Ground Reflections and Green Thunderstorms

FRANK W. GALLAGHER III

School of Meteorology, University of Oklahoma, Norman, Oklahoma

(Manuscript received 1 May 2000, in final form 4 September 2000)

ABSTRACT

It has been suggested that green light often observed in association with severe thunderstorms is caused by sunlight being reflected onto the cloud by green vegetation. Colorimetric observations were recorded of green-colored and blue-colored thunderstorms in conjunction with spectral measurements of the light reflected by the ground beneath the storms. Simple numerical models were used to evaluate the likelihood of ground-reflected light causing the green color in storms. Both the observations and calculations indicate that the green light seen in severe thunderstorms is not caused by light reflected from green foliage.

1. Introduction

Among those who do not discount observations of green thunderstorms completely, some people believe that the green light associated with some severe thunderstorms is directly attributable to reflection by green vegetation. Assertions about the reflection of light by green vegetation are usually not accompanied by physical reasoning or quantitative supporting arguments. The best arguments seem to involve a discussion about direct or diffuse sunlight reflected by green foliage to the bottom of a large thunderstorm. The bottom of the thunderstorm then reflects this green light to the ground-based observer. Freier (1992) has presented an example of this type of thought:

> These storm clouds are very tall, dense clouds, so that absolutely no direct sunlight gets through. Everything gets very dark, but there must be some light because you can still see. I think that most of this dim light is reflected from green foliage on the earth's surface to the cloud. . . . Plants absorb red and blue light, and reflect any green light. When the light is dim, they also orient their leaves and chloroplasts in the leaves to reflect additional green light. Reflected green light becomes the primary source of illumination for seeing the sky with its dark clouds.

Bohren and Fraser (1993) refute this type of thinking with some elementary arguments. They consider observations as a weapon against the notion that light reflected off the ground is intense enough to make a significant contribution such that green color is seen in the light from the cloud base. Bohren and Fraser also ask the contradictory question: Why are not all thunderstorms green when they pass over a large region of green vegetation? Given the previous statement by Freier, we would expect all deeply convective thunderstorms to appear to be green when passing over large expanses of green vegetation. Observations and spectral measurements of the color of light from the cloud base of severe thunderstorms (Gallagher et al. 1996) do not support the hypothesis that the green color is sunlight reflected by the ground. For example, green thunderstorms have been observed for an extended period of time over terrain that was anything but green (Gallagher et al. 1996).

In this study, I concentrate only on the problem of whether light reflected by the ground can cause the green color observed in some thunderstorms. To do so, simple conceptual and analytical models will be used to describe quantitatively the spectrum and radiance of the light that would reach an observer's eyes looking at the light from underneath a large thunderstorm. Observational data will be used to verify the models and to help to confirm the results.

2. Theoretical development

For simplicity, I shall construct my simplest argument around a nonabsorbing, nonscattering atmosphere that contains a horizontally homogeneous cloud that is infinite in lateral extent. The light transmitted through the cloud then uniformly illuminates the homogeneous ground below the cloud. Furthermore, I shall assume that the transmissivity and reflectivity functions are spectrally nonselective. Given these assumptions, Bohren and Fraser (1993) derived a simple equation that

Corresponding author address: Frank W. Gallagher, III, School of Meteorology, University of Oklahoma, Sarkeys Energy Center, 100 East Boyd, Suite 1310, Norman, OK 73019.
E-mail: fgallag@rossby.metr.ou.edu

relates the observed radiance L_{obs} to the incident solar radiance L_s. If a thick cloud is assumed, then essentially all of the incident solar radiation is reflected ($T_c \ll 1$, $R_c \approx 1$; see appendix for definitions) and only a small amount of diffuse light penetrates the cloud. The surface absorbs a significant portion of the incident light, so the reflectivity of light off the ground is small ($R_g \ll 1$). The resulting equation can be written as

$$\frac{L_{obs}}{L_s} = \frac{T_c}{1 - R_c R_g} \approx T_c(1 + R_g). \qquad (1)$$

This equation tells us that the ratio of the radiance observed to be coming from cloud base to the incident solar radiation is a function of the cloud transmissivity and the ground reflectivity only.

