fraser (black cloud) calculation. This calculation results in a dominant wavelength of 580.7 nm and a purity of 76.1%. The sky color would most likely appear as a highly saturated yellow. The observation recorded a dominant wavelength of 580.2 nm and a purity of 46.7%, and observers reported the sky color as bright yellow-white. This description corresponds well with the recorded spectra. In this example, the atmosphere is modeled best by the Fraser simulation, although all model calculations predict the observed dominant wavelengths relatively well.

A second example occurred when a storm moved to the east-southeast of the observer's location at 2239 UTC 24 July 1995 in Ocala, Florida. The sky appeared to be dark gray to the observer, and there was no observed precipitation between the cloud and the observer. In this example, with no rain falling between the observer and the cloud, none of the approximations matched the observation. Figure 10 shows a closeup of the CIE diagram on which the data are plotted. None of the approximations estimated the observed dominant wavelength to within 10 nm.

As has been seen previously, the Fraser theory can produce a green light, albeit of very low purities, for solar zenith angles of approximately 70°. The high solar zenith angle of these two examples suggests that the green light cannot be created by the Fraser method near sunrise or sunset. The addition of a nonblack cloud as a background worsens the situation because substantially reddened light is being reflected by the clouds, and hence the dominant wavelengths predicted by the gray-cloud approximations were higher (redder) than for the Fraser calculations. Most observations of green light from thunderstorms are when the thunderstorm is very near. These calculations show that a large distance to the storm and the proper solar zenith angle are required to produce the green light.

6. Another perspective on the Fraser theory

Many observers have noted that the sky near the horizon, around the time of sunset or sunrise, can take on a somewhat greenish cast. Often, the color is described as a very pale blue or a light green. Fraser's theory may give some insight into this observation. Meinel and Meinel (1983) state that a ''sulfurous green'' is seen to the west between the time of sunset and nighttime. The spectrophotometer is unable to measure such feeble sources of light that Meinel and Meinel suggest is green, but it can measure the greenish coloration of the sky before sunset. Minnaert (1954) states that a mechanism similar to the Fraser theory (see Bohren and Fraser 1993, their Fig. 11) is responsible for ''the lovely green seen in the color of the sky at times.'' To test this common optical phenomenon, a spectrum was recorded at 2354 UTC 21 June 1995 approximately 1 km north of Otis, Colorado, looking to the east. The very weak greenish-

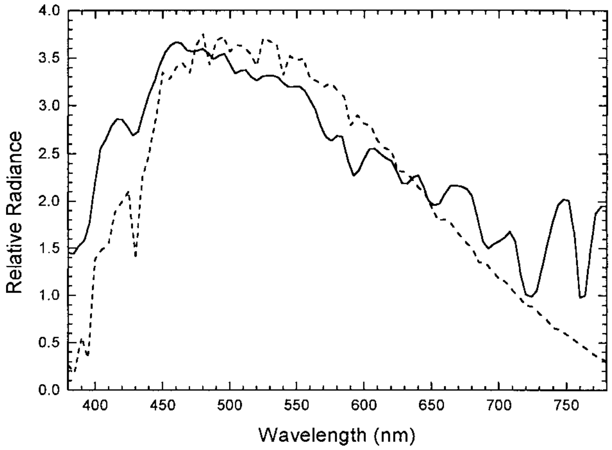

FIG. 11. Comparison of an observation (solid) with a calculated spectrum (dotted) using the Fraser theory. The calculated spectrum is scaled in amplitude to match the measurement. The observation is of a greenish-blue patch of sky looking to the east recorded at 2354 UTC 21 Jun 1995 1 km north of Otis, CO. The observed dominant wavelength is 493.7 nm, and the purity is 3.7%. The calculated spectrum was created using a distance to the storm of 40 km and a solar zenith angle of 63°.

blue color was observed through breaks in some dark clouds approximately 5° above the horizon. The dominant wavelength of the measured spectrum was 493.7 nm, with a purity of 3.68%. This wavelength corresponds to what most people would perceive as a very pale bluish green. Earlier it was mentioned that colors with low purities are difficult to differentiate from white (or gray). In those situations, the assumption was made that the entire cloud had the same color, so there was no contrast with any other color nearby. Therefore, distinguishing a weak color from gray is difficult to do. In the example of the Otis, Colorado, spectrum, the sampled light was juxtaposed with dark gray clouds. Because humans can match colors well and are able to notice small differences in adjacent colors, a high-contrast scene will allow the observer to distinguish colors at lower purity levels than under low-contrast situations. Even at a purity of less than 4%, the observer could tell (approximately) the color of the patch of clear sky between the clouds.

To test the applicability of the Fraser theory in this example, a spectrum was computed that would result from sunlight scattered by molecules in the atmosphere. I assume that the airlight observation path is extremely long and that space acts as the black backdrop instead of a distant thunderstorm. The simulated spectrum was then created by computing the airlight using the equations of the Fraser theory [Eq. (7)]. The measured spectrum (from Otis, Colorado) and the computed spectrum are shown in Fig. 11. Although the computed spectrum was adjusted in magnitude to make it fit the observed data, the shape of the two curves is remarkably similar. The dominant wavelength of the computed spectrum is 489.1 nm, with a purity of 7.8%. This result is in very good agreement with the observed data. This simple example demonstrates that, under appropriate circumstances and even with relatively crude approximations, the Fraser theory does capture the essential features necessary to explain the green color. In almost every case when this mechanism is operating, the purity of the green color is low, indicating a very weak observed color. The Fraser theory can create a weak green color by the combination of the process of sunlight, reddened by the atmosphere, and the process of scattering of the sunlight by the molecules in the atmosphere. The colors are muted or entirely erased by the presence of a background reflector. In nature, this color can sometimes be seen when no thunderstorms are nearby. Often, the green color is masked by stronger background colors and is very difficult to see. This fact may be the reason that green color, under circumstances required by the Fraser theory mechanism, is rarely seen.

7. Summary

The theoretical development presented by Fraser (1978) can produce a spectrum that would be perceived as a very faint green light, assuming a perfectly black background thunderstorm. Introduction of a more realistic slightly reflecting gray background shifts the dominant wavelengths away from the green region of the spectrum. The Fraser theory, with the original black background or the modified gray background, matches fairly well the two spectra observed for examples shown here, neither of which was green. Thus the Fraser theory does predict the observed spectra in certain instances. Introducing a slightly reflective background tends to shift the dominant wavelengths away from the green region. Though technically the Fraser theory can explain a dominant wavelength in the green spectral region under a very narrow set of circumstances, the purity would likely be very low. Observers might not be able to perceive the green color.

Many relatively crude approximations have been employed to enable a rough comparison between calculations using Fraser's theory and some suitable observations. Nevertheless, the results show that the Fraser theory can account for the perceived color of light in the atmosphere under narrowly specified conditions. These results also show that the Fraser theory probably does not account for the relatively frequent observations of green color from thunderstorms in the U.S. Great Plains.

Acknowledgments. This research was supported by a grant from the Physical Meteorology Program, National Science Foundation (NSF) Grant ATM-9400208. Contributions to this work were made by Professors William Beasley of the University of Oklahoma and Craig Bohren of The Pennsylvania State University. The author thanks Erik Rasmussen and Jerry Straka for allowing him to pursue this research in conjunction with project

VORTEX. Much of the vehicle support for VORTEX was provided by the Center for Analysis and Prediction of Storms under NSF Grant ATM-9120009. Additional vehicle support and guidance were provided by the National Severe Storms Laboratory in Norman, Oklahoma.

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