To determine the effectiveness of green grass contributing to the light seen by the observer, we need to know the value of R_g. Wyszecki and Stiles (1982) show a figure of spectral reflectance curves, from data published by Krinov (1953), of various substances, including green grass. The maximum reflectivity in the visible portion of the spectrum for green grass is 0.2 and occurs only in a narrow spectral bandwidth centered near 555 nm. As Bohren and Fraser (1993) conclude, the contribution to the total radiation received by an observer is only slightly modified by reflections from the ground [Eq. (1)]. For typical foliage reflectivities, the radiance from the cloud that includes the light reflected from the ground is on the order of 25% higher than the cloud radiance without the reflected light. The reflected light is probably noticeable by a human observer when compared with the example of a similar cloud without the ground-reflected light. If one wants to capture the fine details of the spectrum, then a much better radiation model would be needed to compute more realistically the reflected light from the cloud base.

3. Simple radiation model

To keep the computations simple, I shall construct this model assuming a nonabsorbing atmosphere that consists only of molecules. I do this to isolate the property of ground reflection to see if there is any similarity between the calculations and observations. Figure 1 shows the geometry of the problem in which the cloud is optically thick and is infinite in horizontal extent. As shown, the observer is on the ground and is looking up at the cloud base. Using an integrated version of the Schwarzchild equation (e.g., Liou 1980) one can write the equation of radiative transfer as

$$I_\lambda(p, \bar{s}) = I_\lambda(p'', \bar{s})e^{-\tau'_\lambda} + \int_0^{\tau'_\lambda} J_\lambda(p', \bar{s})e^{-(\tau'_\lambda - \tau_\lambda)}\, d\tau_\lambda, \qquad (2)$$

where $I_\lambda(p, \bar{s})$ is the radiance at point p along path $\bar{s}$ that is received by the observer. The radiance has two

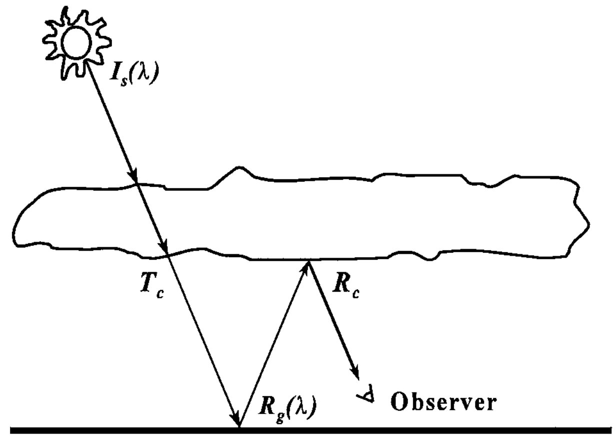

FIG. 1. Schematic representing the geometry of the nonabsorbing ground reflection problem. Here, T_c and R_c are the transmissivity and reflectivity of the cloud, R_g is the spectral reflectance of the ground, and I_s is the spectral solar radiance.

sources: the first is sunlight $[I_\lambda(p'', \bar{s})]$, attenuated by optical depth τ'_λ, and the second is the sum of all of the light scattered to the observer along the observer's line of sight $[J_\lambda(p', \bar{s})]$, attenuated by optical depth. In this analysis, I needed to consider both the light directly from the sun and the light reflected by the ground and then reflected again by the base of the cloud. To simplify the calculation of the optical depths, I assume an atmosphere composed primarily of molecular scatterers and exclude any type of precipitation. I can then write the optical depth between the sun and the cloud as

$$\tau_{\lambda_s} = (s_\lambda \beta_1 + s'_\lambda \beta_2)h, \qquad (3)$$

where s_λ is the scattering coefficient (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). The optical depth between the observer and the cloud base (τ'_λ) can be written as

$$\tau'_\lambda = ds_\lambda, \qquad (4)$$

where d is the distance between the ground and the cloud base and s_λ is the scattering coefficient (m^{-1}). For these calculations, we have assumed a cloud base of 500 m, so only the light scattered by the atmosphere between the cloud base and the ground is included in the $J_\lambda(p', \bar{s})$ source term. To improve upon the Wyszecki and Stiles (1982) spectral reflectivity curve for green grass, a spectrum was recorded of the green foliage underneath a green thunderstorm. Thus, the color of the ground is specified by the spectrum recorded of foliage on 7 May 1995 shown in Fig. 2. The model constraint that the reflecting surfaces are of an infinite extent means that all of the light reflected by the ground falls on the cloud and is then reflected again to the observer. The following equation is used for this model:

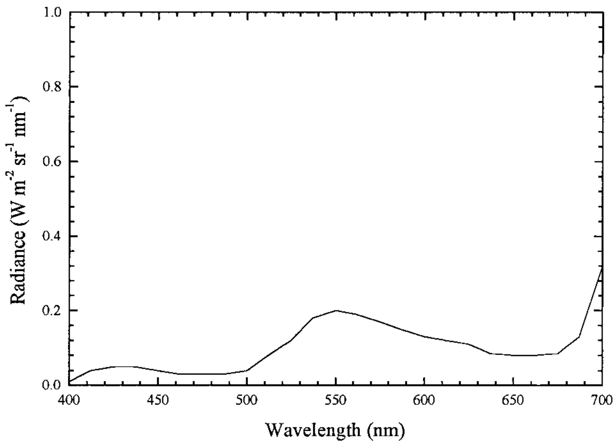

FIG. 2. Spectrum of young wheat growing in a field in Mountain Park, OK. Spectrum was recorded on 7 May 1995 at 2208 UTC looking to the northwest.

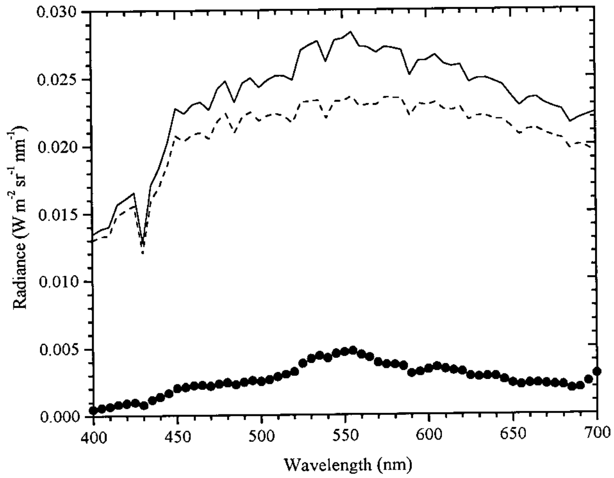

FIG. 3. Computed total radiance (solid), transmitted radiance (dashed), and reflected radiance (dotted). The computed radiance was calculated using a cloud reflectance of 1.0 and a cloud transmission of 10^{-6}. The solar zenith angle was 45°.

$$I_{\text{obs}} = R_c R_{\lambda_g}\left[T_c I_{\lambda_s} e^{-\tau'_\lambda} + \frac{T_c 3\delta\omega_s(1 + \cos^2\theta)}{16\pi} I_{\lambda_s} e^{-\tau_{\lambda_s}}(1 - e^{-\tau'_\lambda})\right] + \left[T_c I_{\lambda_s} e^{-\tau'_\lambda} + \frac{T_c 3\delta\omega_s(1 + \cos^2\theta)}{16\pi} I_{\lambda_s} e^{-\tau_{\lambda_s}}(1 - e^{-\tau'_\lambda})\right]. \quad (5)$$

The first term on the right side represents the light transmitted through the cloud, reflected off the ground, and reflected again off the cloud to the observer. The second term on the right-hand side represents the light transmitted by the cloud directly to the observer. The observer will view the cloud as the combination of light from both sources. The variables are defined in the appendix. A more detailed development of this equation can be found in Gallagher (1997).

Figure 3 shows three computed radiance curves. A realistic solar spectrum (Neckel and Labs 1984) source was used with the assumption of a solar zenith angle of 45°. The first curve (direct) represents sunlight transmitted by the cloud to the observer. The second curve (CG-reflected) represents radiance transmitted by the cloud then reflected by the ground and then reflected by the cloud to the observer. The third curve represents the total radiance or sum of the previous two radiances. Because cumulonimbus clouds are exceedingly thick, they reflect most of the radiation incident upon them in the visual spectrum. To ensure that all of the light reflected by the cloud is a maximum, the cloud-bottom reflectivity R_c in the model was set to 1.0. Furthermore, to simulate a very thick cumulonimbus cloud, the cloud transmissivity T_c was set to 1.0×10^{-6}. Figure 3 indicates that the transmitted radiance is still an order of magnitude greater than the CG-reflected radiance at nearly all wavelengths. Although the model cloud base reflects all of the upwelling visible radiation, the effects of the CG-reflected light are still small as compared with the transmitted light. The question is, although the light reflected by the ground and then by the cloud influences the overall radiance received by the observer, does it alter the color perceived by the observer? We must now consider the colorimetric properties of the light seen by a person on the ground.

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 and the relative amount of the single wavelength light in the mixture is called the purity. Together, the dominant wavelength and purity are a set of values that represent the color that a normal human observer would perceive. Furthermore, an individual spectrum can be represented on a color space (chromaticity) diagram by a pair of chromaticity coordinates (u', v'). The coordinates are arrived at by integrating the spectral power of the observed radiance multiplied by three color-matching functions over wavelength (Wyszecki and Stiles 1982). The Commission Internationale de l'Eclairage (CIE) standard illuminant D_{65} was chosen for the white light (achromatic) source needed to compute the dominant wavelength and purity. The D_{65} standard 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 * on the CIE diagram. 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 determine sensitivities to changes, a standard must be chosen for the purposes of computing the colorimetric quantities. Also, D_{65} is the best CIE standard that represents the perceived color ''white'' from daylight.

The computed dominant wavelengths for each of the three curves in Fig. 3 all indicate that a normal observer would perceive a faint orange–yellow color. The dominant wavelengths for the three radiative components are: transmitted (direct) = 579.1 nm, CG-reflected = 572.1 nm, and total = 577.4 nm. For normal brightness levels and a 1° field of view, Bedford and Wyszecki (1958) show that a typical human observer can discern a difference of greater than 4 nm in wavelength under laboratory conditions across most of the visible spectrum. In a thunderstorm environment, where there is no reference color to base a comparison, one would need a much larger change in dominant wavelength to discern a color shift. However, I have assumed that a 4-nm difference in dominant wavelength represents a just barely perceptible difference in color to the observer.

Using this simple radiation model with a solar zenith angle of 45°, I find that the difference in the dominant wavelength between the transmitted radiance and the total radiance is about 3 times smaller than the difference between the CG-reflected radiance and the total radiance. The dominant wavelength of the total radiance is shifted slightly toward that of the CG-reflected radiance, indicating a possible small bias toward the CG-reflected radiance. Given the previous definition of just barely perceptible difference in color, the observers would be unlikely to be able to detect the change in dominant wavelength between the transmitted-only light and the transmitted-plus-CG-reflected light assuming the two light sources could be placed adjacent to each other. This comparison cannot be done in the environment, so the likelihood of being able to detect a color difference is even more remote. The perceived color would most likely not be the awe-inspiring green color often associated with severe weather (Bohren and Fraser 1993).

Because most green thunderstorms are observed near sunset (Gallagher 1997), a second calculation, with the solar zenith angle set to 85°, is shown in Fig. 4. As before, the cloud-base reflectivity was fixed at 1.0 and the cloud transmissivity was 10^{-6}. The reflected radiance adds less than 10% to the total radiance, except for the near IR spectral band. Given that the setting sun is the only light source in the model, the contribution of green light from the ground to the observed color is almost negligible; there is little effect on the colorimetric properties of the spectrum. The dominant wavelengths of all three radiative components (direct = 582.7 nm, CG-reflected = 579.3 nm, and total = 582.2 nm) are closer to each other than in the 45° example. The transmitted (direct) dominant wavelength is closer to the total-radiance dominant wavelength than is the CG-reflected dominant wavelength. Figure 5 shows the three spectra plotted on a CIE chromaticity diagram. The transmitted (×) and total (○) chromaticity points nearly overlap. As expected, the reflected (□) chromaticity point is slightly greener and somewhat more pure than the other two.

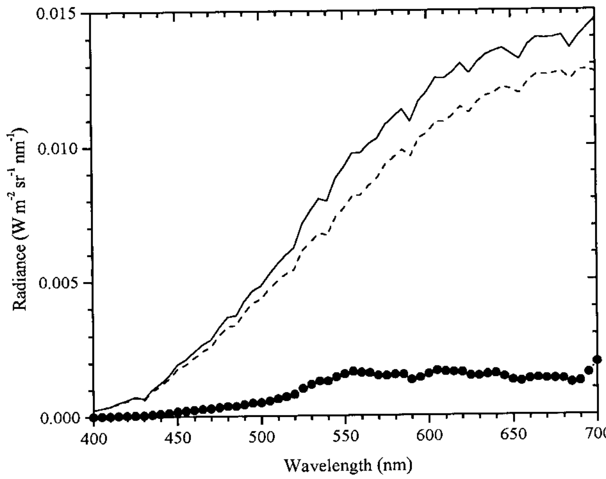

FIG. 4. Computed total radiance (solid), transmitted radiance (dashed), and reflected radiance (dotted) with no solid angle dependence, calculated using a cloud reflectance of 1.0 and a cloud transmission of 10^{-6}. The solar zenith angle was 85°.

The high purities are an artifact of the simplicity of the model. To obtain a lower purity, one must mix white light with the spectral color. This model makes no attempt to do so. The incident light source, a realistic solar spectrum (Neckel and Labs 1984) with a solar zenith angle of 85°, has a high purity. Because the light incident upon the cloud is a very pure light source and we do not add any white light, the light transmitted through the cloud will also have a high purity. The purity is not what is important in this analysis; rather, the dominant wavelength is the most critical parameter. The light from the setting sun, reflected off of a green surface, will have little effect on the perceived color of light emanating from the base of the cloud.

As a check to see if any of these calculations simulate a real storm with any accuracy, a green thunderstorm observation (■) is plotted on the same chart. The green thunderstorm observation is very close to the achromatic point and is not representative of either the model-simulated transmitted or the CG-reflected light. The model puts severe constraints, such as nonabsorption, on the nature of the transmitted light; however, the computed CG-reflected light is depicted more realistically. The grass beneath the storm had a dominant wavelength of 572.6 nm, whereas the CG-reflected light had a dominant wavelength of 579.3 nm. The redder dominant wavelength is attributable to the reddened light source of the sun at a solar zenith angle of 85°. This exercise has shown that, even using a realistic spectral ground reflectivity and a perfectly reflecting cloud, the colorimetric contributions of the CG-reflected light to the overall radiance are small and have essentially no effect on the appearance of the green light in thunderstorms.

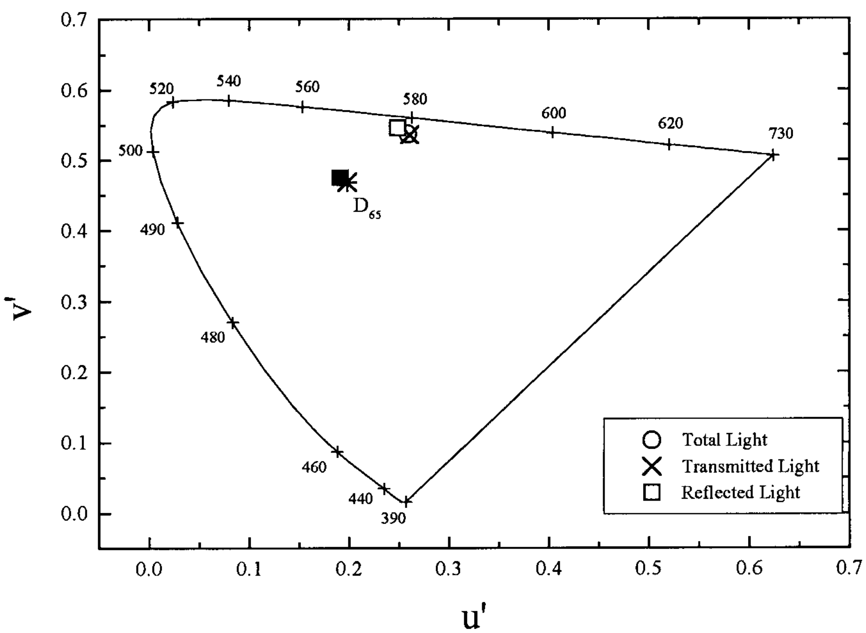

FIG. 5. CIE 1976 Uniform Chromaticity Scale diagram showing the three computed spectra: (○) total light observed, (×) transmitted light, and (□) reflected light. The D_{65} achromatic point is represented by * on the CIE diagram. For comparison, a measurement of a green thunderstorm is shown (■). The computed data were for a solar zenith angle of 85°, cloud reflectance of 1.0, cloud transmittance of 10^{-6}, and no solar solid angle dependance. The observation was recorded on 7 May 1995 at 2232 UTC at Mountain Park, OK.

To further build the case against ground reflections, several examples of observational data are offered.

4. Observational data

To make some relevant quantitative observations, spectra of ground cover in the vicinities of green and nongreen thunderstorms were recorded. All of the measurements made of the ground were at the ground.

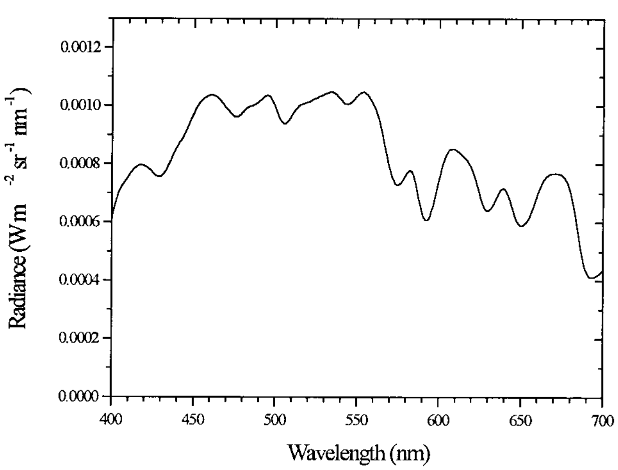

FIG. 6. Spectrum of a green thunderstorm recorded on 7 May 1995 at 2231 UTC 16 km east-southeast of Mountain Park, OK. The view is to the north.

Therefore, the data we collected were representative not of the entire surface beneath the storm but, rather, of a point measurement at the observation position. This does not invalidate my argument. For instance, a spectrum (Fig. 2) of light reflected by the foliage beneath the approaching storm was recorded. This spectrum was chosen as a best-case example of a green surface beneath the storm, because it consisted of a mature wheat crop brightly illuminated by sunlight passing through a thin overcast to the southeast. In actuality, the ground beneath the entire storm was not uniform wheat; it was a mixture of green fields, plowed fields, and mixed residential and commercial property. Any of the nongreen surface color would certainly not contribute to any green coloration of the clouds assuming that the base of the cloud is illuminated by light reflected by the ground. Let us, for a best case scenario, consider the entire surface beneath the storm to be that represented by the green surface spectrum shown in Fig. 2. If the dominant wavelength of the thunderstorm, when it was green, was approximately that of the ground, one could then argue that light from the ground was a possible contributor to the green coloration of some storms. This result was not found in the data. The radiance maximum (with respect to wavelength) in the recorded spectrum of the ground occurred at 552 nm, and the dominant wavelength was 572.6 nm. Both agree with the subjective observation of the wheat color, yellow–green.

A spectrum of a green thunderstorm (Fig. 6) was

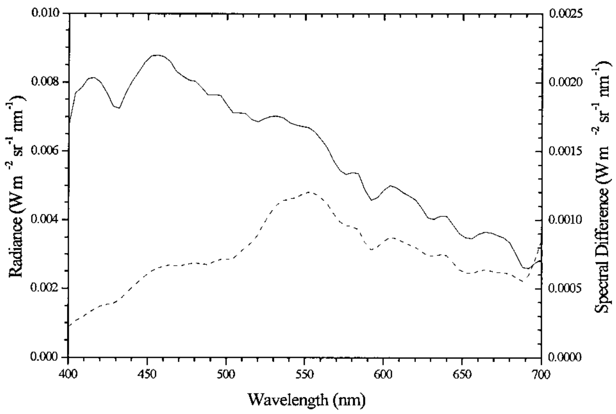

FIG. 7. A comparison of the spectrum of foliage underneath a green thunderstorm (dotted) to a difference spectrum derived from subtracting a green storm spectrum from a blue thunderstorm spectrum (solid). The peak in the difference spectrum does not match the peak in the foliage spectrum.

recorded less than a half-hour later from a position approximately 16 km to the southeast of the location where the foliage spectrum was recorded. By the time the green storm spectrum was recorded, the storm had moved into a position near the site of the green foliage spectrum. Figure 7 shows a comparison of the two light sources. The first spectrum, that of the green foliage, peaks near 550 nm, the same spectral maximum indicated by Wyszecki and Stiles (1982) for green grass. The second curve represents the difference in the green thunderstorm spectrum and a typical blue–gray thunderstorm spectrum. The spectrum of the blue-colored storm was recorded at 2206 UTC in Mountain Park, Oklahoma. The green-colored storm was recorded at 2232 UTC approximately 16 km to the east-southeast of Mountain Park. The difference spectrum shows a maximum (456 nm) in the spectral response at the shorter wavelengths, not in the wavelengths representative of the green surface. If ground reflection, in the ideal case of a carpet of green under the cloud, were the cause of the green color in this example, one would expect the difference spectrum to be at a maximum near 550 nm, at the maximum of the ground reflection curve. I have not observed this to be true.

There is no evidence in the difference spectrum indicating any influence from the ground, green or otherwise. With this one observation I cannot rule out the possibility that, in some cases, reflection of light by vegetation may be important, but it does not seem to be the cause for the shift toward the green in this example. Furthermore, Bohren and Fraser (1993) cite reports of green thunderstorms over ground that was definitely not green. Therefore, reflection by a green surface is not necessary for a thunderstorm to appear to be green.

5. Summary

The problem of ground reflection has been investigated from three different perspectives. The first was a simple radiance argument that resulted in a ratio of the observed radiance to the incident radiance. By including a bulk reflectivity for the ground ($R_g = 0.2$) and the cloud base ($R_c = 1.0$) the resulting ratio of observed radiance to the solar radiance was only slightly larger than the transmissivity of the cloud. According to this simple model, the increase in radiance with the addition of CG-reflected light is at most 25% when compared with the radiance observed without CG reflection. This result indicates that, for this single calculation, the light reflected by the cloud could possibly contribute to green thunderstorms.

A slightly more complex model was created to test the validity of the importance of ground reflections. The model results indicate that the radiance of the CG-reflected light is at least an order of magnitude less than the transmitted light. Also, the most significant contributions of the CG-reflected light occur in the near-IR spectral region, a region in which the human eye is insensitive to radiation. Last, the presentation of several measurements of the light from a green thunderstorm and the light from green foliage underneath a green thunderstorm indicates that the visible spectral maxima of the two green lights do not coincide, indicating that, in the portion of the spectrum where human color vision is operating, the effects of ground reflection are minimal and light from the ground does not create the green light in green thunderstorms.

Acknowledgments. This research was supported under National Science Foundation (NSF) Grant ATM-9400208 from the Physical Meteorology Program, Division of Atmospheric Sciences. Contributions to and critical reviews of this work were made by Drs. William Beasley of the University of Oklahoma and Craig Bohren of The Pennsylvania State University. The author wishes to thank Erik Rasmussen and Jerry Straka for allowing me to pursue this research in conjunction with project VORTEX and Todd Crawford for his careful examination of this manuscript. 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.

APPENDIX

List of Symbols in Eq. (5)

I_{obs} Observed radiance
R_c Cloud reflectivity
$R_{\lambda g}$ Spectral ground reflectance
T_c Cloud transmissivity
$I_{\lambda s}$ Solar radiance at the top of the atmosphere

τ'_λ Optical depth from the observer to the storm
$\delta\omega_s$ Solid angle subtended by the sun
θ Solar zenith angle
$\tau_{\lambda s}$ Optical depth of the path between the sun and the earth's surface

REFERENCES

Bedford, R. E., and G. Wyszecki, 1958: Wavelength discrimination for point sources. *J. Opt. Soc. Amer.,* **48,** 129–135.

Bohren, C. F., and A. B. Fraser, 1993: Green thunderstorms. *Bull. Amer. Meteor. Soc.,* **74,** 2185–2193.

Burrows, J. P., A. Richter, A. Dehn, and B. Deters, 1999: Atmospheric remote-sensing reference data from GOME-2. Temperature dependent absorption cross sections of O_3 in the 231–794 nm range. *J. Quant. Spectrosc. Radiat. Transfer,* **61,** 509–517.

Freier, G. D., 1992: *Weather Proverbs.* Fisher Books, 214 pp.

Gallagher, F. W., III, 1997: Green thunderstorms. Ph.D. dissertation, University of Oklahoma, Norman, Oklahoma, 248 pp. [Available from UMI, 300 N. Zeeb Rd., Ann Arbor, MI 48106-1346.]

——, W. H. Beasley, and C. F. Bohren, 1996: Green thunderstorms observed. *Bull. Amer. Meteor. Soc.,* **77,** 2889–2897.

Kasten, F., and A. T. Young, 1989: Revised optical air mass tables and approximation formula. *Appl. Opt.,* **28,** 4735–4738.

Kondratyev, K. Ya., 1969: *Radiation in the Atmosphere.* Academic Press, 912 pp.

Krinov, E. L., 1953: Spectral properties of natural formations. Technical Translation TT-439, National Research Council of Canada, Ottawa, Canada, 268 pp.

Liou, K. N., 1980: *An Introduction to Atmospheric Radiation.* Academic Press, 392 pp.

Neckel, H., and D. Labs, 1984: The solar radiation between 3300 and 12500 Å. *Sol. Phys.,* **90,** 205–258.

Wyszecki, G., and W. S. Stiles, 1982: *Color Science: Concepts and Methods, Quantitative Data and Formulae.* 2d ed. John Wiley and Sons, 950 pp.